on the application of active open-loop and closed-loop controls on a circular cylinder in the presence and absence of a free surface









On the application of active open-loop and closed-loop controls on a circular cylinder in the presence and absence of a free surface

by.

Gina S. Reid

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School of Graduate Studies Memorial University of Newfoundland St. John's, Newfoundland and Labrador

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② Gina S. Reid

Abstract

This them focusses on the application of active spon-loop and cloud-loop contributes in cortical regimber in the generics and absorb of a few warfsers. For the approximation of the input as a circular clouder of the spon-loop clouder of the spontrans. The input and the spon-loop clouder of the spon-loop clouder times, cer (i) combined streamwise and tanaxees calification, which to its ambries in the sponse of the sponse of the sponse of the sponse of the sponse transverse streamwise and the sponse of the sponse of the sponse of the sponse of the sponse clouder of the sponse of the sponse of the theory of the sponse clouder of the sponse of the sponse of the sponse of the sponse of the clouder sponse of the sponse of t

The matrix is method of the study is hand on the finite-volume discrition in the properlik strangel fracts of two-dimensional control matrix point studies. We derived the properlik strangel fracts of two-dimensional control matrix points and simulations are conducted at a Hypericki semilor of H = 200, for the Froster transtic strange of the strange of the strange of the strange of the h = 0.35, $h \leq 0.35$. The flow characteristics are examined for a maximum excellation angularity h = 0.31, and (fract or guides conditions) for supervise duration correct definition (hyperbolic conditions) are stranged by the Kondreck-wave strateging of the strange strateging of the strange strateging of the Matrix dimension of the strange strateging of the strange strateging of the strange strateging of the strange strateging and the strange strateging the strange strateging strateging

The results detail the link between the Bf force, equivorticity patterns and the pressure fields which was previously uncharted, and paves the way for understanding the application of active flow control mechanisms on coastal and offshore engineering systems.

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Nomenclature

Α	area open to flow (area aperture)	
đ	acceleration of non-inertial frame of reference, $\tilde{X}, \ \ (= \langle a_1, a_2, 0 \rangle)$	
A	forcing amplitude of the recti-linear cylinder oscillation $\ (=A^*/d)$	
C_L	lift coefficient $(=2L/\rho U^2 d)$	
\hat{C}_L	mean lift coefficient	
$C_{L,rms}$	RMS lift coefficient	
C_D	drag coefficient $(= 2D/\rho U^2 d)$	
\hat{C}_D	mean drag coefficient	
$C_{D,ress}$	RMS drag coefficient	
ď	cylinder diameter	
D	drag force per unit length	
Б	total dimensionless mechanical energy	
1	forcing frequency of the recti-linear cylinder oscillation $\ \ (=df^a/U)$	
fo.	natural vortex shedding frequency (i) in the absence of a free surface (df_0/U
	(ii) in the presence of a free surface $\ (=d f^* _{fs}/U)$	
Fr	Froude number $(=U/\sqrt{dg^2})$	
\vec{F}^{ℓ_0}	dimensional external force $(=(F_1^*,F_2^*,0))$	
9°	dimensional gravitational acceleration in inertial	
	frame of reference, $X = (0, g^*, 0)$	

XXV

h	depth of cylinder submergence $(=h^*/d)$
Δh	spatial uniform grid step size
ĥ.	height of the fluid at the outflow boundary
I	length of a fluid-body interface open to flow
L	lift force per unit length
11	outward unit normal vector $(=(n_1, n_2, 0))$
P	fluid property
p	fluid pressure
R	Reynolds number $(= \rho U d/\mu)$
S	control volume boundary
<i>t</i>	time $(= t^*U/d)$
Δt	time step
T	period of forced cylinder oscillation $(=1/f)$
T_0	period of natural vortex shedding in the absence of a free surface $\ \ (=1/$
ŝ.	fluid velocity $(=(u, v, 0))$
U_{-}	uniform flow velocity
ñ.	maximum s-velocity of the fluid in the region directly above the cylinder
ŝ	average a-velocity of the fluid in the region directly above the cylinder
Ŷ	fractional volume open to flow
V_{-}	control volume

XXVI

V(t)	material volume	
v	volume open to flow (volume aperture)	
$\partial V(t)$	material volume boundary	
v_j^*	dimensional velocity of an arbitrary time dependent fluid domain $\Omega(t)$	
÷	velocity of non-inertial frame of reference, $\widehat{\mathbf{X}}, \ (=(v_1,v_2,0))$	
ž	vector of spatial coordinates in inertial frame of reference, X, $\ \ (= (x,y,0))$	
X	inertial frame of reference $(= \{\vec{x}^*, t^*\})$	
Ñ	non-inertial frame of reference $(=(\hat{T}, \hat{T}))$	
x	frame of reference which moves with the uniform flow	
Greek Symbols		
μ	dynamic viscosity of the fluid	
₽'	kinematic viscosity of the fluid $\ \ (=\mu/\rho)$	
p.	fluid density	
ω*	dimensional frequency of the cylinder oscillation $(=2\pi f^*)$	
Ω	arbitrary fluid domain	
$\Omega_{11}:=1.2$	computational domain occupied by the fluid	
$\partial \Omega$	arbitrary fluid domain boundary	
∇	vector differential operator	
∇^2	Laplace operator	

Superscripts

	dimensional quantity
	differentiation by time
Abbrev	iations

- CFD computational fluid dynamics
- PSD power spectral density
- VOF volume of fluid
- RMS root mean square

1. Introduction

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This thesis forcess on the application of active open-loop and closed-loop controls on a circular cylinder in the presence and absence of a free variance. It examines circular cylinders subject to forced (streamwise or transverse) oscillations (active open-loop), and combined forced streammines and transverse oscillations (active does loop). The primary gaid of this research is to understand the physical mechanisms behind the



Figure 1.1: The twisting original Tacoma Narrows Bridge which collapsed on November 7, 1940 in the U.S. state of Washington - opened on July 1, 1940 (http://en.structume.de/structures/data/bebos.cm/TDa=0000074).

response of a cylinder to these forcing methanism. This is achieved by examing the effect of forced cylinder so-fillation frequency on the near-walk errortraws, and the sumerodistributions field idense at a fast docubication amplitude when the cylinder is placed beneath a free surface. The numerical simulations are carried out using the computational fluid dynamics could developed by Dr. S. Nordshylk's research group at Memorical University of Nordsonfillati.

A basic selement that fluctures the physical problem is shown in Figure 1. The potent model insolutes the shown its the regime $R_{\rm eff}$ with the regime $R_{\rm eff}$ and the eff-antiset $\rho_{\rm eff}$ and inframities the shown in Figure 1. The flucture distantion $\rho_{\rm eff}$ and infraministic three shows in the size of the structure of the right with mattering means and of consistent matters, theorem, beam field by part an outling in the physical method mean structure of the structure of the method means of the size $R_{\rm eff}$ of the size of the structure of the structure of the method means of the size $R_{\rm eff}$ of the size $R_{\rm eff}$ of the size of the size of the size $R_{\rm eff}$ of the framing browpersy of an architesy excludes, f_1^{-1} is the dimensional natural verses balanching browpersy of a maximum exclusion, and r = 1 is the dimensional time. The composition dimensions are accurate of the physical problem are do maximum exclusion magnitude. As r = 1/4 of the browpers variable $r_1 = 1/6$, $r_1 = 1/4$, $r_2 = 1/4$, $d_{1/1}$. Using the dimensional case from inproves of the exclution and trading the starting structures. The physical matter, densities I = 1/(2), and I = 1/(2), dimension I = 1/2, $r_1 = 1/2$, $r_2 = 1/2$,



Figure 1.2: Schematic of the problem.

.2

Following the work of Gubanov (2006), it is noted that the dimensionless cylinder velocity, \vec{U}_{budy} at any point (x, y, 0), on the cylinder boundary can be determined by $\vec{U}_{\text{budy}} = (\dot{x}, \dot{y}, 0)$.

Unless the part a stationary similar cylindre is dependent on the value of the Regardle mather as an annual by Hyman and Hubber (1997). Bolts of Bayeable number of the 0, the optimize wales installs and thus worts adouting its out present. The sourcison fram is the signature dama was assumed to the optimer. As the Bayeable number increases, however, there is a transition fram a stable two dependences of the state of the state of the state of the state of the dama state of the optimized mather in the distances which will be effect. As the optimized mather is and the direct on the state with the state of $< < \infty$. As the distance of the state of the state of the state of the state of the periodic state of the periodic state of the state state of the s

The shedding of vortices from a circular cylinder lead to unsteady, periodic forces which act on the cylinder. The forces are comprised of the transverse (lift) force, and the streamvise (drag) force. A stationary cylinder is subjected to a lift force with a natural (Stroublish shedding frequency of f₀, and a drag force equivalent to twice the

1
natural shedding frequency frequency, 2fo (Bishop & Hassan, 1964). An analysis of the relationships between the fluctuating lift force and the influence of the Reynolds number, as well as the fluctuating lift force and near wake flow patterns for flow past a stationary circular cylinder, can be found in the numerical study by Norberg (2003). proaches the natural shedding frequency, the cylinder will oscillate at the imposed forcing frequency. This phenomenon is called "synchronization" or "lock-on." For a streamwise oscillating cylinder, lock-on occurs when the imposed frequency is twice the natural shedding frequency of the cylinder. The mechanism of vortex shedding, and consermently the fluid forces acting on the cylinder, is greatly affected by the forced oscillations to which a cylinder is subjected: that is, transverse, streamwise, rotational (or a combination of these) oscillations. The majority of numerical and experimental studies carried out for forced tranverse and streamwise oscillations have focused on the flow characteristics of a circular cylinder governed mainly by amplitude and frequency of the oscillation. Literature related to the study of flow characteristics of a cylinder subjected to transverse oscillations can be found in Orgoren and Rockwell (1988). Williamore and Roshko (1988). Blackburn and Henderson (1999). Anagnostopoulos (2000) and Pham et al. (2010). Fundamental literature related to flow characteristics of a cylinder subjected to streamwise oscillations can be found in Cetiner and Rockwell (2001a). Cetiner and Rockwell (2001b), Al-Mdallal et al. (2007) and Kim et al. (2009). Little information has been published on cylinders forced to undergo combined transverse and streamwise oscillations (see Li et al. (2009), Leong and Wei (2008), Dahl et al. (2006), Jauvtis and Williamson (2004), and Jeon and Gharib (2001)).

As mentioned previously, the main goal of this research is to understand the physical mechanisms behind the response of a cylinder wake to forcing mechanicms (for three types of forced oscillatory motion) when a cylinder is in the presense of a free surface. Relatively few studies have been carried out on free surface problems concerning the effect of time-dependent streamwise (see Cetiner and Rockwell (2001b), Mironova (2008)) or transverse cylinder oscillations (see Gubanov (2006)) on the vortex shedding process. Cetiner and Rockwell (2001b), considered the vortex shedding modes near the fundamental lock-on region and the resulting fluid forces at R = 917.2075; Fr = 0.07.0.158; A = 0.96; f/fs = 0.44, 1.0; and b = 0.06, 0.19, 11.23. The experiments were conducted for over a hundred cylinder oscillation cycles and it was observed that for certain cases the flow is locked-on over state occurs. Cetiner and Rockwell show that in the event a finite gap exists between the cylinder and the free surface (h = 0.19), jet-like flow through the gap act to destabilize such locked-on states by inducing a negative vortex from the cylinder surface. It was also demonstrated that localized distortions of the free surface appear due to vortical structures shed from both the cylinder and the free surface. Mironova (2008), considered uniform two-dimensional free surface flow simulations were conducted at R = 200, A = 0.13, and $f/f_0 = 1.0, 2.0, 3.0, 4.0$ for three different cylinder submergence depths, h = 0.25, 0.5 and 0.75, and the Froude numbers $Fr \approx 0.0$, Fr = 0.2 and 0.4. Mironova's work demonstrated that it is possible to reperate distinctly different patterns of the vortex formation than that of classical

free surface and the Froude number is high. For the limiting case $Fr \approx 0.0$, three basic musi-locked-on or locked-on asymmetric vortex shedding modes were observed. The coalescence between the vortices in the vortex shedding lawers appears for the frequency ratios. $f/f_0 = 2.0$ at h = 0.5; $f/f_0 = 3.0$ at h = 0.5, 0.75 and $f/f_0 = 4.0$ at h = 0.25, 0.75. In the numerical work by Gubanov (2006), uniform two-dimensional free surface flow simulations of forced transverse oscillations of a circular cylinder was examined. The simulations were carried out at R = 200, for a fixed cylinder submerration 1/6. = 0.95 1.0.2.0.3.0.4.0 Fluid forces and near wake writery patterns were examined to analyze the numerical results and determine if lock-on of vortex shedallowed for the formation of non-classical modes. In particular, the formation of A = 0.25, the presence of a free surface had a slight effect on the vortex shedding modes. Conference was observed at A = 0.5, $f/f_0 > 2.0$ in the presence and absence of a free surface. It was seen at A = 0.5, that the inclusion of the free surface seemed to induce period doubling of C_D at $f/f_0 = 0.95, 1.0$ and $f/f_0 = 3.0$. For all cases, the combination of the forced transverse motion and the inclusion of the free surface did not suppress vortex shedding and consequently the occurence of locked-on vortex

In this thesis, determination of lock-on regimes is based heavily on the work of Ougoren and Rockwell (1988). They clausify lock-on regimes based on the repetition of vortex shedding in the near wake region of a circular cylinder over an integer number of oscillation events. The methods to determine lock-on by Anagroactopoulus (2000) and Cetiner and Rockwell (2001a) are employed as well. Anagnostopoulos (2000) numerically investigated a transversely oscillating cylinder subjected to uniform laminar flow at R = 106, for the frequency ratio range $0.8 \le f/f_0 \le 1.20$, and an oscillation amplitude that was increased to 50% of the cylinder diameter. In his study, ingly the existence of a large peak at the forcing frequency in the power spectra of the lift force, was used to determine if lock-on exists. The dominant frequencies at which the lift and drag forces oscillate can be identified from the PSD of lift and drag coefficents. The firmres are developed by taking the time dependent lift and drag coefficents and transforming them into the frequency domain using Fourier analysis. The work of Cetiner and Rockwell (2001a) examined the streamwise oscillations of a circular cylinder subject to uniform flow in the absence of a free surface for the Reynolds number and frequency ratio ranges $405 \le R \le 2482$ and $0.0 \le f/f_0 \le 3.0$, respectively. The work focused on the relationship between the natterns of vortex shedding in the near wake of the cylinder with the fluid forces, and the corresponding Lissajous patterns and spectra. A Lissajous pattern represents the time change of the lift or drag coefficients as a function of cylinder displacement. Highly congruent Lisshedding frequency of the cylinder. In Chapter 1.2, the link between the direction of the Lissaious patterns of the lift (or drag) force to the transfer of mechanical energy (from cylinder to fluid or fluid to cylinder) is discussed.

The lock-on modes of this work are classified in accordance to the nonsentlature defined by Williamson and Roshka (1988). Williamson and Roshko studied the vortexmodes produced as a result of motion of a transversely oscillating cylinder in the



Figure 1.3: A map of the locked-on vortex modes in the wavelength-amplitude plane near the fundamental lock-on region, as observed by Williamson and Rouhlo (1988). The critical curve marks the transition from one mode of vortex formation to another. The lined area marks where the 'coaliscence' type shedding occurs.

absume of a free-median. They entrustedy mapped the balance avera modes the avantispha-median fagtors as Rayakak numbers and cytokine amplitudes within 300 eeR < 3000 erR < 1000 and < 3, -2, 1002 galaxies, and the state of the state

Quider within a angle event schedup cycle, $T_c \rightarrow T_c$ where t is utilize a harmony or minaryor. The 2⁴ mode sines to the advance ablading contrast restricting vortex pairs from and side of the quincies per T_c . The P 4.5 much refers to the schedup of a contact-scitzing varies path, followed by a single vortex within one cycle. The molecure planeauxon, is the marging of vortices humofields behalf the cylinder, or denotration. Conference is identified to have extend at large any events within within bodies the varies of the entropy. Cylinder is the denotrative abeliage of two particles are also been as the science of the and output of the science is the science of extension.

1.1 Methodology and Governing Equations

The their analysis the result of the model over by Messawa (2008). The model of decode the stretzeric (at hits, b), and b), the tot of lattlee boundary with uniform which (2). A takk hence the cell is the outline boundary of the stretzen of the ingle-fluid flow model over by Gamma (2006). The single-fluid and describe the model and tarkingly associate (2006). The single-fluid model describes the model on additionally model (both infinite flow stretzen flows. The model one as annihomology flowing right, which makes passing of the full infinition of the stretzen of the probability of the stretz (b) and the stretzen of the stretzen strenge comparison of the probability of the stretzen of the stretzen of the stretzen strenge comparison of the stretzen of the stretzen of the stretzen of the stretzen stretzen of the stretzen of the stretzen of the stretzen of the stretzen stretzen of the stretzen of the stretzen of the stretzen of the stretzen stretzen of the stretzen stretzen of the stretzen o

$$\frac{dV^*}{dt^*} + \int_{t^*} (\vec{u} \cdot \vec{u}^*) dS^* = 0,$$
 (1.1)

1.1. Methodology and Governing Equations

$$\frac{d}{dt^*} \int_{Q^*} \tilde{u}^* \, dV^* + \int_{\tilde{u}^*} (\vec{u} \cdot \vec{u}^*) \vec{u}^* \, dS^* = -\frac{1}{\rho} \int_{\tilde{u}^* \setminus \tilde{U}^*} p^* \vec{u} \, dS^* + \nu \int_{\tilde{u}^* \setminus \tilde{U}^*} \vec{u} \cdot \nabla \vec{u}^* \, dS^* + \int_{\tilde{V}^*} \vec{F}^* \, dV^*$$
(1.2)

The associated boundary conditions of the problem include the no-slip conditions at the cylinder boundary

$$v^* = 0$$
, $v^* = 0$.

The inflow and outflow boundary conditions are defined respectively as,

$$u^* = U - v_1^*$$
, $v^* = -v_2^*$;
 $\nu \frac{\partial u^*}{\partial x^*} + g^* \tilde{h}^* = \frac{p^*}{\rho}$, $\frac{\partial v^*}{\partial x^*} = 0$,

and the free-slip conditions at the top and bottom boundaries of the domain

$$\frac{\partial u^*}{\partial x^*} = 0$$
, $v^* = -v_2^*$, (1.3)

where V^* and A^* are the fractional volume and area, respectively, of the computational cell V^* . The dimensional fluid-body interface is defined as $\Gamma_1 \cong *$ is the dimensional velocity; \vec{n} is the outward normal vector to the cell boundary and S^* is the control volume boundary.

Not previously defined dimensionless forms of the parameters found in equations 1.1 and 1.2 are written as

$$u = \frac{u^*}{U}, \quad v = \frac{v^*}{U},$$

 $V = \frac{V^*}{d^2}, \quad S = \frac{S^*}{d}, \quad V = \frac{V^*}{d^2}, \quad A = \frac{A^*}{d}, \quad I = \frac{I^*}{d}.$

In the two fluid model, the dimensionless fluid pressure is defined as $p_i c = p'/\rho_i d^2$, where $c = p_i/\rho_i$ when $\vec{e} \in \Omega_1$, and c = 1 when $\vec{x} \in \Omega_2$. In this then, the fluid density and vicceosity ratios are set to $\rho_i \rho_i = 1/100$ and $\rho_i \rho_i = 1/100$, respectively, which results in a kinematic viscosity ratio of $\rho_i \rho_2 = 1$. Hence $\nu_j = \nu_j$, which can now be referred to z. The governing equations in the dimensionless form are

$$\frac{lV}{dl} + \int_{k} (\vec{u} \cdot \vec{n}) dS = 0, \quad (1.4)$$

$$\frac{d}{dt}\int_{V} \vec{u} \, dV + \int_{k} (\vec{n} \cdot \vec{u})\vec{u} \, dS = -\frac{1}{c} \int_{\vec{n},\vec{n}} p\vec{u} \, dS + \frac{1}{R} \int_{\vec{n},\vec{n}} \vec{n} \cdot \nabla \vec{u} \, dS + \int_{V} \vec{F} \, dV, \quad (1.5)$$

where the external force, $\vec{F} = (-a_1, \frac{1}{Er^2} - a_2, 0)$, is due to the dimensionless gravity force, $\vec{g} = (0, 1/Fr^2, 0)$, and the dimensionless acceleration of the non-inertial frame of reference, $\vec{a} = (a_1^*d_1U^2, a_2^*d_1U^2, 0)$.

It follows that the dimensionless boundary conditions of the problem are the no-slip conditions at the cylinder boundary:

$$u = 0$$
, $v = 0$. (1.6)

The inflow boundary condition, and the outflow boundary condition as proposed by Greeko and Sani (1998), are respectively.

$$u = U - v_1, v = -v_2$$
, (1.7)

$$\frac{1}{R} \frac{\partial u}{\partial x} + \frac{\ddot{h}}{Fr^2} = p, \quad \frac{\partial v}{\partial x} = 0,$$
 (1.8)

and finally the free-slip conditions at the top and bottom boundaries of the domain

are written as

$$\frac{\partial u}{\partial x} = 0$$
, $v = -v_2$. (1.9)

At t = 0, that the free-surface is assumed to be undisturbed.

Cartesian grid. Versteeg and Malalasekera (1995) provide an excellent description of the finite volume method. A second-order accurate central difference scheme in space is used in conjunction with a first-order explicit forward Euler scheme to advance the numerical solution in time. A cell merging procedure is used to preserve second-order a volume-of-fluid (VOF) method proposed by (Hirt & Nichols, 1981). A mass conby Aulisa et al. (2003b), is used. For the moving fluid-body interface, the fractional area/volume obstacle representation method proposed by Hirt and Sicilian (1985). and the cut cell method of Gerrits (2001) are used. In this thesis, the numerical simulations were carried out using the CFD code developed by Dr. Kocabiyik's research mum at Memorial University. Details of the development, and implementation of the code can be found in Mironesa (2008) and Gubaney (2006). The computational code is applied to the model problem of unsteady, laminar, two-dimensional flow of a viscous incompressible fluid must a circular cylinder subject to forced (i) streampresence of a free surface. The unsteady flow calculations are conducted at a fixed Reynolds number of R = 200, and cylinder displacement A = 0.13, for four frequency ratios, f/fn = 1.25, 1.75, 2.25, 2.75 at (i) Fr ≈ 0.0, 0.2, 0.4 at cylinder submergence 1.2. Calculation of Lift and Drug Forces, and Mechanical Energy

depths h = 0.25, 0.5, 0.75; (ii) Fr = 0.2 at h = 0.5; and (iii) Fr = 0.2 at h = 0.5. A comparison of the present results with the reference case $h = \infty$, are included to illustrate the effects cause by the inclusion of a free surface.

1.2 Calculation of Lift and Drag Forces, and Mechanical Energy

The x and y components of the dimensionless force, $\vec{F} = 2\vec{F}^*/(\rho dU)$, corried by the cylinder on the fluid are the dimensionless drug, C_D , and dimensionless lift, C_L , force coefficients are

$$C_D = C_{D\mu} + C_{D\nu}, C_L = C_{L\mu} + C_{L\nu}$$
 (1.10)

respectively, where $C_{D\mu}$ and $C_{L\mu}$ are the contributions due to the pressure gradient, and $C_{D\mu}$ and $C_{L\mu}$ are the contributions due to the viscous shear forces. The pressure contributions are

$$\begin{split} C_{D_F} &= \int_{0}^{2\pi} p\cos\theta d\theta, \ C_{L_F} = \int_{0}^{2\pi} p\sin\theta d\theta \\ C_{D_F} &= \frac{1}{R} \int_{0}^{2\pi} \frac{\partial u}{\partial t} d\theta, \ C_{L_F} &= \frac{1}{R} \int_{0}^{2\pi} \frac{\partial v}{\partial t} d\theta \end{split}$$

where $\vec{n} = (\cos(\theta), \sin(\theta), 0)$ is the outward unit normal to the cylinder boundary. The fluid forces are analyzed based on the power spectrum density of the lift and drag coefficients and the Lissayians trajectories of the force coefficients. In all figures related to find forces that follow, the observed flow regimes in various states (a) periodic quasi-pendice or morphole stars) are induced to limitance the link breaves the values of the stars and the blackmin or the line coefficients. The power queryum chanitis and the Linkyou trajectors of the line and leng coeffistars, L(z) (1) ((z))) and (z < (z) ((z))), comparison of the stars and the black stars of the link of the time intervals corresponding to only of the directorial gradient is are understood with the large of the link and disc coefficients are a discussion of the stars of the link of link of equidant and exists on the dimension of morphical energy times for bievesses the fluid and cylicids, degree of phase-boling or a know fluid with experison of the link of the stars of the dimensioned morphical energy times for bievesses the fluid and cylicids degree of phase-boling or a know fluid dimansional machined or energy transfer between the cylicider and the fluid area or emission. The star of the stars of the theorem the cylicider and the fluid area or particled of realistic coefficients, $T_{\rm eff}$ are discribed by the stars of the stars and produced cylicider coefficients. The one below the cylicider and the fluid area or particle of the stars coefficients, $T_{\rm eff}$ are discribed by the stars of the stars and produced cylicider coefficients, $T_{\rm eff}$ are discribed by the stars of the stars and the stars one produced cylicider coefficients, $T_{\rm eff}$ are discribed by the stars of the stars of

$$E = \int_{0}^{T} C_D \dot{x}(t) dt, \qquad (1.11)$$

where the overdot indicates differentiation with respect to time (Baranayi (2008)).

The total dimensionless mechanical energy transfer between the cylinder and the fluid over one period of cylinder oscillation, T_i for a cylinder undergoing transverse oscillations is defined as

$$E = \int_{0}^{T} C_L \hat{y}(t) dt. \qquad (1.12)$$

For a cylinder undergoing combined streamwise and transverse oscillations, the total dimensionless mechanical energy transfer between the cylinder and the fluid over one period of cylinder oscillation is defined by the sum of equations 1.11 and 1.12. Thus, it follows that the total dimensionless mechanical energy transfer between the cylinder and fluid, over one period of cylinder oscillation, T, for a cylinder performing transverse-streamwise oscillations can be defined as

$$E = \int_{0}^{T} (C_D \dot{x}(t) + C_L \dot{y}(t)) dt = E_1 + E_2.$$

The generational interpretation of F is the signed new methods by the hydroxic loops ($-Q_{1/2}$) and $C_{1/2}$ bere the sign is during the discretion of the Limaysher trajectories (Generation Hardwell (2018)). It all fiquess that follows, the discretion of Cap(d) reduces the discretion of Cap(d) reduces the discretion of Cap(d) r

1.3 Code Validation

In this thing, the power numerical model is validited by convecting numerical mathinum is two solutions, matching humans from (see 10.) a statistically seen submitting the in the dense of a free empters, (10. explaine undergoing transverse semilithratic in the absence of a strength constraints, and the product and the strength constraints in the dense of a free antices. A validation study for free writers for gas as cylinder of difficult in the $I_{\rm constraint}$ of the strength constraints and our scale accurates of the difficult explanation of the product and numerical accurates of holds and λ (2008) with the present numerical model is the presence of the output of the difficult difficult explanation of the strength one of the strength one of the difficult difficult explanation of the strength one of the strength one of the difficult diff A computational gain baseline of 00 mpc dimensive is down for the current interpretation. The mass has approximately 25 = 30 mpc down result of models much dimensional dimension dimensional terms of the stars. In the dimensional dimensiona dimensional dimensi dimensi d

1.3.1 Flow past a stationary cylinder in the absence of a free surface

This section potentia the smaller statement for point a statistancy clydical of Bysolidi methods of R = 500 and 10^4 s. There material simulation of a statistancy clydical for the present model are compared with material results of L1 (2000). From human Methodsimes (2000) (2000). Statement of the statement of L1 (2000) (2000) and Columner (2000) in Figure 1.4. L1 et al. (2000) employed a kinetic-theory-based for the Darkmann model and to appendiment the problem of Hise just a Versideen Cyclick for a Bysolid number of R = 500, stere-smaller (2000) simulated from isotra as predimented in the state of the state of the cyclic state of the state state in the state of the state state in the state of the state state of the state state in the state of the state state in the state of the state state of the state state of the st



Figure 1.4: Equivorticity patterns for uniform flow past a stationary criticler in the absence of a free surface at R = 550: Li et al. (2004) (left), Gubanov (2006) (middle), present work (right) when t = 0.5, 1.5, 2.5 (from top to bottom)

Numerical minimizations are also control on at R = 1000 for the case of uniform loop past a stationary cylinder, Figure 1.5 shows good comparison between the present results and the cose one obtained by Contaneous and Pirzons (1997) experimentally and the numerical results of Al-Mahliki (2004). It is noted that the numerical method of Al-Mahliki is based on a omjugating Fearier spectral analysis with finite-difference appearisminos.

Figure 1.6 displays the early time development of the drag coefficient for uniform flow past a stationary cylinder at R = 550. It can be seen that the figure shows a good comparison between the present results and the results obtained by Ploumhans and



Figure 1.5: Streamline patterns for uniform flow past a stationary cylinder in the absence of a free surface as $R = 10^3$ at the time instances: (a) t = 4, (b) t = 8, (c) t = 12, (d) t = 14,Contrareven and Phrase (1997) (46), A3-Molard (2004) (moldble), present work (right).

Warkshman (2000) and Li et al. (2005). Li et al. (2004) implement the lattice Bahmann method to solve the problem of implivity started flow post a circular equilable for a largestrammer of $R \rightarrow 500$. Frombanes and Warkshmann (2000) use a two-dimensional vectors method based on the variety-stream function formulation of the Noview-Studies equations in combination with the particle strength reshnaps when the diffusion is combination with the particle strength reshnaps



Figure 1.6: The drag coefficient, C_D , for uniform flow part a stationary cylinder in the absence of a free surface at R = 530 : (i) Calumer (2006), (ii) Flowmhans and Wittelebraux (2000), (iii) Let al. (2004), (iv) present work.

the local minimum) showed by Goldanie (2000) in higher (lower) than the more study. The Mandelman Pollandian (2000) is higher (lower) than the dense structure of diffusion boundary conditions for the inter-Bornsman spacebox of the structure of

to have numerical difficulties which arise due to complexity of the application of boundary conditions at the free surface on the non-boundary-fitted Cartesian grid (Gubanov, 2006).

1.3.2 Flow past a streamwise oscillating cylinder in the absence of a free surface

The numerical simulations are carried out at R = 855; A = 0.13, $f/f_0 = 0.5$, 1, 2, 3, 4by setting the rectilinear oscillatory cylinder displacement to

$$x(t) = A \cos(2\pi f t).$$
 (1.13)

In Figure 1.7, the present numerical results of the flow development behind a streamwise oscillaring cylinder are compared with the numerical results of Al-Malilal (2004) and the available experimental results obtained by Ongaren and Rockwell (1988). It can be seen that these commarises are in zood aurement.

1.3.3 Flow past a transversely oscillating cylinder in the absence of a free surface

The numerical simulations in the case of a transversely oscillating cylinder were carried out at Reynolds numbers of R = 200 and R = 855. Figure 1.8 shows the comparison of the present numerical simulations ($R = 200, f/f_0 = 0.8, A = 0.6$) after setting the resultinear cylinder displacement to

$$y(t) = -A \cos(2\pi f t),$$
 (1.14)



Figure 1.7: Comparison of flow visualization of Ongoven and Rockwell (1988)(left), Al-Mdallal (2004) (middle), and computed present equivorisity lines (right) for a streamwise oscillating cylindyr R = 855, A = 0.13 as frequency ratios: (a) $f/f_0 = 0.5$; (b) $f/f_0 = 1$; (c) $f/f_0 = 2$; (d) $f/f_0 = -2$; (e) $f/f_0 = -4$.

with numerical results of Mengdini and Bearman (1995) and Gohmov (2006). Mengdini and Bearman simulated flow about an oscillating cylinder using a discrete vortex method. Figure 1.8 shows good agreement between the present equivortiity patterns in the near wake region with both Mengdini and Bearman (1995) and Gohawo (2006).



Figure 1.8: Equivorticity patterns for a transversely ostillating sylinder at R = 200, A = 0.13 at frequency ratios $f/f_0 = 0.8$. Menophini and Baurman (1995) (left), Gubenov (2006) (middle), present work (right).



Figure 1.9: Comparison of fize visualization of Organess and Rockwell (1988)[hfb], equivorticity patterns by AbJdafal (2001)[mid-bcl), Galaxare (2006](mid-right) and present weak(right) for uniform flow past a transversely oscillating cylinder at R = 855, A = 0.13at frequency ratios: (a) $f/f_R = 0.5$; (b) $f/f_R = 1$; (c) $f/f_R = 2$, (d) $f/f_R = 3$; (e) $f/f_R = 4$.

.25

The memory animations of a transversely oscillating cylindri is also carried out at R = 856, A = 0.13 in the frequency range $10.5 \leq 1/L_0 \leq 4.0$. The present duration of the proteins are oranged with the work of Ouperen and Rockseld (1988) and the numerical results of Al-Malaid (2004) and Galamov (2006) in Figure 1.9. It can be seen that there is good agreement in the near value region of the cylinder for $f/f_0 \leq 2$ with all three sets or results.

Flow past a streamwise oscillating circular cylinder in the absence of a free surface

This chapter formes on the results for flow past a circular cylinder subject to forced streamwise conditions in the absence of a free surface (symbolically represented by $h = \infty$). The numerical simulations are conducted at a Reynolds number of R = 205, for a fixed amplitude, A = 0.13, in the frequency ratio range, $1.25 \le 1/f_0 \le 2.75$, which increases be an increment of 0.5.

2.1 Fluid forces and vortex shedding modes

2.1.1 Fluid forces

The turn knows of the flow time transmission of the flow time (L_{1} , the PSD of L_{2} , and the Lakopus purposes $\Gamma_{1}(L_{2})$, and elogical in Figure 3.1 is a worker that for frequency ratio, $f_{1}(L_{2})$. The trans of C_{1} solubility is provide signature every two cycles of cylinder ratio is also arguested by the corresponding Lineary constant (L_{2} list the frequency ratio is also arguested by the corresponding Lineary matrix (L_{2} list the frequency ratio is also arguested by the corresponding Lineary matrix (L_{2} list the frequency ratio is also arguested by the corresponding Lineary matrix (L_{2} list the transmission L_{2} list L_{2} (L_{2} list L_{2 c ≤ 100, and every 27 for f(f) = 273 within 94.33 ≤ t ≤ 100. In one howes the disc envery model maching neutrons addite composing the composing read product particles and the composing of the particles increases or f(f), for the test 31.23 × 12.33. In struct, that for and howevery one (f), f(f) = 1.53, 11.23.23.23. In the typosite is defined by tack the target and how ind falsons. For each frequency ratio, f(f), for task 11.23.23.23. In the typosite is defined by tack the target part and the first definition of the first of the same definition of the same definition of the first of the same definition of the first of the same definition of the same definition

In Figure 2.2, the time hairs of the drag ordinate, C_{10} the FS0 of C_{20} and be companding Linagian particles, $C_{1/2}$, of C_{20} and C_{20} are produced using the same line hierarch as the same bin C_{10} to drama the the tree entropy of the effect C_{20} terms on the status. It is reduce that the C_{20} terms display about periodic signatumes every near periods of cylother such cases. The M_{10} is M_{10} terms display about periodic signatumes every near periods of cylother such cases. The M_{10} is M_{10} terms display about periodic solutions in M_{10} terms M_{1



Figure 2.1: The time variation of the file coefficient, G_{11} (black) and the streameter diphonematr. (10), (myr) FSD of G_{12} (mayris) persister of G_{13} at R = 100. A = 0.33, $f/R_0 = 125$, 1.75, 2.25, 2.25 where $h = \infty$. The Lineajous and FSD plate for $f/f_0 = 125$, 1.75, 2.25, 2.25, 3.86 and 1.66 with 1.66 with

display congressent patterns with minimal phase shift for $f/f_0 = 1.25, 1.75, 2.25$, and a highly congressent pattern with little to no phase shift for $f/f_0 = 2.75$, indicating periodic behaviour. It can be seen that the hysteresis loops, for all f/f_0 , are minify



Figure 2.2: The time variation of drag coefficient, C_{c0} (Mark) and the streamber dipherematr. (1), $((m_{1}^{2}) + 25) \circ G_{c2}$ (Langelow patterns of C_{c2} at R = 20 . A = 0.3, $f / f_{c} = 1.25$, 1.75, 2.25, 2.75, when $h = \infty$. The Linayions and PSD plots for $((m_{1}^{2}) + 25)$, $((m_$

confined to the upper half-planes. As f/f_0 increases, there is a shift of the patterns of $C_D(x)$ into the lower half plane. The direction of each $C_D(x)$ is counter-clockwise. Hence, the mechanical energy transfer is from the cylinder to the field. It can above seen that as f/f_{10} increases, the area enclosed by $C_0(x)$ increases. This implies that a higher anomal of energy is being transferred from the cylinder to fitth with the increase of f/f_0 from 1.25 to 2.75. For each frequency ratio, f/f_0 the corresponding spectra, FSD, of C_0 holes one dominant peak at f. This indicates that C_0 oscillates at f and for all the operators.

2.1.2 Vortex formation modes

Figures 2.3-2.10 display the equivorticity and streamline patterns, and the pressure contons in the near value of the cylinder when $f/f_0 = 1.25, 1.75, 2.25, 2.75$. The observed flow behaviour is (i) periodic, per 27, for $f/f_0 = 1.75$ and (ii) quasi-periodic, per 77, 97, 37, for $f/f_0 = 1.56, 2.52, 2.75$, respectively.

In Figure 2.3. the equivativity patterns are displayed for $f/h_c = 123$ nor sense produced of polind order (1) and (1) and (1). The vertex should have be in the quasi-abolic or C(1369 ymm ods, per 77, within 60.61 $\pm 1 \pm 100$ (maripointic anal). This is command with the biakness of $C_{1,0}$ of $f_{1,0}$ the bary proper ratio. The first issue product for (< 600), in this mode, free varies develops and hold mean this of the lengthmer err. Thinking, how experime vertex should have one $0 \pm 1 \pm 7$, and size 1 - 277, and the D(2) and particular should be show the discustored in 1077. Also grid to D(2) and the lengthment of the radio bias the discustored is descered in the our wave radio. The secondary require vertex free first is the should be traver wave region. The secondary require vertex free first is the of the collinder, at $t \approx XT$. Similarly, over $10T/3 \le t \le 4T$, two negative co-rotating vortices develop in the upper shear layer of the cylinder. Then, the secondary vortex becomes detached at $t \approx 4T$ and propogates into the downstream of the cylinder, into the downstream of the cylinder at $t \approx 17T/3$. Finally, in the upper vortex shedding region of the cylinder, the primary negative vortex in the near wake of the cylinder at t = 17T/3 continues to develop over $6T \le t \le 20T/3$ and is shed downstream of the cylinder at $t \approx 7T$. Meanwhile in the lower vortex shedding region of the cylinder, a positive vortex developed in the previous shedding cycle elongates and becomes weaker and then sheds into the downstream of the cylinder at $t \approx 2T/3$. Subscinently, the newly formed positive vortex formed over $0 \le t \le T$ elongates, and then detaches from the positive vortex shedding layer at $t \approx 2T$. On the other hand, at t = 8T/3, two positive vortices coalesce to form a single positive vortex which continues to develop over $3T \le t \le 10T/3$, and then becomes detached at $t \approx 11T/3$. The positive vortex attached to the cylinder at t = 4T is forced to elongate, over $13T/3 \le t \le 14T/3$, due to the interaction with the negative vortex in at t = 5T. Finally, a positive vortex developing over $6T \le t \le 20T/3$ is subjected to the interaction with the negative vortices in the upper vortex shedding region, and then consequently sheds into the downstream of the cylinder at t = 7T. Thus, in the crassi-locked-on C(108)* mode, per 7T, five vortices alternately develop from each side of the cylinder. In addition, the first two vortices which develop from each side coalesce to form one single vortex followed by a third vortex shed from each side in the first, second and fifth periods.



Figure 2.3: The equivorisity patterns over seven periods of cylinder oscillation, 77, at R = 200 A=0.13, $f/f_0 = 1.25$ when $h = \infty$ [$T \approx 4.04, 40.66$ if $z \notin \le 88.89$: (157,227)]. The quasi-bodied on C10887 mode, per 77, is observed.

Figure 2.4, displays the pressure contours for the aforementioned case of frequency ratio $f/f_0 = 1.25$ over seven periods of cylinder oscillation, 77. At t = 0T, this figure displays the development of the low pressure region behind the cylinder (near Figure 3.2 displays the exploration junctum for $f/f_0 = 1.71$ more two periods of applicator continuum, T. The terms should junc mode the periods bould-on 2.07 mode, per 27, which the interval BiT $\leq 1 \leq 517$. This is maintened with the C_1 but and with the C_{22} bolarizator at this frequency trait. The files is non-periods for t < 107. And all applies constraining varies develop in the upper two test adults position of the cylindre out $\Omega^{2} \leq \leq 247/6$, and the abund, a pair of positions constituty were abundle position in t = 0.71%. On the stand, a pair of positions that can be assure which of the cylindre bases were abulking regime at the cylindre over $\Omega^{2} \leq \leq 2.017/6$, and the adult is may be assored as t = 1.71%. No the stand $t_{1} = 1.71\%$. So the standard $t_{1} = 1.71\%$. No there allower were advected by the lower were abulking regime at the cylindre over $\Omega^{2} \leq \leq 2.017/6$, and the adult is the standard $t_{1} = 1.71\%$. No the standard $t_{1} = 1.71\%$. No the standard for the train $t_{1} = 1.71\%$ and $t_{1} = 1.71\%$. The standard $t_{1} = 1.71\%$ is the standard $t_{1} = 1.71\%$ is the standard $t_{1} = 1.71\%$ is the standard $t_{1} = 1.71\%$. No the standard for the standard $t_{1} = 1.71\%$ is the standard $t_{2} = 1.71\%$ is the standard $t_{2} = 1.71\%$. Standard $t_{2} = 1.71\%$ is the standard $t_{2} = 1.71\%$ is the standard $t_{2} = 1.71\%$ is the standard $t_{2} = 1.71\%$.



Figure 2.4: The figure caption is given on page 34

2.1. Fluid forces and vortex shedding modes



Figure 2.4: The equivorticity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wake region of the cylinder over seven periods of cylinder oscillation, 77, at R = 200; A=0.3, $f/f_{\rm p} = 1.25$ when $h = \infty$ $(T \approx 4.04, 80.80 \le t \le$ 100.63 < 100.7271. The considering of GBNS² mode, set 7.1; is observed.



Figure 2.5: The equivariaity patterns over two periods of cylinder oscillation, 27, at R = 200; A=0.13; $J/f_{0} = 1.75$ when $h = \infty [T \approx 2.886, 60.88 \le t \le 72.15 : (237, 257)]$. The variable-ford on 29 mode, new 7.7; is observed.

The process contrasts on displayed we have about M^{-1} and M^{-1} and M^{-1} and M^{-1} . The product of product of products, M^{-1} the process control methods the due by high process regular is associated with the dispatiant engine, $M \in \mathcal{M}^{-1}$ is weaked that the top process regular dispersion is the displayed barrier of the optical Hadinguige decoding and the product services in the discover of the displayed Hading is $M = M^{-1} = 272$, as a comparison works of the product services in the displayed Hading is the $M = M^{-1} = 127$, is a contrast of the product services in the displayed Hading is the $M = M^{-1} = 127$, is a relating the service in the service regular, $M \approx 10^{-1}$ for $M \approx 10^{-1}$ for $M \approx 10^{-1}$ $M \approx 10^{-1}$ for $M \approx 10^{-1}$ Input and an the paralies good of works the high to data that t = 327/2, it can be seen that the region of the parameters are worked within the high of the parameters are similar that the high the region to the parameter region, at this time, increases dusticable, Finally, at = 27, the high present region, at this time, increases dusticable, Finally, at = 27, the high present region distribution of the simulation of the signature region with the high present region in the region of the simulation of the simulation of the simulation of the simulation region is constrained one simulation. In general t = -27/2 its high present region is in the dward trend of bolic data and holes the her present regions in the dward trend of bolics.

Figure 2.7 doping the equivarianty parameters near time periods of both oscillations, T_1 of the maps product mass $\log 1/f_1 = -2.5$. How such adduling mode is the grank-holden on CMSP, per 37, which is introval 307 $\leq t \leq 0.07$. This is consistent with the bacherise of t < 0.05 of t > 0.05 mby more ratios. The first is non-meriodic farst t < 0.07. In this mode, four warriss decoding on such side of the cylinder and side admandy over 37. Initially, a regaritive water sheah the developed areas t < 0.5. The solution of the second stress of the transmission of the cylinder at t = 5.7/2. A maps water is more stress admining anging at the cylinder at t = 5.7/2. A maps water is more stress in dealing anging at t = 7/2, and t = 27, continues to show prove $T \leq t \leq 0.7$. The contrasting quarks water is a stress t = 1 = 37, continues to water. These constanting units moments at t = 17, its second stress t = 1 = 37, continues to there values of the cylinder t = 17. A new graview water develops t = 1 = 7, and then modewave with a second mapsitus waters at t = 0.7. This there will be completed and the cylinder of the cylinder. Similarly, a suggivent water, develops on $T \leq t \leq 1.57/2$, and at t = 7, and the conduction of the cylinder.





the typical $\alpha \ell \rightarrow 27$ Manushin, thus have some dodding paging of the typical paralies worth dodding one 2 $\ell \leq 57$, 27, and 40 dots into it have some dodding rapin of the place at $\ell \rightarrow 7$. Thus, a paralies users in branch from the two space of use paralies worth one $\ell \rightarrow 27$. Thus users common in deading and the login is appendix A paralies constainty, users at $\ell \rightarrow 27$. This parallel worth worth the dod the paralies and even itselfs in the asymptotic structure of the dodding the dot dotter of the original paralies $\ell \perp \ell = 27$, and its paralies gain values at the two. The most of the original parallel par



Figure 2.7: The equivariativy patterns over nine periods of cylinder oscillation, 97, at R = 200; A=0.13, $f/f_0 = 2.35$ when $h = \infty$ [7 $\approx 2.246, 80.81 \le t \le 107.74$: [807,487]]. The quasi-loaded one (S88)" mode, per 97, is observed.

coalsees with a primary positive vertex in the near wake of the cylinder. This needy formed positive vertex is subsequently shed into the lower vertex shedding region of the cylinder $t \in 67$. The primary positive vertex in the near wake of the cylinder continues to develop over $67 \le 1 \le 137/2$, and at t = 77, coalesers with a second positive vertex in the near value. This nearly formed positive vertex sheds into the

downstream of the cylinder at $t \approx 8T$.

I/L = 2.25 over nine periods of collector oscillation, 9T. At t = 0T the high pressure the cylinder. Similarly to the case $f/f_{0} = 1.25$ ($h = \infty$), a large number of vortices are shed into the unner and lower sides of the cylinder. As a result of the multiple shadding of single vertices from the unner and lower regions of the cylinder, the concentrations of high and low pressure regions in the vicinity of the near wake of the the high pressure region shifts to the above and below the low pressure region in the downstream of the cylinder. On the other hand for example, at t = T, synonomous with the development, and the shedding, of a positive vortex in the lower vortex shedding region of the cylinder, it can be seen that the low pressure region shifts substantially downstream of the collector, and the high remeasure region shifts mostly occurs, it is evident at t = 3T/2 that the concentration of the low pressure is in the near wales of the collector, and that the birth pressure region shifts to the above and below the low researce region in the downstream of the cylinder. That is, the concentration of the high necessary region dramatically intreases.

For frequency ratio $f/f_0 = 2.75$, the equivorticity patterns in the near wale of the cylinder over three periods of cylinder oscillation, 37, are diployed in Figure 2.9. The shedding of a single negative vortex, and a pair of positive co-rotating vortices

2.1. Fluid forces and vortex shedding modes



Figure 2.8: The figure caption is given on page 41


Figure 2.8: The equivacticity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wake region of the cylinder over nine periods of cylinder oscillation, 07, et R = 200. A=0.13, $f/f_0 = 2.35$ when $A = \infty$ [$T \approx 2.244, 80.89 \le t \le$ 107.74 : (167.471). The runs blocked on C4885' mode, per 571 is observed.



Figure 2.9: The equivorisity patterns over three periods of cylinder oscillation, 37, at R = 300; h = 0.33, $f/f_{\rm B} = 2.75$ when $h = \infty$ [$T = 1.837, 94.83 \le t \le 97.34$: (507, 537)]. The constribution of CP+ S0⁺ mode, per 237, is observed.

accors within three periods of cylindra coefficients, 27. This results in the quark-lock or $C(\mathbf{P} + \mathbf{S}^{0})$ mode, per 37, within the interval B07 $\leq t \leq 817$. This is consistent with the balanciar of (c_{1}) that (c_{2}) at the balancy ratio. The low is non-periodic for t < 507. At t = 0, a pair of positive co-stating vertices has developed, in the inner state abdding rupin, in the previous skedding cycle. The pair of positive co-stating vertices dense at t = 7.5, was provided, so the t = 0.2 (see Finally, at t = T, the pair of positive co-rotating vertices is shed permanently into the near wake of the cylinder. On the therhand, at t = 7T/6, the vertex found from the condensers of two negative vertices, at t = 2T/6, shold into the upper vertices shadding region of the cylinder. Condenserso: of new negative vertices and pairing of positive co-rotating vertices continues to over, but shadding means for the remainder of the origination of the cylinder.

In Figure 2.11, the preserve numbers in the neur wake region of the cyclicle are displayed for the hopping and $F_1/h = 2.75$ cm theory periods of public variability, 3T. At t = 0T, the high pressure spins holes by the two periods V_{t} theory of the two periods V_{t} the high pressure region is not developed in the depulser. At t = 0.72, the high pressure region is the descent range of the high periods $V_{t} = 0.72$, the high pressure region is the descent range of the depulser to above variable, the is pressure region is the descent range of the depulser to above the pressure region is the descent run of the definition V_{t} of the steps of the steps of the depulse of the steps of the steps of the depulse of the descent range of the depulse of the steps of the steps of the depulse of the descent range of the depulse of the steps of the steps of the depulse of the depulse of the depulse of the steps of the steps of the depulse of the depulse of the depulse of the steps of the steps of the depulse of the depulse frame distribution depulse of the steps of the steps of the depulse of the depulse of the depulse of the depulse of the steps of the depulse of $z_{t} > z_{t} > z_{$

2.1. Fluid forest and vortex shedding modes

suggest that $t t = \sigma T/2$ (s = 1.3, 3) the high pressure region extends from the stagnation region of the cylinder to above and below the low pressure region in the extension of the cylinder. It also suggests that $t = \sigma T/2$, (c = 1.3, 3) that the low pressure regions develop in the upper and lower sides of the cylinder following the simultaneous development of regarize and positive vertices in the near wake region of the same time intensee.

<i>11 f</i> o	Vortex shedding mode and flow states	T_{θ}	C_L behaviour $(h = \infty)$	T_{t}	C_D behaviour $(h = \infty)$	T_{v}
1.25	$C(10S)^*$ (60.61 $\le t \le 150$)	71	quasi-periodic $(60.61 \leq t \leq 150)$	7T	quasi-periodic (60.61 $\leq t \leq 150$)	717
1.75	2P (54.83 $\leq t \leq 150$)	2T	periodic $(54.83 \le t \le 150)$	2T	quasi-periodic (54.83 $\leq t \leq 150$)	Т
2.25	$C(8S)^*$ (80.81 $\leq t \leq 150$)	97	quasi-periodic (80.81 $\leq t \leq 150$)	9T	quasi-periodic $(80.81 \leq t \leq 150)$	9T
2.75	$C(P + 8)^*$ (91.83 $\le t \le 150$)	31	quasi-periodic (91.83 $\leq t \leq 150$)	31	periodic (91.83 $\leq t \leq 150$)	2T

Table 2.1: Relationship between the behaviour of the lft and drag coefficients and the vortex shedding modes in the absence of a five surface $(h - \infty)$ for $f/f_0 =$ 1.52 (60.61 $\leq t \leq 100$), $f/f_0 = 1.75$ (54.83 $\leq \leq t$ S0.81 $\leq t \leq 1300$) and $f/f_0 = 2.75$ (91.83 $\leq t \leq 150$). The superscript ^{ass} denotes quasi-looked-on rootes.

In Table 2.1, the relationship between the behaviour of the lift and drag coefficients and the flow rates with the indicated vector-shedding modes for $f/f_0 = 1.25, 1.75, 2.25, 2.75$ are displayed. For the frequency ratios, $f/f_0 = 1.25, 1.75, 2.25, 7.75$ the hole-amountos score very 77, 72, 73 and 37 predicted or Cylin-



Figure 2.10: The equivorticity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wake region of the cylinder over three periods of cylinder oscillation, 37, at R = 200. A=0.13, $f/f_0 = 2.75$ when $h = \infty$ [$T \approx 1.837, 91.83 \le t \le$ 97.41; (207.2017). The canati-banders CDP + S3⁺ mode, per S7, is observed.

der oscillation, respectively. Similarly, the traces of C_L for $f/f_0 = 1.25, 1.75, 2.25, 2.75$ displayed repeatable signatures every 7T, 2T, 9T, 3T, respectively. Thus, the locked-on

votes shedding modes are influenced from the C_L behaviour at each frequency ratio. On the other hand, the tensors of C_D for $f/f_n = 1.28$, 1.78, 2.25, 2.75 displayed almostrepeatable signatures every 77, 7, 97 and 27, respectively, and thus the loded on vortex shedding modes and their periods are consistent with the C_D behaviour at only $f/f_0 = 1.25$ and 2.25.

2.2 Summary and Discussion

The presence contain gives of Figure 2.4.2.3, for $h = \infty$ wells f/(h = 2.5, 13, 2.3, 2.5, 2.3), there we have it at i = 1 of (whice the collabor reactions maximum displacement, (i) = A. (If the high presence sign develops predominantly in the displacement, (i) = A. (If the high present $A_{2,2}$ is developed by the star $A_{2,2}$ of $A_{2,2}$ of



Figure 2.11: The effect of the absence of a free surface, $h = \infty$, and the frequency ratio, $I/f_0(=1.25, 1.75, 2.25, 2.75)$, on the equivorticity patterns at R = 200, A = 0.13.

The effect of the absence of a five surface $h = \infty$, and the frequency ratio, $f/f_0(=1.25, 1.75, 2.25, 2.75)$, on the equiverticity patterns in the near wale region is summarized in Figure 2.11. The samplator are taken at the instant the cylinder rackes maximum displacement, x(t) = A. For the periodic/quark-periodic cases, the samplastic are taken as well them interval in which the flow reaches a periodic/quark

proficie area, I can be seen at the smaller disputper gravity, $||f_1| = 113, 133, that$ there is presented a point within (i) the upper vertex which large to of the other $dor (nur wake region). This is the rans for <math>||f_1| = 233$, but in shiftmen there is als singuises areality in the lower works adding toget of the three limits. The new wake restrictured (14 subjective) gravity means more in the more in the singuisest setting of the singuisers of the limit and the explanation of the singuiser or a singuiser or singuisers are in the new setting constrained of the singuisers of the singuisers of the limit and the singuisers of the limit and the linear weak arrestrome velocity. In the singuisers of $|f_1|$ intervals from 250 as f_2 f_3 (f_1 increases from 1.25 to 2.35 the strents formation length some to denous the transmission of set 803.

3. Free surface flow past a streamwise oscillating cylinder $Fr \approx 0.0$

In this Gauges, a shown incomparable trachial model with a summaries such that gost (rather barches A and gauges (A) for A (A) more A), we oblight A (A) and (A (A)

3.1 Vortex shedding modes at $Fr \approx 0.0$: h = 0.75

Figures 3.1-3.5 display the equivorticity patterns for $f/f_0 = 1.25, 1.75, 2.25, 2.75$. The observed flow behaviour is (i) quasi-periodic for $f/f_0 = 1.25, 1.75, 2.25, 2.75$ per 4T, 2T, 2T, 11T, respectively.



Figure 3.1: The equivarticity patterns over four periods of cylinder oscillation, 4T, at $R = 200: A = 0.13, f/s_0 = 1.25$ when $h = 0.75, Fr \approx 0.0$ [T $\approx 0.04, 56.566 \le t \le 72.727$: (147.1877). The causi-backed on **55** mode, see 4T, is observed.

For largency main $f/f_{1,0} = 1.25$, the fine exhibits quark probet behavior every to provide of synthesis constitution, q^{-1} , while $12 \le 1 \le 247$. The first is nonpossible for l < 1017. Figure 3.1 displays the exploritivity patterns for $f/f_{1,0} = 1.25$ over fing provide of synthese ordination, G^{-1} , while $107 \le l \le 1017$. The vertex displays main the sparse backwards on the mode, there study vertex are advantarily adds from the upper and howe vertex displaying rules that displays which the sparse backward main the previous vertex displaying cycle dash in the issue value of the employment L for J^{-1} . Our $T/T_{1,0} = 0.27T_{1,0}^{-1} \le 17T_{1,0}^{-1} \le$ upper data grape of the cylinder. Then, this waters borouw disturbed dwelly divergence of $(-2T_{1})$ can find ally proposely into the downlamme of the cylinder, added by the downlamme of paratities varies as the heart adselling layer. However, heard disturbed is provided by the cylinder disturbed of the cylinder of the cylinder of the cylinder of the cylinder disturbed of the cylinder of the cylinder disturbed of the cylinder di

The behavior of the first for $f_{11}^{-1}(f_{12}) = 171$ is pumping index ordinal, $g_{11}^{-1}(g_{12}) = 171$. Its pumping the first is morpholds for l < 47. Its Figure 3.2, the exploration purposes new two periods of pulped endlishing, $g_{11}^{-1}(g_{12}) = 100$, $g_{12}^{-1}(g_{12}) = 100$, g_{12 3.1. Vortex shedding modes at $Fr \approx 0.0$: h = 0.75

the the previous wortex abeding cycle. This co-stating positive vortex pir continues to develop over $0^{-1} \leq 2T/6$, and the shoch in the lawer wortex shocking region of the cylinder at t = 5T/6. Hence, in the quasi-locked-on $\mathbb{C}(\mathbf{P} + \mathbf{S})^{+}$ mode, per 2T, a single vortex and a pair of co-stating vortices shed alternativy over 2T. Conference is observed for this degenery ratio.



Figure 3.2: The equivariarity patterns over two periods of cylinder oscillation, 27, at R = 200, A=0.13, $f/f_0 = 1.75$ when h = 0.75, $F \approx 0.0$ ($T \approx 2.86$, $28.860 \le \epsilon \le 20.506$; (107) 127). The canari-hold on CP + S7' mode, ore 27, is observed.

For frequency ratio $f_{1/h}^{-1} = 2.5$, the flow display quasi-prioridic balanciar every 27 within $4T \le t \le 237$, followed by mon-periodic balanciar within 27T < t < 337, and then quasi-periodic balanciar every 27 within $32T \le t \le 247$. Figures 3.3 and 3.4 displays the equiverticity patterns for $f_{1/h}^{-1} = 2.5$ over two periods of cylinder coefficients, The observed works and doubt is the quasi-balancia of C28F modes. per 27, while at $T \leq t \leq 277$ and $327 \leq t \leq 2377$. In this mode, the elements of adjust of a majn structure of appears remains from the resport and bowe show largers accurate which was periods of pholone scattlinks, 277. In Figure 3.4 a, appears the structure of $2 \leq t \leq 2377$, and enabless with a structure of appear accurate by the order period scatter abulating order and the structure of $2 \leq t \leq 2377$. The remains of the structure of $2 \leq t \leq 2377$, and the subscatter and appears on the obspice of the order period scatter abulating regime at the cyclicity at the structure of $2 \leq t \leq 2377$. It can be added to the structure of the order period scatter abulating regime at the cyclicity and the subscatter and the structure and regime version works abulating code cartinus to advect period $2 \leq t \leq 2377$. A positive version work abulating the period version at the abulation of the cyclicity or $2 \leq t \leq 2377$. A positive version work abulating code cartinus to the structure of the cyclicity or $2 \leq t \leq 3377$. A positive version work abulating code cartinus to the frame of the cyclicity or $27 \leq t \leq 2377$. A positive version work abulating code carting were structure abulation abulation at the code structure abulation at the str

The flow of frequency ratio $f/f_{0} = 2.73$, exhibits quarkeridot behaviour every eleven periods of cylinder exciliation, 117, within 97 $\leq t \leq 337$. The flow is nonpublic for t < 0.75, figure 3.3, displays but explorationity pathwares for $f/f_{0} = 2.75$, over decen periods of cylinder oscillation, 117, within 227 $\leq t \leq 337$. The tweets adding mode is the quark-balance (CBS)² mode, per 11.17, within 97 $\leq t \leq 337$.



Figure 3.3: The equivorticity patterns over two periods of cylinder oscillation, 2*T*, at R = 200; A=0.13, $f/f_{\rm H} = 2.28$ when h = 0.75, F = 0.0 ($T \approx 2.267$, $23.088 \le t \le 28.860$); ($ST_{\rm c}$ 1077). The constribution on C285⁵ mode, new 7.7; is observed.

core UT. Thinking a magnitum waters which has dowloaded in the previously were advantage, or do matrims to decay out $T_{2} < 1 \leq r < m d$ doks the for tegre source advantage, upping at the dynamic source and the structure graves and advantage of the structure of the T/T is multiple and the structure source is a then mer which of the dynamic source of the structure of the structure advantage of the structure of the structure of the structure source is a the structure of the st



Figure 3.4: The equivorticity patterns over two periods of cylinder oscillation, 27, at R = 200, $\Lambda = 0.13$, $f/f_0 = -2.5$ when h = 0.75, $Fr \approx 0.0$ [7 = 0.2447, $76.319 \le t \le 80.808$; (347.367). The causi-backed on C235^{*} reads, per 27, is observed.

the new sheaf of the relation. Thus current subsequently values at t = 7.7, and the the resulting positive struct she that we have true doubling response of the explicit d = 3.7. The plasmine structs from from the evolutions response of the structure d = 3.7. The plasmine structure is the random barrier does at d = 3.7. The double structure d = 3.7. The structure d = 3.7 was an evolve structure d = 3.7. The structure d = 3.7 was absorbed we structure d = 3.7. The structure d = 3.7 was a used by formal positive structure d = 3.7 was d = 3.7 which we have the mer who and d = 0.001 we structure d = 3.7 with d = 3.7. This is the mer was and d = 0.001 was d = 3.7. $S \leq 4.5$ with T_{cont} and d = 0.001 with d = 0.001structure d = 3.7 was d = 3.7. $S \leq 4.5$ with T_{cont} and d = 0.001 which in its the mer was and d = 0.001 with $T_{cont} \leq 1.7$. $S \leq 4.5$ with T_{cont} and d = 0.001 we do in structure d = 0.001 with $T_{cont} = 0.7$. $S \leq 5.5$ with $T_{cont} = 0.001$ we do in $T_{cont} = 0.001$ with $T_{cont} = 0.001$ w t = 9T. Thus, in the quasi-locked-on C(8S)^{*} mode, per 11T, four vortices alternately develop from each side of the cylinder. Each vortex that has shed, in this case, was created from coalescence.



Figure 3.5: The equivorticity patterns over eleven periods of cylinder oscillation, 11*T*, at R = 200, A=0.33, $f_1 f_0 = 2.75$ when h = 0.75, F = 0.0 [*T* = 1.837, 40.40 $\leq t \leq 60.66$; (227, 337)). The emulti-back-den CBSS² is observed.

3.2 Vortex shedding modes at $Fr \approx 0.0$: h = 0.5

Figures 3.6-3.9 display the equivorticity patterns in the near wake region of the cylinder for $f/f_0 = 1.25, 1.75, 2.25, 2.75$. The observed flow behaviour is quasi-periodic for $f/f_0 = 1.25, 1.75, 2.25, 2.75$ per 9T, 2T, 2T, 3T, respectively.

The observed behaviour of the flow for the smallest frequency ratio, $f/f_0 = 1.25$, is crussi-periodic every nine periods of cylinder oscillations. 9T, within $4T \le t \le 24T$. The flow is non-neriodic for t < 4T. Figure 3.6 displays the equivorticity rotterns for t/L = 1.25 over nine periods of cylinder oscillations. 9T, within $13T \le t \le 22T$. The observed vortex shedding mode is the quasi-locked-on 148* mode, per 97, within $4T \le t \le 24T$. In this mode, alternate shedding of seven vortices from the upper and lower vortex shedding region of the cylinder, within 9T is observed. From this figure, detach from primary negative vortices in the near wake region. The positive vortices negative vortex formed during the previous vortex shedding cycle sheds downstream in the unner shadding layer of the cylinder. This vortex is then subsequently shed into the near wake region of the cylinder at t = 5T/2. A negative vortex developed cave $3T \le t \le 7T/2$, is forced to shed at t = 4T due to the interaction of a developing positive vortex in the lower vortex shedding region of the cylinder. Over $4T \le$ t < 9T/2, a negative vortex develops in the upper vortex shedding layer of the cylinder. This negative vortex then sheds downstream of the cylinder at t = 5T. The vortex subsequently sheds into the upper vortex shedding laver of the cylinder at t = 13T/2. Similarly, a negative vortex developed over $13T/2 \le t \le 7T$, sheds into the upper vortex shedding region of the cylinder at t = 15T/2. Over $8T \le t \le 17T/2$. a negative vortex develops in the upper shedding layer of the cylinder. Then, this vortex detaches at t = 9T aided by the development of a positive vortex in the lower side of the cylinder. Meanwhile, a positive vortex developed from the previous vortex shedding cycle sheds into the near make region at t = T/2. The development of a the cylinder. This positive vortex then sheds downstream of the cylinder at t = 7T/2. Subsequently, a positive vortex in the near wake region of the cylinder develops over $7T/2 \le t \le 4T$, and is then shed into the lower vortex shedding region at t = 9T/2. The newly formed positive vortex formed over $5T \le t \le 11T/2$, subsequently sheds into the downstream of the cylinder at t = 6T. At the next oscillation period t = 7T a positive vortex, formed over $11T/2 \le t \le 13T/2$, sheds into the lower vortex shedding region of the cylinder. Finally, a positive vortex developing over $15T/2 \le t \le 17T/2$ region, and consequently sheds downstream of the cylinder at t = 9T. Hence, in the quasi-locked-on 14S* mode, per 9T, seven vortices alternately develop from each side

In Figure 3.7, the equivorticity patterns over two periods of cylinder oscillation, 2T, are displayed for $f/f_0 = 1.75$ within $14 \le t \le 16T$. The vortex shedding mode for





Figure 3.6: The equivarticity patterns over nine periods of cylinder oscillation, 97, at R = 200, A=0.13, $f_1/f_D = 1.23$ when h = 0.5, $F_T \approx 0.0$ ($T \approx 4.04$, $52.525 \le t \le 89.883 :$ 0.07, 2277). The cause backed one 148° mode, per 97, is observed.

the how event adulting layer at l=71%. Moreovalle, a pair of positive co-rotating science formed along the province works adulting optic ensuring to the other poser $0 \le l \le 37\%$. This positive vortex pair is then adopted to the interaction of a large graphene vertex in the appre vortex adulting layer and a a round, shold hus the howave vertex adulting required to the Grabe d = 2.7% (Hers, in , the quaribodied GP d = 3% mode, a together vortex and corotating positive vertex pair are simulated and within Te7.



Figure 3.7: The equivarisity patterns over two periods of cylinder oscillation, 2T, 4t $R = 200: A = 0.13, f/f_0 = 1.75$ when $h = 0.5, Fr \approx 0.0$ [$T \approx 2.886, 40.401 \le t \le 44.176$: (147:1673). The enucl-bodied-on CIP + S1^{*} mode, see 27, is observed.

At frequency ratio $f/f_0 = 2.25$, the flow exhibits quasi-periodic behaviour every two periods of cylinder oscillation, 27, within 37 $\leq t \leq 97$, 157 $\leq t \leq 507$, 257 $\leq t \leq$ 317 and 377 $\leq t \leq 417$, respectively. A transition into non-periodic behaviour, of the flow, course within 97 $\leq t \leq 157$, 193 $\leq t \leq 257$, 317 $\leq t < 377$ and 417 c+c eff. Tgper 3.5 displays the equivariary parameter for $//p_{eff}$ = 225 over two probles of physics contrained. The value in get 2 = 100 The worst collection mode is the quark-hold-on COPF random per 2T, is not true interest the first display quark periode baction. It bit marks a single worst during large during the makement of two againets works as the provide source for large and the makement of two againets works as the provide source for large and emissions in a solway quark (≤ 2 T A at at a bacquire source for large during the makement of two againets works as the provide source for a single displays and the mark (≤ 2 T A at at a bacquire source for a single source for the single source at < 2T T A capatities works, formula much encodences of two provides works at < -2T T A capatities works, formula much encodences of two provides works at < -2T T A capatities works, for a single source of the transfer of provides of the transfer of the transfer of the transfer of the transfer source of the transfer of the transfer of the transfer of the transfer source of the transfer of the transfer of the transfer of the transfer source of the transfer of the transfer of the transfer of the transfer source of the transfer of the transfer of the transfer of the transfer source of the transfer of the transfer of the transfer of the transfer source of the transfer of the trans



Figure 3.8: The equivarticity patterns over two periods of cylinder oscillation, 2T, at R = 200, A = 0.13, $f/f_D = 2.25$ when h = 0.5, F = 0.0 [T = 2.247, $35.91 \le t \le 40.40$: (167, 187)). The causi-block-den CC287' is observed.

3.2. Vortex shedding modes at $Fr \approx 0.0$: h = 0.5

conjugation over three periods of cylinder oscillation, 3T, for $f/f_0 = 2.75$, within $30T \le t \le 33T$. The vortex shedding mode observed is the quasi-locked-on $C(28)^*$ mode, ner 3T within 6T < t < 54T. This mode describes the shedding of a single vortex of opposite rotation from the upper and lower vortex shedding regions of the cylinder, within 37. In this figure, a co-rotating negative vortex pair formed during the previous vortex shedding cycle continues to develop $0 \le t \le 2T/6$, and a third negative vortex begins to co-rotate with the pair at t = 3T/6. The three negative vortices co-rotate over $3T/6 \le t \le T$, and the tertiary negative vortex layer of the cylinder at t = 7T/6. It is evident that over this time period, the secondary negative vortex stretches almost parallel to the free-surface. The development and shadding cycle, but shadding of nonative vertices come to occur. Meanwhile, a positive vortex developed during the newsions writes shedding cycle develops over $0 \le t \le$ 2T/6, and then approaches a second positive vortex at t = 3T/6. These two positive vortices coalesce at t = 5T/6, only to separate into two positive vortices which corotate over $T \le t \le 9T/6$. At t = 10T/6, the co-rotating positive vertices coalesce a final time and the resulting positive vortex develops over $10T/6 \le t \le 11T/6$. and then subsequently sheds into the downstream of the cylinder at t = 2T. Hence, the alternate formation and shedding of two vortices within 37. results in the quasilooked on C(28); mode nor 37.



3.3. Vortex shedding modes at $Fr \approx 0.0$: h = 0.25

Figure 3.9: The equivariativy patterns over three periods of cylinder oscillation, 37, et R = 206; $\Lambda = 0.13$, $f/f_0 = 2.75$ when h = 0.5, h' = 0.0 [T = 1.837, $\delta 0.006 \pm \ell \le 0.006 \pm$ (307, 337). The sum-b ideal cone $C(285^\circ)$ mode, per 37, is observed.

3.3 Vortex shedding modes at $Fr \approx 0.0$: h = 0.25

Figures 3.10-3.14 display the equivariaity patterns in the near wals of the cylinder when $f/f_0 = 1.25, 1.75, 2.25, 2.75$. The observed flow behaviour is (i) periodic for $f/f_0 = 1.25, 1.75, 2.75$ per 37, 277, 107 respectively, and (ii) quasi-periodic for $f/f_0 = 2.25$, per 57, respectively. For $I/I_0 = 1.25$, the flow displays a periodic pattern over three periods of cylinder oscillations. 3T, within $2T \le t \le 20T$. The flow is non-periodic for t > 20. In Figure collector coefficient 37 within 10 $\leq t \leq 137$. The sorter shadding mode is the locked. on C(4S) mode, per 3T, within $2T \le t \le 20T$. Figure 3.10, reveals that a negative more vertex shedding laser at t = T/6. The development of a negative vortex occurs negative vortex in the near value region of the cylinder. The resulting negative vortex develops over $4T/6 \le t \le 11T/6$, and then sheds completely into the upper vortex which shed, retain an attachment to the free surface. Meanwhile, a positive vortex formed during the previous vortex shedding cycle develops over $0 \le t \le 4T/6$, and vortex develops and then begins to approach a second positive vortex at t = 9T/6. The positive vortices co-rotate over $10T/6 \le t \le 13T/6$, and then coalesce to form a single positive vortex at t = 14T/6. This positive vortex develops over $15T/6 \le t \le 17T/6$. shadding laws, the nonitive vortex is then forced to shad into the downstream of the collector at t = 3T. Hence, in the locked on C(48) mode, per 3T, two vertices

At $f/f_0 = 1.75$, the flow displays periodic behaviour every two periods of cylinder oscillation, 2T, within $3T \le t \le 34T$. The flow is non-periodic for t < 3T. Figure 3.11 displays the equivorticity patterns over two periods of cylinder oscillation, 2T, within



3.3. Vortex shedding modes at $Fr \approx 0.0$: h = 0.25

Figure 3.10: The equivariative patterns over three periods of cylinder oscillation, $3T_i$ at R = 200 A=0.13; $f_1 f_2 = 125$ when h = 0.25, $Fr \approx 0.0$ [T $\approx 4.040, 40.04 \leq t \leq 52.52 \pm 1007, 137]$. The quasi-folded one C(48) models, per 3T_i is observed.

10% $\leq \epsilon \leq 210$. The were adviced mode darks and a fact balance of $\Omega(S)$ mode $\rho(S) = 0.01$, while $\sigma(\epsilon) \leq 1.01$, this make, one waves developes and barrandy dust on each side of the cylinder over 27, haitaily, a suggestive sector formed during the previous versus doubling cycle dust into the upper absoling layer of the cylinder $\alpha = 7\beta$. The former of each enginest versus second in the manufactor of the versus absoling cycle, but these vertices remain attached to the cylinder. It is barry wave hydrogenergines of the cyclic versus dust dashes one $0 \leq 1 \leq 217\beta$.

3.3. Vortex shedding modes at $Fr \approx 0.0$: h = 0.25

and then begins to approach the primary positive vortex in the near walk region of the cylinder $\mu t = 37/6$. The positive vortices evaluates at t = 47/6, and the resulting positive vortex which develops over $57/6 \le t \le 97/6$, sheds downstream of the cylinder at $t \approx 97/6$.



Figure 3.11: The equivariative patterns over four periods of cylinder oscillation, 27, at R = 200: h=0.33, $f/f_B = 1.75$ when h = 0.25, $F \approx 0.01$ ($T \approx 2.88$, $54.834 \le t \le 60.666$: (197, 217)). The quasi-locked on $\mathbb{C}(28)$ mode, per 27, is observed.

At the frequency triat $f_{1,0}^{L} = 22$, the flow shifts quasiporticle behavior within $U \le t \le 23t$ and $U \le t \le 24t$ and on normalic behavior within $U \le t \le 23t$. The simulation of $U \le t \le 13t$ and $U \le 12t$ and $U \le 12t$ of cylinder solutions, S_1 , within $S^2 \le t \le 30t$ and $20T \le t \le 31t$, respectively for $f_1/f_1 = 22t$. The quasi-based-on Co(S8)ⁿ most is observed our the periods of cylinder solutions, S_1 within $S^2 \le t \le 30t$ and $23T \le t \le 30t$, respectively for F_1 per solution to see with a sample work formed during the previous I = T/3 The shed negative vortex retains an attachment to the free-surface and hence does not shed downstream. This negative vortex begins to approach a negative vortex in the near wake region at t = 2T/3. These negative vortices co-rotate over $2T/3 \le t \le T$, and at t = 4T/3 the co-rotating negative vortices coalesce. The resulting negative vortex sheds into the upper vortex shedding layer at $t \approx 2T$. A negative vortex formed from the coalescence of two negative vortices at t = 8T/3develops over $3T \le t \le 11T/3$. This negative vortex is then shed into the upper vortex shedding region of the cylinder at t = 4T. Meanwhile, a positive vortex formed vortex at t = T/3. These co-rotating positive vortices coalesces at t = 2T/3. The resulting positive vortex develops over $T \le t \le 5T/3$, and then begins to co-rotate with a second doubles vortex in the near wake region over $2T \le t \le 7T/3$. At t = 8T/3, the co-rotating positive vortices coolesce and the newly formed positive nonitive vortex in the near make region at t = 11T/3. The resulting positive vortex develops over $11T/3 \le t \le 14T/3$, and then sheds into the lower shedding layer of the cylinder at t = 5T.

At frequency ratio $f/f_0 = 2.75$, quasi-periodic flow behaviour over ten periods of cylinder oscillation, 107, within $97 \le t \le 307$ is observed. The flow is non-periodic for t < 97. In Figure 3.14, the equivariably patterns of the flow are displayed over ten periods of cylinder oscillation, 107, within $197 \le t \le 297$, for $f/f_0 = 275$. The voters alsofilg mode is the lock-door. (SOS) mode, per 107. In this mode, three

3.3. Vortex shelding modes at $Fr \approx 0.0$: h = 0.25





single strings as a derauficity of the string of the string of the string of the string wave starts chadding cycle shade downtreams of the cyclicke string the previous starts chadding cycle shade downtreams of the cyclicke at v = T. The development of a significe strength streng

3.3. Vortex shedding modes at $Fr \approx 0.0$: h = 0.25





using a length over $3T_{ij}^{2} \leq t \leq 3T_{ij}^{2}$, and then underse with a sector hyperic true at $t \rightarrow 3T$. The sampling regards were two solves with an other amplitus extent in the near wake region of the cylinder $u \in u$, and the near by Found experimtories is thus dual into the domentium of the cylinder u = 1 = T. In the lower vectors thus that also most pointime vectors u denotes the sector of the sector u = 1 of the sector of the sector u denotes the sector u denotes u



3.3. Vortex shedding modes at $Fr \approx 0.0$: h = 0.25

Figure 3.14: The equivarially patterns over ten periods of cylinder oscillation, 107, at R = 200: h=0.33, $f_1 f_0 = 2.75$ when h = 0.37, $F \approx 0.01$ [$T \approx 1.837$, $34.894 \le 4 \le 53.260$: (197, 207): is observed.

to the secondary positive vortex in the near wale region of the cylinder at t = 7T/2. These positive vortices coalesce at t = 4T. The resulting positive vortex develops over $9T/2 \le t \le 5T$ and then shock downstream of the cylinder at t = 11T/2. A positive vortex formed from the coalescence of two positive vortices at t = 7T, develops over $7T \le t \le 17T$, and then shock as a strengy vortex into the lower vortex of shofting region of the cylinder at t = 9T. Hence, in the locked-on C(6S) mode, per 10T, three vortices develop and shed on each side of the cylinder over 10T.

3.4 Summary and Discussion

Tables 3.15 summarizes the effect of the free surface presence for the case Fr re-0.0 k = 0.75 0.5 0.25 when 1/L = 1.25 1.75 2.25 2.75 has on vortex shedding modes and their periods. T., The majority of the occurring vortex shedding modes are a combination of the classical modes as defined by Williamson and Roshko (1988). Unlike the case Fr = 0.2, the presence of the free surface does not lead to the loss of lock on for h = 0.25, 0.5, 0.75. In fact, lock-on modes occur at each 1/1, for each cylinder submergence depth. h. Table 3.15 shows that the period of vortex shedding is 2T for $f/f_0 = 1.75$, regardless of cylinder submergence depth, h. This is also the case for $f/f_0 = 1.75$, in the absence of the free surface. However, it can be seen from this table that with the decrease of h from h = 0.75, 0.5 to h = 0.25, the contact shadding modes of U/L = 1.75 changes from the email behaviors $C/P + S^{+}_{-}$ at h = 0.75, 0.5 to the looked on CONS) mode at h = 0.25. The inclusion of free surface at h = 0.95, 0.5, 0.75 for I/L = 1.75 also results in the occurrence of conference in the vortex shadding modes, as present to the vortex shadding mode in the absence of the free surface $(h = \infty)$. On the other hand, the inclusion of free surface at $f/f_0 = 1.25$, as compared to the vortex shedding mode of $h = \infty$. The flow associated with frequency ratio $f/f_{\rm o} = 2.25$, exhibits the existence of two states of onad-periodic behavior at cylinder relationspinse depicts h = 0.75, 0.5, 0.75. The worther abelies belawise correcting for one disordered from the the $f_{\rm col}$, see equivalent. Hence, there are no charges in modes symmetry with the charge in states for $f/f_{\rm col} = 235$, at $\lambda = 0.75, 0.5, 0.5, 1.7$. The summarily observed modes for this ones are the changin COSym mode, the $C_{\rm col}^{\rm col}$ and $C_{\rm col}^{\rm col}$ modes which are building the repetition of the distantic COSY mode, the $C_{\rm col}^{\rm col}$ and $C_{\rm col}^{\rm col}$ modes which are building the repetition of the distantic COSY mode, the $C_{\rm col}^{\rm col}$ and $C_{\rm col}^{\rm col}$ modes which are building the repetition of the distantic COSY mode, the $C_{\rm col}^{\rm col}$ mode $T_{\rm col}^{\rm col}$ modes $T_{$

The offset of the cylinder schamp area (spin, 4), (-1, 15, 12, 12, 12, 13, 16, 16, 16, 12, 12, 13, 12), and (-10, 12), (-11, 12), (

	h = 0.75		h = 0.5		h = 0.25		$h = \infty$	
11/6	Mode	T_{e}	Mode	12	Mode	ц.	Mode	T_{v}
1.25	-89	ţ;	145*	97	C(4S)	37	C(10S*)	11
	$(10T \le t \le 24T)$		$(tT \le t \le 2tT)$		$(2T \leq t \leq 20T)$		$(15T \le t \le 3TT)$	
1.75	$\mathbf{C}(\mathbf{P}+\mathbf{S})^*$	27	$\mathbf{C}(\mathbf{P}+\mathbf{S})^*$	22	C(25)	27	2P	27
	$(4T \leq t \leq 35T)$		$(tT \leq t \leq 3tT)$		$(3T \leq t \leq 34T)$		$(19T \leq t \leq 51T)$	
2.25	C(28)*	27	C(28)*	27	C(4S)*	ţ,	C(8S)*	97
	$(4T \leq t \leq 27T)$		$(3T \leq t \leq 9T)$		$(4T \leq t \leq 23T)$		$(40T \leq t \leq 66T)$	
	$(32T \leq t \leq 42T)$		$(15T \leq t \leq 19T)$		$(26T \leq t \leq 36T)$			
			$(25T \leq t \leq 31T)$					
			$(37T \leq t \leq 41T)$					
2.75	C(8S)*	11T	C(2S)*	12	C(6S)	loT	$\mathbf{C}(\mathbf{P}+\mathbf{S})^*$	31
	$(9T \le t \le 35T)$		$(6T \le t \le 54T)$		$(9T \leq t \leq 50T)$		$(49T \leq t \leq 81T)$	
].].		ŀ		18

vertex shedding modes and their periods, T_{α} at R = 200: A = 0.13, $J/f_{B} = 1.25$, 1.75, 2.25, 2.75. The superscript the bracket quasi-bedraften modes.



Figure 3.16: The effect of the cylinder submergence depth, h(=0.25, 0.5, 0.75), and the frequency ratio, $f/f_0(=1.25, 1.75, 2.25, 2.75)$, on the equivorticity patterns at R = 200; A = 0.13, Fr = 0.0.

4. Free surface flow past a streamwise oscillating cylinder at Fr = 0.2

Is this Claster, system is incorporable two-fluid model with a streamwise coefficient cylinde branch a free surface is unmerically investigated for the Fronde number one of $P_T = 0.2$, at the colorise almongprose branch a = 0.75, 56,52. The numerical simulations are conducted at a fixed Raymolds number of R = 200, and deplacement amplitude, A = 0.33, in the frequency ratio range, $1.25 \leq f/h \leq 2.75$, by an increment of 0.5.

4.1 Fluid forces and vortex shedding modes

4.1.1 Fluid forces at Fr = 0.2 : h = 0.75

In Figure 1.1, the time binary of the Resolution, C_{11} for FRO of C_{12} and be Lingan patterns of C_{12} endpings the trans of C_{12} endpings the transformation of the transformation transformation (M_{12} = 235 mH/ $_{12}$) = 275, the C_{12} stars of M_{12} = 276, the C_{12} stars of the transformation transformation (M_{12}) = 26 mH/ $_{12}$ =

(1), = 125 diapley quasipended signatures every no periods of epideov collisions, (1), = 125 diapley quasipended and $0 \le \le \le \le X$, magnetism, The quasipendedity of the C₁ patterns for $T_1/h_{--} = 17.2.2$, is also suggested by the corresponding the composition and the C₁ patterns over. As the switching time is model of $T_{--} = 17.2.2$, the turns of C₁ haven responses the second second second second the same distance of the second second second second second second terms of the same of C₁ haven responses the switching the same distance of the periods status) which are highly mesoscensizes at the second second second $T_{--} = 52.2.2$. The question of C₁ houses in the distance of C₁, but in the distance of the magnetism of the distance of the same set $T_{+}/h_{--} = 27.2$, for the $T_{+}/h_{--} = 52.2$. The question of C_{+} houses are $T_{+}/h_{--} = 52.2$, for all the 32.2.1 houses the distance of the distance of the distance of $T_{+}/h_{--} = 12.2$. The question of $T_{+}/h_{--} = 12.2$, for $T_{+}/h_{+-} = 12.2$, for $T_{+}/h_{--} = 12.2$, for $T_{+}/h_{+-} = 12.2$, for T_{+}

In Figure 1.2, the time itsney of the darg coefficient, C_{ijk} is the DS of C_{ijk} , and the Lingan potterm of C_{ijk} independent on the C is the $I_{ijk}^{(L)} = 1.52,23,25.73$ display non-possible display. The transverse for $I_{ijk}^{(L)} = 1.52,23,25.73$ display non-possible displayment. The transfer C_{ijk} for $I_{ijk}^{(L)} = 1.57$ displayer and matrix probed signature every $I_{ijk}^{(L)} = 1.73$, indexes the charactilization of C_{ijk} may I_{ijk} is smaller than C_{ijk} terms $I_{ijk}^{(L)} = 1.73$. The posterior that the ensum is repetitive and experiment of the statistical statistical of C_{ijk} of $I_{ijk}^{(L)}$ statistical and experiment of the statistical statistical statistical statistical statistical $I_{ijk}^{(L)} = 1.57$. The posterior merophonic μ $(I_{ijk}^{(L)} = 1.57$. Add is the decay distribution of $I_{ijk}^{(L)} = 1.57$. The posterior merophonic μ $(I_{ijk}^{(L)} = 1.57$. Add is the distribution of C_{ijk} of $I_{ijk}^{(L)} = 1.57$. The distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. The distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)} = 1.57$. Add is the distribution of $C_{ijk}^{(L)$


at R = 200 : A = 0.13, $f/f_0 = 1.25$, 1.75, 2.25, 2.75 when h = 0.75, Fr = 0.2. The $0 \le t \le 46.2$, $0 \le t \le 42.6$, 1 outh f/f_0 .



0<1<0.6

at l + 3/L. This is infrastrute of the offset of f sensitivity on (L_1) increases from 12 to 13.7. Similarly, the horderiners can be $r \sim r_{1}$ to its m bern (the the hydroxic large for each f/f_{0} are also producinately confided to the appear half plane, and then they digidly shift in the low in f plane ari f/f_{10} increases from 13.75 to 27.5. All the consided beappary series, f/f_{10} denotes of the f/f_{10} increases from the second section of the hydroxic large are constructed sections. This indicatos that the each barries of the hydroxic large hard mergy random is from the earliest the first f is also second the f/f_{10} increases, the area endowed by $C_{0}(d_{1})$ increases and hence the total energy transferred from the endowed to the first terms.

4.1.2 Vortex formation modes at Fr = 0.2 : h = 0.75

Figures 4.3-4.8 display the equivorticity and atramaline patterns, and pressure contours in the max value of the cylinder when $f/f_0 = 1.25, 1.75, 2.25$, and 2.75. The observed flow behaviors is (ii) quasi-periodic per 2T for $f/f_0 = 1.75, 2.25$, and (ii) mon-periodic for $f/f_0 = 1.25, 2.75$.

A series of instantaneous equivoritizity plots over twenty periods of cylinder oscillation, 207, is plotted in Figure 4.3 for $f/f_{0} = 1.25$. This figure shows that the frequency of the vortex absolutions is not looked on to the frequency of the cylinder motion. Conference was not observed for this case.

Figure 4.4 displays the equivorticity patterns over two periods of cylinder oscillations, 2T, for $f/f_B = 1.75$. The shedding of a single vortex and a pair of positive co-rotating vortices occurs within two periods of cylinder oscillation, 2T. This results in the



Figure 4.3: The equivacticity patterns over investy periods of cylinder coefflation, 207, at R = 200 A=0.13, $f/f_0 = 125$ when h = 0.75, Fr = 0.2 ($T \approx 4.04, 20.20 \le t \le 101.01$); (T_{c} 2071) (non-periodic starb.).

quark-ideal eq. QP + SY mode, po 27, within $4T \leq c \leq 167$. This is consistent with the C_0 and C_0 behaviour at this fragmenty ratio. The flow is non-periodic for $c \geq 167$. At c = 0.7, angular wetter, formed during the previous case shadding cycle matimums to develop over $0 \leq t \leq 37/6$, and at t = 47/6, condense with a newly formal negative vectors in the same value of the cycluder. The smalling regular vectors when $(0, 0) \leq 10^{-2} \leq 23/7$, and that the holis tub two wave values of the cycluder. at t \approx 97%. Mean-blic, a pair of positive co-rotating vertices developed during the previous vertex shedding cyclic continues to develop over $0^{-} \le t \le 47/6$, and then shedd into the near value of the region at $t \approx 57/6$. The development of a longitive vertex and the development of a pair of co-rotating positive vertex over we taskability courses for the remainder of the period, within 107/6, $1 \le 27$.



Figure 4.4: The equivariativy patterns over two periods of cylinder oscillation, 2T, at R = 200, A=0.13, $f/f_D = 1.75$ when h = 0.75, $F^{\mu} = 0.2$ [$T \approx 2.886$, $20.99 \le t \le 28.86$; (ST, 1077). The canad-backed on CDP + ST mode, per 2T, is observed.

The pressure optimizer for $f/f_{\rm p} = 1.25$ in the user walls region are presented in the last onlymm of Figure 4.5 at \pm 0.7, the high pressure region has developed in the stagrather might and upper hids of the cylinder, and the lase pressure region has developed mostly in the upper side, and the downterum of the cylinder. *Cover* $T/4 \le t \le 3T/4$, symeomenes with the downterum of a positive vertex in the noise value of the cylinder, the low pressure dilute outly the set risks and domains. At the spinster The high means rights thill us the appendix of the domains. At the spinster is the sheading of a substrate verse part is rule to seen that the high penner region diffusion work plant is the the argument region. The the penner right remains probability distributions and its the lower distribution penner right remains probability distributions and its the lower distribution of the spinster of the spin strate of the sheading of the simple of the low penner site the spinster shead achieved by the sheading of the simple of the low penner is the spin star distribution of the shead strate shead at it the spin strate shead strate shead is the lower distribution of the low penner spin strategies. It is also related at the constration of the high penner region and strategies dreames.

Figure 4.6 displays the supportentity partons now two produced of politor walliants, $S_{11} = I_{11} / I_{12} = -23$ with $S_{12} \leq I_{12} = Th_{12}$ and $S_{12} = I_{12} = I_{12}$



Figure 4.5: The equiversity patterns (eff), streamline patterns (middle) and the pressure contours (right) in the near wale region of the cylinder over two periods of cylinder coefficients, 27, at R = 200. A=0.13, $f/f_0 = 1.75$ when k = 0.75, Fr = 0.2 ($T \approx 2.886$, 33.09 $\leq t \leq 28.86 : (87, 1017)$). The quasi-bolded-on C(P+8)' mode, per 27, is observed.



Figure 4.6: The equivorticity patterns over two periods of cylinder oscillation, 27, at $R = 200: A = 0.13, f/f_0 = 225$ when h = 0.75, Fr = 0.2 [7 $\approx 2.2447, 6.734 \le t \le 11.224 :$ (37, 57)]. The quasi-locked on CDS²) model, per 27, is observed.

In Figure 3.2, the presents contrast of lupungy state $I/I_0 = 22.3$ are dupled for two periods of the other distributions $T_{\rm eff}$. If $\sim T_{\rm eff}$ is the period hyper decodeparate of the the high presents in the comparison ratios of the legal charge bars have increased in the low bars of the other distribution of the legal charge bars in the increase $I_{\rm eff}$ is the low radie of other distribution of the legal charge bars in the increase $I_{\rm eff}$ and $I_{\rm eff}$ is the legal charge distribution of the legal charge materials and have bars preserve regions in the decodeparent of a surror region is and holes the low preserve regions in the decoderations of the relative $I_{\rm eff} = -2T/4$, is no neutrino the surror regions in the decoderation of the relative $I_{\rm eff} = -2T/4$, is the one that the subgroups measure and a decoderation grade variant of the relative $I_{\rm eff}$. $T_{c} \in t \in TT_{c}^{c}(t_{c}, u_{c}, u_{c})$ and intermediates series biggins in the series that the high purposent rights of the model has the series of the high purposent rights of the model back is the stagging static anguing of the clyclass and the back pursues rights all the series of the the symbol star of the clyclass and the back purposes in the symbol star of the clyclass and the star stars and the star back purposes all as if the similar the clyclass is the symbol star of the symporal star of the similar the clyclass is the symbol star of the sympotic and the similar and the clyclass (in the clyclass is the similar the sympoin all distributions in the similar star of the similar the similar the similar the similar distributions in the similar star with the similar star of the similar the almost anisotron in the similar star with a similar the similar the similar star almost an integration of the low pressure regions at $t = TT_{c}TT_{$

Figure 4.8, displays a series of instantaneous equivarity plots over trenty periods of cylinder oscillation for $f/f_0 = 2.73$. This figure displays that the frequency of the vortex shadding is not locked-on to the frequency of the cylinder motion at this particult case (son-periodic stac). Coalescence was observed for this case.

At this frequency main, $I/f_0 = 2T_0$, conformed of co-statially vertices is observed in the near value region of the cycludes. Figure 4.6 displays the conference phenomenon for $I/f_0 = 2T_0$ suce these periods of cycludes assiltants, 37. In this figure, at l = 07, a regaritive vertee, Y^+ and possible vertees T^- have developed from the upper and lower sides of the cycludes, respectively at l = 07. A regarine vertee, Y^+ and positive vertee, Y^- develops from the upper and lower and is of the cycludes vertee $Y^0 \leq l \leq 37/6$.



Figure 4.7: The equivariaity patterns (left), streamline patterns (middle) and the presure contours (right) in the near wale region of the cylinder over two periods of cylinder continuum, r_1 , at R = 200. Avoid. $J_1/f_0 = 2.25$ when h = 0.75, $F^* = 0.2$ $[T \approx 2.26, 11.02 \le t \le 15.71 + (57, 77)]$. The quasi-bolied-on $\mathbb{C}(25)^*$ mode, per 2T, is observed.



4.1. Fluid forces and vortex shedding modes

Figure 4.8: The equivaticity patterns over twenty periods of cylinder oscillation, 207, at R = 200 A=0.13, $f/f_B = 275$ when h = 0.75, Fr = 0.2 [$T \approx 1.837$, 1.837 $\leq t \leq 7.36i$; (T, 217]); (one periodic state).

At (= 47), the two positive series 2⁻ and 2⁻ orderer to frem 1 single points series 2⁻¹ for the last moduling layer of the relation. A regardless werter 3⁻ and pointse water 3⁻¹ develop from the upper and lower adds of the rylinder over 17 $\beta \le 1 \le 27$, The two negative sections ⁻⁰ et and ⁻⁰ conduct to learn the singlesequence waves ⁻¹ = the upper adding layer at -170%. For layer, which, within 37, a regardless water 3⁻¹ and positive series ⁻² are developed from the upper and lawer and the for highlay series 170% to 1570% At 107% of 1570% At 107% of 1570% At 107%.



4.1. Fluid forces and vortex shedding modes

Figure 4.9: Near wake vortex reals scence phenomenon over three periods of cylinder oxclilation, 37, at $R = 200 : A = 0.33 f / f_0 = 2.75$ when h = 0.75, $Fr = 0.2 [T \approx 1.837, 1.837 \le t \le 7.36$; (T.217) (non-periodic state).

and "4+6" coalissee to form a single negative vortex "4+6+8" in the upper sholding layer of the cylinder. However, at t = 3T, the negative vortex "4+6+8," separates and the negative vortices "4+6" and "8" begin to co-rotate.

4.1.3 Fluid forces at Fr = 0.2 : h = 0.5

In Figure 4.10, the time variation of the lift coefficient, C₂, the PSD, of C₂ and the the C₄ traces exhibit non-remeatable signatures. This observation is also surgested by the corresponding Lissalous natterns of the lift coefficients, $C_1(x)$, in which the natterns display highly non-congruent behaviour. This suggests that there are large phase variations between the fluctuating C_1 and the cylinder motion, and hence a loss of lock-on for these frequency ratios. For $f/f_1 = 1.75, 2.25$ the signatures of C_1 suggest that the flow exhibits two regimes. The C_1 trace of $f/f_1 = 1.75$. indicates the transition of the flow from the quasi-periodic state to the non-neriodic state of the near wake. The switchover occurs at $t \approx 16T$. On the other hand, the trace of C_L corresponding to $f/f_0 = 2.25$ suggests that the flow transitions from the non-periodic state to the small-periodic state. The switcheser occurs at I to 287. for this frequency ratio. The C_L trace for $f/f_0 = 1.75$ displays a quasi-periodic signature every two periods of collector oscillation, 2T, within $4T \le t \le 16T$. Once The C_i trace for $f/f_c = 2.25$ displays a non-periodic signature for t < 28T, but seven periods of cylinder oscillation, 7T, within $28T \le t \le 42T$. The quasi-periodic behaviour of $f/f_t = 1.75, 2.25$ within $4T \le t \le 16T$ and $28T \le t \le 42T$, respectively. indicates a look on between the collinder motions and the C. matterns. It is evident, that the consideration behaviour of each freemoney ratio is also successful by the

4.1. Fluid forces and vortez shedding modes

Is ease, hences, that for $f_1/h = 2.2$ the $C_1(r)$ parts of the $C_1(r)$ parts of the $C_2(r)$ parts of the quariperiodic star density are suggested before are suggested over $(c_1(r))$ parts of $c_1/(r)$ and the quariperiodic star. This induces that are f_1/h increases from 1.25 to 2.75. Use the substitution of C_2 is a band be used that the participation of the existence of a quariperiodic star. This induces that are not one only a quari-equival dimension for C_1 , along patch in the PD2 and the quaritary starts of the $C_1(r)$ patterns. In this matigment and the respective starts of the substitution of the starts and starts and part of C_2 on the parts of the part of C_2 on the the dimension part of the analysis of the the starts induce that C_1 conditions predimensing the start and definit property. Is, bland be noted that the start and definit property, h is during the and theorem to the start and the part of C_1/h is a start C_2 . Start for the starts is during the starts in the the parts from the there of C_1/h is starts that the theorem from the the P20 of $T_1/h = 2.75$. This singular, the the quarks that the exploration of C_1/h is a start of the theorem from the the parts that the deriver the parts of the ordeness case $h \to \infty_0$ is no terms that the height theorem height of C_1/h is a start and definit proper form that the the parts that the deriver the the part of C_1/h is a start of the definition of the the start and the the part of C_1/h is a start of the definition of the the start and the definition of the start and the the part of the definition of the start and the definition of the definition of the start and the definition of the definition of

In Figure 111, the time binary of the dags subfields, C_{0} the DFO of C_{0} and Lings. The singe mattering, $C_{0}(2)$ or m displays. It is worken that the C₀ times for 1/(n - 1)/(22) and 2.71 display no assemptable inguiness: On the other band, the Co tambox $\beta = 1$. The display on almost transmission $\beta = 100$, 100, 10





SD of C_D: Lissajous patterns of C_D at R = 200 : A = 0.13, f/h = 1.25, 1.75, 2.25, 2.75 when h = 0.5, Fr = 0.5 inter 4.11: The time variation of draw coefficient, Go. (Mock) and the streamwise displacement.

 $h = \infty \text{ as } f/f_{\beta}$ increases from 1.25 to 2.75, but to a lower extent. The direction of the hyperboxic kaps are constar-clockwise, indicating that the mechanical energy transformed in the cylinder to the fluid. Increases d energy transformed from the cylinder to the fluid increases as f/f_{β} increases from 1.25 to 2.75. This is a result of the increase in the area covered by the hysterwish loop of $C_D(x)$ as f/(x) forwares from 1.25 to 2.75.

4.1.4 Vortex formation modes at Fr = 0.2: h = 0.5

Figures 4.12-4.17 display the equivariative and ateramilian patterns, and pressure contorus in the near wake of the cylinder when $f/f_0 = 1.25, 1.75, 2.25, 2.75$. The observed flow behaviour is (i) quasi-periodic per 27, 77, for $f/f_0 = 1.75, 2.25$, respectively and (ii) momencies for $f/f_0 = 1.25, 2.75$.

In Figure 4.12, the equivorticity patterns for $f/f_0 = 1.23$ are displayed over twenty periods of glinder emiliation, 207. This figures represents the that the vortex shedding is not locked on to the frequency of the cylinder motion as this frequency ratio. No conducence was observed in this figure.

Figure 11 displays the equivativity patterns over two periods of cylinder coefficient, 27, for $f/f_0 = 1.75$. The sholding of a single regular vertex, and a pair of positive constraing vertices over within 27. This is reach in the equivalender of (PF s)? mode, per 27, within 4T $\leq t \leq 167$. This is consistent with the behaviour of C_k and C_0 for this frequency ratio. The first is mono-pendic for t > 167. At t = 0, a matrix works have devided from the preview works sholding ceric ourinance matrix devides of the distribution of the strength of the constraint of the strength of the constraint of the strength of the s





to develop over $UT \leq l \leq 2T/6$, and then coulones with a second arguitw retries in the near walls of the cylinder at t = 4T/6. This vertices reminuses to develop over $3T/6 \leq l \leq T/3$, and then ables into the respere vertex absoluting layer of the cylinder at $t \approx 8T/6$. Moreover, a pair of positive co-stating vertices formed during the positive vertex absoluting cylic nominum to develop over $0T \leq l \leq 3T/6$. This pair is then abled diverse after contrast of the cylinder $t \sim T$.



Figure 4.13: The equivarisity patterns over two periods of cylinder oscillation, 27, at R = 200; A=0.13, $f_1/f_2 = 1.75$ when h = 0.5, $F_T = 0.2$ [$T \approx 2.886$, 1).14 $\leq t \leq 17.32$; (T_1 , T_2). The matrix decides $C \mathbb{CP} + S^2$ mode, are 27, is observed.

The power norms of impure yran $(D_1, D_1 = 1)$ for displayed in the bar solution of Hyper 41. At $i = 0^{-1}$ is the dispersible perturbation of the low power regular balant is at the append she during bar solution of the displayement right strength perturbation of the system of the system of the displayement right strength from the stagnation region of the cyclader and their the law powers region is at the domaximum of the cyclader. In the new value, the law pressure regions and perturbation of the cyclader. In the new value, the law pressure region would be stagnation of the cyclader. In the new value, the law pressure region would be stagnation of the cyclader is the displayement of a synchronic strength of the strength strength strength strength strength strength strength strength adds in stat the arguments equation (strength strength stren is on to seen the the preserve distribution displayed $a^{-1} = 37/2$ that the same of this preserve have one spin allow distributions that the distribution of the preserve regimes. The issue preserve distribution of the upper side of the cylindre and remains that for the distribution of the cylindre energy of $a^{-1}/2.37/2$, which high preserves are regime even the have the comparison of the $a^{-1}/2.37/2$, which high preserves the size of the cylindre energy of $a^{-1}/2.37/2$, which high preserves are regime truth the high the charaction appear to the cylindre and the the large sense the large area of the high theorem and uppear has the comparison region. At the large preserves the high theorem and uppear has the cylindre resonance regime. In a 17.2.237/2, Abole the lower and uppear has the cylindre resonance region.

For frequency main $f/f_{20} = 223$, the waters advallage is now differed to any bound of the streng meansion of the clybical and the shell variants. The free scatters also places a significant rais in the absolution of the source between the data parametry in the clybical explosition of the strength of the parametry in the explosition. Figure 4.3 the data $222 \leq 222$ strength of the data material advanced of cluster conclusion, 177. The vortee shedding mode is the quark isolation on CMMP model, per 477, while $222 \leq 222$. It is this model, in means periodic per 4.2 strength on the other of the explosition of the the intermediate strength of the strength one period is the explosition of the explosition means periodic for 4 < 227. Itaking is suggestion with closely and the period variant 4 = 1.7. A sequence state frame of the 252 $d \approx 22.5 \approx 2.5$ model with strength one was the other QMMP and $4 \approx 177/3.5$. The strength worth, somework explored is at 4 = 177/3, constraints in data data of $4 \approx 17/3.5 \approx 12.5$ model and in the strength and $4 \approx 12.5$. A sequence at $4 \approx 177/3.5$. The strength worth, somework expension for the strength one periodic for $4 \approx 177/3.5$. The strength worth, bowever, appendix =



Figure 4.14: The equiverisity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wake region of the cylinder over two periods of equilater oscillations Z_1 at R = 300. A=0.13, $f/f_0 = 1.75$ when h = 0.5, Fr = 0.2 $[T \approx 2.388, 11.54] \le t \le 11.732$: $(dT_i OT)$. The quasi-locked-on $\mathbb{C}(\mathbb{P} + \mathbb{S})^2$ mode, per $2T_i$ is observed.

so containing angularies stores in the mare value of the cylinder at t = 47/3. There were broken so contain our $T_{2}^{2} \leq 1/3/7$, and on $t \geq 1/3/7$, the regularies vertex pair condence to form a magnitive vertex in the mare value of the cylinder. The remaining arguine vertex is host paramanelity into the apper vertex cholding large at t = 0.47. A superior vertex is the area walte the chylinder becodes over $T \leq 2 \leq 3/73$, and condense with a second arguine vertex t = 107/2. This mody framely imprive vertex where $m_{T}^{2} \leq 1 \leq 5/73$, and the which in the wayme remains of the







cplinder at t = 16T/3. Meanwhile, a positive vortex formed from the coolescence of two positive vortices at t = 2T/3 develops over $T \le t \le 6T/3$, and then sheds into the near wake of the collader at t = 7T/3. Furthermore, two positive vortices coalosce in

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the near weak of the cylindes at $t \rightarrow 37/2$. The resulting positive worthe obsergeous $97.5 \le (\pm 1077, a)$, and the bugins its most role with a sound positive worther, were $117/2 \le (\pm 1077, a)$. At $t \rightarrow 1077$, by gas of d so-notating points worthers on both the resulting positive worther does a source of the cylinder s = 1.5 Finally, a points weat created from the molecures of two points worthers a = 1.5 Timology a points weat created from the molecures of two points worthers a = 1.5 Timology and the dense of the point of the two points worthers a = 1.5 Timology are the source of the two points of the source of the cylinder a = 1.00 M more, in the quark-bolders O(2007) mole, por 77, three workes advanturely dowing and add from each th of the cylinder.

Figure 4.18 displays the present distribution for the frequency state |11/2| = 2.25over some produced of colless |11/2| = 1.25 in the sec |11/2| = 1.25 in the lower limit is an interpret of the theorem preserve rights in the lower size in the section of the origin the sec |11/2| = 1.25 is |11/2| = 1.25 is

.95





Figure 4.16: The figure caption is given on page 101



4.1. Fluid forces and vortex shedding modes

Figure 4.16: The equivorticity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wale region of the cylinder over serves periods of cylinder oscillations, T_1 at R = 200 As-013, f/(R = 220, when h = 0.5, Fr = 0.2 $[T \approx 2.204, 62.851 \le t \le 78.561$: (287, 3577). The quasi-locked on C(68)^{*} mode, per T_1 is observed.

4.1. Fluid forces and vortez shedding modes

ability and by the space of the theory and σ of the objects. As the impurity corner is their in the object of the spin shows the spin show the the spin spin seq and the abs of the objects, and that the the parameter spin shifts makely to the upper sole, and absorbs of the objects. The object of the object of the object of the object parameters of the object of the object of the object of the object parameters regimes at $\tau = 0.275, 7717$ are object on a surrest image of the low parameters regimes at $\tau = 0.275, 7717$ are object on the object of the low parameters regimes at $\tau = 0.275, 7717$ are object on the object object of the low parameters regimes at $\tau = 0.275, 7717, 700$ are object of the low parameters regimes at $\tau = 0.275$ (see ALX, 531, 511, 511; The imparate thing to result of the low parameters parameters at the result on the object of the low parameters of the low parameters regimes at the the result of the low parameters of the low para

Figure 4.17 displays the optioseticity patterns over twenty periods of tylinder oreffation, 207, for $f/f_0 = 275$. At this frequency ratio, the vertex shading is not locked on to the frequency of the cylinder oscillation. That is, no locked on mode occurs for this case. Condenses of vertices occurs for this case.

4.1.5 Fluid forces at Fr = 0.2 : h = 0.25

In Figure 4.18, the 1R coefficient, C_L , the spectra, PSD, and Lisupices patterns, $C_L(x)$, of C_L are displayed. It can be seen that for $f/f_0 = 1.25$, the C_L trace exhibits a non-repeatable signature. Furthermore, the $C_L(x)$ pattern of $f/f_0 = 1.25$ is zoncomputed large phase variations between the flattanting C_L and the motion of the



Figure 4.17: The equivorticity patterns over twenty periods of cylinder oscillation, 207, at R = 200: A = 0.13, $l/f_B = 2.75$ when h = 0.5, $F_T = 0.2$ $[T \approx 1.837, 6.183 \le l \le 45.91 :$ (57, 2577), (some periodic state).

gluids). On the other hand, the C_1 turns for $I_1/h = 1.73,23.73$ followed in the simulation of the same in the quarity profile star to the man periodic stars. The axial house for each I/h_0 accurs at $\approx 117,247,267$, respectively. The C_1 terms for $I/h_0 = 17,22,3,3.73$ edding a quarity periodic approximation provides $I_1/h_0 = 17,23,27,3$. If $I_2/h_0 = 17,22,3.73$ end and $I_2/h_0 = 2.73$ edding a spin section of the dimension of the simulation of the simulation

the mole composing $C_{1}(r)$ partures shalls in signature behaviour at these frequency that is, it is also obtained that the comparing of the $C_{1}(r)$ partners interview at I/kincreases from 1.25 to 2.37. This rapids that there is reduction in plane variations somessare the regulare results on C_{1} , on al non-zero is the calculations of C_{1} to more somessing the regulare results on C_{1} and an increase in the calculations of C_{1} to more somessing the regulare many some size the plane some size $k = \infty_{1}$ the $C_{2}(x)$ partners are confined in that the upper and large that plane. Spectra of C_{2} conversionly the transformation of the some size of the firsting frequency. f On the other hand, the dimining park covers $k \in I_{1}(k = 1.3)$.

Figure 1.15 displays the dags coefficient, C_{inc} power spectras, P(M), and Lingburg structures, $C_{i}(r)$, of (r), non-bown start that (r) = ratios of <math>r/(h) = 1.25, 2.50 display at almost repeatible signatures on star 27. The C_{in} true for r/(h) = 1.35, displays at almost repeatible signatures on star 27. The C_{in} true for r/(h) = 1.35, displays a display and many-probability displays. The companding spectra of C_{inc} both its the quadraperiodic ant many-probability displays. The companding spectra of C_{inc} both its the administration of the star displays and many spectral displays spectra of the star of the star of the star displays and many spectra of the star of the star of the star of the star displays and the star of the star displays and the star of the star of the star displays and the star of the star displays and the star of the star of the star displays and the star of the star of the star displays and the star displays and the star display displays and the star display displays and the star and star displays and the star display displays and the star display displays and the star is a display displays and the star display displays and the star is a display displays into the star half displays the star displays and the star display displays and the star display displays and the star display displays and the star is a display display. The star displays and the star display displays and the star display displays the star displays displays and the star display displays displays and the star display displays displa



of C₁: Lissapus patterns of C₂ at R = 202; A = 0.13, I/f₂ = 1.25, 1.75, 2.25, 2.75, when h = 0.25, Fr = 0.2. The Bow states in the new wake region are indicated for each ///6,

4.1. Fluid forces and vortex shedding mode



The basic and PSD plats for f/(6 - 1.75, 2.75, 2.75 are obtained for quark-periodic states in the following timethere have a state of the states in the following time $to term in 20 and 2 st z <math>\approx$ 23 and 2 st z \approx 23 by 23 and 22 core states of the states in the corresponding to the states in the same wave review and infrared for each f/(6.

4.1. Fluid forces and vortex shedding modes

4.1.6 Vortex formation modes at Fr = 0.2 : h = 0.25

In this section the equivorticity, streamline patterns and pressure contours in the near wale of the cylinder when $f/f_0 = 1.25, 1.75, 2.25, 2.75$ are displayed in Figures 4.20-126. The observed flow behaviour is (i) non-periodic for $f/f_0 = 1.25, (ii)$ quasi-periodic per 27.37, 47, for $f/f_0 = 1.75, 2.25, 2.75$, respectively.

It is noted that the equivariative particular is a cylicher abstrampton edge of k = 0.2for some that we end for the angine or sequence the cylicher observations depind as l = 0.5, 13.7. It is the mass, we stress weak hole of the edge or some addeding enging of the elighted, some the fiber outdrices. It was the solar to see a stress that we refers the set on the new value spins, and have makes the domination of k the distribution of the elighted, some the set of the elighted stress the set of the distribution of the elighted stress the set of the set of the set of the distribution, 20.7 is a stress that the fiber set of the set of the set of the set of the distribution of the set of the distribution of the set of the distribution of the set of the distribution of the set of the set of the set of the set of the distribution of the set of the distribution of the set of the set of the set of the set of the distribution of the set of the

Figure 4.21 displays the experimitiry parterns for $f/f_0 = 1.75$ never two periods of explore and endings, f_1 with $T \le t \le 1.17$. The vertex sholling mode is the quark-lacked on QCBS, per 37, within $T \le t \le 1.17$. The first is many-particle for t > 1.17. This is non-matrix with the behaviour of G_2 and G_3 at the large-part part is the mass t = 1.27 of the large-part parts in the large part t = 1.27. This large t = 1.27 (t = 1.00), and t = 1.27 (t = 0.00) are t = 1.27 (t = 0.00).



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Figure 4.20: The equivorticity patterns over twenty periods of cylinder oscillation, 207, at R = 200 Au.0.3, $f_1 f_0 = 125$ when h = 0.25, Fr = 0.2 $|T \approx 4.04, 20.20 \le t \le 101.01$: (07, 2071) (non-periodic state).

shals into the upper vertex shedding layer at t = 87/6. In the lower vertex shedding region, a positive vertex formed during the previous shedding cycle continues to develop over $0.7 \le t \le 3.7/6$, and then sheds into the sear wake of the cylinder at t = 4.7/6. Hence, the shedding of a positive vertex followed by the shedding of a negative vertex, within 27, results in the quasi-locked-out C258⁺ mode, per 27.

In Figure 4.22, the pressure contours are displayed for $f/f_0 = 1.75$ over two periods of



Figure 4.21: The equivarticity patterns over two periods of cylinder oscillation, 27, at $R = 200: A = 0.13, f/f_0 = 1.75$ when h = 0.25, F = 0.2 [$T = 2.86, 23.068 \le t \le 28.860$: (ST, 107]). The quasi-bodies on C(285)'' mode, per 27, is observed.

cylicles sufficients, 27. K t = 0.7, (6) argo in Fulge present deslops in the upper black of the chylical host is buy present region despite black of chylical is the near wide region, and in the lower old of the cylicale, $R_1 = 27.2$, the high present region is a stress of the descapation is applied of the cylicale. The stress wide factor present regions in the down ratios of the cylicale. The near value region, the law present values and R_1 is the grave dist of the cylicale. The stress regions in the down ratios $R_1 = 0.02$ (R_2) and the dodgener of a significant stress of R_2 (R_1 is stress wide) that the high present region near many frame the down ratios of R_2 (R_2 is stress wide) that the high present region near many frame the engines in the down ratios R_2 (R_2 is stress wide) that the high present region near many frame the engines in the down ratios R_2 is the down ratios R_2 is the distribution of the moment of the her present region in the frameworks are briefly region in the distress the region of the her present region. Box (R_2 more the region is the framework region in the distress the region R_2 is the framework region in the distress the region R_2 is the re pressure at the time. One as negative vector has abed at $t \rightarrow ST(t)$ (see Figure 2.21), in the development of a wave negative, and pository, wetter constructors t - GT(A,it can be sure, that the construction of two pressure increases dimensionly of the sure wave regation of our brighten. Figure pressure can be detected downstreams of the cylinder at this time. However, our $TT/4 \le t \le 2T$, the high pressure region (bound mark) downstream), abilits many large only by first feed mark and hours of the cylinder. This pressure right mith hour by from the front and houts of the cylinder. This is builded the cylinder. The low pressure contours in the saw which the cylinder are able more the time instrument of TT and t = 2T. Hence, the periodic nature of the field field mark the cylinder is repeationed by the low pressure constants is the saw which of the cylinder.

In Figure 12.1, the exploringly partners over three periods of cylinds coefficient, Tar. and dupped of $T_{1}^{-1} = 22$. The verse shealing mode is the quasi-backeton $Q(P + S)^{-}$ mode, per 3*T*, which in Si'z + (z + 2*T*. The flow is many periods for t > 34T. The is constant with the backwars of C_{1} can L_{2} for this flowqueer struct. It is related that a magnitude version formula during the previous worter sheading, which into the new value of the cylinds v = 1 of T/h. It is not worter with the approxtrans matching of T_{1} of T/h_{2} is a shead on t = 1 or T/h_{2} . A decised sing at $t = T/h_{2}$, it is also to a majorize worter in the new value region to the cylinds remains t = 1 or T/h_{2} and the finally during t = 1 or T/h_{2} . Hence, the final data sheading modes at this finally during t = 1 or T/h_{2} . Hence, the final data sheading modes at the single version t = 1 or T/h_{2} for the single version t = 1. The distribution of the magnitude version t = 1 or T/h_{2} for the single version t = 1. The distribution of the distribution of the single version t = 1 or T/h_{2} . The single version is the version is respective to the single version t = 1 or T/h_{2} . The single version t = 1 or T/h_{2} . The distribution of the distribution of the single version t = 1 or T/h_{2} . The version is respective the version of the single version t = 1 or T/h_{2} . The version T/h_{2} of T/h_{2} of the the single version T/h_{2} data single version T/h_{2} data single version T/h_{2} .



Figure 4.22: The equivorticity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near value region of the epithedr over four periods of cylinder contlinition, α_1 at R = 302 : A = 0.33, $f/r_{\rm e} = 1.55$ when R = 0.035, F = 0.2 ($T \approx 2.886 \pm 2.886 \pm (97,1117)$). The quasi-holend on C(68)⁴ mode, per 27, is observed.

pointies were continues to develop over $5T_{ij}^{0} \in t \leq 100\%$, and then begins to constate with a second positive vortex at t = 117/6. The positive vortex pair corotation ever $2T_{ij}^{0} \leq 120\%$ and then ables in the to post wave of the cylinder at t = 1577/6. Hence, the shadding of a negative vortex followed by the shadding of a positive vortex pair, in which one of these positive vortex is formed from conformers, which in the smatchedness OCP = 87\% mode per 21 < 217. 7



Figure 4.23: The equivariative patterns over three periods of cylinder oscillation, 37, at $R = 200: A = 0.13, J/f_0 = 2.25$ when $h = 0.25, F_T = 0.2$ [$T = 2.2447, 00.00 \le t \le 47.14$: (187, 217]). The quasi-locked on C(P + S7) mode, per 37, is observed.


Figure 4.24: The equivariativy patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wale region of the cylinder over three periods of cylinder ordinations, T_{ii} of R = 200, A = 0.33, f/(R = 2.25 when h = 0.25, F = 0.25 f/(R = 0.25), F = 0.25, F =

In Figure 4.24, the pressure contours are displayed for $f/f_0 = 2.25$ over two periods of cylinder oscillation 3T At t = 0T this figure shows the development of the high pressure region in the upper left side of the cylinder and the low pressure region in the upper right side and downstream of the cylinder. Synonomous with the shedding of a negative vortex at t = T/3, it is evident that the region of low pressure is confined reedominantly to the unner and lower sides of the cylinder in the near wake region. The high pressure region is mostly confined to the stagnation region of the cylinder. At t = nT/3 (n = 1.4, 7), the low pressure regions are mainly confined to the upper and lower sides, and downstream of the cylinder. The high pressure region, resides in the starnation region. With the development of new negative and positive vortices at t = 2T/3, it can be seen that the low pressure region shifts substantially to the front and lower side of the cylinder. As a result, the high pressure region shifts downstream of the cylinder. At every t = nT/3 (2.5.8), the high pressure regions seem to be confined to above and below the low pressure regions in the downstream of the cylinder. The low pressure regions in the near wake region, are confined to the front and lower sides of the cylinder at these time instances. Furthermore, synonomous development of new negative and positive vortices at t = 8T/3, as expected, the low pressure region dominates the front, lower side, and downstream of the cylinder. On are mainly confined to behind the cylinder (near wake region), but also to the upper side of the cylinder. Once again, the high pressure region resides prodominantly in the stagnation region of the cylinder. The low pressure contours in the near wake of the cylinder are almost the same at the time instances t = 0T and t = 3T. Hence, the

4.1. Fluid forces and vortex shedding modes

periodic nature of the flow field around the cylinder is reproduced by the low pressure contours in the near wake of the cylinder.



Figure 4.25: The equivariativy pathena over two periods of cylinder oscillation, 27, m R = 200; A = 0.13, $f/f_D = 2.75$ when h = 0.25, Fr = 0.2 ($T \approx 2.2447$, $6.734 \le \le 1.324$; (37, 571). The prasi-locked on CQP + S¹ mode, per 27, is observed.

Figure 3.2 should be expectedly pointers for $f_{1/2}^{1} = 2.1$ sets for periods of quades containing, f_{1}^{1} the sum is holding mode in the quasi-biodened SQP + 87 should per 67, within 127 $\leq t \leq 287$. The flow is non-periodic for t > 287. This is consistent with the C₁ behaviors at the $f_{1/2}^{1}$ hubidly, is require vortex index one the low scalars at t = 7/2. This theory is non-term into a singular vortex in the near value engine of the cylinder at t = 7, and then also one marsure t = 167/2. The Hermiter vortex them is waited by model at t = 167/2, reflexement, this model with t = 17/2. The subscience that the integrities water in the constant t = 1-7/2. The term is structure with region at t = 167/2, reflexement t = 1-7/2. The term is structure with region at t = 17/2, reflexement with the Hermiter with region t = 100 models at t = 57/2. The term is structure to a model of the structure t = 100 models t = 100. The term is structure to a model of the structure t = 100 models t = 100 models t = 100 models t = 100 models t = 100. and 47, respectively, after subsequent detachments from negative vortices in the near wake region of the cylinder. Maamshile, a pair of positive vortices develops over $0 \le t \le T/3$, and then sheds into the lower vortex shedding region of the cylinder at t = 2T/3.

Figure 4.26 displays the pressure contours for the frequency ratio $f/f_0 = 2.75$ over four periods of cylinder oscillation, 4T. At t = 0T, the high pressure region has developed in the stagnation region of the cylinder, and the low pressure region has developed mostly behind the cylinder. Synonomous with the shedding of a negative vortex at t = T/3(see Figure 4.25), it is evident from the pressure distributions displayed at t = T/2that the high pressure region shifts below the cylinder, and also above and below the low pressure regions in the downstream of the cylinder. The low pressure has been forced to the immediate upper and lower sides of the cylinder. On the other hand, synonomous with the shedding of a positive vortex into the upper vortex shedding region at t = 2T/3 (see Figure 4.25), it can be seen from the pressure distributions at t = T that the high pressure region has shifted mostly back to the stagnation region. The low pressure region has shifted to the front and bottom sides, and downstream. of the cylinder (near wake region). In general, at every t = nT (n = 0, 1, 2, 3, 4) the low pressure region is confined predominantly to the downstream of the cylinder. with the highest concentration of low pressure occurring in the near wake region of the cylinder. On the other hand, at t = nT/2 (n = 1, 3, 5, 7), the high pressure region extends from the stagnation region to below the cylinder (near wake region), and above and below the low pressure regions in the downstream of the cylinder. The low pressure contours at t = 0T and t = 4T are nearly reducated in this figure. Hence,





Figure 4.26: The equivarially patterns (hdf), streamline patterns (middle) and the pressure contours (right) in the near wake region of the vylinder over four periods of cylinder continuism, r_{11} at R = 302; A = 0.33, f/R = 255 when R = 0.25, F = 0.25, F

4.2 Summary and Discussion

For the case Fr = 0.2, h = 0.75, 0.5, 0.25 when $f/f_2 = 1.25$, 1.75, 2.25, 2.75 table 4.1 summarizes the effect the free surface newsuce has on the vortex shedding modes and their periods. T., Table 4.1 shows that non-classical modes occur in the presence of the free surface at h = 0.5 for $f/f_{0} = 2.25$ and in the absence of the free surface $(h = \infty)$ for $f/f_0 = 1.25, 2.25$. The new non-classical vortex shedding modes are formed from multiples of the classical C(2S)* mode (see Williamson and Roshko (1988)) and include the C(108)", C(88)" and C(68)" modes, where 10.8 and 6 refers to the total number of vortices shed from the cylinder within the respective periods. the loss lock-on for the smallest frequency ratio, $f/f_0 = 1.25$, at h = 0.75, 0.5, 0.25and the largest frequency ratio, $f/f_0 = 2.75$, at h = 0.75, 0.5. On the other hand, lack on modes occurs at 1/L = 1.75, 2.95, researdless of cylinder submergence denth. sholding period for 116 = 1.25 is two periods of collider oscillation, 27. However, as h decreases from ∞ to 0.25 at $f/f_{0} = 1.75$, the lock-on modes, unlike the vortex shedding periods, change. However at the highest frequency ratio, $f/f_0 = 2.75$, the email.locked.on $C(P + S)^*$ mode occurs at both $h = \infty$ and h = 0.25. It is evident from Table 4.1 that the commonly observed mode is $C(P + S)^*$.

Tables 4.2 display the mean lift, \tilde{C}_{L} , and mean drag coefficients, \tilde{C}_{D} , for $f/f_{0} = 1.25, 1.75, 2.25, 2.75, respectively. It is evident that as <math>h$ decreases from ∞ to 0.25, the \tilde{C}_{L} values witch from positive values (for $h = \infty, 0.75)$ to negative values (h = 0.5, 0.25). It is presence of a few surface, it can be seen that the \tilde{C}_{L} values variable \tilde{L}_{L} values values (h = 0.5, 0.25).

f/fo	$h = \infty$		h = 0.75		h = 0.5		h = 0.25	
	Mode	T_{π}	Mode	T_{*}	Mode	T_{π}	Mode	T_{v}
1.25	$C(108)^*$	7T	non-locked		non-locked		non-locked	
1.75	2P	2T	$\mathbf{C}(\mathbf{P}+\mathbf{S})^*$	2T	$\mathbf{C}(\mathbf{P}+\mathbf{S})^*$	2T	$C(2S)^*$	2T
2.25	C(8S)*	97	$C(2S)^*$	2T	C(68)*	7T	$\mathbf{C}(\mathbf{P}+\mathbf{S})^*$	3T
2.75	$\mathbf{C}(\mathbf{P}+\mathbf{S})^*$	37	non-locked		non-locked		$\mathbf{C}(\mathbf{P}+\mathbf{S})^*$	4T

4.2. Summary and Discussion

Table 4.1: The effect of the free surface inclusion on vortex shedding modes and their periods, $T_{\mu\nu}$ for the case Fr=0.2 when $h=0.25, 0.5, 0.75, \infty$ at R=200: $A=0.13, f/f_8=1.25, 1.75, 2.25, 2.75.$ The superscript ^{ist} denotes quasi-locked-on modes.

which for $\log_{10}-6131\leq C_{15}\leq 10208$ As f/f_{10} terreness from 124 or 2.75, item to small table C_{15} conditions for h=0.25 and h=0.25 terres $f/f_{15}=2137$ in this means for h=0.25 and h=0.25 terres $f/f_{15}=2137$ indices for h=0.25 terres $f/f_{15}=2137$ implies the start h=0.25 terms for $f/f_{15}=2135$ implies the start h=0.25 terms for $f/f_{15}=2135$ implies the start h=0.25 term $f/f_{15}=2135$ implies the start h=0.25 term $f/f_{15}=2135$ implies the $f/f_{15}=2135$ implies the start $f/f_{15}=2135$ terms for the start h=0.25 term $f/f_{15}=215$ terms for the start h=0.25 te

	\hat{c}_{ι}				\widehat{C}_D				
115	$h=\infty$	$\lambda=0.75$	h = 0.5	$\Lambda=0.25$	$h = \infty$	k=0.75	b = 0.5	$\Lambda = 0.25$	
1.25	0.0055	0.1183	-0.00714	-0.4756	1.2467	1.5212	1.5640	1.6486	
1.75	0.0044	0.1566	-0.0330	-0.5428	1.4123	1.6752	1.7630	1.67649	
2.25	0.0007	0.1826	-0.04745	-0.56279	1.2610	1.7029	1.7020	1.6331	
2.75	0.0130	0.1346	-0.10166	-0.6131	1.2235	1.6362	1.70417	1.60959	

Table 4.2: The effect of the free surface inclusion on the mean lift, \widehat{C}_L , and drag, \widehat{C}_D , coefficients for the case Fr = 0.2 when $h = 0.25, 0.5, 0.75, \infty$ at R = 200 : A = 0.013, 1/(h = 125, 1.75, 2.52, 2.75).

1/5	CLema				CDyma				
	$h = \infty$	h=0.75	h = 0.5	h=0.25	$h - \infty$	k=0.75	h = 0.5	k = 0.25	
1.25	0.4925	0.7966	0.7503	0.8431	1.3157	1.6156	1.6886	1.9001	
1.75	0.7411	1.0815	1.0612	0.9538	1.5851	1.8802	2.0452	2.3049	
2.25	0.4205	0.9149	0.8558	1.0851	1.7617	2.1955	2.3842	2.7946	
2.75	0.3302	0.7589	0.8455	0.9864	2.2544	2.5887	3.0679	3.5943	

Table 4.3: The effect of the free surface inclusion on the RMS lift, C_{Lrms} , and drag, C_{Drms} , coefficients for the case Fr = 0.2 when $h = 0.25, 0.5, 0.75, \infty$ at R = 200: A = 0.13, I/5, p = 1.25, 1.75, 2.25, 2.75.

In Table 4.3, the root mean square (RMS) values of the lift and drug coefficients, C_{Lrows}, C_{Rrows} , are displayed for cylinder aubmergence depths h = 0.75, 0.5, 0.25, and the arbitrary case $h = \infty_c$, respectively. In this context, the RMS values are used to measure the varying quantities of the lift, C_{L1} and drug, C_{D2} , coefficients. The C_{LRMS} and C_{LRMS} and C_{LRMS} which coefficients called the lift, C_{L1} and drug, C_{D2} , coefficients.

$$C_{Lorms} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (C_{L_i})^2}, \quad C_{Borns} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (C_{D_i})^2}.$$

It is easily, in the transmitted of the $C_{\rm exc}$, where a runde larger in the presence of the free entrops. A = 1.5 Mos. Str. thus the 100 Section of the thermodynamic theory and the transmitter $h_{\rm exc}$ is the grant, as it a beams from x to 17.5. the $C_{\rm exc}$, wellers on the memory of the h=12.52 st. Th, with the h=2.5 . The $C_{\rm exc}$, wellers of $f_{\rm e}/h=1.52$ st. Th, with the h=2.5 . The $C_{\rm exc}$, where the ord $f_{\rm e}/h=1.52$ st. Th, with the entropic of $C_{\rm exc}$, wellers of the $f_{\rm e}/h=1.52$ st. Th, which is the state of $f_{\rm e}/h=1.52$ st. The $f_{\rm exc}/h=1.52$ st. The order of 1.54 st. The st

Figures 4.5-4.26, display the pressure contour plots of h = 0.75, 0.5, 0.25 when $f/f_0 =$

1.25, 1.75, 2.25, 2.75. The pressure contour plots at h = 0.75 when I/L = 2.25, h = 0.5 when $f/f_b = 1.75$ and h = 0.25 when $f/f_b = 2.75$ indicate that at t = 0T the high pressure region develops mostly in the stagnation region of the cylinder. The high pressure region at h = 0.75 when $f/f_2 = 1.75$, h = 0.5 when $f/f_4 = 2.25$, and h = 0.25 when $f/f_0 = 1.75, 2.25$, develops in the stagnation region and the upper left side of the cylinder. For $f/f_0 = 1.75$ at h = 0.75, 0.5, the low pressure region initially develops in the unner side of the cylinder and downstream. On the other lower side of the cylinder and downstream. For $f/f_{0} = 2.25$ at h = 0.75, 0.5 the low downstream of the cylinder. At h = 0.25, the frequency ratio $f/f_0 = 2.75$ initially displays the development of the low pressure region in the upper side of the exlinder and downstream. In general, the low pressure regions develop in the near scale of the cylinder, where the velocity is highest (formation of new vortices) and hence simificantly affect the fluctuating lift forces acting on the circular cylinder. Positive and negative vortices which have shed downstream of the cylinder, are represented by the low pressure region (blue contours) for all f/f_0 . Another interesting aspect of the low pressure contours of the circular cylinder is that for some cases, mirror imares of the structures of loss measure are observed in the near woke region of the cylinder. Specifically at h = 0.75 when $f/f_0 = 2.25$, the low pressure regions at t = 0.7/4.37/4.7are mirror images of the low pressure contours at $t = T_1 5T/4_1 7T/4_2 T$ (see Figure 4.6). At h = 0.5 when f/L = 2.25, the low pressure regions at t = 0(2T, 5T, 7T) are almost mirror images of the low pressure contours at t = T(3T.6T). On the other

4.2. Summary and Discussion

hand, for this frequency ratio, the structures of low pressure at t = 77/2 is much y replica of the low pressure regions at t = n7/2 (n = 3, 5, 7, 9, 11, 10) (see Figure 4.9 c) is also interesting in the low field for t = 100 (n = 50, the light pressure region at t = n7/2 (n = -1, 3, 5, 7) ended boxs the stagmation region of the cylinder to below the cylinder (anse walse region) and above and below the low pressure regions in the downstream of the cylinder for the Toper 4.30.



Figure 4.27: The effect of the cylinder submergence depth, h(=0.25, 0.5, 0.75), and the frequency raiso, $f/f_0(=1.25, 1.75, 2.25, 2.75)$, on the equivorticity patterns at R = 200, R = 0.13, Fr = 0.2.

In Figure 4.27, the effect of the collisive submergines depth $h_i = 0.20, 0.0, 0.5, 0.$ and the longency ratio, $f/A_i = 1.25, 1.75, 2.25, 2.75$, on the equivacisity patterns in the near weak regime are summitted. The simplexity are taken at the instant, z(t) = A. For the periodic/quasi-periodic cases the snapshots are taken over the time interval in which the flow nearbox a periodic/quasi-periodic state. For morpolocide cases, the commonly appearing equivalent patterns that. For morpolocide cases, the commonly appearing equivalent patterns that D_i and D_i are defined by the size of the time interval $0 < t \le 100$, are displayed. It can be seen that the deformations vortex structures in the lower shedding layer display significant changes, as opposed interact greatly with the free surface, and as a result experience rapid diffusion across the free surface at this cylinder submergence depth. The vortex shedding is skewed symmetric in favor of the positive vortices. For each h value, the shed vortices are relatively oval shaped, but as the cylinder submergence depth is reduced from ∞ to 0.25 the major axes of the shed vortices downstream of the rylinder he more parallel to the free surface. For all cylinder submergence depths h = 0.25, 0, 5, 0.75, the flow behaviour becomes more complicated as f/f_0 increases. It is evident that the behaviour of the near wake region at h = 0.75 for each I/f_c is similar to the reference case $h = \infty$, whereas a noticeable difference occurs for the smaller exlinder submergence depths k = 0.25, 0.5 as I/f_0 increases from 1.25 to 2.75. In general, an increase in the frequency ratio, f/fe, from 1.25 to 2.25 results in the decrease of vortex formation length (maximum length by 44%) for the cylinder submergence depths h = 0.25, 0.5, 0.75. In addition, the length of the upper vortex shedding layer increases as f/f_3 increases in the presence of a free surface at h = 0.25, 0.5, 0.75.

Free surface flow past a streamwise oscillating cylinder at Fr = 0.4

In this Chapter, a viscous incomposable two-fluid model with a streamwise confilingly cylindre branch a first surface is numerically investigated for the Proofse number one of $B^{-} = 0.4$, at the following numerically disording the 0 = 0.75, 0.510. The numerical simulations are conducted at a fixed Reynolds number of R = 200, and displacement anglitude, A = 0.33, in the frequency ratio range, $1.25 \le f/f_{\rm p} \le 2.75$, where $f/f_{\rm p}$ increases for a increase of d.

5.1 Fluid forces and vortex shedding modes

5.1.1 Fluid forces at Fr = 0.4 : h = 0.75

The time index of the Bi confisions c_{ij} , the FBO of C_{ij} and the corresponding Line transport for (C_{ij}, C_{ij}) , are chapter with gravitant of Linger three stress f_{ij} is a single stress of the stress of f_{ij} is a single stress of the stress of

Figure 12, applicy the two links of refs the dispersion of the softward C_5, the PDB of C_2 and the companying Links and partons of C_5. A bit homosen watar $M_1^2 = 1.15 \times 175$, the C_5 inters exhifts an expectable signature. The C_5 inters is $M_1^2 = 1.15 \times 175$, the C_5 inters exhifts an expectable signature are true of orly of the softward intergraph of the softward intersection of the softward interpret behaviour for the morphode situation of the first $M_1^2 = 1.15 \times 121$ and $M_2^2 = 1.15 \times 121$ in and $M_2^2 = 1.15 \times 121$ and $M_2^2 = 1.15 \times 121$ in and $M_2^2 = 1.15 \times 121$ in the softward interpret behaviour for the morphode situation of the first of $M_1^2 = 1.15 \times 121$ and $M_2^2 = 1.15 \times 121$ and $M_2^2 = 1.15 \times 121$ in the parton for a softward in the M_2^2 in the source of behaviour in the interpret behaviour and the so and intermed to the softward interpret the interchard in energy during it is the softward interpret in the intervent of the interchard intergraph of ends in the order intermed in the Hermitian distribution that the methanistic energy during it is during of the intervent of the intervent of the intervent of the intervent origin at the softward intervent is M_2^2 finding the intervent of a model and the intervent of the inter







large peaks at f and f + 5 $f_8/4$, with the dominant peak occuring at f + 5 $f_8/4$. Hence, it is evident that the effect of f, on C_D , weakens as f/f_0 increases from 1.25 to 2.75.

5.1.2 Vortex formation modes at Fr = 0.4 : h = 0.75

In this section the equivorticity and streamline patterns and the pressure contours in the max wake of the cylinder when $f/f_0 = 1.25, 1.75, 2.85, 2.75$ are displayed in Figures 5.3–5.8. The observed flow behaviour is (c) non-periodic for $f/f_0 = 1.25, 2.75$ and (ii) quasi-periodic, per 27, for $f/f_0 = 1.75, 2.25$, respectively.

In Figure 5.3, a series of instantaneous equivativy plots over twenty periods of cylinder coefficients, 207, is plotted for $f/f_0 = 1.25$. This figure shows that the frequency of vectors shedding is not looked on to the frequency of the cylinder motion, for this frequency ratio. Coaliscence is not observed in this figure.

Figure 15, findings the explorating patterns in the new solar of the optimal results incrediated of minimum statismus. The baryons of $M/L_{2} \sim 15$. The baryons dealing on a gaugine voters from the upper voter dealing range, more used in the pattern statismus of the distribution of the distribution from the larger voters dealing range, more within the pattern dealing of equivalent and the distribution of $C_{1} \simeq 10^{-2}$. The isometry of the distribution of the distribution of $C_{1} \simeq 10^{-2}$. The isometry of $C_{2} \simeq 10^{-2}$ for the barrow material that $C_{1} \simeq 10^{-2}$. This is smallern with the behavior of C_{1} and C_{2} for the barrow matching distribution of $C_{1} \simeq 10^{-2}$. The barrow matching distribution of $C_{2} \simeq 10^{-2}$. The barrow matching distribution of $C_{2} \simeq 10^{-2}$. The barrow matching distribution of $C_{2} \simeq 10^{-2}$. The barrow matching distribution of $C_{2} \simeq 10^{-2}$. The barrow matching distribution of $C_{2} \simeq 10^{-2}$. The barrow matching distribution of $C_{2} \simeq 10^{-2}$ for the barrow matching distribution of $C_{2} \simeq 10^{-2}$. The barrow matching distribution of $C_{2} \simeq 10^{-2}$. The barrow matching distribution of $C_{2} \simeq 10^{-2}$ for the barrow matching distribution of $C_{2} \simeq 10^{-2}$. The barrow matching distribution of $C_{2} \simeq 10^{-2}$ for the barrow matching distribution of $C_{2} \simeq 10^{-2}$. The barrow matching distribution distribution of $C_{2} \simeq 10^{-2}$ for the barrow matching distribution distributio

shole into the upper vertex abeling region of the optimizer t = 1.1776 and the interaction of a spin-rest vertice in the lower vertex deading region. On the other hand, a pair of positive co-coxisting vertices developed in the previous vertex shading cycle continue to co-coxist our $0.07 \le 1.57$, for all we addressively add in the wave what of the origin s = 1.7. Its the transmission of the period under consideration, $T_{17}^{0.05} \le 1.57$, a positive pair of co-rotating vertices and a regular vertex develop. In cosme to abolt.

The presence outsoms in the new value region of the cubble for $(H_{1} \sim 1.5)$ were presented in the incoming Physics 5 over twe present on cubble relations. The $A \in = 0$, the high presence region develops in the strap and the region of the presence region is the strap and the experised. For a strap of the the strap of the presence region is most relation of the strap of the experiments of the directly constrained on the strap of the strap of the of the plusht. The high presence regions must to full its inter clocked scretized of the plusht. The high presence regions must to full its inter clocked scretized of the plusht. The high presence regions must to full its inter clocked scretized in general direct strap of the strap of the plusht presence region (here) the lock and the large blue is larger at t = 1, it is evident for the the high presence region along high presence high measures the full its the clocked measures in the inter work of the clocked scretized is the strap of the presence region in court is the strap of the clocked scretized is the strap of the strap of the strap of the presence region in courts of the clocked measures of the strap of the presence region in courts of the strap of the clocked scretized is the presence region in courts (here the strap of the clocked scretized is the specific erg and the strap of the type region A = 0.000 (here the strap of the clocked scretized is the specific erg and the strap of the high presence has all to all the strap of the specific erg and the strap of the high presence has all to all the the clocked for the trans of the the presence has all to all the presence has all to all the specific erg and the strap of the high presence has all to all the the clocked for the trans of the specific erg and the the presence has all to all the specific erg and the specific erg



Figure 5.3: The equivorticity potterns over twenty periods of cylinder oscillation, 207, at R = 200: A = 0.33, $f_1 f_2 = 1.25$ when h = 0.75, Fr = 0.4 $|T \approx 4.04$, $20.20 \le t \le 101.01$: (077.2377) (core-secondic state).

region has a significant pensence above and below the low pressure regions in the downstreams of the cylinder. The pressure contours at time instances t = 0T and t = 2T are nearly identical to each other. Hence, the quasi-periodic nature of the flow is repredoming the the pressure contours.

Figure 5.6 displays the equivorticity patterns in the near wake of the cylinder over two periods of cylinder oscillation, 2*T*, for frequency ratio $f/f_p = 2.25$. This figure displays

5.1. Fluid forces and vortex shedding modes



Figure 5.4: The equivarticity patterns over two periods of cylinder oscillation, 27, at R = 200; A=0.13, $f_1f_2 = 1.75$ when h = 0.75, $F_P = 0.4$ [$T \approx 2.886, 20.10 \le t \le 28.86$: (07, 107)]. The quash-bolied on C(P + 87) mode, per 27, is observed.

the sholding of a positive source has the upper stars a sholding region, Bobsel V has showing of a spin version that noise version shoulding region, within 27. The rambing mode the quasi-bolest on $(228)^{-1}$ mode, per 2.7, which 27.5 ± 5 mode of 2.5 ± 4 the frequency ratio. A sequence waves dowshop over $10^{-2} \le 12^{-2}$ 7.72 and subsymptotic positions with a sourced anguitres werther in the more wave region of the spin-should region of the spin strength str



Figure 5.5: The equivorisity patterns, streamline patterns and the pressure distibution in the near value region of the cylinder over two periods of cylinder oscillation, 27, at R = 200. A=0.13, $f/f_0 = 1.75$ when h = 0.75, Fr = 0.4 [$T = 2.886, 23.00 \le t \le 28.86 : (87, 107)$]. The mass-bodyn-of CPF $\approx 5^{\circ}$ work, see 27, k bolarwed.



Figure 5.6: The equivoriality patterns over two periods of cylinder oscillation, 27, at R = 200; A=0.13, $f/f_{\odot} = 2.23$ when h = 0.75, Fr = 0.4 [$T \approx 2.237$, $13.468 \le t \le 17.508$: (07,87)]. The quasi-local-on $\mathbb{C}(28)^{\circ}$ mode, per 27, is observed.

subsequently shed into the lower vortex shedding region of the cylinder at t = 5T/6. New negative and positive vortices develop over $T \le t \le 2T$, but cause to shed.

In Figure 3.7 the pressure contains in the near walks of the cylinder are displayed for $(M_{1}-25)$ on two poinds of cylinder collinder. $(M_{1}-25)$ core two poinds of cylinder collinder, $(M_{1}-25)$ core two poinds of cylinder collinder $(M_{1}-25)$ core two poinds in the designation of the strengthest methods of the designation of the designation of the strengthest core $(M_{1}-25)$ core two poinds of the designation of the poind of the designation of the designation of the strengthest core $(M_{1}-25) \leq 2M_{1}/2$. It can be not the block pointerval function built to the lower alow of the cylinder, are set. The Mag pressure regime shifts then explands are set. The Mag pressure regime shifts the destance matrix in the de









of the cludes at t = 3T/4. One the positive vortex has shot at t = 3T/6 (see Figure 5.0), it can be seen from the presence directionic and plaqued at t = -7 that the area of high pressure shifts muchly back to the singulation region of the cludes. The region of low pressure similar markly in the barry with of the cluther. In constrain, with the devolgant of a new mapping vortex in the serve value of the cylinder, it can be seen that over $3T/4 \le t \le 3T/4$, the sens of high pressure affilts mattericity of the similar voltage of the devolgant of the cluther the cylinder. In one has that over $3T/4 \le t \le 3T/4$, the sens of high pressure affilts mattericity of the devolgant of a new started by the thread startistic region of the devolgant of

1.90

of the cylindri to above and balow the low parsaure contours in the divergences of the cylindric. The lower region data may be a set of the spectra of the theory of the obcylindre to the upper radie. Once the arguint worth, the old of at $\sim 117\%$ (for Figure 5.6), can be seen in the spectra divergination display at $l \sim 27$ March the thick playment region reades probabundly in the stagnation region and the the parameter region reades probabundly in the stagnation region and the the parameter region reades probabundly in the stagnation region and the the parameter region reades probabundly in the cylindre $d \sim 1-0277.1/27.172.174$ and an advance attra region of the the probabund region is the own value region of the cylindre $d \sim 1-273/1.4/271/1.27$. Therefore, the problem ratios of the free findre and the cylindre restored and the promoter outron.

Figure 5.8 displays the equivariaity patterns for $f/f_0 = 2.75$ over twenty periods of cylinder coefficients, 207. This figure displays that the frequency of vector shedding is not locked-on to the frequency of the cylinder motion, for this frequency ratio. Coalescence is observed at this frequency ratio.

5.1.3 Fluid forces at Fr = 0.4: h = 0.5

Figure 5.0 displays the time bitrary of the 10 cellf-one Ω_c , but F8D of Ω_c and the Linkaport patterns, $\mathcal{O}_a(t)$. The \mathcal{O}_a trace of $f/f_0 = 2.75$, sublists as morphical elements of the fill contrast of the 10 cellforms, $\mathcal{O}_a(abla quasi-prioride)$ signatures over 57 for $f/f_0 = 1.25$ within $31^{-2} \le 1.27$, respectively. At $I \approx 137^{-1}10^{-2}27$, the Ω_c $137^{-2} \le 107$, and $47^{-2} \le 227$, respectively. At $I \approx 137^{-1}10^{-2}27$, the Ω_c an operiodic agrarams. The corresponding spectra of C_1 alloys a simulation pairs at the learned bodding transport, for $\pi/f_1 = -13$, the over a diamat pairs of $\pi/f_1 = 13$, and $2\pi/f_2$, respectively, and there well defined pairs of $f_2 = 23/f_1$ and $f_1 = 227$. Spectro flow paragraph at $r_1 = 10^{-1}$ and 10^{-1} $(21/f_1) = 127$, and 10^{-1} $(21/f_2) = 127$, $(21/f_2) = 1$

The turn integral of the dags confision, C_{12} (so the PD3 of C_{23} and the Hamilton pactures C_{23}/c_{13} (s) and package in Figure 3.15. In this new relat the C_{13} terms C_{23}/c_{13} (s) C_{13}/c_{13} (s)

opposed to the hysteresis loops of C_h displayed in Figure 5.9. Similarly to the case $F_r = 0.4$ when h = 0.75, it can be seen that $m \neq f_h$ increases them 1.25 to 2.7. Just the angle between the hysteresis loop and the x-axis increases. The direction of each hysteresis loop is constant-disclosize and therefore the transfer of mechanical energy is from the cluster to the mercurology field.

5.1.4 Vortex formation modes at Fr = 0.4: h = 0.5

In Figures 6.11-5.17, the equivorticity and streamline patterns and the pressure contourn in the near wake of the cylinder when $f/f_{h} = 1.25, 1.75, 2.25, 2.75$ are displayed. The observed flow behaviour is (i) quasi-periodic, per 5T for $f/f_{h} = 1.35$, and per T for $f/f_{h} = 1.75, 2.25$, respectively and (iii) non-periodic for $f/f_{h} = 2.75$.



5.1. Fluid forces and vortex shedding modes



S f < 22T, respectively.</p> 'SD of C_D : Lissajous patterns of C_D at R = 200 : A = 0.13, $f/f_0 = 1$.

 $4T \le t \le 12T/\lambda$, and is in the super-verse adeding layer of the clubter $t = -11/\lambda$. Momentic the lower verse adeding (eqs, a partice verse formed during the previous during eqs) which is no its near value of the clubter at $t = T/\lambda$. A positive verse formed from the molecones of two positive verses $t = t = T/\lambda$. More, a positive vertex develops our $T \le t \le 0.7T$, and then adobe during the $t = 0.3T/\lambda$. More, a positive vertex develops verse $T \le t \le 0.7T$, and then adobe during the t = 0.7T. More, the positive vertex develops verse $T \le t \le 0.7T$, and then adobe are waveles of the clubter develops over $TT \le t \le 0.7T/\lambda$, and then adobe are survely evertex in the true value of the clubter develops over $TT/\lambda \le 0.7T/\lambda$, and then adobe are survely vertex in the to how reverse adultation of the clubter t = 0.7T.



Figure 5.11: The equivorticity patterns over five periods of cylinder oscillation, 57, at $R = 200; A = 0.13, f/f_B = 1.25$ when h = 0.5, Fr = 0.4 [$T \approx 4.040; 20.20 \le t \le 40.40$: (57,1071). The quade holebook on CORS⁵ mode, per 57, is observed.

In Figure 5.12, the pressure contours are displayed for the frequency ratio $f/f_0 = 1.25$ over five periods of cylinder oscillation, 5T. At t = 0, the high pressure region has developed in the stagnation region, and the low pressure region in the front, unper and lower side of the cylinder. There is significant development of low pressure low preserve in the near wake region of the collinder is very high over the five periods of collinder oscillation ST. At t = nT/2 (n = 1, 3, 5, 7, 9), the high pressure region is mainly confined to the unner left side of the cylinder. At t = nT (n = 0, 1, 2, 3, 4, 5). the concentration of high pressure has dramtically decreased in the upper left side of the cylinder. It is evident, however, that over 57 that the high pressure region also extends above and below the low pressure regions in the downstream of the cylinder. With the development of new vortices, it is evident that the low pressure regions favor the side of the cylinder on which the development of these new vort never. For example, at t = T/2 we noncomous with the development of a new negative vortex in the upper side of the cylinder, the region of low pressure shifts mostly to the upper side of the cylinder. That is the concentration of high pressure is greatest in the upper side of the cylinder at this time instance. On the other hand, as a new nonition water basing to develope at t = 3T/2 the low resource region is seen to shift mostly to the lower side of the cylinder (near wake region). Consequently the concentration of low pressure is greatest in the lower side of the cylinder. The low pressure structures in the near wake region at t = 0T and t = 5T are nearly identical. these the emassionerically nature of the flow is reproduced in this figure.

Figure 5.13 displays the equivorticity patterns for $f/f_0 = 1.75$ over two periods of cylinder oscillations, 27, within $15 \le t \le 177$. The vortex shedding mode is the quasi-



Figure 5.12: The equivariativy patterns (left), streamline patterns (middle) and the pressure contours (right) in the near value contrastion, for M=200, M=10.3 $f_{\rm eff}=125$ when h=0.3, F=0.4 $(17\simeq 4.000, 30.20\leq t\leq 40.40$: (37,107)]. The quasi-locked-on C(88)⁴ mode, per 5.7, is observed.

below GRP mode, per 27, with $\Pi_{1}^{2}\leq j\leq 207$. The fact is morperiod for j< 207. The in source with the behavior of j on G $_{2}$ at the hyperperiod j on G $_{2}$ at the strength mode in the mappen of the section of hegin regimes in strength one gradies most rest. An elimination of the experime is the strength one gradies in the strength of the strength mode in the strength of the strength mode is gradies most rest. The strength mode is gradies most rest develops one $TT^{2} \leq j \leq TT^{2}$ and the strength mode is the strength mode in the strength mode is the strength mode in the strength mode is the strength mode in the strength mode is mode in the strength mode in the strength mode is mode in the strength mode in the strength mode is mode in the particle mode in the strength mode in the strength mode is mode in the particle mode in the strength mode in the strength model model is model in the strength model model in the strength model model is model in the strength model model in the strength model model model model is model in the strength model model model model in the strength model model model is model in the strength model model model in the strength model in the strength model model

The designer rate $f_{1/2}^{(1)} = 17$, the purposes extraton are displayed are two product of opticals architex, r = 1, P = P = 1, $M = \ell = 0$, the display means describe in the signation range on all the large purpose rights in the spectra that distantions of the clyclack growth region. It much display is the order of a large display of the the high purpose region access to be confloid above and black the large purpose ranges in the descention of the clyclack. The the purpose regions are confider for the sagnation for the displayed in the display $\ell = 0$. Alter the shares $\ell = 0$ and $\ell = 0$, which is the display $\ell = 0$ and $\ell = 0$.



Figure 5.13: The equivariativy patterns over two periods of cylinder oscillation, 27, at $R = 200: A = 0.13, f/f_0 = 1.75$ when $h = 0.5, F_F = 0.4$ ($T = 2.886, 0.29 \le t \le 0.06$: (57) (57)). The must below on C285'' is observed.

were into the upper wates shading rapin, it is a vident that the high presence maps has shading outputs on the finar of the tables of the two presence rapin has adding outputs of the dynamic rapin and instantian presence of the presence in the operation of the tables of the development of a positive number of the dynamic region addits mostly behind the clydics. At the presence region addits mostly behind the clydics, the higher and the rapid sector of the tables of the presence region is confident in the strength region (the clydics) in the upper sector rapin is confident in the strength region (the description (the tables). The high presence region is confident in the strength region (the distribution (the tables) and the tables) and the presence region is confident in the strength region (the tables). The high presence restorements in the near wells region at $t = C_{\rm eff}$ and $t = T_{\rm eff}$ are strengly identify that the quaraperturbation of the first field is repredended in this figure.



Figure 5.14: The equivorticity patterns, streamline patterns and the pressure distilution in the near wake region of the cylinder over two periods of cylinder oscillation, 2*T*, at $R = 200 : A = 0.13, f/f_0 = 1.25$ when h = 0.5, Fr = 0.4 $|T = 2.886, 43.29 \le t \le 49.06 :$ (157, 1771). The quasi-foldes on C(258)" mode, per 2*T*, is observed.



Figure 5.15: The equivarisity patterns over two periods of cylinder oscillation, 27, at $R = 200: A = 0.13, 1/f_0 = 2.25$ when $h = 0.5, F_P = 0.4$ [$T \approx 2.245, 20.53 \le t \le 31.42$: (127) 147). The matricipation on C283⁵ is observed.

In Figure 3.16, the exploration potential are displayed for $f/h_{c} = 2.27$ are two periods of piloth estimations. The two star defaulty on the h the quark identic CBBF model, per T_{c} which $G_{c}^{c} \leq \pm 2.27$. The finst s is majorized is for t > 2.27. The incommon that the holdshift of G_{c} of the flowpary ratio. A magnitude control, fraund has the modelsment of the magnitude star 1 = 7/2, double over $T/S \geq 1.17$. Then, this regards we watce adult has the $T_{c} = 2.5$ models of s = 1. Single at t = 2.7. Manuality and its parability article and the model regard and the shading error ($S \geq 1.17$). Then, this regards we watce adult have the gravit and the shading error ($S \geq 1.17$). Then, the magnet we watce adult have the gravit and the shading error ($S \geq 1.17$). Then $S \geq 1.5$ art $T_{c} = 1.5$ models are the star shading error in the star budter water is a $T \geq 1.5$. A model is the star shading error in the star budter is $t \geq 1.5$.

Figure 5.16 displays the pressure contours for frequency ratio $f/f_0 = 2.25$ over two


Figure 5.16: The equivarisity patterns, streamline patterns and the pressure distibution in the near wake region of the cylinder over two periods of cylinder coefficient, 27, at $R = 200: A = 0.13, f/f_0 = 2.25$ when $h = 0.5, F^2 = 0.4$ [$T \approx 2.243, 26.03 \le t \le 31.42$: (127, 1471). The mean-benched mean C255⁴ mode, see 27, is observed.



Figure 5.17: The equivorticity patterns over twenty periods of cylinder oscillation, 207, at R = 200; A=0.13, $f/f_0 = 2.75$ when h = 0.5, Fr = 0.4 [$T \approx 1.837$, $9.183 \le t \le 45.91$: (07.2077) (non-neriodic state).

produk of cylindra sulfitzin, 227. Al = 0, the high pressure regults has destigated in the sequences regults of the cylindra such the presence rights has the destigated in the paper side, and downstream, of the cylindra. Over $0 \le t \le 327/4$ as the parative stores dessigns, it is related that the bay pressure regults with mostly from the upper side of the cylindra to the here is ofthe cylindra rad downstream. The high pressure region shifts in a choice-in direction during this time. Symposeme with the downsignees of the sequence vectors on $T \le t \le 37$, the here pressure

region align much box the lower and or the related to the appendix. The high permutation of the state of the relation of the state of the relation of the state of the explosion region is not start - stated in detection around the bit state of the explosion region is not only high in the stargarding relation that the presence of the high presence region is not only high in the stargarding relation that the domain and the high collection with The bits we presence reasons at t = 0.274. Alter the domain and the bit collection are the state of the fore which is result. The start of the the state is more relations at t = 0.274 and the state of the the state is state of the fore which is result, where the quasi-periodic nature of the fore which is results in the fore.

Figure 5.17 generates the equivariative partners for $f_1/f_0 = 2.75$ for over trenty periods of cylindre excitingians, 207. This figure is presented in accompositionit with the lift and Linsajons patterns and the power density spectrum of frequency ratio $f_1/f_0 = 2.75$ to conclude that indeed no lock-on mode exists for this case. Conference is observed at this frequency ratio.

5.1.5 Fluid forces at Fr = 0.4 : h = 0.25

Figure 31 for dipples the time binary of the III coefficient C_{11} and the PSD and Linger fragments $p_{11}^{-1}(r_{12}, r_{12}) < C_{11}$. Its relates the the massists and Engent fragments units, $p_{11}^{-1}(r_{12}, r_{12})$, the C_{1} inverses which above spatialist digrature energy in gravity of $p_{11}^{-1}(r_{12}, r_{12})$, the $C_{1}^{-1}(r_{12}, r_{12}) < C_{12}^{-1}(r_{12}, r_{12})$, respectively. The quasi-position, σ_{11}^{-1} where $r_{12}^{-1}(r_{12}, r_{12}) < r_{12}^{-1}(r_{12})$, respectively. The quasi-position $\sigma_{11}^{-1}(r_{12}) < r_{12}^{-1}(r_{12}) < r_{12}^{-1}(r_{12})$, respectively. The quasi-position $\sigma_{12}^{-1}(r_{12}) < r_{12}^{-1}(r_{12})$, respectively. The quasi-position $\sigma_{12}^{-1}(r_{12}) < r_{12}^{-1}(r_{12})$. The trues of the large-range ratio displaces position $R_{12}^{-1}(r_{12}) < r_{12}^{-1}(r_{12})$. The trues of the large-range ratio displaces position $R_{12}^{-1}(r_{12})$, respectively. The end position $r_{12}^{-1}(r_{12}) < r_{12}^{-1}(r_{12})$. The trues of the large-range ratio displaces position $R_{12}^{-1}(r_{12})$, respectively. The end position $r_{12}^{-1}(r_{12}) < r_{12}^{-1}(r_{12})$. The trues of the large-range ratio displaces position $R_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$. The trues of the large-range ratio displaces position $R_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$. The true of the large-range ratio displaces position $R_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$. The true of the large-range ratio displaces position $R_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$. The true of the large-range ratio displaces position $R_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$. The true of the large-range ratio displaces position $R_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$ and $r_{12}^{-1}(r_{12})$.

of $f_1/f_0 = 123_{\pm}$ (32, 232, indicate that the respective C_1 were scaling at the difficult parally probe over at $2 + 3d_2/2$ and $2 \parallel d_2 = f_1/f_2/3$. But 2.23, respectively. It is intermedian to main the set of the structure probe of the structure of

In Figure 3.13, the time islancy of the darg coefficient, C_{00} the BF0 of C_{00} , and the imagine pattern of C_{00} endplaced. Humbler is to shar we observe the C_{0} for $f/f_{00} = 1.25$, the C_{0} time duplace simulates behavior over the network of explander socilitation, dt. The C_{0} time for $f/f_{0} = 1.25$ as basin prioritod rescale over gH or a simulate over the $f/f_{00} = 1.25$ and f_{00} the C_{0} time. Non permitted pattern for $f/f_{00} = 1.25$ and $f/f_{00} = 1.55$ and f/f_{00} the darge duplace duplace duplace dT_{00} are observed for $f/f_{00} = 1.55$ and $f/f_{00} = 1.05$ and f/f_{00} the darge duplace duplace $f/f_{00} = 1.55$ and $f/f_{00} = 1.55$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.55$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.55$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.05$. Or where the $f/f_{00} = 1.55$ and $f/f_{00} = 1.05$ and $f/f_{00} = 1.05$. See the other limit, the $C_{0}(d)$ parametes for $f/f_{00} = 1.05$ and $f/f_{00} = 1.75$. 2.25 for the overpredict starts of the darged parameter values were during and the compared starts and the complete values are values in the interpresson parameters. On the other limit, the $C_{0}(d)$ parameters for $f/f_{00} = 1.05$ and $f/f_{00} = 1.75$. 2.25 for the f/f_{00} = 1.05 and $f/f_{00} = 1.75$. 2.25 for the complete values of the model parameters and the complete values of the complete





Figure 5.19. The time vari

shapes. Similarly to the reference case, $k = \infty$, it is evident that the $G_0(x)$ patterns are essentially confined to the upper half plane. The direction of the hysteresis loops for $G_0(x)$ is counter-declosive and his suggests that the transfer of mechanical energy is from the cylinder to the fluid.

5.1.6 Vortex formation modes at Fr = 0.4: h = 0.25

In Figures 5.20-5.25 the equivorticity and streamline patterns, and pressure contours in the max wake region of the cylinder when $f/f_0 = 1.25, 1.75, 220, 2.75$, are displayed. The observed flux behaviour in (i) quasi-periodic, per 47, for $f/f_0 = 1.25, 2.75$ and (ii) non-periodic for $f/f_0 = 1.75, 220$.

In Figure 3.20, the equivariative parameter $|h| = 1/\hbar = 1/\hbar$ and displayed over four period of rphilos conditions, IT. The votext adsolution into the quasi-balance on $C(45^{\circ})$ and $p \approx dT$, which $T \leq 12$. If The fibe becomes associated at 1 > 12. This can examine the thermitrow of C_{10} or 10° which energy terms of $(1 > 12)^{\circ}$. This can examine the thermitrow of C_{10} or 10° or 10° spectra methylications of the matrix of C_{10} or 10° or 10° or 10° spectra methylications of the matrix of C_{10} or 10° or 10° or 10° spectra decays one $T_{10} \leq 1 \leq T_{10}$. This sources in h(h) and into the traper advaller decays one $T_{10} \leq 1 \leq T_{10}$. This sources in h(h) and into the more when C_{10} embedded and $T_{10} \leq 1 \leq T_{10}$. The meaning in equivalence with the net mether d_{10} embedded and $T_{10} \leq 1 \leq T_{10}$. The meaning weight worths in the net weight d_{10} embedded and $T_{10} \leq 1 \leq T_{10}$. The meaning weight worths in the net weight d_{10} embedded and $T_{10} \leq 1 \leq T_{10}$. The meaning weight weight is the net weight d_{10} embedded and $T_{10} \leq 1 \leq T_{10}$. The meaning weight weight is the net weight d_{10} embedded and $T_{10} \leq 1 \leq T_{10}$. The meaning weight weight is the net weight d_{10} embedded and $T_{10} \leq 1 \leq T_{10}$. The meaning weight weight is the net weight d_{10} embedded and $T_{10} \leq 1 \leq T_{10}$. The meaning weight weight is the net weight $d_{10} = 10^{\circ}$ or 10° s $d_{10} = 10^{\circ}$ s $d_{10} = 10^{\circ}$ s $d_{10} = 10^{\circ}$ s $d_{10} = 10^{\circ}$.





and as a result sheds into the upper vortex shedding layer at t = 7T/3. Meanwhile in the lower vortex shedding region, it can be seen that the positive vortex developed in the newsions shedding cycle sheds downstream of the cylinder at t = T/3. Over

 $2T/3 \le t \le 4T/3$, two positive vortices co-rotate, and then coalesce at t = 3T/2. The resulting positive vortex is then shed into the downstream of the cylinder at $t \approx 2T$.

For $(f_{12}^{-1} - 12)$, the powers contours in the new solut of the cylinder and dupped one fram periods of quick one efficient (G. 1999, FO 1997, M. et el. (b) the low powers mere rigin develops description, G. (F. 1999, FO, 31, M. et el. (b) the low power end on the periods of quick one might develops in the damption region dup to the quick. The high power might develops in the anomphase built due cylinder denominating denomination of the strength of the quick of the quick of the quick measurement of the strength of the quick of the quick of the quick denomination of the quick of the quick of the quick of the quick denomination of the quick of the quick of the quick of the quick denomination of the quick of the quick of the quick of the quick and the concentration of the presence induce duration (d), the quick of the quick are at gradient large outches in the denomination of the quick of the quick denomination of the quick denomination of the quick of quick of the dup density of quick of the quick of the quick of the quick of the presence of the quick of the quick of the quick of the quick of the the presence of the quick of the quick of the quick of the the presence of the field the quick of the (f_{12} = 13).

Figure 5.22 and 5.23 display the equivariary patterns for $f/f_0 = 1.75$ and 2.25, respectively over twenty periods of cylinder oscillation, 207. From both Figures, it is evident that the frequency of the vertex shedding is not locked-on to the frequency of the cylinder motion. Coalescence is observed at both frequency ratios.

Figure 5.24 displays the equivorticity patterns of $f/f_{\theta} = 2.75$ over four periods of







Figure 5.22: The equivorticity patterns over twenty periods of cylinder oscillation, 207, at R = 200, A=0.13, $f/f_{h} = 1.75$ when h = 0.25, Fr = 0.4 [$T \approx 2.896$, $14.43 \le t \le 72.15$: (ST_{1} (ST)] (non-periodic state).

c fluider outfilling, af. The vertex shoulding mode is the quasi-bodiene G(28)¹ to mode, pert G', which is $S \leq 2.5$. The fluid to morphicalis for $\ell > 2.7$. This is constant with C_1 behaviour for this frequency ratio. This figure duplays the advantation of a should be abadding of our single vertex from both the toper and there vertex shoulding region of the $G(05C-OOS) \leq 2.5$. The angular vertex found bring the previous vertex abadding cycle curritum is abadely in the approxformal bring the previous vertex abadding cycle curritum is abadely in the approxformal bring. The fluid bring the should be should be should be should be should be vertex where the should be should be vertex should be should be vertex should be should be should be vertex should be should be should be vertex should be should b





attacked to the best matthen. A new regarities worket begins to descloped at this ites mass that its co-state with the secondary sequely works in the near walks of the vyfikket over $2T/\beta \le t \le T/\beta$. A third angular varies forms in the near walk region at t =dT/2 and the theore arguings matrices on-solutation out $T/2 \le t \le T/\beta$. A the $-1T/\beta$ be primary and associative varies on-solutation that wave having in. The primary matrix solution is the law wave region. The resulting varies then on-sontants with the new sources out $T/\beta \le t \le T/\beta$ and $t \le T/\beta$. It is the law t = 2T disc association works adds in that dupper variation disc and the transformation of transformation of the transfor



Figure 5.24: The equivariativy patterns over seven periods of cylinder oscillation, 4T, at R = 200, A = 0.13, $f/f_D = 2.75$ when h = 0.25, $F^{\mu} = 0.4$ $[T \approx 1.24, 40.40 \le t \le 47.75 : (227, 3571)$. In equasi lock-on $\mathbb{O}(287)$ is observed.





vortex shedding layer, it can be seen from that a positive vortex developed from the previous shedding cycle, continues to develop over $0T \le t \le T$. This positive vortex sheds from the lower vortex shedding layer of the cylinder at t = T.

In this late characterized theorem is a strength of the stren

5.2 Summary and Discussion

Table 5.1 summarizes the effect free surface inclusion has on the flow regimes, the vortex shedding modes and their periods, $T_{0.}$ for the case Fr = 0.4 at h = 0.75, 0.5, 0.25when $f/f_0 = 1.25, 1.75, 2.25, 2.75$. Table 5.1 displays that for the case Fr = 0.4, the presence of the free surface at h=2.53 senses to leavely up the periodicity of seven the obding websy $[I_{1}, = 51, 52, 52$. Boundhards into of the free adsocs one start is the cluber strengers depths h=0.16 websy $I_{1}, = 125, 225$. The addition of the free adsocs on the the cluber strengers are abreed to the more regime in the strenger scale h=1, 2, 3, 3, 3. Summitty in to true it what the period of sevenes absoluling by T for $|I_{1}|=-125$, at $h=\infty, 15, 25, 55$. Minimity, the period of sevenes absoluling by T for $|I_{1}|=-125$, at $h=\infty, 15, 25, 55$. Minimity, the more dasheding by T for $|I_{1}|=-125$, at $h=\infty, 15, 25, 55$. Minimity, the more dasheding by T for $|I_{2}|=-125$, at $h=\infty$ for the decrement in cyclical sensitivity and the decrement in cyclical sensitivity of the dasheding modes. A seventian the strenger explosition relationstress distributions in sevents absolutions between the strenger explosition of the decrement in the strenger explosition of the decrement in the strenger explosition of the dasheding modes. A sevent in the strenger explosition of the dasheding in the strenger explosition of the dasheding in the strenger explosition of the dash web accred. The community absenced modes for the case Fr=0.16 is the chaster of the dash accreding the strenger explosition of the form in the strenger explosition of the dasheding the strenger explosition of the dasheding the dasheding the strenger explosition of the dashed

5/5s	$h = \infty$		h = 0.75		h = 0.5		h = 0.25	
	Mode	T_{v}	Mode	T_{v}	Mode	T_{π}	Mode	T_{i}
1.25	$C(108)^{\circ}$	7T	non-locked		C(8S)*	5T	$C(4S)^*$	47
1.75	2P	2T	$\mathbf{C}(\mathbf{P}+\mathbf{S})^*$	2T	$C(2S)^*$	2T	non-locked	
2.25	$C(8S)^*$	9T	C(2S)*	2T	$C(2S)^*$	2T	non-locked	
2.75	$C(P+S)^*$	3T	non-locked		non-locked		$C(2S)^*$	47

Table 5.1: The effect of the free surface inclusion on vortex shedding modes and their periods, T_{ee} for the case Fr = 0.4 when $h = 0.25, 0.5, 0.75, \infty$ at R = 200: $A = 0.13, f/f_5 = 1.25, 1.75, 2.25, 2.75$. The superscript "*" denotes quasi-locked-on modes.

Table 5.2 displays the values of the mean lift and drag coefficients \widehat{C}_L and \widehat{C}_D , for the parameters Fr = 0.4, R = 200; A = 0.13, h = 0.75, 0.5, 0.25, ∞ when $f/f_0 =$ values of \widehat{C}_{ℓ} are negative, whereas those in the absence of a free surface, $h = \infty$, are positive. It can be seen that the magnitude of each \widehat{C}_t value, in the presence of a free surface at h = 0.75, 0.5, 0.25, are much larger than the \widehat{C}_{ℓ} values in the absence of a free surface, $h = \infty$. Furthermone, it is evident that \widehat{C}_L varies within the range $-0.8245 \le \widehat{C_L} \le -0.1950$ when the free surface is present. Also, as h decreases from 0.75 to 0.25, it can be seen that the values of \widehat{C}_L decrease substantially (Q:Can this contribute to the $C_1(x)$ patterns shifting substantially into the lower 1/2 plane). When in the presence of a free surface, the \widehat{C}_L values of each f/f_0 decrease as f/f_0 increases from 1.25 to 2.75, with the exception of $f/f_0 = 1.75, 2.25$ when h = 0.25Analyzing the mean drag coefficient, $\widehat{C}_{\mu_{1}}$ values it is evident that there is not much fluctuation in these values as h decreases from 0.75 to 0.25. Each \widehat{C}_D values are positive and are confined with the range $1.4477 \le \widehat{C_D} \le 1.8790$ when the free surface is present. Similarly to \widehat{C}_{L} , the values of \widehat{C}_{D} increase as f/f_{0} increases from 1.25 to 2.75, with the exception of $f/f_0 = 2.75$ at h = 0.75, h = 0.5 and $f/f_0 = 1.25$ at

Table 5.2 displays the BMS values of the lift and drag confinitions, C_{ABM} , C_{ABM} , T The RMS values of the lift and drag coefficients are presented for h = 0.75, 0.55, 0.55and compared to the BMS values of the relevance case $h = \infty$. It is evolved that as the cylinder submargance depth is decreased from ∞ to 0.25, the values of the RMS fill coefficient, C_{ABMS} , increase, with the enception of $f/f_{h} = 1.26$, 1.72, 2.55where h = 0.57. Particularly, h = 0.07, f_{h} for each Sec 1 to 2.07, the

	\hat{c}_{L}				\widehat{C}_D				
f/f_0	$h = \infty$	h=0.75	h = 0.5	h=0.25	$h = \infty$	h = 0.75	h = 0.5	h = 0.25	
1.25	0.0055	-0.1950	-0.3720	-0.8245	1.2467	1.6301	1.550	1.5405	
1.75	0.0044	-0.2039	-0.2918	-0.6676	1.4123	1.636	1.6006	1.4477	
2.25	0.0007	-0.2144	-0.4485	-0.8077	1.2610	1.879	1.7336	1.4950	
2.75	0.01.30	-0.2744	-0.4405	-0.8775	1.2235	1.6796	1.6114	1.5549	

Table 5.2: The effect of the free surface inclusion on the mean lift, \widehat{C}_L , and drag, \widehat{C}_D , coefficients for the case Fr = 0.4 when $h = 0.25, 0.5, 0.75, \infty$ at R = 200: A = 0.13, 1/6 = 1.25, 1.75, 2.52, 2.75.

1/5	CLynus				C _{D,rms}				
	$h=\infty$	h=0.75	h = 0.5	h = 0.25	$h=\infty$	h=0.75	h = 0.5	h = 0.25	
1.25	0.4926	0.6262	0.6292	0.9565	1.3157	1.6781	1.6418	1.6971	
1.75	0.7431	0.8353	0.7825	0.8914	1.5951	1.7485	1.7054	1.5783	
2.25	0.4205	0.9726	0.9925	1.6087	1.7617	2.165	2.0289	1.7469	
2.75	0.3302	0.7166	0.7195	1.0971	2.2544	2.3071	2.1857	2.0534	

Table 5.3: The effect of the free surface inclusion on the RMS lift, C_{Lyms} , and drag, C_{Dyms} , coefficients for the case Fr = 0.4 when $h = 0.25, 0.5, 0.75, \infty$ at R = 200: A = 0.13 / (h = 1.25, 1.75, 2.25, 2.75).

 C_{Addrev} takes increase, enough the free cases $f_1 f_2 = 120$ when $h = 0.25 (f_1 f_2 = 22)$ where $h_1 = -0.25 (f_1 f_2 = 20)$ was the $h_2 = 0.25 (f_1 f_2 = 20)$ with $h_2 = 0.25 (f_1 f_2 = 20)$ of 3.25. From Table 5.2. is a velocit that where the relation with any enough $h_2 = 0.25 (f_1 f_2 = 20)$ with the comparison of $f_1 f_2 = 0.25 (f_2 = 0.25 (f_2$



Figure 5.26: The effect of the cylinder submergence depth, h(=0.25, 0.5, 0.75), and the frequency ratio, $f/f_0(=1.25, 1.75, 2.25, 2.75)$, on the equivorticity patterns at $R = 200 \cdot A = 0.13$. Fr = 0.4.

Figures 5.5-5.25, display the pressure contour plots of h = 0.75, 0.5, 0.25 when $f/f_0 = 1.25, 1.75, 2.25, 2.75$. The pressure contour plots at h = 0.25, 0.5, 0.75 for each f/f_0 , periodic/quasi-periodic behaviour is exhibited, display the development of the hyperpensaure readon in the stanzation region of the excitone. For $f/f_0 = 1.75, 2.25$ at the upper, lower, front (closer proximity to near wake than stagnation region) sides, In ceneral, the low pressure regions develop in the near wake of the cylinder, where fuctuating lift forces acting on the circular cylinder. Positive and negative vortices which have shed downatzeam of the cylinder, are represented by the low presregion (blue contours) for all f/fs. Another interesting aspect of the low remaure contours of the circular cylinder is that for some cases, mirror images of the structures of low pressure are observed in the near scalar region of the cylinder. Succifically at h = 0.75 when $f/f_0 = 2.25$, the low pressure contours in the near wake region of the regions in the near wake region of the cylinder at $t = T_1 5T/4.6T/4.7T/4.2T$ (see (1.25) at I = 0.772 T are similar to images of the low resource structures at I =this thesis is the researce of the high nessane regions above and below the low pressure contours in the downstream of the cylinder. At h = 0.75 when $f/f_0 = 1.75$, the high pressure region has significant presence above and below the low pressure regions in the downstream of the cylinder at t = 0.T/2.3T/4.6T/4.7T/4.2T. Similarly, at h = 0.5 when $f/f_s = 1.75, 2.25$ the high pressure regions extend above and below the low pressure contours in the downstream of the cylinder at t = 0.3T/4.7T/4 and

t = 0.5T/4, 7T/4, respectively (see Figures 5.14-5.16).

The effect of cylinder submergence depth, h = 0.25, 0.5, 0.75, and the frequency ratio, $f/f_0 = 1.25, 1.75, 2.25, 2.75$ on the equivorticity patterns for the case R = 200, A =0.13 when Fr = 0.4 is displayed in Figure 5.26. The reference case $h = \infty$ is presented to help demonstrate the changes the vorticity undergoes in the near wake of the cylinder with the inclusion of free surface. All snapshots are taken at the instant the cylinder reaches maximum displacement, x(t) = A and are taken within the time interval the flow reaches a periodic/quasi-periodic state. For non-periodics cases, the snarshots are taken within $0 < t \leq 100$. It is immediately evident that amount of opposite signed vorticity is present at the free surface and in the flow. h = 0.5, 0.25 for each f/f_{h} . At each cylinder submergence depth, h, shed negative vortices seem to be lifted up towards the free surface aided by the propogation of resultion costicity into the upper shedding layer. As a result, these negative vortices dispanate ranielly, and become weak, as they are much the free surface. Hence, the crinder submergence depth decreases from ∞ to 0.25. It can be seen that the major to the free surface for the larger cylinder submergence depths, $h = 0.5, 0.75, \infty$. On

5.2. Symmary and Discussion

the other hand, the major area of the magnetic warrise at h = 0.251 and b to frame where dimensional thro the free words. This is a small of the strang minarctana with the free surface and the mpid diffusion of three vartiess after constants in the absolute angeing b on the all poperties warrises in the discussion of the copied, except that the poperties vartiess in the discussion of the poperties. In general, the except the model poperties of the poperties of

6. Flow past a transversely ocillating circular cylinder

The Chapter analyses the results for far part a transversely oscillation (relation: The manufact dimetalization on correction out as 1 hypothele number of H = 200, at (relater interpreted by the strength of the section) and h = 0.5 (mmutlet) in the dimetalization of the strength of the section of the 1 hypothetical strength of the strength of the strength of the strength of 1.28 $\leq f/h_{\odot} \leq 2.7h_{\odot}$ shows f/f_{\odot} increases by intermeters of 6.5. The results are addeniand by analysing the field itera strengt on the cycluder and by mours of the results addeniand in the field wave strength on the cycluder. In the absence 4 has the methods, well its emagnetic to those obtained in the thermatical strength the correspondence of the cycluder. It has also be with the correspond on the cycluder is a dimensional strength on the strength of the strength on the cycluder is a strength on the strength of the strength of the cycluder. The mathing the strength cycluder is a strength on the strength of the strength on the strength of the strength of the strength of the strength on the strength of the strength of the strength of the strength on the strength of the strength of the strength of the strength on the strength of the strength

6.1 Flow past a transversely ocillating circular cylinder in the absence of a free surface

6.1.1 Fluid Forces $(h = \infty)$:

Figure 6.1 displays the time history of the fluctuating lift coefficient, C_L , and the PSD of the lift coefficient. For $f/f_0 = 1.25$ and 1.75, the traces of the lift coefficient display 6.1. Flow past a transversely ociliating circular cylinder in the absence of a free surface 17.

In Figure 3.2, the time history of the fractionarity diag coefficience, C_{co} , and the FISO 2of (c_{c}) independent. The trace of the data coefficient height about respectively the interpret for $T/L_0 = 1.25, 1.25, 2.25, 2.25, every <math>97, 97, 77$ and 37, supportionly. It is evident from Figure 2. that such spacets displays multiple peaks for each hyperper value $F(f) = 1.55, 1.25, 2.25, 2.55, the obtaining and sources at <math>f_1/2/3, f_2/3, 5/3/4$ of $T_2/4$, impaction the spacets displays and the peak over at $f_1/2/3, f_2/3, 5/3/4$ on $T_2/4$, impacting the hyperbalance of $f_1/2$ is observed from dominant peak to dominant peaks of $f_1/2$ increases from 2.37.

In Figure 6.3, the Linssipus partons of $G_{11}^{-1}(q_{11})$ and $G_{22}^{-1}(q_{11})$, and $G_{22}^{-1}(q_{11})$, and $G_{22}^{-1}(q_{12})$. The spin of $G_{22}^{-1}(q_{12})$ and $G_{22}^{-1}(q_{12})$, and $G_{22}^{-1}(q_{12})$, and $G_{22}^{-1}(q_{12})$, and $G_{22}^{-1}(q_{12})$. The spin of $G_{22}^{-1}(q_{12})$ and $G_{22}^{-1}(q_{12})$, and $G_{22}^{-1}(q_{12})$. The spin of $G_{22}^{-1}(q_{12})$ and $G_{22}^{-1}(q_{12})$, and $G_{22}^{-1}(q_{12})$. The spin of $G_{22}^{-1}(q_{12})$ and $G_{22}^{-1}(q_{12})$.



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6.1. Flow past a transversely ocillating circular cylinder in the absence of a free surface II

Figure 6.3: Line/new potterns of $C_L(y)_1(a)_1(b)_1$ and $C_L(y)_1(c)_1$ for $R = 200, A = 30, A = \infty$, and $I_f(F = 1.25, 1.75, C)_2$ to the total to $C_L(y)$ patterns for $f_f(f_0 = 1.25, 1.75)$ in cohuma b are shown for two periods of cylinder and fluid. The Line(y) patterns for a single between cylinder and fluid. The Line(y) and $C_0(b) = I_{1,1}^{(0)} (I = 1.25, 1.75, 2.15, 2.75)$. The second secon

6.1. Flow past a transversely ocillating circular cylinder in the absence of a free surface 170

disply the change in the rando of acculation larger. The discrim of $C_{11}(c)$, for (1, -1), S. 1.7, diagonal from a construct observation fractions in a clocked discrimin. Therefore, is hold asso, the mechanical energy is transformed between the clydical and find. The discrime of the dynamic larger (1, -1), (

6.1.2 Vortex formation modes (h = ∞):

In Figure 6. the exploretizely patterns are displayed over mine probased of clubber distances, we for $|I_1| = 1.2$. The otherwork balance mode is the quark-balance L48² mode, por 97, within $10^{-2} \le \le 2.07$. This is constant we like the balances Ω_{12} and Ω_{23} at this displayed part of the probased set of Ω_{12} . This this mode, some variation declosed pand then alternatively abed on much alise of the cylinder, within 97. A regular sector formed simulation theory is previous vectors abeling $\Omega_{12} \le 2.07$, and much ables that the primary magnetized for t < 5.17 for the prime $\Omega_{12} \le 2.07$, and much ables that primary magnetizes vectors in the upper abiding layer of the cylinder at t = 4.17. A magnitive vector decologies of we $3.17 \ge 4.52$ of 3.07 we prime vector developes, and it thus from from all particular size of $1.07 \ge 0.07$ m $17 \le 5.12$ of a suppise vector developes, and its thus from the outper anterman. The 1.07 L3 model 0.00 = 1.07 L3 6.1. Flow past a transversely ocillating circular cylinder in the absence of a free surface 177

were a hold from the upper were a holding layer at i = 117/2. A sequite were mean owner that the Gardan has the upper varies challing layer at i = 137/2. Furthermore, a significe sector developed over 37 $\leq i \leq 137/2$, and then the hold in the result of the layer of the sector developed from the sector developed from the periods were developed result of $\leq i \leq 137/2$, and then show the sector developed from the periods were developed result of $\leq i \leq 37/2$, and then show developed from the periods were developed $\leq i \leq 37/2$, and then show developed $\leq i \leq 27/2$, and then show developed $\leq i \leq 27/2$, and then show developed $\leq i \leq 27/2$, and then show developed $\approx 17/2 \leq i \leq 37/2$, and then show developed $\approx 17/2 \leq i \leq 37/2$, and then show the sector model $\approx 10^{-1}$. The other sector developed $\approx 17/2 \leq i \leq 37/2$, and then show the sector model $\approx 10^{-1}$. A possible varies developed $\approx 10^{-1}$, $i \geq 137/2$, and then show the sector $i \geq 137/2$, and then show the sector $i \geq 137/2$, and then show the result $i \geq 137/2$, and then show the result $i \geq 137/2$. A possible varies developed $i \approx 17/2 \leq i \leq 137/2$, and then show the result $i \approx 10^{-1}$. A possible varies developed $i \approx 17/2$, $i \geq 137/2$, and then developed $i \approx 1 + 67/2$. A possible varies the developed $i \approx 17/2 \leq i \leq 137/2$, and then developed $i \approx 1 + 67/2$. A possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$. The possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$. The possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$. The possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$ and $i \approx 10^{-1}$. The possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$ and $i \approx 10^{-1}$. The possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$. The possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$ and $i \approx 10^{-1}$. The possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$ and $i \approx 10^{-1}$ and $i \approx 10^{-1}$. The possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$ and $i \approx 10^{-1}$ and $i \approx 10^{-1}$ and $i \approx 10^{-1}$. The possible varies $i \approx 10^{-1}$ and $i \approx 10^{-1}$ and $i \approx 10^{-1}$. Th

Figure 3.5 diploys the presence entroms for $f/h_c = 1.3$, one min product of f/h_c or continus, 0^{-1} . Initially, this figure disploys the downlymmat of the hypersence in the lower half seen of the signation region, and the hist presence region in the appender side and downstream of the explosion. The side of the signation region region reduces the single size and the single size of the side of the size of the size of the single size and the size of the size transmission of the high presence regions also matters fielded with the size size of the size size of the size size of the s





Figure 6.4: The equivorticity patterns over nine periods of cylinder oscillation, 9T, at $R = 200: A = 0.33, f/f_0 = 1.28$ when $h = \infty$ [$T \approx 4.04, 52.525 \le t \le 80.880$: (13T, 22T)]. The mask lock-on 148° mode, per 9T is observed.

right in much confided to the lower side, and downstream of the cyliche' (neussio). At t = 7.72, $G_{\rm c}$ for the low preserve region in radial probabilisativity to the downstream of the cylinder. For example at t = 37/2, symmetres with the devolupment of the positive vertex in the lower vertex shoulding layer, this to preserve prior addition much be to be seen risk and downstream of the cylinder. As the according pairine vertex distribute, and a new positive vertex is formal, at t = 37. The low reserves risk at the lower risk of the children. It is evit = 37. The low reserves risk in that we possitive vertex is formal, at 6.1. Flow past a transversely seillating circular cylinder in the absence of a free surface 139

dont that the structure of the pressure contours, in the near value of the cylinder, at t = 0T (07), T/2, T/2, T/2, T/2, T/2, T/2, T/2, T/2 are almost infror images of the low pressure regions at t = 9T/2, T_1 , 1T/2, $0T_1$, 1T/2, T_1 , 1T/2, T_1 , 1T/2, respectively. Therefore, the pressure contours recrease the periodic nature of the flow field around the cylinder at this frequency ratio.

In Figure 6.6, the equivorticity patterns are displayed for $f/f_1 = 1.75$ over nine periods of cylinder oscillation, 9T. The observed vortex shedding mode is the quasilocked-on 108^a mode, per 97, within $5T \le t \le 34T$. This is consistent with the previous vortex shedding cycle develops over $0 \le t \le T$, and then sheds from the upper side of the cylinder at t = 3T/2. Over $2T \le t \le 3T$, a negative vortex develops and then sheds downstream at t = 7T/2. A negative vortex developed over $4T \le t \le 5T$, vortex develops and is then shed from the upper side of the cylinder at t = 7T. A negative vortex developed over $15T/2 \le t \le 17T/2$, sheds into the near wake of the exlinder at t = 9T. In the lower vortex shedding region, a secondary positive vortex is shed in the near wake of the cylinder at t = T. Over $T \le t \le 2T$, a positive vortex develops in the lower side of the cylinder and is then shed downstream of the cylinder at t = 5T/2. A positive vortex develops over $3T \le t \le 7T/2$, and then separates from the primary positive vortex in the near wake of the cylinder at t = 4T. Furthermore, over $9T/2 \le t \le 11T/2$ a positive vortex develops. This vortex is then shed from the lower side of the ordinder at t = 6T. A positive vortex develops over $13T/2 \le t \le 15T/2$, and then sheds downstream of the cylinder at t = 8T.



6.1. Flow past a transversely ocillating circular cylinder in the absence of a free



6.1. Flow past a transversely ocillating circular cylinder in the obsence of a free

Figure 6.5: The equivorticity patterns(left), streamline patterns(middle) and the pressure contours(right) in the near wake region of the cylinder over nize periods of cylinder overlation, 97, at R = 200: A=0.13, $f/f_D = 1.25$ when $h = \infty$ [$T \approx 4.04, 52.55 \le t \le 80.889$: (137, 227]). The quasi-bolic of MS^* mode, per 97, is observed.



6.1. Flow past a transversely osillating circular cylinder in the absence of a free surface

Figure 6.6: The equivariativity patterns over nine periods of cylinder oscillation, 9T, at R = 200: h = 0.13, $f/f_B = 1.75$ when $h = \infty$ [$P \approx 2.880, 37.6 \le t \le 63.49$: (137,227)]. The quasi-bodied on 1065° mode, per 6T is observed.

6.1. Flow past a transversely ocillating circular cylinder in the absence of a free surface 18

of the cylindry, M = 277 (n = 0.5, 4.6, 8.102, 1.24, 1.83.10), the high premer regimes more bin control for the low perturb the the damatian mign andmanner backyon, the low persure regimes in the descretion of the cylindoft, <math>M = - 377, and m is a neutral target, the low persure regime in major outshift to the upper able and builds the cylindr. M = -377, where in it and off larget, the large persure regime is mostly conduct in the low serie data and the cylindry. The large persure regime is mostly conduct in the low serie data and the cylindry of the series regimes in and cynomical table from the regres of all off cylindry to the larget state and the that for the damager data, set do series that the cylindry of the larget data and the larget data and the series that the cylindry of the larget data and the larget data and the series of the persures theorem in the larget data and the larget data and the persures of the larget data and t = 0.07 (M = 17.5, M = 17.5, M = 17.6, M = 10.7, M = 17.6, M = 10.7, M = 17.6, M = 10.7, M =



6.1. Flow past a transversely ociliating circular cylinder in the absence of a free surface

Figure 6.7: The figure caption is given on page 18


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Figure 6.7: The equivorisity patterns(left), streamline patterns(middle) and the pressure contours(right) in the near value region of the cylinder over nise periods of 52 Vinder orcilation, 97, at R = 200, A = 0.3, $f/f_{\rm B} = 1.75$ when $h = \infty$ ($T \approx 2.896, 37.52 \le t \le 63.43$): (337, 227). The same bicked on 100^{87} mode, per ST is observed.

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vortes shelling eyels sheds into the near wals at $t - T/\lambda$. Over $T/2 \le t \le T/\lambda$, the development of a second positive vortex occurs. This positive vortex is shell from the lower ideal of the collings $t - t = 3T/\lambda$. Thus, a positive vortex of developing over 107/3 $\le t \le 14T/\lambda$ is adjust to interaction with a segative vortex in the upper shedding layer and consequently sheds into the downstream of the cylinder at t = 3T. Colleverses was not shewed in this flavor.

In Figure 6.9, the pressure contours of $f/f_0 = 2.25$ are displayed for over seven periods of cylinder oscillation, 7T. At t = 0T, this figure displays the development of the low pressure region in the upper side of the cylinder and downstream (near wake region). The development of high pressure occurs in the stagnation region. At t = nT/2 (n = 1, 3, 5, 7, 9, 11, 13), the high pressure region is confined mostly to the starnation region, and moreso above, than below, the low pressure regions in the downstream of the cylinder. Furthermore, the low pressure regions are positioned region. At t = nT/2 (n = 0, 2, 4, 6, 8, 10, 12, 14), the high pressure region seems to be confined to the lower portion of the stagnation region and moreso below, than above, the low pressure regions in the downstream of the cylinder. Furthermore, the low pressure regions are positioned in the upper side of the cylinder, but also behind the cylinder in the near wake region. For example as the negative vortex sheds at t = T, the area of high pressure is situated in the lower left portion of the stagnation region and the low pressure is situated in the upper side of the cylinder. As the positive vortex begins to shed over $T \le t \le 2T$, the high pressure region shifts crounter clockwise. At t = 5T/2, the high pressure region is positioned in the upper portion of the stagnation region, and the low pressure region in the lower side





Figure 6.8: The equivorticity patterns over seven periods of cylinder oscillation, 77, at $R = 200: A = 0.13, I/f_0 = 2.25$ when $h = \infty$ [$T \approx 4.04, 00.61 \le t \le 88.99$: (157, 227)]. The quasi-bodies on 98" smoke, per 77, is observed.

of the cylinder. It is interesting to note that the structure of the pressure contours at t = 0.7 (T7), T, T, T3/13, ZT, 577/2, 377 as a simulat initror images of the low pressure regions at t = 77/2, 47, 197/2, 57, 117/2, 67, 137/2, respectively. Therefore, the sociale nature of the flow field are execution in the pressure contours. 6.1. Flow past a transversely ocillating circular cylinder in the absence of a free surface





6.1. Flow past a transversely oscillating circular cylinder in the absence of a free surface

Figure 6.9: The equivericity patterns[left), streamline patterns(middle) and the pressure consours(right) in the near wake region of the cylinder over serven periods of cylinder oscillation, 77, at R = 200; A = 0.13, $f/f_B = 2.25$ when $h = \infty$ [$T \approx 2.245$, $44.833 \le t \le 60.615$: (307, 277]). The quasi-lockine on 68° mode, per 77, is observed.

6.1. Flow past a transversely ociliating circular cylinder in the obsence of a free surface 19

The optimizing spaceme on displays if $x_1/(f_p) = 2.5$ mer thus protod of yields expanded on the 20 space of the theorem with the integration with the equiquark-indexed B_2 space II. while $B_2 \leq 1 \leq 3.7$. This is consistent with the G_1 and G_2 submitting with the display merity of the structure of the theorem with the mode dwords the dismannia sholding of a angle votex from the rapper and lower watera double, grapping of the optime training the theory results of the effect of the optime of the effect of the structure of the structure of the effect of the optime of the effect of the structure of the effect of the structure of the effect of the works formed during the provious works is both adding regins, and work formed during the provious works is both adding regins, and work for the effect of the effect

In Figure 5.1, the present during the starting of the start start for spin of the start of the present has been during the start start of the start start start of high systems the doublest in the layer of the cluster, for large the density means right in doublest in the users of the cluster, for large the density means right in doublest in the users of the cluster, for large the density means right in doublest in the user out of the cluster, for large the density means right in doublest in the user out of the cluster, for large the density means right in doublest in the user of the target means the field in the lower through the singular angle, and have the present methics the the law start of the densities right means the themps from singular distributions the law law start of the singular angle, and present methy means require in startly confident to user period the singular distribution of the during and dendspress of a singular work at it. – The theorem were during the during law start is startly confident to a track theory of the singular distribution of the law start is startly confident to a track the during and dendspress at a singular start is a track the during and densities work at during at the track theory of the singular distribution. As the start and the singular distribution of the track start is a start of the during the means this first is a start distribution work at during at the track region means this from the start is means the singular distribution of the during the means this first in the start distribution work at during at the track region means this from the singular means the singular start is the singular start at the start is start at the start at the start is start at the start at the



6.1. Flow past a transversely ocillating circular cylinder in the absence of a free surface 15

Figure 6.10: The equivorticity patterns over three periods of cylinder oscillation, 37, at $R = 300: A = 0.13, f/f_{20} = 2.75$ when $h = \infty$ [$T \approx 1.187, 55.10 \le t \le 60.621$: (307, 537)]. The mass-location ∞ **25**' mode, per 37, is observed.

side of the cylinder (at t = 2T) to the lower side. The structure of the pressure contours at t = 0T (3T), T_2T , T are almost mirror images of the low pressure regions at t = 3T/2, 2T; 5T/2, respectively. Therefore, the periodic nature of the flow field are reproduced in the pressure contours.



6.1. Flow past a transversely ocillating circular cylinder in the absence of a free surface 15

Figure 6.11: The equivorticity patterns, streamline patterns and the pressure distibution in the near value region of the cylinder over three periods of cylinder oscillation, 37, at R = 200. A=0.13, $f/f_0 = 2.75$ when $h = \infty$ [$T \approx 1.837, 0.0.40 \le t \le 45.91$: (227, 257)]. The quasi-locked on 28° mode, per 37, is observed.

6.2.1 Fluid forces at Fr = 0.2: h = 0.5

The time binary of the life coefficient, C_{iii} , and the spectra of C_{ii} are displayed in Figure 0.12. The C_{ii} target of $[f] = \pm 2.7$ displayed signature every Tr within $T_{i}^{2} \le 327$, followed by a non-periodic signature of r > 327. On the method hand, the C_{ii} target of $[f] = 5 \pm 347$ (see a subjectived signature for Twithin $4T \le t \le 54T$ ($0T \le t \le 47$, offers to the transition state). The C_{ii} target for $[f] f_{ii} = 1.5$, 1.5 finding two periodic signature. The spectrum corresponding to the morphodic state of this despiner ratio, displaye a single park of T ($f_{ii} = 1.5$) and $(f_{ii} = 1.5) \approx 1.6$, $f_{ii} = 1.5$ and $(f_{ii} = 1.5) \approx 1.6$, $f_{ii} = 1.5$ and $(f_{ii} = 1.5) \approx 1.6$, $f_{ii} = 1.5$ and $(f_{ii} = 1.5) \approx 1.6$. The generic morphodic is at σ of the form the display σ advantage park of T. For expertum corresponding to the morphodic state of this despiners ratio, display σ single σ and $f_{ii} = 1.5$. The display morphodic and no spectrate of $(f_{ii} = 1.5) \approx 1.6$, $f_{ii} = 1.5$.

Figure 3.1 displays the time biasey of the dag coefficient, $C_{p,i}$ and the spectra of C_D . It is evident that each C_D trace, corresponding to $f/f_0 = 123, 175, 223, 275,$ comparisonly, displays no periodic signatures. The corresponding periodic signatures and largely dominant peaks at the forcing frequency, f_i with the exception of the spectrum of $f/f_D = 273$ which displays an employing peak at $f \rightarrow 3\delta_D/2$. Hence, once again infomitories of the submet effect of f and f.

It is evident that the composing Landyon patterns of $C_{1,C}(x_{1,C})$ of Figure 12. arc conduct to both the low-and targen kall places. On the other hand, the $C_{2,Q}$ patterns of Figure 6.13 are confined mostly to the appen kall-places. It is evident that as $J/f_{1,C}$ interms from 2.15 to 2.75, that the total area second and the emergence of the Landyon patterns into the lower kall place. For $J/f_{1,C} = 1.75$, and $J/f_{2,C} = 1.75$, the minimal and $T_{2,C}$ interms constant and the second sec

6.2.2 Vortex formation modes at Fr = 0.2: h = 0.5

Figures 6.14-6.19 display the equivorticity and streamline patterns, and pressure contours in the near wake of the cylinder when $f/f_0 = 1.25, 1.75, 2.25$, and 2.75. The observed flow bihariour is (i) quasi-prioridic par 7T for $f/f_0 = 2.25$, and per 3T for $f/f_0 = -2.75$ and (ii) non-periodic for $f/f_0 = 1.25, 1.75$.

A series of instantaneous equivarisity plots over tensity periods of cylindra cullitation, 2017, for 17/f, = 173 and 1.75 are pelotid in Figures 6.14-6.15. Both figure show that the frequency of the vertex shadding is not locked-on to the frequency of the cylinder motion at these frequency ratios. Coalescence was not observed for both frequency ratios.

Figure 6.16 displays the equivorticity patterns over seven periods of cylinder oscillation, 77, of the quasi-periodic state when $f/f_0 = 2.25$. The vortex shedding mode is







Figure 6.14: The equivorticity patterns over twenty periods of cylinder oscillation, 20T, at $R = 200; h = 0.13, f/f_0 = 1.33$ when h = 0.5, Fr = 0.2 $[T \approx 4.04, 4.04 \le t \le 84.84 : (17, 21T1) (non-orticide state)].$

the quark-hold-on $C(30^{\circ})$ mode, per T_{c} , within $3^{\circ} \le t \le 30^{\circ}$. This is constant, with the C_{c} balancies, but an $C_{c,p}$, with foregroup with. The first is competitivity for $t > 20^{\circ}T_{c}$. In this mode, these variess develop on anh side of the cylinder and advantady and our ever. The index relation from this figure that condences of varieties advantady and our ever the backing here (right the partiest wereints experimes runbency). A sequent variation water, it is even the structure at t = 277. The modilur partiest varieties develops with a word matrix to at t = 127. The modilur partiest varieties every develops



Figure 6.15: The equivorticity patterns over tsearty periods of cylinder oscillation, 207, at R = 200, A=0.13, $f/f_0 = 1.75$ when h = 0.3, Fr = 0.2 $|T \approx 2.886$, $2.886 \le t \le 00.001$ (T, 2271) (non-normidic state).

over $T \leq t \leq T/3$, and shuch into the upper vertex shelding range at $t \in W/3$. A singular works decomposes with $T/3 \leq t \leq T/3$ and then condenses with another largedine vertex at $t \in T/3$. This vertex develops over $W \leq t \leq t \leq W/3$, and then about into the near value of the ophicar of $x \in W/3$. A sequetor vector is from 6 from the modesses of $t \in roots predictive vectors <math>t = t = 1/3$. A sequetor vector is from 6 from the modesses of $t \in roots predictive vectors <math>t = 1/3$. A sequetor vector is from 5 from W/3. A sequetor W/3 is a sequence of W/3 and W/3 and W/3 W/3. A sequetor W/3 is a sequence of W/3 is a sequence of W/3 and W/3. We consider the sequence of W/3 is a sequence of W/3 and W/3. We consider the sequence of W/3 is a sequence of W/3 is a sequence of W/3. We consider the sequence of W/3 is a sequence of W/3 is a sequence of W/3. We consider the sequence of W/3 is a sequence of W/3 is a sequence of W/3. We consider the sequence of W/3 is a sequence of W/3 is a sequence of W/3. We consider the sequence of W/3 is a sequence of W/3 is a sequence of W/3. We consider the sequence of W/3 is a sequence of W/3 is a sequence of W/3. We consider the sequence of W/3 is a sequence of W/3 is a sequence of W/3. We consider the sequence of W/3 is a sequence of W/3 is a sequence of W/3 is a sequence of W/3. We consider the sequence of W/3 is a sequence



Figure 6.16: The equivoriality patterns over seven periods of cylinder oscillation, 77, at R = 200 A=0.13, $f_1/f_0 = 2.25$ when h = 0.5, $F_T = 0.2$ [$T \approx 2.245$, $26.93 \le t \le 42.66$; (127, 1971). The quasi-focked on **C**(**88**)^{*} mode, per 77, is observed.

from the upper side of the cylinder at t = 20T/3. Meanwhile, a positive vortex formed during the previous wortex abshedding cycle continues to develop over $0T \ge t \le 2T/3$. This positive vortex is also downstream of the cylinder at $t \approx T$. A positive vortex develops over $T/3 \le t \le TT/3$, and u t = 8T/3 sheds downstream of the cylinder

aided by the protrusion of a negative vortex into the lower shedding layer. A positive vortex developed over $8T/3 \le t \le 14T/3$, sheds from the lower side of the cylinder at $t \approx 5T$.

In Figure 6.17, the pressure contours in the near wake region of the cylinder are displayed for the frequency ratio $f/f_0 = 2.25$, over seven periods of cylinder oscillation, 77. At t = 0T, the high pressure region has developed in the stagnation region, and shows and below the low nessure regions in the downstream of the cylinder. The low nessure region has developed mostly in the upper side, and downstream of the cylinder. At t = T/2, the high pressure region has shifted mostly to the upper side of the cylinder, and the low pressure region has dramatically increased in concentration and has shifted below and downstream of the cylinder. Note that the concentration of high pressure is very low downstream of the cylinder at t = T/2. Overall, this develops in the lower side, and downstream of the cylinder. The high pressure region has been forced mustly to the upper side of the cylinder in the very near wake. Interesting to note is that at t = nT/2 (n = 2, 4, 6, 8, 10, 12, 14), the positioning of the high and low pressure regions are almost mirror images of the positions of the high and low pressure mentioned above. That is, the high pressure region is largely confined to the starration region, lower side, and above and below the low pressure regions in the downstream of the cylinder. In return, the low pressure region is forced

In Figure 6.18, the equivorticity patterns for $f/f_0 = 2.75$ are displayed for over three peridos of cylinder oscillation, 37. The shedding of two vortices occur within the



Figure 6.17: The figure caption is given on page 202



Figure 6.17: The equivorticity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near volor region of the cylinder over seven periods of cylinder coefficients, T_1 at R = 0.5, h = 0.13, $T_1 = 2.25$ when h = 0.5, F = 0.2 $[T \approx 2.243, 33.17 \le t \le 53.88$: (177, 247)]. The quasi-lacked on C(68)⁴ mode, per T_1 is observed.



Figure 6.18: The equivorticity patterns over three periods of cylinder oscillation, 37, at R = 200; A=0.13, $f_1 f_5 = 2.75$ when h = 0.5, Fr = 0.2 [$T \approx 1.857$, $91.83 \le t \le 97.34$; (907, 1837). The omai-backet on **28**⁺ moder one **37**, is observed.

over $0T \le t \le 11T/6$, and then sheds downstream of the cylinder at t = 14T/6. A positive vortex develops over $15T/5 \le t \le 3T$, but remains attached to the cylinder. Coolescence was not observed at this frequency ratio.

Figure 6.19 displays the pressure contours for the frequency ratio $f/f_0 = 2.75$ over three periods of cylinder oscillation, 3T. At t = 0T, the high pressure region has developed in the stagnation region and the upper left side of the cylinder, and the low pressure region in the upper side and downstream of the cylinder. At t = T/2. near wake of the cylinder, the low measure shifts above, below, behind the cylinder (near wake), and in the stagnation region. The high pressure region has been forced downstream. As the negative vortex has shed at t = 4T/6 (see Figure 6.18), it can be seen at t = T that the high pressure region has shifted mostly back to the unner left side of the cylinder (in the starmation region) and the low pressure region mostly to the upper side of the cylinder in the near wake, and very far downstream. Overall, it is evident that at t = nT/2 (n = 0, 2, 4, 6) that the high pressure region is located in the upper left side of the cylinder (stagnation region) and the low pressure region in the upper side of the cylinder and far downstream. On the other hand, at t = nT/2 (n = 1, 3, 5) the concentration of the low pressure region is very high in the revices of the cylinder. The high pressure region is located very far downstream. The structures of the low pressure regions at t = 0T and t = 3T are somewhat similar and thus the quasi-periodic nature of the flow field is reproduced in this figure.



Figure 6.19: The equivorticity patterns (left), stressmine patterns (middle) and the presrate contours (right) in the mass wake region of the cylinder over three periods of cylinder oscillation, 3T, at R = 200: A=0.3, $f/f_{\rm H} = 2.75$ when $h = \infty$ $[T \approx 1.837, 91.83] \le t \le$ 97.34; [507, 3737]. The quasi-below on 28° mode, per 37; belowered.

6.3 Summary and Discussion

Table 13 derivative the observed the absence relative two subsets (k = ∞) and the threshold in the 3 mode is the threshold in the structure of the fraction of the thre transverse of the structure of the stru

In Figure 2.1 the effect of the free study in the field h=0.1 and frequence ratios $[f_{11}(\dots, \dots, f_{12}), \dots, f_{12}, \dots, f_{12}), \dots, f_{12})$ and the modulated strenger transfer is momentation. It is immufated velocities that E is required to all masses, with the encayplicities of $f/f_{1}=1.2$, and the explorition of the field strength h=0.5. This is infinitely of the transfer of the tra

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$h = \infty$		
f/fa	Mode	T.

148° 108° 68° 28'

6.9. Summary and Discussion

at these frameway mains, hence the transfer of mechanical energy is bettern the opticient end find. 1: is combined that mappings of the value of E the dension of the Linsiport partners much be taken into account where establishing the transfer of the Linsiport energy E=100 and E=100 . The second second

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	Mechanical	Direction of $C_L(y)$		
f/f_0	$h = \infty$	h = 0.5		
1.25	2.460	-0.583	cylinder \leftrightarrow fluid	
1.75	-2.309	-2.272	$\operatorname{cylinder} \leftrightarrow \operatorname{fluid}$	
2.25	-11.475	-5.224	cylinder \rightarrow fluid	
2.75	-30.159	-9.792	$\mathrm{cylinder} \to \mathrm{fluid}$	

Table 6.2: The effect of the free surface inclusion, h(= 0.5), and frequency ratio, $f/f_0(= 1.25, 1.75, 2.25, 2.75)$, on the mechanical energy transfer, E, for the cases F = 0.2 when h = 0.5, so at $R = 200 : A = 0.13, f/f_0 = 1.25, 1.75, 2.25, 2.75$.

Table C summarian the offset of $H_{f_{1}}^{1}$ and λ on the mass H confinut, C_{i} , and λ or the mode of C_{i} where are directed by the parents of λ from hard heighten C_{i} where are directed by the parents of λ from and h_{i} and h_{i} = 1.23 Γ_{i} fs. the atom and λ = 1.6 Is $1.15 \leq f_{1}/f_{1} \leq 2.33$. The form h_{i} means of λ is non-finite at $\lambda = 0.5$, are larger due the sarely are C_{i} values at λ = out the interms, and the C_{i} values at λ = 0.5 L_{i} for the mode $\lambda = 0.5$. In Figure 4.6 L_{i} is the mode $\lambda = 0.5$ in the mode $\lambda = 0.5$ in the form L_{i} is $\lambda = 0.5$. In the form $\lambda = 0.5$ is $\lambda = 0.5$, where $\lambda = 0.5$ m L_{i} is $\lambda = 0.5$. The form $\lambda = 0.5$ m L_{i} is $\lambda = 0.5$ m L_{i} is $\lambda = 0.5$. The form $\lambda = 0.5$ m L_{i} is $\lambda = 0.5$. The form $\lambda = 0.5$ m L_{i} is $\lambda = 0.5$.

In Table 6.4 the values of the root mean square (rms) lift and drag coefficients, $C_{L_{CPRH}}$ and $C_{D_{CPRH}}$, are displayed. It is evident that with the inclusion of a free surface at h = 0.5 that the $C_{L_{CPRH}}$ values increase. The maximum increased observed for $C_{L_{CPRH}}$ values is by a factor of 1.30. As f/f_p increase from 1.25 to 2.75, it is evident that the C_{LPMA} values at $h = \infty, 0.5$ formass. Similarly to the C_{LPMA} values, the C_{LPMA} values increase with the indusion of the free surface at h = 0.5. The maximum increase is by a factor of 1.38. A value 0.01 lower them the maximum increase of the C_{LPMA} values. A weak, as f/f_p is increased, the C_{LPMA} values.

The effect of spindse absorption dapk, $h_i \in 0.5$, and the largency trule $f_i(h_i) \in 0.5$, $h_i \in 0.5$, h

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\widehat{C}_L		\widehat{C}_D		
f/f_0	$h = \infty$	h = 0.5	$h = \infty$	h = 0.5
1.25	0.001547	0.03367	1.329	1.6209
1.75	0.004122	0.02259	1.335	1.6509
2.25	0.007328	0.002126	1.353	1.7241
2.75	0.01372	0.006427	1.3589	1.7100

Table 6.3: The effect of the free surface inclusion on the mean lift, \widehat{C}_L , and drag coefficient, \widehat{C}_D , for the cases Fr = 0.2 when h = 0.5, ∞ at R = 200: A = 0.13, $f/f_0 =$ 1.25, 1.78, 225, 2.75.

	CLens		$C_{D,rms}$		
f/fo	$h = \infty$	h = 0.5	$h = \infty$	h = 0.5	
1.25	0.7306	0.9090	1.3340	1.6709	
1.75	1.0550	1.3533	1.3391	1.7188	
2.25	1.558	2.1609	1.3585	1.8190	
2.75	2.1910	2.1878	1.3621	1.8748	

Table 6.4: The effect of the free surface inclusion on the rms lift, C_{Lrms} , and drag coefficient, C_{Drms} for the case Fr=0.2 when h=0.5, ∞ at R=200: A=0.13, $I/f_8=1.25$, 1.75, 2.53, 2.75.

6.3. Summary and Discussion



Figure 6.20: The effect of the cylinder submergence depth, h (=0.5), and the frequency ratio, f/f_0 (=1.25, 1.75, 2.25, 2.75), on the equivorticity patterns at R = 200. A = 0.13, F = 0.2 from transverse motion.

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7. Flow past a circular cylinder under combined streamwise and transverse oscillations

The Chapter analyses the results for flam gas a studied relation waveleves the contradict of the control of th

7.1. Flow past a circular cylinder under combined oscillations in the obsence of a free surface 21:

7.1 Flow past a circular cylinder under combined oscillations in the absence of a free surface

7.1.1 Fluid Forces $(h = \infty)$:

Finnes 7.1 displays the time history of the fluctuating lift coefficient, C₁, and the PSD of C₁ for 1/L = 1.25, 1.75, 2.25, 2.75. It is evident, that similarly to the streamwise case when $h = \infty$, the C_L trace of $f/f_0 = 1.75$ displays a periodic signature every two cycles of cylinder oscillation. 27. This periodic behaviour is observed within $7T \le t \le 34T$. The periodic nature of C₄ for this frequency ratio is also suggested of cylinder oscillation. The C_L traces for $f/f_0 = 1.25, 2.75$ display quasi-periodic signatures every three periods of cylinder oscillation, 3T, within $5T \le t \le 24T$ and $5T \le t \le 54T$, respectively. The C_L trace for $f/f_L = 2.25$ displays a quasi-periodic signature every seven periods of cylinder oscillation, 7T, within $8T \le t \le 44T$. The quasi-periodic behaviour of each C_L trace, for $f/f_0 = 1.25, 2.25, 2.75$, is also suggested by the corresponding $C_1(y)$ patterns which display congruent behaviour. It is evident, however, that the congruency of the Lissajous patterns increase as f/f_0 increases from 1.25 to 2.75. It can be seen that the hysteresis loops of C_L , for each 1/1, are mainly confined to both the upper and lower half-planes. As f/fe increases, there is a slight shift of the $C_1(y)$ patterns into the lower half-plane. It is orident that for each frequency ratio, f/fn, the corresponding spectra display peaks at fo and f, with the dominant peak occuring at f. An additional peak at f + 2f/3 is also 7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface 214

observed in the spectrum for $f/f_0 = 2.75$, indicative of the weakened effect of f on



From T.1: The time variation of life coefficient, C_{41} , (black) and the transverse displacements of β_{1} (gray): FEO of C_{12} at R = 200 (A = 0.13 A, a = 0.5, A = 0.5, A = 0.15, a = 1.25, 1.75, 2.25, 2.25. The Linasjons and FEO plots for $f/f_{20} = 1.25$, 1.75, 2.55, 2.75. The Linasjons and FEO plots for $f/f_{20} = 1.25$, 1.75, 2.55, 2.75. The Linasjons and FEO plots for $f/f_{20} = 1.25$, 1.75, 2.57, 2.75. The Linasjons and FEO plots for $f/f_{20} = 2.57$, 2.75, 2.57. The Linasjons and FEO plots for $f/f_{20} = 2.57$, 2.75, 2.57. The second second

In Figure 7.2, the time history of the fluctuating drag coefficient, C_D , and the PSD of C_D for $f/f_0 = 1.25, 1.75, 2.25, 2.75$ is displayed. The behaviour of the C_D traces and



Figure 7.2: The time variation of drag coefficient, G_{0} , (black) and the streamwise displacements, $c_{1}(f_{1})$ (grav); F830 G G_{0} as R - 200; a - 0.3, $b - \infty / |f_{1}| = 1.25$, 175, 225, 275. The biassignes and P8D places for $|f|_{0} = 1.25$, 175, 225, 275. The biassignes and P8D places for $|f|_{0} = 1.25$, 175, 225, 275. The biassignes and P8D places for $|f|_{0} = 1.25$, 175, 225, 275. The biassignes and P8D places for $|f|_{0} = 1.25$, 175, 226, 275. The biassignes and P8D places for the following time intervals $M^{2} \leq t \leq 4M^{2}$, respectively. The corresponding flow states are also indicated for each $|f|_{0}$.

the spectra for each f/f_1 display similar behaviour to the traces and spectra associated with C_k in Figure 7.1. Similarly to the traces of C_k , the C_D traces display almost repeatable signatures every 3T for $f/f_D = 1.25$, 2.75, and 7T for $f/f_D = 2.35$. The C_D trace of $f/f_D = 1.75$, displays a repeatable signature every 3T. It is seen that the

	$h = \infty$				
f/f_0	Ε	Direction of	Direction of		
	(Numerical value)	$C_L(y)$	$C_D(x)$		
1.25	-3.911				
1.75	-5.800		**		
2.25	-12.435				
2.75	-23.527				

7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface 21

Table 7.1: The mechanical energy numerical values, E_c and direction of Lissajous patterns $C_L(y)$ and $C_D(x)$ as $R = 200: A = 0.13, f/f_0 = 1.25, 1.75, 2.25, 2.75$ when $A = \infty$. The transfer of mechanical energy between c_1 winder and fluid is represented by c_{-n} (remerviolate to fluid by c_{-n} and finally, from fluid to cylinder by c_{-n} .)

Linkings mattern comparing in $f/f_{-1} = 1.75$ displays highly compress significant. The Linkings matterns corresponding to $f/f_{-1} = 1.52$, 3.82, 3.83 display compress behaviour. It is some that as f/f_{+} immunes, the compress of dual basics are pattern immune. The main has be seen that the Linkings pattern moduli to the bases had plane as $f/f_{+} = 1.52$, 1.27, 1.25, 1

It is noted that Lissajous patterns $C_L(y)$ and $C_D(x)$ are presented in Figures 7.1 and 7.2, respectively, in accordance with the equation of mechanical energy transfer 7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface 217

11.1. Equation 11.1 determine the total dimensions mechanical energy tunnel of a cylobic subscription dimension in term of $C_{12}^{(i)}$ and $C_{12}^{(i)}$. Table 7.1 summarises the total mechanical energy values, E_{i} and the divertion dense of $M_{i} = 125, 127, 127, 227, 227 at <math>b \sim \infty$. Its mess from that the block the body mechanical energy values, E_{i} are negative and thereby the transfer of mechanical energy is from the cylinder to fluid, in each f_{i}/f_{i} . Bissews, it is are constructed we enclose the distribution of C_{i}/g_{i} and $M_{i}/f_{i} \sim 125, 127, 223, 236, 407 c/s/g)$ where $f_{i}/f_{i} \sim 175$. Otherwise, the distribution of the language patterns are constructed with C_{i}/g_{i} and $f_{i}/f_{i} \sim 125, 226, 237.$

7.1.2 Vortex formation modes $(h = \infty)$:

Figures 7.3–7.10, display the equivorticity, streamline patterns and the pressure contours in the near value of the cylinder when $f/f_0 = 1.25, 1.75, 2.25, 2.75, The observed$ $flow behaviour is (i) periodic, per 27, for <math>f/f_0 = 1.75$ and (ii) quasi-periodic per 37 for $f/f_0 = 1.35, 275$ and per 77 for $f/f_0 = 2.5$, respectively.

In Figure 12 the equivariary parame an displaced are three periods of (Tables outliness, W, for 1/h = 1.25. The directed balance much be the quark-blacket of (25)* + 249° mode, por 37, which $57 \le 1 \le 247$. This is consistent with the blacketon of C₂ and C₂ at this frequency ratio. This mode describes the alternative dialog of a parime and magnitive waves (Frequencies to the direction the alternative should be approximated frequencies). Allowed by the alternative should be a paritive and magnitive waves. (Recard mines the aversion wave abading curve constitution is devices over 9 < 1 < 577.6.



7.1. Flow past a circular cylinder under combined oscillations in the obsence of a free surface 21.

Figure 7.3: The equivorticity patterns over three periods of cylinder oscillation, 3T, at $R = 300: A = 0.13, 1/f_0 = 1.23$ when $h = \infty$ [$T \approx 4.04, 0.0.61 \le t \le 72.73$: (137, 137)]. The quasi-bodies on $C(287) + 28^{\circ}$ mode, we 3T, is observed.

and then shole denotations at the collimity at i = 87 Å. A mapping wave fragments from condensess or i = 0.75 (Fig. 7b, mapping subscripts of the is also downstreams of the cylinder at i = 177 Å. In the lower vortex sholding region, a pointive water developed from the permuta vortex sholding cylinde do warrawm of the cylinder at i = 177 Å. A pointive water thereafts much subscripts i = 0.76, develops one 27 ($\beta \leq 1 \leq 107$), $\beta_{\rm m}$ and then abeds downstream of the cylinder at i = 170,



7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface 21:

Figure 7.4: The equivariative patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wake region of the cylinder over three periods of cylinder oscillation, 37, at R = 200; A=0.13, $f/f_0 = 1.25$ when $h = \infty$ (T $\approx 4.04, 0.061 \le t \le$ 2.73; (152, 1577). The case-identic on C2587 + 255° mode, per 37, is observed.

The pressure contours for $f/f_0 = 1.25$ are displayed in the last column of Figure 7.4. At t = 0T, it can be seen that the high pressure region develops in the stagnation region of the cylinder, and that the low pressure region mostly develops behind the 7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface 220

Cylinds (zure sules rights). It is evident over 2T, that the high pressent remains producing the production respin of the cylinds wave get $t = t - T_{c}T_{c}T_{c}T_{c}T_{c}T_{c}$ where it also existing above and below the loss pressure region in the downtrams the droublest symmetry models in the low relation of a positive vertex of t $-T_{c}$ the rights of the pressure reades mustly in the here side of the cylinds. To the the low low T_{c} are compared wave relative vertex of $t - T_{c}$ the right of the cylinds r non-low new the display in the new value rights of the cylinds r non-low new that the droughnest value requires in this size space radius of the cylinds r non-low new that the low pressure region mustles in the space radius of the cylinds r non-low new that the space value region T_{c} are non-lybor vertex of the right results of the right value region T_{c} are non-right vertex value rights. The new value rights the choice results wave region T_{c} are non-right vertex value rights in the space radius of the right vertex of the right region T_{c} are non-right vertex value right T_{c} and T_{c} are non-right vertex value right T_{c} and T_{c} are non-right vertex of the right T_{c} are non-right vertex value right T_{c} and T_{c} are region region region results in the space radius T_{c} are non-right vertex of T_{c} are non-right vertex of T



Figure 7.5: The equivorticity patterns over two periods of cylinder oscillation, 27, at R = 200 A=0.13, $f/f_{2} = 1.75$ when $h = \infty$ [$T = 2.886, 66.38 \le t \le 72.15$: (227,257)]. The locid-on C(P + S) mode, per 27, is observed.




Figure 7.6: The equivarisity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wake region of the cylinder over two periods of cylinder oscillation, 27, at R = 200: A=0.13, $f/f_0 = 1.75$ when $h = \infty$ $|T \approx 2.886, 66.38 \le t \le$ 72.15: |237, 277.31. The boles on CPP + 81 modes, per 27, is observed.

In Figure 7 the asymptotic patterns are no produced of bulker coefficients, $T_{\rm eff}$ are discupsed for $f_{1/2}^{-1} = 1.75$ mostors during manufaction is the quark-boldered of CP = 40 ands, per $T_{\rm eff}$ and $T_{\rm eff}$ of $T_{\rm eff}$ is a mattern with the bulkers of C, and $C_{\rm eff}$ and $T_{\rm eff}$ and $T_{\rm eff}$ is $T_{\rm eff}$ and $T_{\rm eff}$ are straight of by the dubking of a parameter scatter matrix matrix matrix framework found for discussion. The approximation matrix matrix matrix framework found for discussion $T_{\rm eff}$ and the development of a scatter matrix matrix framework in $T_{\rm eff}$ of $T_{\rm eff}$ of the approximation of the approximation of $T_{\rm eff}$ of the approximation of 7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface 222

vortex pair sheds into the downstream of the cylinder. It is evident that this vortex pair decays rapidly as it flows downstream. Meanvalit, a positive vortex formed during the previous vortex shadding cycle continues to develop over $0 \le t \le 37/6$, and then sheds into the downstream of the cylinder at t = 47/6.



Figure 7.7: The equivorticity patterns over seven periods of cylinder oscillation, 77, at R = 300: A = 0.33, $f/f_0 = 2.23$ when $h = \infty$ [$T \approx 2.245$, $33.64 \le t \le 49.38$: (157, 227)]. The quasi-fockies on $C(88^{\circ})$ mode, per 37, is observed.

7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface 225

The pressure anothene are displayed in the last or obtain of Figure 7.16 for [1/4, b-1.26], or the particle of quick corelins, z_{i}^{2} , $z_{i}^{2} = -Q_{i}^{2}$, it is related the the last pressure dracking in the upper dis and dwarmtenn of the quicks. The $b_{i}^{2} \leq 27.1$, as the particle neutron develops in the hore right of the quicks. The $b_{i}^{2} \leq 27.1$, as the particle neutron develops in the hore right of the quicks. The $b_{i}^{2} \leq 27.1$, as the particle neutron develops in the hore right of the quicks. The $b_{i}^{2} \leq 27.1$, as the particle neutron develops in the hore right of the quicks. The $b_{i}^{2} \leq 27.1$, as the particle neutron develops in the hore right of the holding of the approximation part of the dwarmins of the quicks. On the starts hand, as a rangine versus pair of stories from the traper version develops in the dwarm of $a_{i} < 27.1$, the hore measure rapin add hance the quicks in the low version $d_{i} < 27.1$ (here, here hore) and holding the integration of the quicks. The therm value right pairs region in the targeneous rights in the dwarm starts in the neutron of the quicks. The high pressure region addition data holding the equipment of the travel value right, and holding and holding the targeneous regions. In generic, at i = 27.1 (here). The independence and holding the parameter region in the dwarm harmonic of the quicks. The independence of the region of the strangeneous region in the dwarm mean or strates in the neuron where c_{i} the neuron where c_{i} the rest value region of the regulation strates in the parameter region in the high mean regions regions relations. The neuron where c_{i} the integration of the regression region in the dwarm region in the parameter region in the high mean regions relations in the parameter region relations.

Figure 2.7 displays the equivativity pattern for l/h = 2.30 over seven probled of epidlane originari, m < 1. The showerd mode for this frequency ratio is the quarilocation (GSW) mode, per 77, within 87 $\pm 1 \pm 447$. This is constant with the behaviors of C4 and C₀ and L₀ within gamma of $\pm 1 \pm 447$. This is constant with the original displays the epidemion of the simulation of the simulation of the simulation statistical for the cyclinder and are alternatively duel over 77. In the upper vertex, shading layor, a magnitus vertex doubup over $0 \pm 1 \pm 77$, and then coaleses with a second mignitus vertex of $\pm 1 = 277$. The multiling magnitus vertex develops over 7.1. Flow past a circular culinder under combined oscillations in the absence of a





7.1. Flow past a circular cplinder under combined oscillations in the absence of a free variase 22

Figure 7.8: The equivorisity patterns (left), streamline patterns (middle) and the preserve centours (right) in the near wake region of the cylinder over seven periods of cylinder coefficient, 77, at R = 200; $\Lambda = 0.13$, $f/f_B = 2.25$ when $h = \infty$ [$T \approx 2.245, 44.89 \le t \le$ 0.615: (207, 727)). The regard-based-on COSS⁴⁷ words, see 77, is observed.

7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface 220

 $T \leq t \leq T_{11}$ and thus shock downsmum of the cylinder at $t = T_{11}$ A supplies user fracting frame frames downs or its transmission witten as in $t = 10^{-7}$. As obvious out $E \leq t \leq t$ and then endown with a third negative varies at t = 1172. The heavy samples or starts and do structures of the cylinder at $t = 10^{-7}$ and then endown with a third negative varies the shows are shown of the cylinder $t = 1 + 10^{-7}$. The towns are shown we have the observation of the cylinder at t = 177. The barres the shows are shown of the cylinder t = 1 + 177. The towns developes our 177 ($\beta \leq t \leq 1077$), and then shows we have only one $0^{-7} \leq t \leq 1077$. The towns developed from the previous vortex absolute cylinder at t = T. A nominity the shows are assolid as cylinder at t = T. The nominis with a distributive structure of the cylinder at t = T. The nominis the shows are assolid as cylinders and the previous vortex absolute t = 4. The model previous vortex absolute t = 177. The tower for the previous structure in the new value of the cylinder at t = 177. The lense with the the cylinder and the previous vortex absolute t = 177. The nodel previous the transmitter t = 177. The tower (t = 1777. The tower (t = 1777. The nodel previous t = 1777. The tower (t = 17777. The tower (t = 17777. The tower (t = 17777. The

Figure 3.5 adopts the pressure contrasts for the buyeness ratio 1/h = 2.5 our sum particula of glubal coefficient. Tet. At each the high pressure rapins develops in the argumentan region, and the low pressure region develops in the upper tasks and downstreams of the cylinder. As a rand of the multiple sholling of only writers in the target and law rapins of the cylinder, the constraintion all tables and by pressure regions in the viewing of the new value of the cylinder the trate downstreams of $(-\alpha/2)^2 (\alpha + 1.5, A, 3, 1, 1, 1, 3, 1, 1, the disposure region for the view pre-$





Figure 7.9: The equivorticity patterns over three periods of cylinder oscillation, 37, at R = 200; A = 0.13, $I/f_{0} = 2.75$ where $h = \infty$ ($\Gamma = 1.837, 60.61 \le l \le 66.12$: (337, 307)). The causi-bodie-len CDP + 80^o mode, per 37, is observed.

also if its ciplicity, and above and before the low pressure regions in the downtrum of the cliphice. On the either hand for example, it is -27, on a regarditw vertex in the report vertex absoluting region of the symbol builds, and to the specific detail of the cliphice. The sense of high presense ability more by the dot against high of the cliphice. The sense of high presense ability more by the dot against more prelation the lower preparation distribution, and the downlymment of a positive vertex in the lower weeks addedimention of the C build occurs. It is weeks at $(z \rightarrow 17724 \text{ mb})$

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7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface - 22



Figure 7.10: The equivariaity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wake region of the cylinder over three periods of cylinder coefficient, 37, at $R = 20^{\circ}$, A=0.13, $f/f_B = 2.75$ when $h = \infty$ $[T \approx 1.837, 0.40] \le t \le$ $0.61 + (227, 227)^{\circ}$. The combi-fixed-one CP4 + 85^o ready, are 27.16 is observed.

the concentration of the low pesseure is quite high in the near wake of the cylinder. The high pressure region, at this time, shifts above and below the low pressure regions in the downstream of the cylinder. The susceptote at t = 0T are nearly 7.1. Flow past a circular cylinder under combined oscillations in the absence of a free surface 225

identical, thus the quasi-periodic nature of the flow field is reproduced in this figure.

In Figure 7.5 the exploration parameters $|k|/|k_c = 2.57$, are displayed one three proofs of e (where estimations: The vector scheding mode it is they estimated on the test expression of |k| where |k| < 2.51. The test is malter with the |k| behavior $\mathbb{C}(p + k)$ would perform |k| within $|k'| \leq ||k||$. The is random with the behaviour of \mathbb{C}_p and \mathbb{C}_p at the large state is a solution vectors followed by the doubling of a singular vector within the particule of optical vectors. In filteration, the magnetize vector scheding matching is a singular vacuum kinetic doubling of a singular vacuum kinetic doubling of a singular vacuum kinetic doubling of a singular vacuum kinetic doubling and the singular vacuum kinetic doubling at ||k| < ||k||. Although the downward and the calculate at ||k|| < 2.71/k obvious proves doubling alphages, pair of positive varies formed during the previous matching ends (a) downward and the calculate at ||k|| < 1.75. Moreover, doubling alphages, pair of positive varies formed during the previous magnetization ($k_{\rm c}$) down and during etc. ||k|| < 1.75.

The presence motions for $|f|_{0} = 173$ serie displayed in the last toulous of Figure 7.10. Initially, the high presence spine dendupt in the acquariant regime of the cylichler. The low presence major dendupt is built, and in the upper air do the cylichler. The low $f = 10^{-2} (T_{c}^{-1} = 0.40, 0.40, 0.40, me)$ represence regime is positioned in the law of the d = 0.72 ($t_{c} = 0.42, 0.40, 0.4$

7.2 Free surface flow past a cylinder under combined oscillations at Fr = 0.2

7.2.1 Fluid forces at Fr = 0.2: h = 0.5

In Figure 7.12, the time history of the drag coefficient, C_D , the PSD of C_D and the corresponding Lissajous patterns, $C_D(x)$, of C_D are displayed. It is evident that the





	$h = \infty$			
51%	E	Direction of	Direction of	
	(Numerical value)	$C_L(y)$	$C_D(x)$	
1.25	-0.7364			
1.75	-11.32	**		
2.25	-4.210(-12.43)			
2.75	-47.46			

Table 7.2: The mechanical energy runnetial values, E_i and direction of Disayious patterns $C_i(y)$ and $C_0(x)$ at $R = 200 : A = 0.13, f/f_0 = 1.25, 1.75, 2.25, 2.75$ when A = 0.5, P = 0.2. The transfer of mechanical energy between cylinder and Huli is represented by '++,' from cylinder to fluid by '++' and finally, from fluid to cylinder be' '--.'

 C_0 taxes of (1/h) = 135, 135, 135 diaple quasi-product equivatives over (47.77), and 37, respective). For the cost for (1/h > 2.53), which use for (1/h > 2.53), and 1/h > 100, respectively. For the cost (1/h > 1.53), which the form a quasi-periodic signatures per 27 and 1×93 , Halmed b + quasi-periodic signature per 57 with 147×12 m 27.1 h is inderred to the Lineary main increases in singurant (1/h) mericuss from 12 m 25.7 h with, the foranging particle singurant (1/h) mericus from 12 m 25.7 h with, the foranging particle singurant (1/h) mericus from 12 m 25.7 h with, the forally (1/h) = 135, 135, 132, 132 diaples a simulation of 1/h where there ever that (1/h) = 135, 132, 132, 132 diaples a simulation of 1/h where there ever that (1/h) = 135, 132, 132, 132 diaples a simulation of 1/h with the infinitive of the warkword field of 10×10^{-1} ($1/h \times 10^{-1}$ for 1/h is infinitive of

In table 7.2, the total mechanical energy values, E, and the direction of energy transfer for $f/f_3 = 1.25, 1.75, 2.25, 2.75$ at h = 0.5, when Fr = 0.2 are summarized. It is seen

from this tokic that it is not a mechanical surger values, E_{i} are equivises only being the transfor of mathemistic marger is then the closel to test $[1, 5] \sim h^{2}/h_{i}^{2}$ immume from 1.25 to 2.75 the values of E immume arbitrariating $[1, 5] \sim h^{2}/h_{i}^{2}$ immume from 1.25 to 2.75 the values of E immume arbitrariating $[1, 5] \sim h^{2}/h_{i}^{2} > 1.25$, 1.75 and $(1, 5) \sim h^{2}/h_{i}^{2} > 1.25$, 1.75 and $(1, 5) \sim h^{2}/h_{i}^{2} > 1.25$, 1.75 and $(1, 5) \sim h^{2}/h_{i}^{2} > 1.25$, 1.75 and $(1, 5) \sim h^{2}/h_{i}^{2} > 1.25$, 1.75 and $(1, 5) \sim h^{2}/h_{i}^{2} > 1.25$, 1.75 and $(1, 5) \sim h^{2}/h_{i}^{2} > 1.25$, 1.75 and $(1, 5) \sim h^{2}/h_{i}^{2} > 1.25$, 2.75 and $(1, 5) \sim h^{2}/h_{i}^{2} > 1.25$,

7.2.2 Vortex shedding modes at Fr = 0.2: h = 0.5

Figures 7.13-7.22 display the equivorticity and streamline patterns, and pressure contours in the near value of the cylinder when $f/f_0 = 1.23, 1.75, 2.23$, and 2.75. The observed flue behaviour is (i) quari-periodic per 47, 27, 27 (57), 3T for $f/f_0 = 1.25, 1.75, 2.25$, respectively.

Pages 2.13 displays the majoratizity partitum for $f/f_0 = 1.55$ over four periods of options or (0.105), $r_1(0.105)$ $r_2 < 1 \le 10^{-1}$ be vortex sholling mode is the quarkalence at this displays part of r_1 such as $T \le 1 \le 10$. This is constitution with G_1 behaviour at this displays part with, but red L_2 is the mediaty vortex are advantarily all forms the part and here worted solviding region. A supervision are distribution wortex found along the previous worted solviding region. A supervise vortex are distribution wortes found along the previous worte sholling region completely disclass. Inon the paramety stores, in the target vortex sholling region $r_1 = 2T/\Delta_1$. A supervise store found along $f(r_1 < 1 \le 1)$, $r_2 < 1 \le 1$, r_3 , and r_4 is the target vortex.

In Figure 7.14, the pressure concurse for $f/f_{\rm B} = 1.23$ are displayed for owe He periods of cyclindre endingses. C. Brindly, the big pressure region develops in the singular negline of the cyclindre and the law pressure region develops bedden, and in the upper axis of other functor. At r=7/2, symmetry with the development of $A_{\rm C}$ are produce version. The high pressure region limit to the lower of of the functor, and domatranam. The high pressure region limit to the singular region models of choices $r = 1 - T_{\rm C}$ the hyper mergin function of the observed of the observ



Figure 7.13: The equivariativity patterns over four periods of cylinder oscillation, 47, at $R = 200: A = 0.13, f/f_0 = 1.25, Fr = 0.2$ when h = 0.5 [7 $\approx 4.04, 76.768 \le \le 92.929$; (97, 327)]. The quasi-location (O(289) + 488; mode, per 47, is observed.

to the upper hild mixed of the quinker, and the hor pressure region the addited black is a the appert of the quinker, and the presence between set t = 0.7, M t = -372, it can be sense that the memorarization of the presence has domained by increased, and that there is no dimensionly presence of the high pressures region in the new value or domained and the quinker. It is known that the distribution of the pressure in the mass make of a splitskic highly dynamics at the frame value or domains, at t = -372 commons with the distribution of a positive scores. It has pressure right, all the start the start the start the start value of a splits value score that the pressure right, all the start the start of the start the start value of the pressure right, all the start has a start of the start value of a splits value region. If the start has a start of the start the start region differs matching at t = -372 and anguing wavelet for the start of the start with the pressure right of the low pressure which we distribution (start of the start of the start of the distribution) of the start of the



Figure 7.14: The equivorticity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wake region of the cylinder over four periods of cylinder coefficients, $d_{12} \approx R = 200 \pm 0.013$ ($f_{12} = 1.25$, $F_1 = 0.2$ when R = 0.5($T \approx 4.04$, $R \approx 0.85 \le t \le 92.929$: (107, 237)). The quasi-locked-on C(68)⁴ mode, per 27, is observed.

to pressure in the near value of the emission functions in two by high. It can be send to be pressure comparisody curvatures the prime trans. There is reducerable pressure of high pressure in the near value of estimations of the clubble at minimum pressure of the comparisod structure of the clubble at minimum pressure of the clubble of the clubble. The low pressure region is found mody to the sequentian region of the clubbler. The low pressure region is not demonstrate the clubble of the clubbler. The low pressure is similar within the the sequence of the clubble and demonstrates (near walk), at these time instances. The structure of low pressure at t = 0 and t = 0 are smoothed allow a labora the major pressure at t = 0 and t = 0 are smoothed allow.



Figure 7.15: The equivariativy patterns over two periods of cylinder oscillation, 27, at R = 206; A=0.13, $f/f_0 = 1.75$, F = 0.2 when h = 0.5 [T = 2.866, $60.28 \le t \le 72.15$: (207) 207): In the quasi-location ($\mathbf{P} + \mathbf{S}^T$) mode, per 27], is observed.

Figure 7.15 displays the equivorticity patterns for $f/f_0 = 1.75$ for over two periods of cylinder oscillation, 27, within $23T \le t \le 25T$. The vortex shedding mode is the

quarkades of $|\Psi| \cdot |\Psi|$ and $|\psi| \cdot |\Psi|$, while $|\Psi| \leq ||\xi| + ||\xi||$. In the upper strucduality, here, a signation were developed from the previous vertex deading repriadual constraints of the cylinder at = 277 is. In the lower vertex adeding repriadual constraints of the developed $||\xi| = 277$, and here priority the developed in the second positive vertex developed one of $||\xi| \leq 277$, and here priority the prior to extra over $||\xi| = 277$, and the priority term pair is developed in the downtoness of the cylinder at |= 0776. The restriction were constraints over $||\xi| = 2776$, and the priority term pair is dual completely into the downtonum of the cylinder at |= 0776. The subscence plenumerons was not downtread in this case.

The power contours for $f_{1/h}^{-1} = 1.75$ are displayed in the late channe of Pegers (26. M t t = 0.77), in each that the skip powers respins it obsolvaps in the upper signation region of the cylinder, and the low powers region in the support is and inducentions of the displars. At t = 7.27, it is relater that the low powers region in a dished badro and above the cylinder in the new region, and that the high powers region is addied to addie powers region in the signature of the signature region. The displane set is the signature is the distribution of the signature region. The displane set is the signature region is and here the signature of the signature region in the distribution of the signature region is displaned as the signature region. Signature regions that the displane region region haddle on step (to the signature region. Signature excitation of the signature region is displaned intervely to the signature region of the signature region and deconstraints of the critication of the low region of the signature region and deconstraints of the critication and the powers region handling disregulation of the cylinder. In the constraints and haddle methy down the charged region is displaned intervely to the constraints of high powers region handling thereing down that the cylinder. The signature region is displaned by the powers region handling the region that the constraints of high powers hand handling the region down is adding to the signature region in the t = 2.77 can be seen that the haddling energy down the adding to the power right for the low powers region handling the region of the region t = 3.77 can be seen that hadd been regions of region handling the regions of regions and the haddling the regions of regions adding the regions are the regions and regions and regions are regions and the haddling the regions of regions. The regions are the regions are regions are regions are regions are regions and regions are regions are regions are regions are regions are reginstres



Figure 7.16: The equivariativity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near value region of the equinder continue periods of equinder continues, T_{t} is $R = 0.02 \times h{-}013$, $T_{t}^{0} = 1.75$, Fr = 0.2 when $h = 0.5 \times I^{-}$, $T_{t}^{0} = 0.28$, $\theta_{0.03} \approx 1.55$, $F = 0.2 \times I^{-}$, $T_{t} \approx 1.03$, $\theta_{0.03} \approx 1.55$, $F = 0.2 \times I^{-}$, $T_{t} \approx 1.03$, $\theta_{0.03} \approx 1.55$, $F = 0.2 \times I^{-}$, $T_{t} \approx 1.55$, $F = 0.2 \times I^{-}$, $T_{t} \approx 1.55$, $F = 0.2 \times I^{-}$, $T_{t} \approx 1.55$, $F = 0.2 \times I^{-}$, $T_{t} \approx 1.55$, $F \approx 1.55$,

cylinder, but mostly downstream of the cylinder. The high pressure region has shifted to the staggardiun region of the cylinder. It is the case that the quasi-periodic nature of the flow field has been reproduced in this figure since the snapshots at t = 07 and t = 27 are next identical.

For frequency ratio $f/f_0 = 2.25$, the flow displays quasi-periodic behaviour every two periods of cylinder oscillation, 2T, within $3T \le t \le 9T$ and every five periods of

cylinder oscillation, 5T, within $14T \le t \le 32T$. Within $10T \le t \le 13T$ and t > 32T $C(2S)^*$ mode, per 2T, within $3T \le t \le 9T$. In this mode two vertices of opposite rotation are alternately shed from the bottom and top of the cylinder, respectively. In the upper vortex shedding layer, it is evident that a negative vortex has developed in the previous vortex shedding cycle. This vortex continues to develop over $T/6 \le t \le$ 2T/6, and coalesces with a second negative vortex at t = 3T/6. The resulting negative t = 8T/6. In the lower vortex shedding region, a positive vortex formed during the previous vortex shedding cycle detaches from the primary vortex in the near wake $t \le 32T$. The vortex shedding mode is the quasi-locked-on $|C(P + S) + C(2S)|^{*}$ mode, per 5T, within $14T \le t \le 32T$. In this mode a pair of positive vortices and a single negative vortex are alternately shed, from the top and bottom of the cylinder, followed by the alternate shedding of two single vortices of opposite rotation. In the upper vortex shedding region, a negative vortex formed from the coalescence to detachment from the primary negative vortex in the near wake of the cylinder at t = 3T. Furthermore, a negative vortex develops over $3T \le t \le 10T/3$, and then coalesces with a second negative vortex at t = 11T/3. The resulting negative vortex

The pressure matum of $T/f_0 = 2.25$ are displayed for over two periods of collabors, T_{11}^{-1} for gravity T_{12}^{-1} . At t = 0 of the hipsenses replay to idveloping in the signature rapins of the cyclude, and the law pressure region is mainly developing in the superiod is of the cyclude and a startmark. As cognitive and produces were developed in the same wake of the cyclude at $u = T_{12}^{-1} T_{12}^{-1} T_{12}^{-1}$ is the veloce that the hopemanic raping annihils match: (i) the first, space and lawsr and of the cycludes and and developed in the constraint of the play powers is very low to both instances. On the other hand, $u.t = T_{12}^{-1} T_{12}^{-1}$ the high powerser region reduces results in the anguation anguing the cyclude cyclude powerse region reduces results the the anguation anguing the cyclude cyclude powerse region reduces results that the play resources the cyclude of the cycludes and the cycludes are the two powerse region reduces results the cyclude of the cycludes and the cycludes are the two powerse region reduces results the superior hand the cycludes are the two powerse region reduces the the law pressures the superior hand the cycludes are the horizon by the rad u < -0 related -0



Figure 7.17: The equivariative patterns over two periods of cylinder oscillation, 27, at R = 200; A = 0.13; $f_1 f_2 = 2.25$, Fr = 0.2 when h = 0.5 [7 = 2.245,8479 $\pm t \le 13.488$: (27,67)]. The quasi-looked on C(28)³ model, per 27, is observed.

hence the quasi-periodic nature of the flow field is reproduced in this figure.

In figure 7.20, the pressure matures is $P_1/f_0 = 2.32$ are displayed for rew for probation of calculus calculation, $I_1 = 0$, the high pressure grade soddys in the ortangamius region and be its pressure region develops dwardmann, and in the upper to field the cylinder. At t = aT/2 (s = 1.3, 3, 5, 50), the region of the grammer is highly commutated in the mare wake of the cylinder. It is confined mostly to its flow, upper and here risked the cylinder, we will as downtrame. The high pressure regions at here the inclusions is noticed mostly the top cylind is def the cylinder and above and below the box pressure region in the downtrame of the cylinder and above and below the box pressure region in the downtrame of the cylinder and the concentration of the pressure transition the terms. Box, at t = aT/2 (h =



Figure 7.18: The equivarisity patterns (left), streamine patterns (middle) and the pressure contains (right) in the near value region of the cylinder over two periods of epidedre conditions, T_{1}^{*} at R = 2026, R = 2256, R = 0.2 when k = 0.5 $[T \approx 2.2456, 8399 \le t \le 13.468 \pm (07.677)]$. The quasi-locked-on C(28)⁴ mode, per 27, is observed.

0.2.4.6.8.1%, the high pressure rapid is made) confind to the rapiditor angles of the cylinder, and determines of the cylinder have write registric. For example, as a positive vertex is shell at t = 77/3 (see Figure 7.18), and the development of a new positive and surgifier works occurs at $\ell = 327/2$, is rais best that the burper positive structures of the cylinder. The high pressure region modes above and balance the pressure entents in the development, the development of the cylinder. The development of the cylinder. The high pressure region modes above and balance the pressure entents in the development of the cylinder.



Figure 7.19: The equivariative patterns over four periods of cylinder oscillation, 57, at R = 200 A=0.13, $f_1 f_2 = 223$, Fr = 0.2 when h = 0.5 [$T \approx 2.246$, $60.996 \le < 57.825$: (277.327)]. The cause locked on [C(P + 2S) + C(2S)]" mode, per 57, is observed.

are nearly identical at t = 0T and t = 5T, hence the quasi-periodic nature of the flow field is reproduced in this figure.

In Figure 7.2 the equiversity patterns for $f_1 f_0 = 2.5$ see dissipated for over three periods of cylinder conflictions, $3T_1$ with $35T \leq 4 \leq 2.8T$. The vertex sheldling mode in the quasi-boliced on O(287), per $3T_2$ within $5T \leq 4.5T$. At 4 = 0.7, the regarities vertex in the mass value of the cylinder continues to develop until t = 3T/6 when at this time it candacces with a second negative vertex is the regarities to correct from the considerence decision or $\sigma = 5 \approx 1171$ (sum at t = 27 fields to correct the transformed on the context of the second seco



Figure 7.20: The equivorticity patterns (left), streamline patterns (middle) and the pressure contours (right) in the near wake region of the cylinder coefficient positions of cylinder coefficients, ST, as R = 200. A -0.13, $f/p_{\rm e} = 2.5$, $F_{\rm e} = 0.2$ then R = 0.5 $[T \approx 2.245, 60.006 \le t \le 7.8.29$: (227, 327)]. The quasi-backed-on [C(P + 8) + C(28)]⁴ mode, per ST, is observed.

with a second range its vertex, only to show this is applied were at -127%, whereas the theorem of the transmission of the second second second constanting uncertain his free developed in the previous were advalling cycle. This provides the developed second second second second second second proteins the developed mit = 27% the proteins were pair ratications to proper second seco

In Figure 7.21, the exploration protons of $f/f_{\rm p} = 2.3$ one three periods of Guidan confidints, and $T_{\rm s}$ are displayed. A surgistive worth develops over $0 \le t \le 47/6$ and then measures with a second anguative vector, at t = -7/6. The resulting angular vectors, at t = -7/6. The resulting angular vectors at t = -37/6. A positive vector, pink found them down around of the cylinder at t = 137/6. A positive vector, pink found the fitted during the previous worths adoding cycle estimates of t = 77/6.

Figure 32, displays the pressure standards for $f_1f_0 = 2.5$, see that periods of pickness scalars, m_1^2 . This highly, this figure highly the development of the high pressure is the signature region of the cylinder and the its pressure region his appeared on addressment of the cylinder. It is not is sent that with the development of the pickness states of the cylinder. The state is the state of the displayed manaly descentions of the cylinder. The large pickness region hills manaly descentions of the cylinder. The large pickness region hills are been single on the pickness region in the pickness region in the state heat, appear allows risk of the cylinder. It is the pickness region in the $t = aT_0T_0 = 0.3, 0.40$, that the isor pressure signs in handly conduct to the pickness and the high pressure region is marked to the pickness region in simple



Figure 7.21: The equivarisity patterns over three periods of cylinder oscillation, 3J, at $R = 200: A = 0.33, f/f_0 = 275, Fr = 0.2$ when $h = 0.5 |T \approx 1.837, 653.04 \le t \le 51.423$: (257, 587). The quask-hole-d-on C(289) mode, per 3J, is observed.

confined to the stagnation region. On the order hand, at = aT/2 (t = 1, 3.3), the bar persons region is used as such that the start start of the cyclinder, dominating the near wals: at these times. The high persons moves further domainsmin. It is evident that the concentration of high persons moves further domainsmin. It is evident that the concentration of high persons moves in the cyclinder, high persons t = T/2 are spins the start T/2 and T/2. The low persons attention of the singulation at t = T/2 are evident in T/2. Since the singularity the singularity matching of the field width t is produced in the field in T/2. The singularity the singularity the singularity the singularity of the field t is produced in the field t.



Figure 7.22: The equivorticity patterns (left), streamline patterns (middle) and the presure contours (right) in the sace value region of the cylinder over three periods of $\sqrt{2}$ hole or continuous, 77, at $R = 200 \times A = 0.13$, $f/f_R = 2.25$, $F_F = 0.2$ when A = 0.5 $f/\approx 1.837$, $6.594 \le t \le 51.433$: (257, 287)]. The quasi-locked-on C[28]⁴ mode, per 37, is observed.

7.3 Summary and Discussion

Table 72 displays the dirst the low surface presence at h = 0.8, when f_1/h_{-} = 1, 17, 12, 23, 25, 25, 36 ms – sources aboding mode of a \sim sylicate undersping transverse remains mutain, and the probed, T., Fet $(f_1 - 112, 112, 123, 25, 13)$. Also modes were based over M, M, T, R, T, M, T, Synty (M, S), the structure durbing probe that magnetism of the cylicate administrator dependence of the $f_1/h_{-} - 125, 23$ at h = 0.3, is equal to be watera aboding proton $f_1 = 27 \cdot 35$, for $f_1/h_{-} = 125$ at h = 0.3, is equal to be watera aboding proton $f_2 = 27 \cdot 35$, for $f_1/h_{-} = 125$ at h = 0.3, is equal to be watera aboding modes and $f_2 = 77$. For $f_1/h_{-} = 120$ at $h = \infty$. The weak standard dependence of the standard dependence of the standard dependence of the standard Q(P * 8) - CS(N), for $f_1/h_{-} = 225$. These modes are combinations of the matter and Radaka to the 1998 strady of a transversely oscillating cylinder in the aboves of a four endorm

Table 74 assumings in the offset explained subsequence depth A, and (1), has not the neural II to effective, (3) and the neural quere offsets, (5). The total supposed that the values of C_{0}^{2} are affected by the inducion of the bare surface at h = 0.5 for $1.05 \le f_{1}/h_{2} \le 1.5$. The C_{0}^{2} shows are regarding on addition that the same-21100 g $C_{0}^{2} \le 4.0112$ at $h = \infty$ and within $-4.000 \le C_{0}^{2} \le -4.1200$. One summary, the \tilde{C}_{0} values at $h \approx \infty$ are protect than these $h \approx -0.35$. As f_{1}/h_{1} to reason from 1.25 to 2.5. The \tilde{C}_{0}^{2} subsections $\tilde{C}_{0} \approx -3.6$. Since $\tilde{L}_{0} \approx 0.5$, $\tilde{L}_{0} \approx 0.5$, $\tilde{L}_{0} \approx 0.5$, $\tilde{L}_{0} \approx 0.5$, $\tilde{L}_{0} \approx 0.5$. The \tilde{C}_{0} subsection $\tilde{L}_{0} \approx 0.5$.

	$h = \infty$		h = 0.5	
f/f_0	Mode	T_{v}	Mode	T_v
1.25	$\mathbf{C}(\mathbf{2S})^* + \mathbf{2S}^*$	3T	C(68)*	4T
1.75	$\mathbf{C}(\mathbf{P}+\mathbf{S})$	2T	$(\mathbf{P} + \mathbf{S})^*$	2T
2.25	C(6S)*	7T	C(28)*	2T
			$[\mathbf{C}(\mathbf{P}+\mathbf{S})+\mathbf{C}(\mathbf{2S})]^*$	5T
2.75	$\mathbf{C}[\mathbf{P}+\mathbf{S}]^*$	37	C[2S]*	3T

7.3. Summary and Discussion

Table 7.3: The effect of the free surface inclusion, at Fr = 0.2, h = 0.5 and the frequency ratio, f/f_{01} compared to the absence of a free surface when $h = \infty$, on vortex shedding modes and their periods, T_{e1} at R = 200 : $A = 0.13, f/f_{0} =$ $1.25, 1.75, 2.25, 2.75. The suprescript <math>^{-\infty}$ decrets causi-locked-on modes.

the values of \widehat{C}_D^- do no increase by more than a factor of 1.20 for all f/f_r . Each \widehat{C}_D value is positive, and vary within the range 1.338 $\leq \widehat{C}_D \leq 1.832$. As f/f_0 increases from 1.25 to 2.75, the \widehat{C}_D values rand to decrease for $h \sim \infty$, with the currents on $f/f_D = 1.25$. On the other hand, the \widehat{C}_D values at h = 0.5, tend to decrease at f/f_0 increases from 1.25 to 2.75, with the encryption of $f/f_D = 1.25$.

 the magnitude of the $C_{L,rms}$ values at $h = 0.5, \infty$ are lower than the $C_{D,rms}$ values at $h = 0.5, \infty$.

In Figure 7.23, the effect of cylinder submergence depth, h(=0.5), and the frequency region of the cylinder is summarized. The snarshots are taken at x(t) = A. For periodic/quasi-periodic cases the snapshots are taken within the time intervals the flow reaches a periodic/quasi-periodic state. For the non periodic cases, the snapshots are taken with $0 < t \le 100$. The reference case is also displayed in this figure. It is seen at h = 0.5, that the free surface deformations are pronounced. Only moderate compared to the reference case, $h = \infty$. The negative vortex structures associated with $f/f_{\theta} = 1.25, 1.75$ differ more dramtically than those of $h = \infty$, whereas the positive vortex structures differ slightly. It is evident from this figure that there is presence of opposite signed vorticity near the free surface. It is evident from this figure that the vortex structures as f/fs increases from 1.25 to 2.75 vary highly as 2.75. Hence, the increase in f/f_0 for this case results greatly affect the formation of the vortex structures. As h decreases from ∞ to 0.5, it is evident that the vortex same, with the exception of $f/f_0 = 1.25, 1.75$ whose positive vortex structures seem to decrease in length (maximum by 22.9%). When $h = 0.5, \infty$ the negative vortex

	\widehat{C}_L		\widehat{C}_D	
f/f_0	$h = \infty$	h = 0.5	$h = \infty$	h = 0.5
1.25	-0.1012	-0.1259	1.326	1.6394
1.75	-0.1495	-0.2509	1.6168	1.852
2.25	-0.1919	-0.4510	1.4428	1.7477
2.75	-0.1816	-0.3580	1.4248	1.8340

Table 7.4: The effect of the free surface inclusion on the mean lift, \widehat{C}_{L} , and drag coefficient, \widehat{C}_{D} , for the cases Fr = 0.2 when h = 0.5, ∞ at R = 200 : A = 0.13, $f/f_0 =$ 1.25, 1.75, 2.25, 2.75.

	$C_{L,ras}$		$C_{D,res}$	
I/f_0	$h = \infty$	h = 0.5	$h = \infty$	h = 0.5
1.25	0.7659	0.9903	1.3812	1.7819
1.75	1.2190	1.5107	1.7836	2.3172
2.25	1.5697	1.7060	1.8865	2.6593
2.75	2.1928	1.7707	2.3758	3.5837

Table 7.5: The effect of the free surface inclusion on the rms lift, C_{Lrms} , and drag coefficient, C_{Drms} for the case Fr = 0.2 when h = 0.5, ∞ at R = 200 : A = 0.13 // h = 1.25, 1.75, 2.52, 2.75.



Figure 7.23: The effect of the cylinder submergence depth, h(=0.5), and the frequency ratio, $f/f_0(=1.25, 1.75, 2.25, 2.75)$, on the equivorticity patterns at R = 200. A = 0.13, $F_T = 0.2$ for a cylinder subjected to two-degrees of freedom.

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