EXPERIMENTAL STUDY OF THE EFFECT OF FORWARD SPEED AND FOLLOWING WAVES ON ROLL DAMPING OF FISHING VESSELS

CENTRE FOR NEWFOUNDLAND STUDIES

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SUIMIN ZHANG
Experimental Study of the Effect of Forward Speed and Following Waves on Roll Damping of Fishing Vessels

by

©Suimin Zhang, B.Sc.

A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Master of Engineering

Faculty of Engineering and Applied Science
Memorial University of Newfoundland

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St. John’s Newfoundland Canada
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This Thesis is dedicated to

my parents
Abstract

An extensive experimental program has been carried out to estimate roll damping parameters for three models of fishing vessels having different hull shapes and moving with forward speed. Roll damping parameters are determined using a novel method. This method combines the Energy method and the Modulating Function technique. The results show that this method gets better estimates compared with the original Energy method.

A data processing system was designed to process the experimental data. A parameter $C_{error}$ was introduced to measure the error in roll damping identification. A database system was developed using VAX-Pascal to store the analytical results and perform various kinds of analyses. The data management and processing system in this research work has proved to be very efficient.

The effect of forward speed, initial angle and natural frequency on roll damping is discussed. The effect of forward speed on roll damping was found to be nonlinear. The effect of initial angle is strong at zero and low forward speeds and decreases as the forward speed is increased. The effect of natural frequency was found to be weak.

Ikeda's method was used to predict the roll damping coefficient. The results were compared with the experimental data. It was found that Ikeda's method overestimates the roll damping at higher forward speeds for all three models. This method fails in predicting the eddy damping for ship forms with hard chines. It was noticed that as models move with forward speed, their mean drafts increase. A modification to Ikeda's formula is proposed, making use of this observation. The values predicted by the modified formula fit the experimental data very well.

A preliminary experiment has been done to investigate the effect of following waves on roll damping. It has been found that estimating roll damping parameters,
without allowing for the time variation in the restoring moment, results in overestimating the values of these parameters. Further work is needed in this area.
ACKNOWLEDGEMENTS

In my pursuit of the Master's degree in Engineering, I have received valuable advice and assistance from a number of people and groups, the help of these people and groups is very much appreciated. In particular, I would like to thank:

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\( l \)  
length of waterline

\( B \)  
beam of waterline

\( d \)  
draft

\( U \)  
forward speed of the model

\( C_M \)  
midship coefficient

\( C_B \)  
block coefficient

\( \Delta \)  
model mass (kg)

\( GM \)  
metacentric height

\( KG \)  
height of the center of gravity above keel

\( KB \)  
height of the center of buoyancy above the keel

\( BM \)  
distance from the center of buoyancy to the metacenter

\( \overline{OG} \)  
distance between the rolling center and the water level

\( \overline{OG}_0 \)  
distance between the rolling center and the still water level at zero forward speed.

\( \mu_1, \mu_2 \)  
parameters of restoring moment

\( \phi \)  
roll angle

\( \phi_0 \)  
initial roll angle

\( \dot{\phi} \)  
roll velocity

\( \ddot{\phi} \)  
roll acceleration

\( N(\phi, \dot{\phi}) \)  
damping moment per unit virtual moment of inertia

\( D(\phi) \)  
restoring moment per virtual moment of inertia

\( \omega \)  
natural frequency

\( \zeta \)  
nondimensional linear damping coefficient

\( \xi \)  
nondimensional nonlinear damping coefficient
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_e$</td>
<td>equivalent linear damping coefficient</td>
</tr>
<tr>
<td>$C_{error}$</td>
<td>error coefficient in roll damping identification</td>
</tr>
<tr>
<td>$b$</td>
<td>slope of $\overline{OC}$</td>
</tr>
<tr>
<td>$B_{F0}$</td>
<td>friction damping at zero forward speed</td>
</tr>
<tr>
<td>$B_F$</td>
<td>friction damping in the presence of forward speed</td>
</tr>
<tr>
<td>$B_{E0}$</td>
<td>eddy damping at zero forward speed for one section</td>
</tr>
<tr>
<td>$B_{Eut}$</td>
<td>eddy damping at zero forward speed for the whole ship form</td>
</tr>
<tr>
<td>$B_E$</td>
<td>eddy damping in the presence of forward speed</td>
</tr>
<tr>
<td>$B_L$</td>
<td>lift damping</td>
</tr>
<tr>
<td>$B_{w0}$</td>
<td>wave damping at zero forward speed</td>
</tr>
<tr>
<td>$B_w$</td>
<td>wave damping in the presence of forward speed</td>
</tr>
</tbody>
</table>
Chapter 1
Introduction

Although roll damping has been extensively studied by many researchers in the past twenty years, very little attention has been paid to the effect of forward motion. Roll damping suffers both quantitative and qualitative variations as a result of forward motion. As the ship speed increases a new roll damping component comes into play: the lift component. The effect of the lift damping becomes predominant at higher speeds.

Barr and Ankudinov[1] considered the roll damping of a ship hull without bilge keels or other damping devices to arise from two sources, wavemaking and viscosity. Viscosity is responsible for damping caused by vortex shedding at areas on the hull which suffer from large slope changes. Schmitke[2] used a similar reasoning to find estimates for damping moment for a warship hull form. He included the contributions from lifting surfaces such as the rudder, skeg and propeller shaft brackets. Both these works ignored the contribution of the bare hull as a lifting surface.

Due to the fact that the ship's hull has poor section shape as a lifting surface and because of its extremely low aspect ratio, it might be expected that the hydrodynamic forces and moments generated by the lift mechanism are much smaller than that generated by the rudder. However, one may quote Crane et al.[4], "... because of its very large profile area, a ship's hull does in fact generate forces and
moments far larger than the control forces and moments generated by its rudder, to show that this is not true. This component is very important when the ship is moving with a non-zero forward speed. As a matter of fact, as the forward velocity of ship increases, one should expect the lift component of the roll damping moment to constitute the most significant part of the roll damping moment.

One of the well known methods of roll damping estimation is the one presented by Ikeda et al. [3]. In this method, roll damping for a ship hull is assumed to consist of five components. These are friction damping, wave damping, eddy damping, naked hull lift damping and bilge keel damping. Different empirical formulae are introduced for the calculation of the different components. In calculating the lift component, Ikeda et al. [3] assumed the hull to be a lifting surface with a surface area equal to its length multiplied by draft. The angle of attack is equal to the ratio of an effective lateral velocity caused by the rotation of the hull about a center of roll to the forward velocity of the vessel. A semi-empirical expression for the slope of the lift coefficient with respect to the angle of attack, as a function of the ship's length, beam, draft and the midship section coefficient, was presented. It seems that the expression for the slope of the lift coefficient used in Ikeda's function is an empirical modification of that provided by Jones formula for a low aspect ratio wing, see Crane et al. [4]. The modification involves using an effective aspect ratio for the hull equal to \(2d/L\) and adding a function in both the beam length ratio and the midship section coefficient. This function reflects the fact that a thick wing has higher slope for the lift curve. Ikeda's formula implies that the lift coefficient is a linear function of the angle of attack. It also assumes that the lift coefficient is independent of the forward speed and of the angle of roll.

An experimental study of the roll damping of a warship hull moving with forward speed by Cumming et al. [5] showed the inviscid damping component to be a
nonlinear function of the forward velocity.

Blok and Aalbers[6] investigated the roll damping characteristics for 13 models from MARIN's systematic series of high speed displacement hull forms (FDS series). They reported poor correlation between experimental damping coefficients obtained for these models and estimations obtained using ikeda's empirical method. After modifying the estimation of the lift damping component using the theory of trimmed flat plates by Shuford[7], in addition to other modifications introduced by Schmitke[2] and Graham[8] for the calculations of bilge keel eddy damping, damping coefficients estimates agreed well with those obtained from free roll decay tests.

An experimental investigation of the lift component of roll damping has been done by Haddara and Leung[9]. The models were towed in calm water with different forward speeds at a yaw angle with the hull in the upright condition. The magnitude and the point of action of the lift force are determined by measuring the moment and force acting on the model. It has been found that the equivalent linear damping coefficient due to lift is a nonlinear function of the forward speed of the model. It was also found that ikeda's formula underestimates the lift component in higher forward speed. This experiment was done under a static condition in which the models were not allowed to heave. It may yield different results when the model is allowed more degrees of freedom.

It thus seems, that a further study of the roll damping moment of a ship moving with forward speed is warranted. The accuracy of the assumptions underlying ikeda's method and its limitations should be investigated. It is the main objective of this work to investigate experimentally the roll damping moment of the ship models moving with forward speed.

A few roll decay tests were also obtained for the model in following waves. The main objective of this preliminary investigation is to see what effect following waves
have on roll damping.

In roll damping experiments, a large number of roll decay curves are usually obtained. These curves are usually processed one by one. In this work, a new data processing and management technique is used so that the experimental data can be processed and analysed quickly, correctly and completely.
Chapter 2

Experiment

The experiments were performed in the wave tow tank of Memorial University of Newfoundland. The wave tank has inside dimensions of 58.27 m in length, 4.57 m in width, and 3.04 m in depth. Regular and irregular waves can be generated by a piston type wave generator at one end of the tank. At the other end of the tank a parabolic beach, consisting of an aluminum frame covered by wooden slabs, is intended to absorb and dissipate the energy contained in the incident wave and maintain a minimum reflection coefficient. A towing carriage is available for towing tests, resistance tests, current probe calibration, and self propulsion experiments. The carriage has a net weight of 3.9 tonnes and attains a maximum speed of 5 m/s.

2.1 The Models and Experimental Set Up

Models for three small fishing vessels were used in this investigation. They all represent fishing vessels of the less than 25 meters length class. They are all of similar dimensions but have quite different hull forms. Model M363 has a hard chine while M366 has a round bilge. Model M365 has a round bilge with a small rise of floor. The principal dimensions of these models are shown in Table 2.1 and the line plans are shown in Figure 2.1, Figure 2.2 and Figure 2.3.
Table 2.1: Principal Dimensions For Models

<table>
<thead>
<tr>
<th>Model</th>
<th>M363</th>
<th>M365</th>
<th>M366</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>1:12</td>
<td>1:91</td>
<td>1:68</td>
</tr>
<tr>
<td>L(m)</td>
<td>1.551</td>
<td>1.336</td>
<td>1.590</td>
</tr>
<tr>
<td>B(m)</td>
<td>0.507</td>
<td>0.506</td>
<td>0.506</td>
</tr>
<tr>
<td>d(m)</td>
<td>0.221</td>
<td>0.215</td>
<td>0.205</td>
</tr>
<tr>
<td>LCB(m)</td>
<td>-0.109</td>
<td>-0.052</td>
<td>-0.1375</td>
</tr>
<tr>
<td>Δ (kg)</td>
<td>79.5</td>
<td>54.5</td>
<td>69.5</td>
</tr>
<tr>
<td>C_M</td>
<td>0.746</td>
<td>0.705</td>
<td>0.612</td>
</tr>
<tr>
<td>C_B</td>
<td>0.4575</td>
<td>0.3750</td>
<td>0.4214</td>
</tr>
</tbody>
</table>

In the experiment, the models were only allowed three degrees of freedom: roll, heave and pitch. The experimental setup is shown in Figure 2.4. Part A is composed of two rollers which guide a rod fixed to the carriage, this keeps the model moving along the tank and allows it to pitch, heave and roll. Part B is a universal joint, which allows the model to move in roll and pitch. The universal joint is connected to a rod which is supported by two linear bearings. The linear bearings allow the model to heave. The model is moved forward by the action of a force transmitted from the carriage to the universal joint.

Part A and B were mounted on a board as shown in Figure 2.4. The rolling centers of Part A and B are at the same horizontal level. The vertical position of the board can be adjusted. As a result, the roll center can be changed. In addition, a
Figure 2.1: Lines’ Plan for M363

Figure 2.2: Lines’ Plan for M365
Figure 2.3: Lines' Plan for M365

Figure 2.4: Experimental Setup
Figure 2.5: Key arrangement on the board

Figure 2.6: Picture of Experimental Setup
gyro is mounted on the board to measure the roll angle. To give the model an initial heel angle at the start of the test, an arm connected to the model at its center of floatation is pushed to the side and then let go. The key arrangement on the board is shown in Figure 2.5 and a picture showing the experimental setup is in Figure 2.6.

2.2 Experimental Parameters

In this experiment, the model was constrained against sway. The metacentric height $GM$ can be changed by changing the position of the center of gravity. This changes the natural frequency of the model. The models were tested under different $GM$ values as shown in Table 2.3, Table 2.4 and Table 2.5 where the natural frequencies were directly measured from the decay curves and L.D. is a character used to identify each $GM$ value and make up file name for each decay curve.

For every $GM$ value, the models were tested at 8 forward speeds varying from 0.0 to 1.5 m/s as shown in Table 2.2. At each forward speed, the roll decay curves were measured for 7 initial angles varied from $7^\circ$ to $25^\circ$. At zero forward speed, free roll decay tests were also performed without the joint (Part A) so that the influence of the joint could be found. Therefore, for each $GM$ value, 63 decay curves (8 forward speeds $\times$ 7 initial angles + 7 initial angles without joint) were obtained. More than 1300 decay curves were obtained in total.

The determinations of $GM$, $\overline{OG}_0$ and $\mu_1, \mu_2$ are stated in the following sub-sections.

Table 2.2: Forward Speed for Test (m/s)

| 0.0 | 0.3 | 0.5 | 0.7 | 0.9 | 1.1 | 1.3 | 1.5 |

10
### Table 2.3: Experimental Parameters for M363

<table>
<thead>
<tr>
<th>L.D.</th>
<th>GM(cm)</th>
<th>$\omega$</th>
<th>$\overline{G^c}(cm)$</th>
<th>$\mu_1$</th>
<th>$\mu_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.33</td>
<td>3.796</td>
<td>3.98</td>
<td>0.8052</td>
<td>-1.1035</td>
</tr>
<tr>
<td>B</td>
<td>4.54</td>
<td>3.572</td>
<td>4.77</td>
<td>0.9666</td>
<td>-1.2682</td>
</tr>
<tr>
<td>R</td>
<td>3.82</td>
<td>3.310</td>
<td>5.10</td>
<td>1.1924</td>
<td>-1.5388</td>
</tr>
<tr>
<td>C</td>
<td>3.64</td>
<td>3.180</td>
<td>5.67</td>
<td>1.2616</td>
<td>-1.6221</td>
</tr>
<tr>
<td>D</td>
<td>3.24</td>
<td>2.952</td>
<td>6.06</td>
<td>1.4448</td>
<td>-1.8362</td>
</tr>
<tr>
<td>S</td>
<td>3.12</td>
<td>2.951</td>
<td>6.19</td>
<td>1.5131</td>
<td>-1.9140</td>
</tr>
<tr>
<td>E</td>
<td>2.15</td>
<td>2.455</td>
<td>7.16</td>
<td>2.2844</td>
<td>-2.7878</td>
</tr>
</tbody>
</table>

#### 2.2.1 The Measurement of $GM$ Values

$GM$ is the metacentric height which denotes the distance from the center of gravity to the metacenter, positive upward. $GM$ values can be measured by inclining experiments. In these experiments a small weight is moved a known transverse distance and the heel angle is measured. $GM$ value is calculated by the following equation:

$$GM = \frac{md}{\Delta \cdot \tan \theta}$$  \hspace{1cm} (2.1)

where $m$ is the mass of the small weight, $\Delta$ is the mass of the model, $d$ is the distance of the small weight from the center and $\theta$ is the heel angle. The experiment should be repeated several times and an average value obtained for $GM$.

In the experiment, $GM$ values were obtained by moving the small weight in several known distances and the the average value was calculated.
Table 2.4: Experimental Parameters for M365

<table>
<thead>
<tr>
<th>I.D.</th>
<th>GM(cm)</th>
<th>ω</th>
<th>(\bar{OG}_0(cm))</th>
<th>(\mu_1)</th>
<th>(\mu_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.22</td>
<td>4.457</td>
<td>6.51</td>
<td>-0.4957</td>
<td>-1.0220</td>
</tr>
<tr>
<td>1</td>
<td>4.00</td>
<td>3.990</td>
<td>7.73</td>
<td>-0.5909</td>
<td>-1.3431</td>
</tr>
<tr>
<td>1</td>
<td>3.96</td>
<td>3.838</td>
<td>7.77</td>
<td>-0.5887</td>
<td>-1.3737</td>
</tr>
<tr>
<td>2</td>
<td>3.39</td>
<td>3.605</td>
<td>8.34</td>
<td>-0.6635</td>
<td>-1.5888</td>
</tr>
<tr>
<td>J</td>
<td>3.28</td>
<td>3.484</td>
<td>8.15</td>
<td>-0.6868</td>
<td>-1.6202</td>
</tr>
<tr>
<td>3</td>
<td>2.57</td>
<td>3.217</td>
<td>9.16</td>
<td>-0.8261</td>
<td>-2.0661</td>
</tr>
<tr>
<td>K</td>
<td>2.40</td>
<td>2.986</td>
<td>9.33</td>
<td>-0.8597</td>
<td>-2.2430</td>
</tr>
</tbody>
</table>

2.2.2 The Determination of the Center of Gravity

The height of the center of gravity above the keel can be determined by the following equation:

\[
KG = KB + BM - GM
\]  

(2.2)

where \(KB\) is the height of the center of buoyancy above the keel, \(BM\) is the distance from the center of buoyancy to the metacenter. The values of \(KB\) and \(BM\) for the test models were specified in the hydrostatic particulars list provided by IMD. If the roll center coincides with the center of gravity, the distance between the roll center and the still water level at zero forward speed can be determined by:

\[
\bar{OG}_0 = KG - KD
\]  

(2.3)

where \(KD\) is the distance between the still water line to the keel.
The expression for the Restoring Moment

The expression for the restoring moment is needed for the identification of the roll damping parameters. The restoring moment \( D(\phi) \) can be expressed in the following form:

\[
D(\phi) = GM \cdot \Delta \cdot g(\phi + \mu_1 \phi^3 + \mu_2 \phi^5)
\]

(2.4)

where \( g \) is the acceleration due to gravity (\( m/\text{sec}^2 \)), \( \Delta \) is the model mass (kg) and \( \phi \) is the inclining angle.

The parameters \( \mu_1, \mu_2 \) can be regressed from the \( GZ \) curve of a ship with the relationship:

\[
D(\phi) = GZ(\phi) \Delta g
\]

(2.5)

where \( GZ \) represents the lever arm of the buoyancy force. The \( GZ \) curves for the three models are shown in figure 2.7. Each \( GZ \) curve was obtained for a specific \( GM \)
value. Assume the GZ and GM values for the GZ curves in Figure 2.7 are $GZ_0(\phi)$ and $GM_0$. The GZ curve for other GM value can be obtained by the following expression:

$$GZ(\phi) = GZ_0(\phi) + (GM - GM_0) \sin(\phi)$$  

(2.6)

* -- M363(GM = 0.056m)
+ -- M365(GM = 0.106m)
\(x\) -- M366(GM = 0.086m)

Figure 2.7: GZ curves for three models
Chapter 3
Identification of Roll Damping and Data Processing

3.1 Identification of Roll Damping

The damping parameters for the model were estimated from the free roll decay curves using a novel method. The method combines the Energy method, Haddara and Bennett[10] and a modified version of the Function Modulation Technique introduced by Shinbrot[11], see Haddara and Wu[12]. This method has been called "Modified Energy Method". Both methods are described and compared in the following sections.

3.1.1 Energy Method

The free rolling of a model can be described by the following differential equation:

\[ \ddot{\phi} + N(\phi, \dot{\phi}) + D(\phi) = 0 \] (3.1)

where \( \phi \) is the angle of roll, \( N(\phi, \dot{\phi}) \) and \( D(\phi) \) are the damping and restoring moments per unit virtual mass moment of inertia of the model.

The damping model can be expressed in the following nonlinear forms:

\[ N(\phi, \dot{\phi}) = 2\zeta \omega (\dot{\phi} + \epsilon \abs{\dot{\phi}} \dot{\phi}) \quad \text{Linear angle dependence} \] (3.2)

\[ N(\phi, \dot{\phi}) = 2\zeta \omega (\dot{\phi} + \epsilon \abs{\dot{\phi}} \dot{\phi}) \quad \text{Quadratic} \] (3.3)
\[ N(\phi, \dot{\phi}) = 2\zeta\omega(\dot{\phi} + \epsilon \phi^2) \quad \text{Cubic} \tag{3.1} \]
\[ N(\phi, \dot{\phi}) = 2\zeta\omega(\dot{\phi} + \epsilon \phi^2 \dot{\phi}) \quad \text{Quadratic angle dependence} \tag{3.5} \]

where \( \zeta \) and \( \epsilon \) are the nondimensional linear and nonlinear damping coefficients, \( \omega \) is the natural frequency of the linear roll equation.

In many cases, it is very useful to replace the nonlinear damping moment in equation 3.1 by an equivalent linear damping moment, especially in investigating the effect of different factors on roll damping, such as the effect of forward speed, natural frequency, initial angle, etc. In this case the roll damping moment can be expressed as:

\[ N(\phi, \dot{\phi}) = B_c \dot{\phi} \tag{3.6} \]

where \( B_c = 2\zeta\omega \) denotes the equivalent linear damping coefficient.

The restoring moment is a function of the form of the underwater part of the ship hull which has been discussed in Chapter 2.

Rewriting the ship roll decay equation (eq. 3.1) in the following form:

\[ \ddot{\phi} + D(\phi) = -N(\phi, \dot{\phi}) \tag{3.7} \]

and multiplying both sides by \( \dot{\phi} \) gives:

\[ \dot{\phi}\ddot{\phi} + \dot{\phi}D(\phi) = -N(\phi, \dot{\phi})\dot{\phi} \tag{3.8} \]

Writing the left hand terms of above equation in the following form:

\[ \dot{\phi}\ddot{\phi} = \frac{1}{2} \frac{d}{dt}(\dot{\phi}^2) \]
\[ D(\phi)\dot{\phi} = \frac{d}{dt}(G(\phi)) \tag{3.9} \]

yields:

\[ \frac{d}{dt}\left[ \frac{1}{2} \dot{\phi}^2 + G(\phi) \right] = -N(\phi, \dot{\phi}) \tag{3.10} \]
where
\[ G(\phi) = \int_0^\phi D(x)dx \]

Integrating equation 3.10 from \( t_i \) to \( t_{i+1} \) yields
\[ V(t_i) - V(t_{i+1}) = \int_{t_i}^{t_{i+1}} N(\phi, \dot{\phi}) \dot{\phi} dt \]

(3.11)

where \( t_i \) and \( t_{i+1} \) are two successive instants of time. \( V(t) \) is the total energy of the model per unit virtual moment of inertia at time \( t \)
\[ V(t) = \frac{1}{2} \dot{\phi}^2 + G(\phi) \]

(3.12)

Equation 3.11 shows that the energy loss during a small interval of time \( dt \) is equal to the energy dissipated in damping in the same interval. Assume the damping model is the Cubic form. Then substituting 3.4 into 3.11 yields
\[ V(t_i) - V(t_{i+1}) = \int_{t_i}^{t_{i+1}} 2\zeta \omega (\dot{\phi}^2 + \epsilon \dot{\phi}^4) dt \]

(3.13)
or
\[ Q_i(t) = b_1 n_{i1} + b_2 n_{i2} \]

(3.14)

where
\[ Q_i = V(t_i) - V(t_{i+1}) \]
\[ b_1 = 2\zeta \omega \]
\[ b_2 = 2\zeta \omega \epsilon \]
\[ n_{i1} = \int_{t_i}^{t_{i+1}} \dot{\phi}^2(t) dt \]
\[ n_{i2} = \int_{t_i}^{t_{i+1}} \dot{\phi}^4(t) dt \]

(3.15)

\( Q_i \) and \( n_{i1}, n_{i2} \) can be determined numerically from the roll decay curve. A least square method can then be used to find the coefficients \( b_1, b_2 \) which makes the sum of the squares of the difference between the two sides of equation 3.14 a minimum. The parameters of other roll damping models can be obtained in the same way.
3.1.2 Modified Energy Method

A modulating function operator is defined as:

$$\Psi[f(t)] = \int_0^T f(t) A^k(\tau) \, dt \quad (k = 0, 1, \cdots, n)$$

(3.16)

where

$$A^k(\tau) = \exp(-\tau^2/2) H_k(\tau) = (-1)^k \frac{d^k}{d\tau^k} \exp(-\tau^2/2)$$

(3.17)

and \(H_k(\tau)\) is Hermite polynomial of order \(k\) and

$$\tau = \frac{t}{T} (T_0 + T_s) - T_s = \beta t - T_s$$

(3.18)

where

$$\beta = \frac{(T_0 + T_s)}{T}$$

The function \(A^k(\tau)\) satisfy the following orthogonal relationship

$$\int_{-\infty}^{\infty} \exp(-\tau^2/2) A^m(\tau) A^n(\tau) \, d\tau = \sqrt{2\pi} \delta_{mn}$$

where \(\delta_{mn}\) is Kronecker delta. They also satisfy the following recursion relationships:

$$\tau A^n(\tau) = A^{n+1}(\tau) + nA^{n-1}(\tau)$$

$$\frac{dA^n(\tau)}{d\tau} = -A^{n+1}(\tau)$$

Substituting the expression for \(N(\phi, \dot{\phi})\) in equation 3.4 and operating on equation 3.1 using \(\Psi_k\), one gets

$$\Psi_k[\dot{\psi}] = -2\zeta \omega \{\psi_k[\dot{\phi}^2] + c\psi_k[\dot{\phi}^4]\}$$

(3.19)

In equation 3.19,

$$\Psi_k[\dot{\psi}] = \int_0^T \dot{V}(t) A^k(\tau) \, dt$$

$$= V(T) A^k(T_0) - V(0) A^k(T_s) - \beta \int_0^T V(t) \frac{dA^k(\tau)}{d\tau} \, dt$$

$$= V(T) A^k(T_0) - V(0) A^k(T_s) + \beta \psi_{k+1}[V(t)]$$

(3.20)
Then equation 3.19 can be expressed as

\[ 2\zeta \omega_n \{ \Psi_k[\dot{\phi}^2] + \epsilon \Psi_k[\dot{\phi}^4] \} = -V(T)A^k(T_e) + V(0)A^k(-T_s) - \beta \Psi_{k+1}[V(t)] \]

\[(k = 0, 1, \cdots, n) \tag{3.21} \]

Using different values of \(k\), one can generate a number of equations similar to equation 3.21 equal to the number of the unknown parameters in equation 3.4. In this case, we need only two equations to solve for \(\zeta\) and \(\epsilon\). One can also generate a larger number of equations and use a least square technique to find the unknown parameters.

When the equivalent linear damping form is used, let \(\epsilon = 0\) and \(\zeta\) can be determined by

\[ \zeta = \frac{-V(T)A^k(T_e) + V(0)A^k(-T_s) - \beta \Psi_{k+1}[V(t)]}{2\omega \Psi_k[\dot{\phi}^2]} \tag{3.22} \]

or

\[ B_r = \frac{-V(T)A^k(T_e) + V(0)A^k(-T_s) - \beta \Psi_{k+1}[V(t)]}{\Psi_k[\dot{\phi}^2]} \tag{3.23} \]

### 3.1.3 Comparison of Energy Method and Modified Energy Method

The energy and modified energy methods were used to estimate the damping parameters from the decay curves. The damping parameters obtained by both methods were used to generate free decay curves for the three models. These curves are compared with the decay curves obtained from experiment. The results are shown in Figure 3.1 to Figure 3.3. One can see that the modified energy method provides better predictions than the original energy method and that it is consistent in predicting the damping parameters.
Figure 3.1: Comparison between experiment and predicted response M363

Figure 3.2: Comparison between experiment and predicted response M365
3.2 Data Acquisition, Processing and Management

As stated in Chapter 2, more than 1300 decay curves were measured in the experiment. Usually, the decay curves will be processed one by one. It may take a few weeks of hard work to finish the whole process. In the present work, a special scheme has been designed to process the data in batches. This scheme had to be designed before the experiment, because the file names have key effect on the batch processing. The file names must be composed using certain regulations so that the processing programs can compose the file names automatically and process them one by one. In order to perform batch processing, it takes more time in program design and testing so that the programs work properly. Batch processing gives the benefit that it may only take a few hours in data processing instead of a few weeks of tedious work on the single file processing. It also gives a tidy arrangement of the output files in each processing stage and produces a standard format of results.
Figure 3.4: The flowgraph of data processing

which provides the possibility of using database techniques in data management and analysis. The flowgraph of data processing is shown in Figure 3.4.

3.2.1 Data Acquisition

In the experiment, a gyroscope was used to measure the roll decay curves. A program named ‘S575’ was used in data acquisition and plotting using the Keithley system and IBM PC interrupts. This program was developed in the Wave Tank Laboratory of M.U.N. using Microsoft C. The information of each decay curve was stored in a file. For the batch processing requirement, the file names were defined
in the following way:

File Name = I.D. + Forward Speed No. + Initial Angle No.

Forward Speed No. = [00, 03, 05, ..., 15] for corresponding forward speeds listed in Table 2.2. For the roll decay test without joint (Part A) at zero forward speed, the Forward Speed No. is [03] for M363, [65] for M365 and [66] for M366. Initial Angle No. = [01, 02, 03, ..., 07] for initial angles varying from 7° to 25° in increments of about 3°. I.D. is the identification mentioned in Chapter 2. A few examples of the file names are listed as follows:

<table>
<thead>
<tr>
<th>File Name</th>
<th>Forward Speed</th>
<th>Initial Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0001</td>
<td>0.0 m/s</td>
<td>1 ( \approx 7° )</td>
</tr>
<tr>
<td>S0502</td>
<td>0.5 m/s</td>
<td>2 ( \approx 10° )</td>
</tr>
<tr>
<td>S1503</td>
<td>1.5 m/s</td>
<td>3 ( \approx 13° )</td>
</tr>
<tr>
<td>S6304</td>
<td>0.0 m/s</td>
<td>4 ( \approx 16° ), Without joint</td>
</tr>
<tr>
<td>H6305</td>
<td>0.0 m/s</td>
<td>5 ( \approx 19° ), Without joint</td>
</tr>
<tr>
<td>Y6606</td>
<td>0.0 m/s</td>
<td>6 ( \approx 22° ), Without joint</td>
</tr>
</tbody>
</table>

where 'S' is the I.D. for M363 \((GM=3.12\text{cm})\) as shown in Table 2.3, 'H' is the I.D. for M365 \((GM=5.22\text{cm})\) as shown in Table 2.4 and 'Y' is the I.D. for M366 \((GM=4.35\text{cm})\) as shown in Table 2.5. In different stages of analysis, the file name will be the same but with different extension, as will be explained in detail in the following. The files in the stage of data acquisition do not have extensions.

A file named ‘S0507’ is shown in Appendix A as an example. The data from three channels were collected in the file in three columns. The first column gives the roll angle, the second column gives the pitch angle and the third column gives the forward speed. The integers in the columns indicate the amount of voltages measured by the gyroscope. Offsets and slopes in the file are used to translate the
where \( I \) is the integer in the file, \( S \) is the slope and \( O \) is the offset.

### 3.2.2 Translation of Experimental Data

Equation 3.2.4 was used to obtain calibrated data. In this stage and the following stages, the data were processed in batches. Input a file such as `S` will process all the 63 files (8 forward speeds \times 7 initial angles + 7 initial angle without joint) at the same time. The program composes the file names automatically and processes the files one by one. A program named "TRSBAT" developed in PASCAL was used to do the translation. The source program is listed in Appendix D. The output files in this stage have the extension `.AGL`. An example of the translated values named `S0507.AGL` is shown in Appendix B, where the first column is roll angles, the second is pitch angles and the third is forward speed.

### 3.2.3 Rearrangement of the Data

The translated files still need some rearrangement before they can be used in roll damping parameter identification. A program named `DAMABAT` written in FORTRAN was used to do this work. The source program is listed in Appendix E. The function of the program is listed as follows:

1. Cut off the first half cycle of the data. As stated in Chapter 2, the initial angle was generated by hand through an arm attached to the model. Some heave and pitch coupling are inevitable in the beginning of the rolling. Therefore the first half cycle of the data was not used in the analysis.

2. Adjust the x-axis. In the experiment, the gyroscope may not be parallel to the water level and the roll decay curves may have some bias. The x-axis was
Figure 3.5: Roll decay curve before and after the rearrangement

adjusted to minimize the bias.

3. Measure the natural frequency from the decay curve.

4. Create a file for the identification of roll damping parameters.

The output files in this stage have the extension ‘.USE’. An example of the output file named ‘S0507.USE’ is shown in Appendix C. The first five values are sampling frequency(1/s), natural frequency and coefficients of restoring moment(1/μ₁, μ₂). From sixth to end are the rolling angles. The pitch angle and forward speed were not included in the file in order to save space. Figure 3.5 shows the roll decay curve before and after the rearrangement.

3.2.4 Calculation of Roll Damping Parameters

A program named ‘MODFBAT’ developed in FORTRAN is used to calculate the roll damping parameters by using Modified Energy Method. The source program is listed in Appendix F. The files obtained by the previous process such as ‘S0507.USE’
were used as input. A coefficient was used to measure the error. The coefficient is defined as:

\[ C_{\text{error}} = \sum_{i=1}^{n} (A_i - \overline{A}_i)^2 \]  

(3.25)

where \( A_i \) is the amplitude of each half cycle of the decay curve obtained from experiment. \( \overline{A}_i \) is the amplitude of each half cycle of the decay curve generated by the roll damping parameters obtained by Modified Energy Method and \( n \) is the number of the amplitude of half cycle. \( n \) was assigned 5 in the calculation.

An example of the output of the program is shown in Table 3.1. In the table, line 01) is the input file name. Line 02) is the natural frequency. Lines 03) to 12) are the amplitudes of half cycles. Lines 13) to 16) are the nonlinear damping coefficients \((2\omega \zeta, 2\omega \xi)\) defined in equation 3.2 to 3.5 and the \( C_{\text{error}} \) defined in equation 3.25. In line 17), the first value is linear equivalent damping coefficient \( (B_e) \) and the third value is \( C_{\text{error}} \). As we can see in Table 3.1, the errors of nonlinear models are smaller than the error of linear equivalent model, which indicates that the nonlinear models fit the experimental data better than the linear equivalent model.
Table 3.1 A Output of Program MODFBAT

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>S0507.USE</td>
<td>2.004248</td>
<td>-2.0049789</td>
</tr>
<tr>
<td>02</td>
<td>0.2869402</td>
<td>-0.1474881</td>
<td>0.0929921</td>
</tr>
<tr>
<td>03</td>
<td>-0.1196999</td>
<td>-0.0797468</td>
<td>0.0016441</td>
</tr>
<tr>
<td>04</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.0000000</td>
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<td>0.0000000</td>
</tr>
<tr>
<td>06</td>
<td>0.000000</td>
<td>0.000000</td>
<td>0.0000000</td>
</tr>
<tr>
<td>07</td>
<td>0.0045932</td>
<td>2.036703</td>
<td>2.2077649E-04</td>
</tr>
<tr>
<td>08</td>
<td>0.2950082</td>
<td>0.580191</td>
<td>8.1270322E-05</td>
</tr>
<tr>
<td>09</td>
<td>0.4054145</td>
<td>7.767272</td>
<td>3.0916181E-04</td>
</tr>
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<td>10</td>
<td>0.4267024</td>
<td>0.581354</td>
<td>1.3132309E-04</td>
</tr>
<tr>
<td>11</td>
<td>0.6101135</td>
<td>0.000000</td>
<td>1.0751081E-03</td>
</tr>
<tr>
<td>12</td>
<td></td>
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</tr>
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<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 4

Management and Analysis

4.1 Management of the Experimental Results Using Database Techniques

4.1.1 Introduction of the Database Management System

As we saw in the previous Chapter, the output of the calculation is in simple file style (text file). Usually, investigators will analyse the data according to these files, which can be referred to as "simple file approach" [13]. This may work well if the amount of data is small and the relationships between the different components of the data are simple. In the present work, there are more than 1300 results as the one shown in Table 3.1. The usage of the data is quite diverse. Usage includes:

- Output data for different initial angles at a specific forward speed
- Output data for different forward speed at a specific initial angle
- Output data for different natural frequencies at a specific forward speed

As we can see, the data are used in different applications.

When simple file approach is used, it has the following problems:

1. Data redundancy. It is unavoidable that some data elements are used in number of applications as the situation stated above. Since data is required by multiple applications, it often is recorded in multiple data files. In most cases,
the data is stored repeatedly, which may jeopardize the integrity of the data, as well as putting pressure on storage.

2. Data availability constraints. When data are scattered in a number of files, it takes a lot of time and effort to search for the proper data to be used (usually done manually), which may lead to incomplete analysis of the data.

3. Data loss. In simple file approach, the various utilities of the operating system, such as copying, sorting, merging and editing, have to be used to handle the files and prepare data for further calculation or plotting. A small mistake can cause data loss and it will be unrecoverable. As there are many files in the storage, it is easy to forget the name and directory of the file, which may also lead to data loss.

The solution to such problems lies in database management systems (DBMS). DBMS is widely used in business and has spread to science and technology [13]. A database can be defined as [14]: “a common pool of shared data in which the data is interrelated, where each item of the data is stored only once and which represents a service to a wide range of applications.”

The most popular database model is the relational model. The relational database can be simply considered as a two-dimensional table. The column is called data item or field and the row is called record. All records are distinct (no duplicate records are allowed). To ensure that all records are distinct, each record has a key. A key can be one field or a combination of a number of fields in the record. The records in the database can be indexed (or sorted) by the key in ascending or descending order.

A data management system is a computer software that builds and uses the database [13]. The capabilities of data management systems are shown in Figure 4.1. The advantages of using a database management system are:
1. Redundancy is minimized. Because the data is only stored once. This saves storage space and guarantees the integrity of the data.

2. In a data management system, the data is isolated from the application programs. Changes in data file format, such as increasing a field length or adding a new field, and access methods, do not force modification in the application programs which use the files. This feature is referred as “data independence”[15].

3. With the help of a database, application programs can be developed, maintained, and enhanced easily and quickly.

4. With the help of the key field, one can retrieve the required data easily.

5. The data in the database can be shared by different users, which is an important feature in business DBMS and is important in science and technology.
applications when a group of people participate in the same project and analyse different aspects of the data.

6. In data management systems, many functions are similar, such as appending, updating, deleting, listing, etc. It is possible to develop a set of common subroutines which can be used by different databases with a little change, which will save time and effort in programming, especially in large research projects which involve the processing of a great amount of data with different structures.

4.1.2 The Creation of a Database

A database created by PASCAL is used to store the results such as the one shown in Table 3.1. PASCAL is better in the field of data management than many other languages such as FORTRAN. The reason is that PASCAL offers a richer repertoire of structured data types[16]. Here record data type is used. The record is a structure with named components which can be of different types. The result of analysis of each decay curve, as shown in Table 3.1, can be considered as a record.

The definition of the database can be written as follows:

```pascal
type
  key_type = packed array[1..5] of char;
  t_rec = record
    id : [key(0, ascending, nochanges, noduplicates)] key_type;
    omega : real;
    speed : real;
    amplitude : array[1..10] of real;
    b-14 : array[1..5, 1..3] of real;
  end;

var
  f : file of t_rec;
```

where 'id' is the field to store the file names of the decay curves such as 'S0507'. This is the key field in the record. The file is accessed in an index mode offered by
VAX-PASCAL[17][18]. To create a database, the file can be opened by:

```pascal
open(f, 'lab0801.dat', history:=unknown,
    organization:=index, access_method:=keyed);
rewrite(f);
```

To read or update the database, the file can be opened by:

```pascal
open(f, 'lab0801.dat', history:=old,
    organization:=index, access_method:=keyed);
resetk(f, 0);
```

where 'lab0801.dat' is the name of the database. A record can be located by:

```pascal
indx(f, 0, 'S0507')
```

where 'S0507' is the key of the record to be found.

A program named 'LABDATA' has been developed to create and manage the database. The source program is listed in Appendix G. The program has two sub-routines. One is for data management, the other is for data analysis and reporting.

### 4.1.3 The functions of the data management sub-routine

The functions of data management sub-routine are listed as follows:

1. Create (or rewrite) database.

2. Append analytical results obtained by Modified Energy Method. The analytical results such as the one shown in Table 3.1 will be added into the database.

3. Data examination. In this function, $C_{error}$ of each record will be compared with a specified value. The program will list all the records in which $C_{error}$ is greater than the specified value. In the analysis, it has been found that
when $\text{Error} > 0.01$, the predicted damping coefficient is unacceptable, which means the decay curve generated by the predicted damping coefficients do not fit the decay curve obtained in the experiment well. In this case, the damping coefficients have to be re-estimated according to other results with better conditions. There are more than 1000 records in the database, only 2~3% of the results needed to be re-estimated, which indicates that the Modified Energy Method has given a very good estimation of the roll damping coefficient.

1. Update analytical result. In this function, the data in a record can be modified.

5. List records in the database.

4.1.4 The functions of the data analysis and reporting subroutine

As soon as all the analytical results are stored in the database, we can output the results in various combinations. In the analysis, equivalent damping coefficient is used in most of the cases. So without specification, the output damping coefficient is the equivalent damping coefficient.

The main functions of the data analysis and reporting subroutine are listed as follows:

1. Find error caused by the joint by comparing two sets of data. As stated in Chapter 2, at zero forward speed, both experiments with and without the joint were tested. Two sets of data were compared to find the error caused by the joint. In this function, the average error caused by the joint is calculated and the data were output for plotting. The results are shown in Figure 4.2 ~ Figure 4.4. We can see that the error caused by the joint is almost constant.
Table 4.1: Damping Coefficient $V=0.5m/s$, id='S'

<table>
<thead>
<tr>
<th>Initial Angle (rad.)</th>
<th>$2\zeta_\omega$</th>
<th>$2\zeta\omega t$</th>
<th>$C_{error}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.09734</td>
<td>0.31164</td>
<td>0.0</td>
<td>3.705E-05</td>
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<td>0.0</td>
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<td>0.0</td>
<td>6.508E-04</td>
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<tr>
<td>0.25176</td>
<td>0.58284</td>
<td>0.0</td>
<td>7.910E-04</td>
</tr>
<tr>
<td>0.28694</td>
<td>0.61011</td>
<td>0.0</td>
<td>1.075E-03</td>
</tr>
</tbody>
</table>

Table 4.2: $B_e$ as a function of forward speed and initial angle, id='S'

<table>
<thead>
<tr>
<th>Fr</th>
<th>Initial Angle</th>
<th>7°</th>
<th>9°</th>
<th>11°</th>
<th>13°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000</td>
<td></td>
<td>0.3644</td>
<td>0.4512</td>
<td>0.5420</td>
<td>0.6092</td>
</tr>
<tr>
<td>0.0769</td>
<td></td>
<td>0.3200</td>
<td>0.3778</td>
<td>0.4504</td>
<td>0.5045</td>
</tr>
<tr>
<td>0.1282</td>
<td></td>
<td>0.3171</td>
<td>0.4123</td>
<td>0.4317</td>
<td>0.4685</td>
</tr>
<tr>
<td>0.1795</td>
<td></td>
<td>0.3831</td>
<td>0.4191</td>
<td>0.4382</td>
<td>0.4592</td>
</tr>
<tr>
<td>0.2308</td>
<td></td>
<td>0.4961</td>
<td>0.5093</td>
<td>0.5324</td>
<td>0.5428</td>
</tr>
<tr>
<td>0.2821</td>
<td></td>
<td>0.6102</td>
<td>0.6409</td>
<td>0.6653</td>
<td>0.6487</td>
</tr>
<tr>
<td>0.3334</td>
<td></td>
<td>0.7943</td>
<td>0.7572</td>
<td>0.7406</td>
<td>0.7608</td>
</tr>
<tr>
<td>0.3847</td>
<td></td>
<td>0.6518</td>
<td>0.7441</td>
<td>0.7647</td>
<td>0.7380</td>
</tr>
</tbody>
</table>

at different initial angles. In the analysis, the error will be deducted from the damping coefficients obtained from the experiments with joint.

2. Output damping coefficients of one forward speed. An example of the output is shown in Table 4.1.

3. Output damping coefficient as a function of speed and initial angle. An example of the output are shown in Table 4.2, where the initial angles are input as many as the user wants.

4. Output damping coefficients a function of $\omega$ (natural frequency) and speed. An example of the output is shown in Table 4.3. The user has to specify an initial
Figure 4.2: Effect of the Joint M363 GM = 3.12

Average error = 0.0719

Figure 4.3: Effect of the Joint M365 GM = 3.39

Average error = 0.0830
angle at first and then select the values of $\omega$ by selecting the I.D. listed in Table 2.3, Table 2.4 or Table 2.5.

5. Least square regression. In this function, a straight line is created to fit the data for different initial angles with the same forward speed. Example of using this function can be shown in Figure 4.2 to Figure 4.4.

Table 4.3: $B_e$ as a function of $\omega$ and forward speed, initial angle=11°

<table>
<thead>
<tr>
<th>I.D.</th>
<th>$\omega$</th>
<th>Forward Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0</td>
<td>0.3</td>
</tr>
<tr>
<td>A</td>
<td>3.796</td>
<td>0.443</td>
</tr>
<tr>
<td>B</td>
<td>3.572</td>
<td>0.445</td>
</tr>
<tr>
<td>R</td>
<td>3.310</td>
<td>0.554</td>
</tr>
<tr>
<td>C</td>
<td>3.180</td>
<td>0.492</td>
</tr>
<tr>
<td>D</td>
<td>2.952</td>
<td>0.488</td>
</tr>
<tr>
<td>S</td>
<td>2.951</td>
<td>0.542</td>
</tr>
<tr>
<td>E</td>
<td>2.455</td>
<td>0.499</td>
</tr>
</tbody>
</table>
4.2 Analysis and Discussion

The effects of different factors on roll damping have been investigated in detail by the help of the functions provided by the database system introduced in previous section.

4.2.1 Effect of Forward Speed on Roll Damping

The effect of forward speed on the equivalent linear damping coefficient of the models M363, M365 and M366 is shown in Figure 4.5 to 4.7, respectively. It can be seen from Figure 4.5 that there is a minimum point in the damping coefficient of M363 at a Froude number around 0.1 to 0.2. This phenomenon has been observed by several investigators, see Cox and Lloyd[19] and Cumming et al.[5]. The decrease in damping is attributed to a vortex cancellation mechanism caused by the bilge keels. However, model M363 does not have bilge keels but has a hard chine which could be causing the vortex cancellation mechanism in this case. The velocity at which the minimum roll damping occurs can be estimated by the “reduced frequency” relationship[19]:

\[
\frac{\omega L_{hk}}{U} = 2\pi
\]

In the case of the data in Figure 4.5, \( \omega = 3.796 \) and \( L_{hk} \) can be taken as the length of the hard chine which is about 1.0 meter long. Then we get \( U = 0.6042 \) and \( Fr = 0.155 \) which is approximately the value observed in Figure 4.5.

In addition, it has been noticed that as the forward speed increases there is a rapid decrease of the eddy damping accompanied by a slow increase in the lift damping until a certain speed is reached. As the forward speed increases beyond this value, lift damping increases rapidly and this causes a steady increase in the total damping of the model. For all three models the damping coefficient increases in a nonlinear manner. Actually, for M363 the damping coefficient reaches a peak at a
Froude number of about 0.33 then decreases again as the velocity is increased. This may be attributed to the deterioration in the lift generating mechanism at higher speeds. The reason that damping for the other models does not behave similarly can be attributed to the fact that model M363 has the highest midship section coefficient which may cause separation of the flow and thus a deterioration in the lift generation.

It should also be pointed out that model M366 has superior damping qualities over model M363 when they are moving with forward speed, in spite of the fact that the reverse is true when they are rolling at zero forward speed. This shows that estimating the damping qualities of ship models at zero forward speed can yield misleading results.

### 4.2.2 The Effect of The Initial Angle of Heel

The effect of the initial angle of heel, at which the free roll decay starts, on the damping coefficient has been studied. The results can also be seen in Figure 4.5 ~ Figure 4.7 for the models M363, M365 and M366, respectively. The initial angle of heel has the greatest effect near zero speed. At zero and near zero speed, roll damping consists of friction, wave and eddy making components. These three components are functions of the roll amplitude. At speeds near, but greater than, zero the contribution of lift to damping moment is small. As the forward velocity increases, lift effects become predominant and roll damping becomes almost independent of the initial heel angle, as seen from the experimental results shown in Figure 4.5 to 4.7. Roll amplitude has the greatest effect on model M363 damping at zero speed. The effect is less in the case of model M365 and still less in the case of model M366. The fact that M363 has a hard chine while M366 has a round bilge explains this behaviour. At zero forward speed, most of the damping of model M363 is viscous
Figure 4.5: Effect of $F_r$ and $\phi_A$ on roll damping M363

Figure 4.6: Effect of $F_r$ and $\phi_A$ on roll damping M365
while most of the damping of model M366 is caused by wave generation. Model M365 represents a case in between these two models.

4.2.3 The Effect of Natural Frequency

In the experiments, we changed natural frequency of the model by changing the GM value. As shown in Table 2.3, Table 2.4 and Table 2.5. The square of the natural frequency $\omega^2$ is proportional to GM value. The effect of changing the natural frequency on the equivalent linear damping coefficient is shown in Figure 4.8 to 4.10 for models M363, M365 and M366, respectively. It is seen that the damping is a nonlinear function of the natural frequency. This has been observed in the case of a warship hull at zero forward speed, see Cumming et al.[5].

It also can been seen in the Figures that the effect of natural frequency on roll damping is not very significant. Generally speaking, the increase of frequency will increase damping in vibration. But for ship rolling, the increase of natural frequency is obtained by the increase of GM value, which will decrease the vertical height of
the center of gravity. As a result the magnitude of the damping force arm will be
decreased. The combined effect may be the cause that the effect of natural frequency
on roll damping is small.
Figure 4.8: Effect of natural frequency on roll damping M363

Figure 4.9: Effect of natural frequency on roll damping M365
Figure 4.10: Effect of natural frequency on roll damping M366
Chapter 5
Prediction of Roll Damping

The total damping of a small fishing vessel moving with forward velocity can be divided into four components: friction, wave, lift and eddy damping, where eddy damping can be separated into two parts, one caused by the hull and the other caused by the skeg. Each component can be predicted separately[3][20][21]. In this Chapter, the prediction method for each component as proposed by Ikeda and other investigators will be described. Estimated values will be compared with experimental results and suggestions for modification of the present estimating method will be proposed.

5.1 Component Analysis
5.1.1 Friction Damping

Friction Damping is caused by the skin-friction stress on the hull surface. In predicting the value of friction damping, we ignore the effect of waves and regard the ship hull form as an equivalent axisymmetric body. Then the skin friction laws for a flat plate in steady flow are applied to roll motion of the body.

Cited here is Kato's formula modified by Hiyemen[21](no forward speed):

$$B_{F0} = 0.787 \rho S_f r_j^2 \sqrt{\omega v} [1 + 0.00814 \left( \frac{r_j^2 \phi^2 \omega}{\nu} \right)^{0.386}]$$  (5.1)
the first term in the brackets gives the result for laminar flow, which is used for the
naked model hull, while the second term gives the modification for the turbulent
flow by Hugh's formula, applicable to both the model hull with bilge keels and the
actual ship hull. \( S_f \) represents the wetted surface area of the ship hull and \( r_f \) the
average radius of roll. They can be expressed approximately by the formula:

\[
S_f = L(1.7d + C_B B)
\]

and

\[
r_f = \frac{1}{\pi} \left\{ (0.887 + 0.145C_B) \frac{S}{L} + 2 \cdot \bar{O}G \right\}
\]

In the presence of the forward speed, the friction damping can be expressed
as (Tamiya et al. [22]):

\[
B_F = B_{F0} (1 + 4.1 \frac{U}{\omega L})
\]

(5.2)

where \( B_{F0} \) represents the friction damping at zero forward speed, which can be
predicted by Kato's formula stated above.

5.1.2 Eddy Damping (Naked Hull)

In the absence of ship speed, this component is caused by the flow separation
at the bottom of the ship hull near the stem and stern or at the bilge circle near
the midship portion. The pressure drop in the separation region gives rise to this
damping.

In recent times, it has been found that the drag coefficient of a body in an
oscillatory motion varies with the amplitude of the oscillation. The same situation
may occur in the case of roll damping. Ikeda et al. [23] investigated this point
experimentally for a number of two-dimensional cylinders with ship-like sections.
They confirmed through the analysis of the experimental data that the eddy damping
coefficient can safely be considered as a constant in case of ship rolling. They further
proposed a formula for the eddy damping for ordinary ship hull forms. This can be written in terms of the two dimensional cross-sectional coefficient:

\[ B_E = \frac{4}{3\pi} \rho d^4 \omega \sigma \left( \frac{r_{\max}}{d} \right)^2 \cdot F\left[ \frac{R}{d}, H_0, \sigma, \frac{\partial G}{\partial r} \right] \cdot \zeta_p \]  

(5.3)

where \( r_{\max}, R, \sigma \) denote the maximum distance from the center of gravity to the hull surface, bilge radius, area coefficient of the section, respectively. The function \( F \) can be determined only by the hull shape and the pressure coefficient \( \zeta_p \), by the ratio of the maximum relative velocity to the mean velocity on the hull surface, \( \gamma = v_{\max}/v_{\text{mean}} \). This can be calculated approximately by a formula given by Ikeda et al., details can be found in reference[3]. The eddy damping for the whole ship form can be obtained by integrating the sectional values over the ship length.

In the presence of ship forward speed, on the other hand, the separated eddies flow away downstream, with the result that the eddy damping decreases rapidly. In this case, the eddy damping can be corrected by the following empirical formula given by Ikeda et al.[3]

\[ B_E = B_{E0} \cdot \frac{(0.04K)^2}{1 + (0.04K)^2} \]  

(5.4)

where \( B_{E0} \) is the eddy damping for the whole ship form at zero forward speed and \( K \) is the reduced frequency \( (K = \omega L/U) \).

5.1.3 Lift Damping

As mentioned before, as the forward speed increases the eddy damping decreases rapidly and lift damping prevails. Therefore the lift component becomes the most important part in investigating ship roll damping with forward speed. Yumuro derived a simple formula by applying the lateral force formula used in ship maneuvering research field to the problem of roll damping. This formula was modified by Ikeda.
et al.[3]. The formula is given in the form of an equivalent linear damping as below

\[ B_L = \frac{1}{2} \rho U L d k_N l_R (1 + A \frac{\overline{OG}}{l_R} + 0.7 \frac{\overline{OG}^2}{l_R l_R}) \]  

(5.5)

where

\[ k_N = 2\pi \frac{d}{L} + k(4.1B/L - 0.045) \]  

(5.6)

\[ k = \begin{cases} 
0 & C_M \leq 0.92 \\
0.1 & 0.92 < C_M \leq 0.97 \\
0.3 & 0.97 < C_M \leq 0.99 
\end{cases} \]  

(5.7)

\( k_N \) represents the derivative of the lift coefficient of the hull towed obliquely. \( l_o \) is the lever defined in such a way that the quantity \( l_o \dot{\phi}/U \) corresponds to the incidence angle of the lifting body. \( l_R \) denotes the distance from the roll center to the center of lift force. \( l_o \) and \( l_R \) were given by Ikeda et al. as

\[ l_o = 0.3d \quad , \quad l_R = 0.5d \]  

(5.8)

According to Ikeda's formula, the lift damping is linear, proportional to ship speed and independent of roll amplitude.

5.1.4 Wave Damping

In the case of zero Froude number, the wave damping can be obtained by using the strip method. In this paper, a subroutine of the program SHIPMO[8][24] developed by National Defence Department based on the Close-fit theory was used to calculate the wave damping at zero forward speed.

In the presence of ship speed, it is quite difficult to calculate the wave roll damping theoretically. Ikeda et al calculated the energy loss in the far field due to a pair of horizontal doublets and compared the results with experiments for models of combined flat plates. Through these elementary analyses they proposed an empirical formula for roll damping of ordinary ship forms:

\[ \frac{B_{e}}{B_{n4}} = 0.5 \{ [(2A_2+1)+(A_2-1) \tanh 20(\tau - 0.3)] + (2A_1-A_2-1) \exp \{ -150(\tau - 0.25)^2 \} \} \]  

(5.9)
where \( A_1 = 1 + \xi_d^{-1.2} \cdot e^{-2\xi_d} \)
\[ A_2 = 0.5 + \xi_d^{-1} e^{-2\xi_d} \]
\[ \xi_d = \omega^2 d/g \quad \tau = \nu \omega / g \]

The terms \( A_1 \) and \( A_2 \) represent the maximum at the point \( \tau = 1/4 \) and the constant value of \( B_w/B_{w0} \) where the value of \( \tau \) is large. The term \( B_{w0} \) stands for the value at zero forward speed.

### 5.1.5 Eddy Damping due to the Skeg

Most small fishing vessels have skeds to improve their manoeuvrability performance and for the convenience when they are docked on the slipway. Ikeda et al. found that the sked decreases wave damping and increases eddy damping\([20]\). They attributed the decrease of wave damping to the fact that the phase of the wave created by the sked is much different from that created by the main hull.

The creation of eddies at the edge of the sked leads to an increase in eddy damping. Eddy damping due to a sked can be divided into two components. One is the normal force component which is created by the pressure variation on a sked. The other is the hull surface pressure component which is created by the pressure variation on the main hull surface due to the sked. The normal force component is always positive, while the surface pressure component may be negative.

Ikeda et al.\([20]\) proposed a simple prediction method of eddy component of roll damping due to sked. A simple pressure distribution on the sked and on the bottom of a vessel is assumed as shown in Figure 5.1. The pressure coefficient \( C_{pF} \) and \( C_{pH} \) on the front and the back faces the sked and the length of the negative pressure...
region $S$ are assumed on the basis of the experimental results as follows

$$
C_{PF} = 1.2 \\
C_{PR} = -3.8 \\
S = 1.65l_sK_e^{2/3}
$$

(5.10)

where $l_s$ denotes the length of a skeg, $K_e$ is Keulegan-Carpenter number defined as $U_{max} \cdot T/l_s$, where $U_{max}$ denotes the maximum speed of the edge of the skeg, $T$ the period of the roll motion. Strictly, the value of $C_{PR}$ depends on $K_e$ number, but it is assumed to be constant for simplicity. Integrating the assumed pressure on the skeg and on the hull surface, the roll damping moment $M_r$ for unit length of the hull section can be obtained as follows

$$
M_r = \frac{1}{2} \rho U_{sk}^2 \{(C_{PF} - C_{PR})l_1 l_3 - \frac{1}{2} C_{PF} l_2 + \frac{3}{4} C_{PR} S l_3 \}
$$

(5.11)

where $U_{sk}$ denotes the velocity of the edge of the skeg, and $l_1, l_2$ and $l_3$ the moment levers as shown in Figure 5.1. The equivalent linear damping of the skeg can then be expressed as

$$
B_{sk} = \frac{1}{3\pi} \rho \omega \phi A \left[ (C_{PF} - C_{PR})l_1 l_1 - \frac{1}{2} C_{PF} l_2 + \frac{3}{4} C_{PR} S l_3 \right]
$$

(5.12)

when $l_1$ is the distance from the center of gravity to the edge of the skeg.

Figure 5.1: Pressure distribution due to a skeg (after Ikeda et al. [20])
The experimental study by Ikeda et al. indicates that the above formula predicts the eddy damping due to the skeg very well.

5.2 Comparison of Predicted Values with Experimental Results

As stated above, the roll damping of a fishing vessel is composed of four components, namely, friction damping, wave damping, lift damping and eddy damping for naked hull and skeg. These components are calculated using the formulae described in the last section. As many as possible estimated values have been calculated and compared with the experimental data. It was found that the results are quite similar for different conditions (GM values and roll amplitudes) for a specific model. Two figures are selected for each model as shown in Figure 5.2 and Figure 5.3 for M363, Figure 5.4 and Figure 5.5 for M365 and Figure 5.6 and Figure 5.7 for M366.

At zero forward speed, the predicting method gave quite accurate results for M365 and M366, but lower estimates for M363. As stated previously, M363 has a hard chine which will increase the eddy damping. Ikeda et al. [20] investigated the effect of the hard chine and drew the conclusion that it has twice the value as that calculated for a round bilge vessel, but the results of the present work show that the difference is larger than that. The main reason is that the estimated value obtained by Ikeda's formula gave a very small value for the eddy damping, which suggests that an accurate estimated method of eddy damping for a vessel with hard chine is still lacking. On the other hand, the estimated formula of the skeg proposed by Ikeda gave quite reasonable results based on the fact that the estimating method predicted good results for M365 and M366 at zero forward speed.

In the presence of forward speed, the predicted method over estimates the roll damping for all three models and the difference becomes larger with the increasing
Figure 5.2: Predicted results using Ikeda’s formula \( M363 \) \( GM=5.33\text{cm} \)

Figure 5.3: Predicted results using Ikeda’s formula \( M363 \) \( GM=3.12\text{cm} \)
Figure 5.4: Predicted results using Ikeda's formula M365 GM=5.22cm

Figure 5.5: Predicted results using Ikeda's formula M365 GM=3.96cm
Figure 5.6: Predicted results using Ikeda's formula M366 GM=3.82cm

Figure 5.7: Predicted results using Ikeda's formula M366 GM=4.35cm
forward speed as shown in the Figures. This leads us to conclude that Ikeda’s formula over estimates lift damping. A modification of Ikeda’s formula is therefore suggested based on a phenomenon observed during the experiments.

5.3 Modification of Ikeda’s Formula

During the experiments, it was observed that the model sinkage increases with the increase in forward speed. This can be explained easily by basic theory of Fluid Mechanics. When the ship moves in the water, the fluid speed on the ship hull will increase, which creates a low pressure area under the ship hull. The ship’s draft increases with forward speed to balance the decreasing pressure under the ship hull. As a result, the distance between the rolling center and the water level \( \overline{OG} \) will decrease with the increase of forward speed.

As stated above, all damping components have relationship with \( \overline{OG} \) value, but at high forward speed, only lift and wave component need to be considered. Calculations have been done to investigate the effect of \( \overline{OG} \) value on the estimation of wave and lift damping. As shown in Figure 5.8, wave damping at zero forward speed shows a minimum around \( OG/d \) of 0.15 to 0.25. Therefore, the effect of a change in \( \overline{OG} \) value on wave damping is uncertain, depending on the value of \( OG/d \). The calculation of the lift component shows that lift damping is proportional to \( \overline{OG} \) value, which can be explained by the fact that the lever arm of the lift moment is proportional to \( \overline{OG} \) value.

The relationship between \( \overline{OG} \) and forward speed may be found using the laws of hydrodynamics. Because of the lack of research work in this field, we simply assume that the relationship is linear, i.e.

\[
\overline{OG} = \overline{OG}_0 - b \cdot F_r
\]  

(5.13)

where \( \overline{OG}_0 \) is the \( \overline{OG} \) value at zero forward speed, \( b \) is the slope and \( F_r \) is Froude
Figure 5.8: Effect of $\bar{OG}$ values on Wave Damping

Figure 5.9: $\bar{OG}$ slopes predicted from experimental data
number. For the lift damping component, the modification can be made by replacing $\overline{OG}$ in equation 5.5 by equation 5.13 i.e.

$$B_L = \frac{1}{2} \rho U L d k_N l_d R \left( 1 + 1.4 \frac{\overline{OG}_0 - b \cdot F_z}{l_R} + 0.7 \frac{(\overline{OG}_0 - b \cdot F_z)^2}{l_d l_R} \right)$$

(5.14)

For the wave damping component of a model moving with forward velocity, one can calculate $\overline{OG}$ values using equation 5.13, then use this $\overline{OG}$ value to calculate the wave damping at zero forward speed $B_{w0}$ using strip theory and, finally calculate $B_w$ using eq. 5.9.

![Graph showing the relationship between slope $b$ and block coefficient.](image)

Figure 5.10: Relationship between slope $b$ and block coefficient.

The slope $b$ is determined by comparing the experimental data with the estimated values. The search is done automatically by a program which finds a value for $b$ that makes the predicted curve closest to the experimental data. The calculation has been carried out for different $GM$ values. For each $GM$ value, only one or two initial angles have been selected, considering the fact that the effect of initial angle is small at high forward speed as stated in chapter 4. The results are shown in Figure 5.9. It was found that $b$ is almost constant for each model which gives a conclusion
that \( b \) is only a function of ship form. For M363 \( b \) is about 0.115, for M365 0.185 and for M366 0.151. It has been found that \( b \) has a linear relationship with the block coefficient \( C_B \) as shown in Figure 5.10. The relationship can be expressed as:

\[ b = -0.8485C_B + 0.5032 \]  

(5.15)

The final modification of Ikeda's formula can be expressed as:

\[
H_L = \frac{1}{2} \rho l/L d_{kN} l_0 l_R \left\{ \left[ \frac{OC}{l_R} - (-0.8485C_B + 0.5032) \cdot F_r \right] + 0.7 \left[ \frac{OC}{l_0 l_R} - (-0.8485C_B + 0.5032) \cdot F_r \right]^2 \right\} 
\]

(5.16)

The modified results are shown in Figure 5.11 ~ Figure 5.16. Three curves are given in each Figure. One is the curve predicted by Ikeda's formulae. Second one is the curve in which the lift damping has been modified. The third one is the curve in which both wave and lift damping have been modified. For M363 and M366 the second and third curves are quite close, but for M365 the third curve fits the experimental data better, which suggests that both the lift and the wave components need to be modified, especially for ship forms with large value of wave damping component, such as M365. As shown in the figures, the modified curves fit the experimental data much better than the curve predicted by the original Ikeda's formulae. For M366, the modified curves give a perfect fit on the experimental data. For M363 the modified curves fit the experimental data very well except at zero and low forward speed values where eddy damping is underestimated as stated before. For M365 the modified curves still have some difference with experimental data in the range of 0.05 < \( F_r < 0.25 \), which suggests that the relationship between \( OG \) value and forward speed may not be linear for some ship forms. Actually it was noticed in the experiment that M365 has larger sinkage than the other two model, which may be attributed to the flat bottom of M365.
Figure 5.11: Predicted results using Modified Ikeda's formula. M363 GM=5.33 cm

Figure 5.12: Predicted results using Modified Ikeda's formula. M363 GM=3.12 cm
Figure 5.13: Predicted results using Modified Ikeda's formula M365 GM=5.22cm

Figure 5.14: Predicted results using Modified Ikeda's formula M365 GM=3.96cm
Figure 5.15: Predicted results using Modified Ikeda's formula M366 GM=3.82 cm

Figure 5.16: Predicted results using Modified Ikeda's formula M366 GM=4.35 cm
Chapter 6

Effect of Following Waves on Roll Damping

An experiment has been done to investigate the effect of following waves on roll damping. When a ship is moving in a following wave, the water surface around the ship will change with the transmission of the wave, which will generate heave and pitch and affect the behaviour of roll motion. An experiment was designed to investigate this effect. The details will be stated in the following sections.

6.1 The Experiment

The experiment setup is shown in Figure 6.1. The model was only allowed two degrees of freedom — roll and heave. A dynamometer was used to measure the motion in roll and heave. The rolling center was adjusted to the same level of the center of gravity. An arm was fitted on the model to generate initial angles.

Model M363 was used in this experiment. The principal dimension of the model is listed in Table 2.1. A regular wave was transmitted along the model from the stern to the bow. The wave length was taken to be equal to the length of the model, i.e., \( \lambda_w = 1.551m \) and the wave period \( T_w \) is 1.0 second. Four different wave heights were used in the experiment. These have nominal values of 0.0cm, 5.0cm, 7.0cm and 9.0cm. A probe was set 4.22m away from the midship to measure the incident
wave. The measured wave height is not usually the same as the nominal value. The comparison of the nominal values and measured values is in Table 6.1. The GM values, natural frequencies, periods of rolling and parameters of restoring moment are listed in Table 6.2. The determination of these values have been explained in Chapter 2.

Table 6.1: Wave height in the experiment

<table>
<thead>
<tr>
<th>Nominal value (cm)</th>
<th>5.0</th>
<th>7.0</th>
<th>9.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured value (cm)</td>
<td>3.68</td>
<td>6.12</td>
<td>7.31</td>
</tr>
</tbody>
</table>

Three channels were used to collect the data, one for rolling, the second for heaving and the third for the incident wave. An example of the collected data is
shown in Figure 6.2 to Figure 6.4. The phase of the wave was measured with respect to a coordinate whose origin is located at the midship. The phase of the incident wave was found to be close to the phase of the heave motion and they have same period (1.0 second).

The same data processing and management technique presented in Chapter 3 and Chapter 4 were used to process the data. For each GM value, there are 7 initial angles and 4 wave heights. The wave height can be treated as the same as forward speed. The programs presented in the Chapter 3 can be directly used for processing the data here. The analytical results are stored in the same database discussed in Chapter 4 and analysis was done by the help of the same data management system. A few new procedures were introduced in the system to meet the specific need of this experiment.

### 6.2 Analysis and discussion

The effect of following wave on the equivalent linear damping coefficient is shown in Figure 6.5 to 6.8, respectively. These figures show that damping coefficient in
waves are larger than those measured in calm water. There may be three reasons for this. First, damping parameters were estimated neglecting time variations in the restoring moment. This may have caused a false increase in the values of the damping parameter. Second, the increase in the surface area of the model as a result of the passing wave. Third, the effect of coupled heave motion. As can also be seen from the figures, there is much scatter in the results. The scatter for $GM = 5.04\text{cm}$ is more pronounced than the other two cases. For the $GM = 5.04\text{cm}$ the roll natural period is almost twice the wave period which may indicate a parametric resonance effect.

This is a very preliminary investigation. Further research work needs to be done in the following aspects:

- The mathematical modeling for identification of roll damping coefficients needs to be improved. The method of roll damping identification stated in Chapter 3 is used in this analysis. As we can seen in equation 3.1, the restoring moment is considered to be independent of time. This is correct in still water condition. When ship moves in waves, the restoring moment is changing with time. Therefore a new function $D(\phi, t)$ has to be found to express the restoring moment of a ship moving in regular waves.

- The phase difference of the incident wave and roll motion may have an effect on roll damping. This should be investigated in experiment, which can be done by collecting the roll decay curves in the same conditions ($GM$ value and initial angle) for many times and comparing the results.

- Effect of parametric resonance should be investigated.

- Effect of the coupling of heave and pitch into roll should be investigated.
Figure 6.2: Roll decay curve with following wave

Figure 6.3: Record of heave motion with following wave
Figure 6.4: Incident wave

Figure 6.5: Effect of following wave on roll damping, GM=5.04
Figure 6.6: Effect of following wave on roll damping, GM=4.07

Figure 6.7: Effect of following wave on roll damping, GM=3.13
Figure 6.8: Effect of following wave on roll damping, $GM=2.34$
Chapter 7

Conclusions

A method which combines the Energy and the Modulation Function methods was used to analyse the decay curves obtained from the free roll decay experiments using models of three small fishing vessels. This method has proved to give better estimates for the roll damping parameters than Energy method.

A database system created using VAX-Pascal is used to store the analytical results and perform various kinds of analyses. It has been shown that this system is very useful in the analysis of the experimental results.

Ikeda’s method was used to predict the roll damping coefficient. The estimated values predicted by Ikeda’s method do not fit the experiment data well. The main reason is that Ikeda’s method overestimates roll damping at higher forward speed. In addition, Ikeda’s method is not suitable for estimating the eddy damping of a ship form with hard chine. It was observed that the model’s sinkage increases with the increase of forward speed. A modification of Ikeda’s formula has been proposed based on the modification of the distance between the center of gravity and the water line. The values predicted by the modified Ikeda’s formula give better fit to the experimental data. The modified Ikeda’s formula was proposed based on the experiment of the three models of fishing vessels. Further research is needed for other ship forms.
The following conclusions can be obtained from the results of the analysis of the experimental data:

1. At higher forward speed, roll damping is nonlinear for all three models.

2. For M363 it has been found that the damping coefficient reaches a peak at a Froude number of about 0.33 then decreases again as the velocity is increased. This may be attributed to the deterioration in the lift generating mechanism at higher speeds and the high values for the midship section coefficient of M363.

3. The effect of initial heel angle is strong at zero and low forward speed but becomes weak when the forward speed increases, which indicates that the lift damping can be considered to be independent of the roll amplitude.

4. The effect of the natural frequency on roll damping is not very strong, which may be caused by the fact that the increase of the natural frequency decreases the magnitude of the damping force arm.

5. Roll damping in following wave is an area where much work is still needed.
References


Appendix A. Content of File S0507

* Roll Damping tests
DATE: Tue Nov 03 14:47:10 1992
SCALE_HI: 10.000000
SCALE_LO: -10.000000
SAMPLE: 20.00
NUMCHAN: 3
TOTIME: 9.000000
Chan Gain Offset Slope
OFF_SLOPE:
1 5 -7.58437619E+001 2.31460325E-003 Roll (deg)
2 5 -7.58437619E+001 2.31460325E-003 Pitch (deg)
3 2 -4.92759072E+000 1.19645144E-004 Speed(m/s)
NUMPOINTS 181
END

22041 31612 36292
22397 31623 36279
22952 31611 36290
23840 31613 36268
24872 31607 36279
26068 31573 36295
27408 31539 36271
28794 31491 36277
30178 31457 36268
31563 31408 36278
32890 31348 36271
34170 31306 36280
35393 31279 36271
36476 31246 36274
37427 31236 36255
38268 31219 36264
38929 31224 36240
39427 31222 36244
39745 31237 36249
39864 31252 36273
39824 31264 36261
39600 31266 36254
39234 31278 36272
38737 ...
### Appendix B. Content of File S0507.AGL

-0.43332 -0.01668 0.50333  
-0.41894 -0.01623 0.50139  
-0.9652 -0.01591 0.50303  
-0.6065 -0.01661 0.49974  
-0.31896 -0.01688 0.50139  
-0.27064 -0.01825 0.50378  
-0.21651 -0.01963 0.50019  
-0.16052 -0.05157 0.50109  
-0.10461 -0.05294 0.49974  
-0.04866 -0.05192 0.50124  
0.00195 -0.05734 0.50019  
0.05666 -0.05904 0.50153  
0.10606 -0.06013 0.50019  
0.14981 -0.06138 0.50064  
0.18823 -0.06187 0.49779  
0.22221 -0.06256 0.49914  
0.24691 -0.06235 0.49555  
0.26903 -0.06243 0.49615  
0.28187 -0.06183 0.49690  
0.28668 -0.06122 0.50049  
0.28506 -0.06074 0.49869  
0.27602 -0.06066 0.49764  
0.26123 -0.06017 0.50034  
0.24115 -0.06021 0.49914  
0.21695 -0.06078 0.49959  
0.18965 -0.06062 0.50034  
0.15810 -0.06005 0.50109  
0.12590 -0.06138 0.49989  
0.09112 -0.06138 0.50064  
0.05565 -0.06130 0.50034  
0.02074 -0.06126 0.50079  
-0.01388 -0.06082 0.50288  
-0.04781 -0.05981 0.49974  
-0.07839 -0.05944 0.49854  
-0.10691 \[\ldots\]
Appendix C. Content of File S0507 USE

```
0.05
2.922418
1.0
-1.5131
-1.9140
0.2869402
0.2853242
0.2762752
0.2614901
0.2114121
0.2172141
0.1899062
0.1583551
0.1261584
9.1376141E-02
5.5907138E-02
2.1004137E-02
-1.3616863E-02
-1.7549862E-02
-7.8130864E-02
-0.1066519
-0.1337589
-0.1558959
-0.1741159
-0.1881329
-0.1977479
-0.2035649
-0.2049789
-0.2007369
-0.1920119
-0.1819929
-0.1670459
-0.1482609
-0.127389
-0.1048739
-8.1362866E-02
```
Appendix D. Program TRSBAT.PAS
Translation of Experimental Data. Original experimental data is integers which indicate the amount of voltages measured by the equipments, such as gyroscope. The Translation is done by the formula:

\[ A = I*S + O \]

where \( I \) is the integer in the file, \( S \) is the slope and \( O \) is the offset.

program trsbat(input, output, newf, oldf, nf);
const
  n_angle=7;
  n_speed=9;
type
tname = packed array[1..35] of char;
var
  newf, oldf, nf: text;
  angle: array[1..n_angle] of string(2);
  speed: array[1..n_speed] of string(2);
  i, j: integer;
  in_f, out_f: tname;
  X: char;
  X1: string(4);

{ subroutine for translation of experimental data }
procedure trsl(in_f: tname; out_f: tname);
var
  i, mm : integer;
  a1, a2, b1, b2, c1, c2, l1, l2, l3: real;
begin
  { Open input and output file }
  open(oldf, in_f, history:=old);
  open(newf, out_f, history:=unknown);
  reset(oldf);
  rewrite(newf);
  { Skip 9 lines of message }
  for i:=1 to 9 do
    readln(oldf);
  { Read offset and slope }
  read(oldf, mm);
  read(oldf, mm);
  read(oldf, a1);
  read(oldf, a2);
  readln(oldf);
  read(oldf, mm);
  read(oldf, mm);
  read(oldf, b1);
  read(oldf, b2);
  readln(oldf);
read(oldf, mm);
read(oldf, mm);
read(oldf, cl);
read(oldf, c2);
readln(oldf);
readln(oldf);
readln(oldf);
readln(oldf):

while not eof(oldf) do 
begin
\{(Read data of roll, pitch and forward speed)\}
read(oldf, l1);
read(oldf, l2);
readln(oldf, l3);
\{(Do translation)\}
l1:=l1*a2 + a1;
l2:=l2*b2 + b1;
l3:=l3*c2 + c1;
l1:=l1*3.14159/180.0;
\{(Output results)\}
end;
close(oldf);
close(newf);
end;

\{(Main program)\}
begin
\{ 7 initial angle numbers \}
angle[1]:='01';
angle[2]:='02';
angle[3]:='03';
angle[4]:='04';
angle[5]:='05';
angle[6]:='06';
angle[7]:='07';
\{ 8 forward speed\}
speed[1]:='00';
speed[2]:='03';
speed[3]:='05';
speed[4]:='07';
speed[5]:='09';
speed[6]:='11';
speed[7]:='13';
speed[8]:='15';

open(nf, 'trsbat_n.dat', history:=old);
\{ trsbat_n.dat contains I.D. and name of subdirectory of the files. Example of context:\

A
reset(nf);

while not eof(nf) do
begin
  readln(nf, X);  \{ read I.D. \}
  readln(nf, X1);  \{ read name of sub-directory\}
  speed[9] := substr(X1, 3, 2);
  \{ forward seed number for test without joint, 63 for M363, 65 for M365 and 66 for M366 \}
  writeln(speed[9]);
  for i := 1 to n_speed do
  begin
    for j := 1 to n_angle do
    begin
      \{ compose input file name with sub-directory \}
      in_f := 'grad.szhang.roll.'+X1+'.'+X+
             speed[i] + angle[j] + '.inz';
      writeln(X+speed[j]+angle[j]);

      \{ compose output file name with sub-directory \}
      out_f := 'grad.szhang.roll.'+X1+'.'+X+
               speed[i] + angle[j] + '.agl';
      trs1(in_f, out_f);
    end;
  end;
end.
Appendix E. Program DAMABAT.FOR
* DAMABAT.FOR
* Rearrangement of data
* VAX-FORTRAN
* 
* Suimin Zhang

real Y(600), NH(50), NO(50), XH(50), XX(5), YY(5), MM0, MM1, MM2
character *5, in_f*35, out_f*35

* Input coefficient of restoring moment
print*, 'input MM1, MM2'
read*, MM1, MM2

* HH is the interval of measurement
HH = 0.05

open(7, file='N_FILE1.DAT', status='old')
* N_FILE1.DAT contain name of the input file
* produced by NAMEMK.PAS

open(17, file='N_FILE2.DAT', status='old')
* N_FILE2.DAT contain name of the output file
* produced by NAMEMK.PAS

do while (.true.)
    read(7, '(A)', end=111) in_f
    read(17, '(A)', end=111) out_f
    open(9, file=in_f, status='old')
    open(8, file=out_f, status='unknown')
    READ(9, *) Y(1)

    IF (Y(1) .GT. 0) THEN
        TU=-1.0
    ELSE
        TU= 1.0
    END IF
    Y(1) = TU*Y(1)
    I=1
    do while (.true.)
        I=I+1
        read(9,*, END=11) Y(I)
        Y(I) = TU*Y(I)
    end do

11 close(9)
N=I-1
PRINT*, 'N=', N

* Find amplitude of half cycle
CALL DASEL(Y, N, XH, NH, NO, 3)

XX(1)=NH(1)
XX(2)=NH(3)
XX(3)=XH(5)
YY(1)=XH(1)
YY(2)=XH(3)
YY(3)=XH(5)
XINT=NH(2)

CALL LAGINT(XX, YY, 3, XINT, YOUT)
E1 = XH(2) + YOUT
DO I=1,N
   Y(I)=Y(I)-E1/2.0
END DO

TT=HH * ( (NO(3)-NO(1)) + (NO(4)-NO(2)) ) / 2.0
WW=6.2832/TT
WRITE(8,*) HH
WRITE(8,*) WW
WRITE(8,*) MM0
WRITE(8,*) MM1
WRITE(8,*) MM2
DO I = NH(1), N
   WRITE(8,*) Y(I)
END DO

CLOSE(8)
CLOSE(9)
END DO

CLOSE(7)
END

* Find the amplitude of half cycle of the decay curve

SUBROUTINE DASEL(Y,N,XH,NN,NO,NUB)
REAL Y(*), XH(*), NN(*), NO(*)

IF (Y(1).LT. 0.0) THEN
   KID=1
ELSE
   KID=2
END IF

IF (KID.EQ. 1) THEN
   SIGN=1.0
ELSE
   SIGN=-1.0
END IF

X0=SIGN*Y(1)
NSTEP=1
DO I=1,N

    IF ( SIGN*Y(I) .GT. XO) THEN
        XO=SIGN*Y(I)
        NO=I
    END IF

    IF ( (SIGN*Y(I) .GT. 0.0).AND. (NSTEP .EQ. 1) ) THEN
        NSTEP=2
        J=1
        NO(J)=I
    END IF

    IF ( (SIGN*Y(I) .LE. 0.0) .AND. (NSTEP .EQ. 2) .AND. (NO=NN(J-1)) .GT. NUB ) THEN
        XH(J)=Y(NO)
        NN(J)=NO
        J=J+1
        NO(J)=I
        SIGN=-1.0*SIGN
        XO=SIGN*Y(I)
    END IF

    IF ( (I.EQ.N) .AND. (SIGN*Y(I) .GT. 0.0) .AND. (SIGN*Y(I) .LT. XO) ) THEN
        XH(J)=XO/SIGN
        NN(J)=NO
        J=J+1
        SIGN=-1.0*SIGN
        XO=SIGN*Y(I)
    END IF

END DO

NH=J-1
XH(J)=0.0
XH(J+1)=0.0
XH(J+2)=0.0

END

*  Program cited from [25]
SUBROUTINE LAGINT(X,Y,N,XINT,YOUT)
C  THIS SUBROUTINE PERFORMS LAGRANGIAN
C  INTERPOLATION WITHIN A SET OF (X,Y) PAIRS TO GIVE THE Y
C  VALUE CORRESPONDING TO XINT. THE DEGREE OF THE INTERPOLATING
C  POLYNOMIAL IS ONE LESS THAN THE NUMBER OF
C  POINTS SUPPLIED
C
C  X -- ARRAY OF VALUES OF THE INDEPENDENT VARIABLE
C  Y -- ARRAY OF FUNCTION VALUES CORRESPONDING TO X
C  N -- NUMBER OF POINTS
C  XINT -- THE X VALUE FOR WHICH ESTIMATE OF Y IS DESIRED
C  YOUT -- THE Y VALUE RETURNED TO CALLER

85
REAL X(N), Y(N), XINT, YOUT, TERM
YOUT = 0.0
DO I = 1,N
   TERM = Y(I)
   DO J = 1,N
      IF (I .NE. J) THEN
         TERM = TERM * ( XINT - X(J) )/( X(I) - X(J) )
      END IF
   END DO
   YOUT = YOUT + TERM
END DO
END

(A program developed in Pascal to compose the name of files
I.D. and name of subdirectory are needed
This program needs to be compiled separately from the Fortran codes list above)

program name(input, output);
const
   n_angle=7;
n_speed=9;
type
tname = packed array[1..35] of char;
var
   oldf, outf, nf: text;
   angle: array[1..n_angle] of string(2);
   speed: array[1..n_speed] of string(2);
i, j: integer;
in_f, out_f: tname;
X: char;
X1: string(4);
begin
   angle[1]:='01';
   angle[2]:='02';
   angle[3]:='03';
   angle[4]:='04';
   angle[5]:='05';
   angle[6]:='06';
   angle[7]:='07';
   speed[1]:='00';
   speed[2]:='03';
   speed[3]:='05';
   speed[4]:='07';
   speed[5]:='09';
   speed[6]:='11';
   speed[7]:='13';
speed[8] := '15';
speed[9] := '63';
write('input EXP_ID:');
readln(X);
write('input name of subdirectory:');
read(X1);

(open file for storing the file name with *AGL extension)
open(nf, 'n_file1.dat', history:=old);
rewrite(nf);

(open file for storing the file name with *USE extension)
open(outf, 'n_file2.dat', history:=unknown);
rewrite(outf);

speed[9] := substr(X1, 3, 2);
writeln(speed[9]);
for i := 1 to n_speed do
begin
  for j := 1 to n_angle do
  begin
    in_f := '[grad.szhang.roll.'+X1+']'+ X + speed[i] + angle[j] + '
    out_f := '[grad.szhang.roll.'+X1+']'+ X + speed[i] + angle[j] + 
    writeln(X+speed[i]+angle[j]);
    writeln(nf, in_f);
    writeln(outf, out_f);
  end;
end;
end.
Appendix F. Program MODFBAT.FOR
PROGRAM MODFBAT.FOR
VAX-FORTRAN
Roll damping parameter identification using
Modified Energy Method

Suimin Zhang

REAL PH(250), Y(250), H(250, 1), PHD(250), A(250, 10),
! E(4, 5),
! PSN1(10), PSN2(10), PSN3(10, 10), EN(5, 250), VK(250),
! VP(250),
! V(250), OM, MM0, MM1, MM2, MUSA,
! B44(4,2), CQ2(4), SPHDQ(4), ENG(5),
! NH(10), XH(10), B_L(2), NH_A(10), XH_A(10)

CHARACTER XXX*1, XXX1*4, IN_F*35, ANGLE(7)*2,
! SPEED(9)*2

PI = 3.1415926
TS = 0.0
TE = 5
KC = 4
ITER = 5
OPEN(15, FILE='ID_DIR.DAT', STATUS='OLD')
* ID_DIR.DAT contain I.D. and name of subdirectory of the files.
* of the files. It is the same file used in TRSBAT.PAS and
* DAMABAT.FOR. Example of context

A
* T363
* H
* T365
* Y
* T366

OPEN(20, FILE='MODF_RST.DAT', STATUS='UNKNOWN')
* MODF_RST.DAT is a file for outputing analytical result

DO WHILE (.TRUE.)
READ(15, '(A)', END=113) XXX
! Read I.D
READ(15, '(A)', END=113) XXX1
! Read name of subdirectory

7 initial angle numbers
ANGLE(1)='01'
ANGLE(2)='02'
ANGLE(3)='03'
ANGLE(4)='04'
ANGLE(5)='05'
ANGLE(6)='06'
ANGLE(7)='07'
* 8 forward speed numbers
SPEED(1)='00'
SPEED(2)='03'
SPEED(3)='05'
SPEED(4)='07'
SPEED(5)='09'
SPEED(6)='11'
SPEED(7)='13'
SPEED(8)='15'

* Forward speed number for test with joint
* '63' for M363, '65' for M365, '66' for M366
* Obtain the value for name of subdirectory (T363, T365 and T366)
SPEED(9)=XXX1(3:4)

DO L = 1,9
  DO M = 1,7
    * Compose the file name including subdirectory
    IN_F='[GRAD.SZHANG.ROLL.'/XXX1/']/XXX1/SPEED(L)
    ! //ANGLE(M)'/'.USE'
    WRITE(20,*) IN_F(24:)
    OPEN(77, FILE=IN_F, STATUS='OLD')
  
  * Read data for the file
  READ(77,*) DT
  READ(77,*) OM
  READ(77,*) MM0
  READ(77,*) MM1
  READ(77,*) MM2
  MM0=1.0
  TPER = 2.0*PI/OM
  
  SOM = OM**2
  I=0
  DO WHILE (.TRUE.)
    I=I+1
    READ(77,*, END=11) PH(I)
  END DO
  11
  N=I-1
  end of reading

* Begin roll damping identification by
* Modified Energy Method

PERIOD= N*DT
ALFA = (TE+TS)/PERIOD

* A - Function calculations
DO I = 1, N
  TSM = (I-1)*DT
  TAU = TSM*ALFA-TS
  H(I, 1) = 1.0
\[ H(I, 2) = TAU \]
\[ \text{DO } K = 3, KC+1 \]
\[ H(I, K) = TAU \times H(I, K-1) - (K-1-1) \times H(I, K-2) \]
\[ \text{END DO} \]
\[ \text{END DO} \]

\[ \text{DO } I = 1, N \]
\[ TSM = (I - 1) \times DT \]
\[ TAU = TSM \times \text{ALFA} - TS \]
\[ \text{DO } K = 1, KC+1 \]
\[ A(I, K) = H(I, K) \times \text{EXP}(-TAU**2/2.0) \]
\[ \text{IF } (I \leq 6) \text{ THEN} \]
\[ \text{WRITE(88,*)} I, K, A(I, K) \]
\[ \text{END IF} \]
\[ \text{END DO} \]
\[ \text{END} \]

\[ \text{Calculation of the roll velocity} \]
\[ \text{PHD}(I) = -(PH(3) - 4.0 \times PH(2) + 3.0 \times PH(1)) / (2.0 \times DT) \]
\[ \text{PHD}(N) = (3.0 \times PH(N) - 4.0 \times PH(N-1) + PH(N-2)) / (2.0 \times DT) \]
\[ \text{DO } I = 2, N-1 \]
\[ \text{PHD}(I) = (PH(I+1) - PH(I-1)) / (2.0 \times DT) \]
\[ \text{END DO} \]

\[ \text{----------} \]
\[ \text{DO } I = 1, N \]
\[ \text{PHS} = PH(I)**2 \]
\[ \text{PHDS} = \text{PHD}(I)**2 \]
\[ \text{PHC} = PH(I)**3 \]
\[ \text{PHQ} = PH(I)**4 \]
\[ \text{MUSA} = 0.5 \times MM1 \times \text{PHS} + MM2 \times \text{PHQ} / 3.0 \]
\[ \text{V}(I) = 0.5 \times \text{PHS} \]
\[ \text{VK}(I) = 0.5 \times \text{PHS} \times (1.0 + \text{MUSA}) \]
\[ \text{VP}(I) = \text{VK}(I) + \text{VP}(I) \]
\[ \text{EN}(1, I) = \text{PHDS} \]
\[ \text{EN}(2, I) = \text{ABS(PH(I)}) \times \text{PHDS} \]
\[ \text{EN}(3, I) = \text{ABS(PH(D)(I))} \times \text{PHDS} \]
\[ \text{EN}(4, I) = \text{PHS} \times \text{PHDS} \]
\[ \text{EN}(5, I) = \text{PHDS}**2 \]
\[ \text{END DO} \]

\[ \text{----------} \]
\[ \text{Calculation of the integrals} \]
\[ \text{DO } K = 1, 2 \]
\[ \text{SUMN1} = 0.0 \]
\[ \text{SPHDS} = 0.0 \]
\[ \text{SPHDQ}(1) = 0.0 \]
\[ \text{SPHDQ}(2) = 0.0 \]
\[ \text{SPHDQ}(3) = 0.0 \]
\[ \text{SPHDQ}(4) = 0.0 \]
\[ \text{DO } I = 2, N-1 \]
\[ \text{SUMN1} = \text{SUMN1} + V(I) \times A(I, K+1) \]
\[ \text{SPHDS} = \text{SPHDS} + \text{EN}(1, I) \times A(I, K) \]
\[ \text{SPHDQ}(1) = \text{SPHDQ}(1) + \text{EN}(2, I) \times A(I, K) \]

91
SPHDQ(2) = SPHDQ(2) + EN(3,I)*A(I,K)
SPHDQ(3) = SPHDQ(3) + EN(4,I)*A(I,K)
SPHDQ(4) = SPHDQ(4) + EN(5,I)*A(I,K)
END DO

CC1 = V(1) * A(1,K+1) + V(N) * A(N,K+1)
PSN1(K) = DT * (CC1 + 2.0*SUMN)/2.0

CQ1 = EN(1,1)*A(1,K) + EN(1,N)*A(N,K)
PSN2(K) = DT*(CQ1 + 2.0*SPHDQ)/2.0

CQ2(1) = EN(2,1)*A(1,K) + EN(2,N)*A(N,K)
CQ2(2) = EN(3,1)*A(1,K) + EN(3,N)*A(N,K)
CQ2(3) = EN(4,1)*A(1,K) + EN(4,N)*A(N,K)
CQ2(4) = EN(5,1)*A(1,K) + EN(5,N)*A(N,K)

PSN3(K,1) = DT* (CQ2(1) + 2.0 * SPHDQ(1)) / 2.0
PSN3(K,2) = DT* (CQ2(2) + 2.0 * SPHDQ(2)) / 2.0
PSN3(K,3) = DT* (CQ2(3) + 2.0 * SPHDQ(3)) / 2.0
PSN3(K,4) = DT* (CQ2(4) + 2.0 * SPHDQ(4)) / 2.0
END DO

* Calculation of the matrix elements
DO II=1,4
  DO K = 1,2
    J = K
    E(J,1) = PSN2(K)
    E(J,2) = PSN3(K,II)
    E52 = V(N) * A(N,K) - V(1) * A(1,K)
    E(J,3) = -(E52 + ALFA*PSN1(K))
    IF (II.EQ.1) THEN
      B_L(K)=E(J,3)/E(J,1)
      PRINT*, 'B_L', K, B_L(K)
    END IF
  END DO
END DO

DO 300 I = 1,2
  IF (E(I,I).EQ.0) THEN
    GOTO 300
  END IF
  PIVOT = E(I,I)
  DO J=I,3
    E(I,J) = E(I,J)/PIVOT
  END DO
  DO 200 K = 1,2
    IF (K.EQ. I) THEN
      GOTO 200
    END IF
    SOB = E(K,I)
    DO J = I,3
      E(K,J) = E(K,J) - SOB * E(I,J)
    END DO
200   CONTINUE

92
CONTINUE
B44(II,1)=E(1,3)
B44(II,2)=E(2,3)
END DO

WRITE(20, *) OM
N_OLD=N
N1=0
N2=0
X01=PH(1)

* Find the amplitude of half cycle of the experimental decay curve
CALL DASEL(PH, N1, N2, N, NH, XH, NUB)
WRITE(20, *) X01
DO I=1, 9
  IF (I.LE. NUB) THEN
    WRITE(20, *) XH(I)
  ELSE
    WRITE(20, *) 0.0
  END IF
END DO

DO I =1, 5
  IF (I.NE.5) THEN
    B1=B44(I,1)
    B2=B44(I,2)
    KK=I
  ELSE
    B1=B_L(1)
    B2=0.0
    KK=1
  END IF

* Produce a decay curve from the analytical roll damping coefficients using Louger-Kuto
CALL DEMKBAT(Y, DT, OM, MM0, MM1, MM2, B1, B2, KK, N_OLD, X01)

* Find the amplitude of half cycle of analytical decay curve
CALL DASEL(Y, N1, N2, N_OLD, NH_A, XH_A, NUB_A)
ENG(I)=0.0

* Calculate the error coefficient
DO K=1, ITER
  ENG(I)=ENG(I) + (XH(K)-XH_A(K))^2
END DO

PRINT*, I, ENG(I)
END DO

DO I = 1, 5
    IF (I .NE. 5) THEN
        WRITE(20, *) B44(I, 1), B44(I, 2), ENG(I)
    ELSE
        WRITE(20, *) B_L(1), 0.0, ENG(I)
    END IF
END DO
CLOSE(77)
END DO

113 print*, '--------END--------'
END

* Subroutine for finding the amplitude of half cycle
  * of the decay curve
SUBROUTINE DASEL(Y, N1, N2, N, NH, XH, NUB)
REAL Y(*), NH(*), XH(*)
IF (Y(1) .LT. 0.0) THEN
    KID = 1
ELSE
    KID = 2
END IF
IF (KID .EQ. 1) THEN
    SIGN = -1.0
ELSE
    SIGN = -1.0
END IF
X0 = SIGN * Y(1)
NSTEP = 1
I = 1
DO I = 1, N
    IF (SIGN * Y(I) .GT. X0) THEN
        X0 = SIGN * Y(I)
        N0 = I
    END IF
    IF ((SIGN * Y(I) .GT. 0.0) .AND. (NSTEP .EQ. 1)) THEN
        NSTEP = 2
        J = 1
    END IF
    IF ((SIGN * Y(I) .LE. 0.0) .AND. (NSTEP .EQ. 2)) THEN
        NH(J) = N0
        XH(J) = X0 / SIGN
        J = J + 1
        SIGN = -1.0 * SIGN
        X0 = SIGN * Y(I)
* Subroutine for producing analytical decay curve* using RUNGE_KUTTA method

```fortran
SUBROUTINE DEMKBAT(Y, HH, WW, MMO, MM1, MM2, B1, B2, ! KK, N, X01)

INTEGER I, N
REAL Y(*), X0(2), X(2, 600), F(2), XEND(2), XWRK(4,4),
& HH,WW,MMO, MM1,MM2,TT

X0(1)=X01
X0(2)=0

TT = 0.0

* Solve differential equation by the RUNGE_KUTTA method

X(1,1)=X0(1)
X(2,1)=X0(2)
CK_FLOW=0.0
DO I = 2, N
    CALL RKSYS(TT, HH, X0, XEND, XWRK, F, 2, WW, MMO,
&          MM1, MM2, B1, B2, KK, CK_FLOW)
    X(1,I) = XEND(1)
    X(2,I) = XEND(2)
    TT = TT + HH
    X0(1) = XEND(1)
    X0(2) = XEND(2)
END DO

DO I = 1, N
    Y(I)=X(1,I)
END DO
20 FORMAT(X, I4, 3F10.4)
END
```
**RUNGE_KUTTA Method, Program from [25]**

SUBROUTINE RKSYS(T0, H, XO, XEND, XWRK, F, N, WW, MM0, & MM1, MM2, B1, B2, KK, CK_FLOW)

This subroutine solves a system of \( N \) first order differential equations by the RUNGE-KUTTA method. The equations are of the form

\[
\frac{DX1}{DT} = F1(X, T), \quad \frac{DX2}{DT} = F2(X, T), \quad \text{etc,}
\]

where \( X = (X1, X2, X3, \ldots, Xn) \)

**DERIVS** - A subroutine that computes values of the \( N \) derivatives.

It must be declared external by the caller.

**T0** - The initial value of independent variable

**H** - The INCREMENT TO \( T \), THE STEP SIZE

**XO** - The array that holds the initial values of the functions

**XEND** - An array that returns the final values of the functions

**XWRK** - An array to hold the values of the RK formula, \( K1, K2, K3, K4 \).

**N** - The number of equations to be solved

**F** - An array that holds the derivatives

```
REAL XO(N), XEND(N), XWRK(4,N), F(N), H, T0, WW, MM0 & MM1, MM2, B1, B2
INTEGER I, N, KK

Get K1
CALL DERIVS(XO, T0, F, N, WW, MM0, MM1, MM2, B1, B2, KK, CK_FLOW)

IF (CK_FLOW.EQ.1.0) GOTO 999
DO I = 1, N
   XWRK(1,I) = H * F(I)
   XEND(I) = XO(I) + XWRK(1,I)/2.0
END DO

Get K2
CALL DERIVS(XEND, T0 + H/2.0, F, N, WW, MM0, MM1, MM2, B1, B2, ! KK, CK_FLOW)
IF (CK_FLOW.EQ.1.0) GOTO 999
DO I = 1, N
   XWRK(2,I) = H * F(I)
   XEND(I) = XO(I) + XWRK(2,I)/2.0
END DO

Get K3
CALL DERIVS(XEND, T0 + H/2.0, F, N, & WW, MM0, MM1, MM2, B1, B2, KK, CK_FLOW)
IF (CK_FLOW.EQ.1.0) GOTO 999
DO I = 1, N
   XWRK(3,I) = H * F(I)
```

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XEND(I) = X0(I) + XWRK(3,I)
END DO

* Get K4
CALL DERIVS(XEND, T0 + H, F, N,
& WW, MMO, MM1, MM2, B1, B2, KK, CK_FLOW)
IF (CK_FLOW.EQ.1.0) GOTO 999

DO I = 1, N
   XWRK(4, I) = H * F(I)
END DO

* Compute result
DO I = 1, N
   XEND(I) = X0(I) + (XWRK(1,I) + 2.0*XWRK(2,I) + 2.0 * XWRK(3,I)
& + XWRK(4,I) ) / 6.0
END DO

999 RETURN
END

* Subroutine for calculation of damping moment of different models and restoring moment

SUBROUTINE DERIVS(XEND, T, F, N, WW, MMO, MM1, MM2, B1,
& B2, KK, CK_FLOW)
REAL XEND(N), T, F(N), B1, B2, WW, MMO, MM1, MM2
INTEGER N, KK

F(1) = XEND(2)

* Linear angle dependence
IF (KK.EQ.1) THEN
   IF ((ABS(XEND(1)).GT.9999) .OR. (ABS(XEND(2)).GT.9999)) THEN
      CK_FLOW=1.0
   END IF
   F(2) = -B1 * XEND(2) - B2 * ABS(XEND(1)) * XEND(2) - WW**2
& * (MMO*XEND(1) +MM1*XEND(1)**3 + MM2*XEND(1)**5)
END IF

* Quadratic
IF (KK.EQ.2) THEN
   IF ((ABS(XEND(1)).GT.9999) .OR. (ABS(XEND(2)).GT.9999)) THEN
      CK_FLOW=1.0
   END IF
   F(2) = -B1 * XEND(2) - B2 * ABS(XEND(2)) * XEND(2) - WW**2
& * (MMO*XEND(1) +MM1*XEND(1)**3 + MM2*XEND(1)**5)
END IF

* Quadratic angle dependence
IF (KK.EQ. 3) THEN
  IF (((ABS(XEND(1)).GT.9999) .OR. (ABS(XEND(2)).GT.9999)) THEN
    CK_FLOW=1.0
  END IF
  F(2) = -B1 * XEND(2) - B2 * XEND(1)**2 * XEND(2) - WW**2
  & (MM0*XEND(1) + MM1*XEND(1)**3 + MM2*XEND(1)**5)
END IF

Cubic
IF (KK.EQ. 4) THEN
  IF (((ABS(XEND(1)).GT.9999) .OR. (ABS(XEND(2)).GT.9999)) THEN
    CK_FLOW=1.0
  END IF
  F(2) = -B1 * XEND(2) - B2 * XEND(2)**3 - WW**2 *
  & (MM0*XEND(1) + MM1*XEND(1)**3 + MM2*XEND(1)**5)
END IF
END
Appendix G. Program LABDATA.PAS
program labdata(input, output);

label
   11, 13; {for exit}

function for getting the friction effect of the joint)

{ Clear screen}
procedure clearsc;
var
   i : integer;
begin
   for i:=1 to 3 do
      begin
         writeln;
      end;
end;

{ Definition of database for storing the result of list square regression)
lsr_rec = record
   lsr_id : [key(0, ascending, nochanges, noduplicates)] tkey;
   lsr_a  : real;
   lsr_b  : real;
   lsr_err : real;
   lsr_gm : real;
   lsr_sp : real;
end;

var
   f : file of f_rec;
   f_lsr : file of lsr_rec;
   m_select, m_choice : integer;
   m_yn : char;

{ Definition of database for storing the analytica result)
f_rec = record
   _id : [key(0, ascending, nochanges, noduplicates)] tkey;
   speed : real;
   i_angle: real;
   omega : real;
   amp : array[1..10] of real;
   b_eng : array[1..5, 1..3] of real;
end;

by Suimin Zhang
Sept. 1992, Engineerin?. M.U.N. }
function friction(id: char) : real;
label
19;
var
  idd  : char;
  rr, omega : real;
  fcomp : text;
begin
  open(fcomp, 'compl.txt', history := old);
  reset(fcomp);
  friction := 0.0;
  while not eof(fcomp) do
    begin
      readln(fcomp, idd, rr, omega);
      if (idd=id) then
        begin
          friction := rr;
          goto 19;
        end;
      end;
    end;
  19:
  close(fcomp);
end;

/*function for getting the natural frequency*/
function w(id: char) : real;
label
19;
var
  idd  : char;
  rr, omega : real;
  fcomp : text;
begin
  open(fcomp, 'compl.txt', history := old);
  reset(fcomp);
  w := 0.0;
  while not eof(fcomp) do
    begin
      readln(fcomp, idd, rr, omega);
      if (idd=id) then
        begin
          w := omega;
          goto 19;
        end;
      end;
    end;
  19:
  close(fcomp);
end;

/*Create database(LAB0801.DAT) by file type: f*/
procedure cr_db;
var
n_f: text;
id_key: tkey;

begin
  open(f, 'lab0801.dat', history:=unknown,
       organization:=indexed, access_method:=keyed);
  rewrite(f);
  open(n_f, 'n_0801.dat', history:=old);
  reset(n_f);
  while not eof(n_f) do
    begin
      readln(n_f, id_key);
      writeln(id_key);
      f'.id:= id_key;
      put(f);
    end;
  close(f);
  close(n_f);
  writeln;
  writeln('*** database created ***');
  writeln;
end;

{Data Examination}
procedure exam_db;
lable 15;
var
  f_check : text;
  f_name : packed array[1..10] of char;
  i, kk : integer;
  id_key : tkey;
  err : real;
begin
  open(f, 'lab0801.dat', history:=unknown,
       organization:=indexed, access_method:=keyed);
  resetk(f, 0);
  write('Damping form(1.5):');
  readln(kk);
  write('Error Level:');
  readln(err);
  write('Output file name:');
  readln(f_name);
  write('Begin ID_EXP (Press RETURN if from top):');
  readln(id_key);
  if (f_name<>''') then
    begin
      open(f_check, f_name, history:=unknown);
      rewrite(f_check);
    end;
  if (id_key<>''') then
    begin
      findk(f, 0, id_key);
      if ufb(f) then
begin
write('ID_KEY Phi0 B1 B2 Error');
i := 1;
while ((i<22) and (not eof(f))) do
begin
if ((f^.b_eng[kk,3] > err) or (f^.b_eng[kk,1] = 0)) then
begin
write(f^.id,' ',f^.amp[1]:8:5,' ',f^.b_eng[kk,1]:8:5,' f^.b_eng[kk,2]:8:5, f^.b_eng[kk,3]);
if (f_name<>')') then
write(f_check, f^.id,' ',f^.amp[1]:8:5,' ',
f^.b_eng[kk,1]:8:5, ',
f^.b_eng[kk,2]:8:5, f^.b_eng[kk,3]);
i := i+1;
end;
get(f);
end;
writeln('--------------------------------------------------------');
m_yn:= 'Y';
write('Continue? (Y/N)');
readln(m_yn);
if ((m_yn='N') or (m_yn='n')) then
goto 15;
end;
15:
close(f);
end;

(List items in the database)
procedure ls_db;
label 15;
var
   i, kk : integer;
   id_key : tkey;
begin
   open(f, 'lab0801.dat', history:=unknown,
       organization:=indexed, access_method:=keyed);
   resetk(f, 0);
   write('Damping form(1-5):');
   readln(kk);
   write('Begin ID_EXP (Press RETURN if from top):');
   readln(id_key);
   if (id_key<>')') then
begin
   findk(f, 0, id_key);
end;
if ufb(f) then
begin
  writeln(id_key, ' not found! Press any key to return');
  read(id_key);
  goto 15;
end;
end;
while not eof(f) do
begin
  writeln('ID_KEY Phi0 B1 B2 Error');
  i := 1;
  while ((i<22) and (not eof(f))) do
begin
  writeln(f^.id, ', f^.amp[1]:8:5, , f^.b_eng[kk,1]:8:5, ,
  f^.b_eng[kk,2]:8:5, f^.b_eng[kk,3]);
  get(f);
  i := i + 1;
end;
  writeln('-----------------------------');
  m_y:= 'Y';
  writeln('Continue? (Y/N)');
  readln(m_y);
  if ((m_y='Y') or (m_y='n')) then
  goto 15;
end;
15:
  close(f);
end;

{natural frequency average}
procedure rpt_omega;
label 15;
var
  kk : integer;
  id_key : tkey;
  i, omega : real;
begin
  open(f, 'lab0801.dat', history:=unknown,
  organization:=indexed, access_method:=keyed);
  resetk(f, 0);
  readln;
  writeln('ID:');
  readln(id_key);
  if (id_key<>'') then
  begin
    findk(f, 0, id_key);
    if ufb(f) then
    begin
      writeln(id_key, ' not found! Press any key to return');
      read(id_key);
      goto 15;
    end;
  end;
end
else
    goto 15;

omega := 0.0;
i := 0.0;
while ((substr(id_key, 1, 1) = substr(f^id, 1, 1)) and (not ufb(f))) do
begin
    omega := omega + f^omega;
i := i + 1.0;
    get(f);
end;
writeln('Omega = ', i, omega / i);
readln(kk);
15:
close(f);
end;

{ Update forward speed from measured value }
procedure update_sp;
var
    lab_f : text;
    lab_fn : packed array[1..9] of char;
    id_key : tkey;
i, sp, sp_i, qq : real;
begin
    open(f, 'lab0801.dat', history := old,
        organization := indexed, access_method := keyed);
    resetk(f, 0);
    while not eof(f) do
begin
    id_key := f^id;
    lab_fn := id_key + ' .agl';
    open(lab_f, lab_fn, history := old);
    reset(lab_f);
i := 0.0; sp := 0.0;
    while not eof(lab_f) do
begin
    read(lab_f, qq);
    read(lab_f, qq);
    readn(lab_f, sp_i);
    sp := sp + sp_i;
i := i + 1.0;
end;
    close(lab_f);
    sp := sp / i;
    f^speed := sp;
    writeln(lab_fn, ' speed = ', f^speed:5:3);
    update(f);
    get(f);
end;
close(f)
(Update initial angle)
procedure upd_ag10;
var
  ang_f : text;
lab_fn : packed array[1..9] of char;
id_key : tkey;
ag11, agl2 : real;
begin
  open(f, 'lab0801.dat', history:=old,
       organization:=indexed, access_method:=keyed);
  resetk(f, 0);
  open(ang_f, 'agl0801.dat', history:=old);
  reset(ang_f);
  while not eof(ang_f) do
  begin
    readn(ang_f, id_key, ag11, agl2);
    writeln(id_key, ag11, agl2);
    findk(f, 0, id_key);
    if not ufb(f) then
    begin
      f^.i_angle := ag11;
      update(f);
    end
    else
    begin
      writeln(id_key, ' not found!');
    end;
  end;
  close(f);
end;

(Append data from *.rst)
procedure appe_db;
var
  eng_f : text;
id_key, disp_k : tkey;
ttt : string(10);
in_file : packed array[1..20] of char;
i, j : integer;
gtem : real;
begin
  readline;
  write('Input file name (Such as: MODF1112.RST)');
  readline(in_file);
  open(f, 'lab0801.dat', history:=old,
       organization:=indexed, access_method:=keyed);
  resetk(f, 0);
  open(eng_f, in_file, history:=old);
  reset(eng_f);
  while not eof(eng_f) do
begin
  readln(eng_f, ttt);
  id_key:=substr(ttt, 2, 5);
  findk(f, 0, id_key);
  if ufb(f) then
    begin
      writeln(id_key);
      f^.id := id_key;
      readln(eng_f, f^.omega);
      for i:=1 to 10 do
        begin
          readln(eng_f, f^.amp[i]);
        end;
      for i:=1 to 5 do
        begin
          read(eng_f, f^.b_eng[i, 1]);
          read(eng_f, f^.b_eng[i, 2]);
          readln(eng_f, f^.b_eng[i, 3]);
        end;
      put(f);
    end
    else
    begin
      writeln(id_key, 'already exist, record not appended');
    end;
  end;
  close(f);
end;

{ Update data from file *.RST }
procedure updtdb;
var
  eng_f : text;
  id_key, disp_k : tkey;
  ttt : string(10);
  i, j : integer;
  in_file : packed array[1..20] of char;
  gitem : real;
begin
  readln;
  write('Input file name (Such as: MODF1112.RST)');
  readln(in_file);
  open(f, 'lab0801.dat', history:=old,
       organization:=indexed, access_method:=keyed);
  resetk(f, 0);
  open(eng_f, in_file, history:=old);
  reset(eng_f);
  while not eof(eng_f) do
    begin
      readln(eng_f, ttt);
      id_key:=substr(ttt, 2, 5);
      findk(f, 0, id_key);
if not ufb(f) then
  begin
    writeln(f'.id);
    readln(eng_f, f'.omega);
    for i:=1 to 10 do
      begin
        readln(eng_f, f'.amp[i]);
      end;
    for i:=1 to 5 do
      begin
        read(eng_f, f'.b_eng[i,1]);
        read(eng_f, f'.b_eng[i,2]);
        readln(eng_f, f'.b_eng[i,3]);
      end;
    update(f);
  end
else
  begin
    writeln(id_key, 'not found');
  end;
end;
close(f);
end;

{Output damping coefficients of one forward speed}
procedure rpt_b;
var
  rpt_f       : text;
  rpt_fn      : packed array[1..10] of char;
  id_key      : tkey;
  speed       : packed array[1..2] of char;
  i, j, kk    : integer;
  speed_v     : array[1..8] of real;
  len         : real;
begin
  speed_v[1]  := 0.0;
  speed_v[2]  := 0.3;
  speed_v[3]  := 0.5;
  speed_v[4]  := 0.7;
  speed_v[5]  := 0.9;
  speed_v[6]  := 1.1;
  speed_v[7]  := 1.3;
  speed_v[8]  := 1.5;
  open(f, 'lab0801.dat', history:=old,
       organization:=indexed, access_method:=keyed);
  resetk(f, 0);
clearsc;
readln;
write('Damping form(1-5):');
readln(kk);
write('Output file name:');
readln(rpt_fn);
write('KEY NAME:');
readln(id_key);
speed:=substr(id_key, 2, 2);
findk(f, 0, id_key);

if not ufb(f) then
begin
    open(rpt_f, rpt_fn, history:=unknown);
    rewrite(rpt_f);
    clearsc;
    writeln('file amp file b1 b2 error');
    i:=1;
    while (substr(f^.id, 2,2)=speed) and (not ufb(f)) do
    begin
        writeln(f^.id, f^.amp[1], f^.b_eng[kk,1],
                f^.b_eng[kk,2], f^.b_eng[kk,3]);
        writeln(rpt_f, f^.amp[1], f^.b_eng[kk,1],
                f^.b_eng[kk,2], f^.b_eng[kk,3]);
        get(f);
        i:=i+1;
    end;
end;
else
    writeln('File not found!');
close(f);
end;

(Output damping coefficient of forward speed via initial angle)
procedure rpt_va;
type
tspeed = packed array[1..2] of char;
tangle = packed array[1..2] of char;
var
    rpt_f : text;
    rpt_fn : packed array[1..10] of char;
speed : packed array[1..2] of char;
id_key : tkey;
speed_a : array[1..8] of tspeed;
speed_v : array[1..8] of real;
    angle : array[1..7] of tangle;
i, j, kk, m : integer;
    len : real;
ex_id : char;
begin
    open(f, 'lab0801.dat', history:=old,
        organization:=indexed, access_method:=keyed);
    resetk(f, 0);
clearsc;

    kk := 5;
    write('len:');
    readln(len);
write(' exp_id:');
readln(exp_Id);
writeln(exp_id);

write('Output file name:');
readln(rpt_fn);

speed_a[1] := '00';
speed_a[2] := '03';
speed_a[3] := '05';
speed_a[4] := '07';
speed_a[5] := '09';
speed_a[7] := '13';
speed_a[8] := '15';
speed_v[1] := 0.0;
speed_v[2] := 0.3;
speed_v[3] := 0.5;
speed_v[4] := 0.7;
speed_v[5] := 0.9;
speed_v[6] := 1.1;
speed_v[7] := 1.3;
speed_v[8] := 1.5;
angle[1] := '01';
angle[2] := '02';
angle[3] := '03';
angle[4] := '04';
angle[5] := '05';
angle[6] := '06';
angle[7] := '07';
open(rpt_f, rpt_fn, history:=unknown);
rewrite(rpt_f);
clearsc;
for m:=1 to 8 do
begin
  id_key := exp_id + speed_a[m] + '01';
speed:=substr(id_key, 2,2);
  writeln(id_key);
  findk(f, 0, id_key);
  if not ufb(f) then
    begin
      write(rpt_f, speed_v[m]/sqrt(9.8*len), ', ');
      while (substr(f^.id, 2,2)=speed) and (not ufb(f)) do
        begin
          write(rpt_f, f^.b_eng[kk,1], ', ');
          get(f);
        end;
      writeln(rpt_f):
    end;
end;
else
    writeln(' File not found!');
end;
close(f);
end;

{Output damping coefficient of a specific
 initial angle}
procedure rpt_ampl;
label 17;
type
tspeed = packed array[1..2] of char;
tangle = packed array[1..2] of char;
var
    rpt_f : text;
rpt_fn : packed array[1..10] of char;
speed : packed array[1..2] of char;
id_key : tkey;
speed_a : array[1..8] of tspeed;
speed_v : array[1..8] of real;
angle : array[1..7] of tangle;
i, j, kk, m : integer;
len, err : real;
exp_id : char;
amp1, amp3, ang1, b441, ang2, b442, ang, b44, ee : real;
any_key : packed array[1..1] of char;
begin
    open(f, 'lab0801.dat', history:=old,
        organization:=indexed, access_method:=keyed);
    resetk(f, 0);
clearsc;
    kk := 5;

    write('_en:');
    readln(len);
    write(' exp_id:');
    readln(exp_id);
    err := friction(exp_id);
    writeln(exp_id, ',', err);

    while true do
        begin
            (loop added)
            writeln;
            writeln;
            ampl:=0.0;
            write('amplitude (0 exit):');
            readln(ampl);
            if (ampl=0.0) then goto 17;
            write('Output file name:');
readln(rpt_fn);
ampl := ampl*3.1416/180.0;

speed_a[1] := '00';
speed_a[2] := '03';
speed_a[3] := '05';
speed_a[4] := '07';
speed_a[5] := '09';
speed_a[7] := '13';
speed_a[8] := '15';

speed_v[1] := 0.0;
speed_v[2] := 0.3;
speed_v[3] := 0.5;
speed_v[4] := 0.7;
speed_v[5] := 0.9;
speed_v[6] := 1.1;
speed_v[7] := 1.3;
speed_v[8] := 1.5;

angle[1] := '01';
angle[2] := '02';
angle[3] := '03';
angle[4] := '04';
angle[5] := '05';
angle[6] := '06';
angle[7] := '07';

angle[l] := '01';
angle[2] := '02';
angle[3] := '03';
angle[4] := '04';
angle[5] := '05';
angle[6] := '06';
angle[7] := '07';
begin
    b442 := b441;
    ang2 := 0.0;
end;
end
else
begin
    ang2 := amp3;
    b442 := f.b_\_\_g[kk, 1];
    ee := 1.0;
    if (j = 1) then
    begin
        b441 := b442;
        ang1 := 0.0;
    end;
end;
get(f);
    j := j + 1
end;
b44 := b441 + (b442 - b441) * (ampl - ang1) / (ang2 - ang1);
writeln(ang1, ampl, ang2, b441, b44, b442);
writeln(rpt_f, b44-err);
end
else
    writeln('File not found!');
end;
close(rpt_f);
{ loop added }
end;
17:
close(f);
end;

(Output damping coefficient of different natural frequency \( \Omega \))

procedure rpt_freq;
type
    tspeed = packed array[1..2] of char;
tangle = packed array[1..2] of char;

var
    rpt_f : text;
rpt_fn : packed array[1..10] of char;
speed : packed array[1..2] of char;
id_key : tkey;
speed_a : array[1..8] of tspeed;
speed_v : array[1..8] of real;
angle : array[1..7] of tangle;
i, j, kk, m : integer;
ex_id : char;
\( \Omega \), ampl, amp3, ang1, b441, ang2, b442, ang, b44, ee, err : real;

begin
open(f, 'lab0801.dat', history:=old, organization:=indexed, access_method:=keyed);
resetk(f, 0);
clearsc;

kk := 5;
write('amplitude:');
readln(ampl);
write('Output file name:');
readln(rpt_fn);
ampl := ampl*3.1416/180.0;

speed_a[1] := '00';
speed_a[2] := '03';
speed_a[3] := '05';
speed_a[4] := '07';
speed_a[5] := '09';
speed_a[7] := '13';
speed_a[8] := '15';

speed_v[1] := 0.0;
speed_v[2] := 0.3;
speed_v[3] := 0.5;
speed_v[4] := 0.7;
speed_v[5] := 0.9;
speed_v[6] := 1.1;
speed_v[7] := 1.3;
speed_v[8] := 1.5;

angle[1] := '01';
angle[2] := '02';
angle[3] := '03';
angle[4] := '04';
angle[5] := '05';
angle[6] := '06';
angle[7] := '07';
open(rpt_f, rpt_fn, history:=unknown);
rewrite(rpt_f);
clearsc;
write(' exp_id(0 exit):');
readln(exp_id);
err := friction(exp_id);
writeln(exp_id, ',', err);

while (exp_id <> '0') do
begin
omega := w(exp_id);
writeln('Omega = ', omega);
write(rpt_f, omega);
for m:=1 to 8 do
begin
   id_key := exp_id + speed_a[m] + '01';
speed:=substr(id_key, 2, 2);
writeln(id_key);
findk(f, 0, id_key);

if not ufb(f) then
begin
  ee:=0.0;
  j:=1;
  while (substr(f^id, 2, 2)=speed) and (not ufb(f)) and (ee=0.0) do
  begin
    amp3 := abs(f^.amp[1]);
    if (amp3 <= ampl) then
    begin
      ang1:=amp3;
      b441:=f^.b_eng[kk,1];
      if (j=7) then
        begin
          b442:=b441;
          ang2:=0.0;
        end;
      end
    else
    begin
      ang2:=amp3;
      b442:=f^.b_eng[kk,1];
      ee:=1.0;
      if (j=1) then
        begin
          b441:=b442;
          ang1:=0.0;
        end;
    end;
  end;
  get(f);
  j:=j+1
end;
b44 := b441 + (b442-b441)*(ampl - ang1)/(ang2-ang1);
writeln(ang1, ampl, ang2, b441, b44, b442);
write(rpt_f, b44 - err, ' ');
end
else
  writeln(' File not found!');
end;
writeln(rpt_f);
write(' exp_id(0 exit):');
readln(exp_id);
err := friction(exp_id);
writeln(exp_id, ' ', err);
end;
close(f);
end;

(Compare two set of file)
procedure comp;
var
  rpt_f : text;
  rpt_fn : packed array[1..10] of char;
  id_key1, id_key2 : tkey;
  speed : packed array[1..2] of char;
  i, j, kk : integer;
  sum1, sum2, no : real;
begin
  open(f, 'lab0801.dat', history:=old,
       organization:=indexed, access_method:=keyed);
  resetk(f, 0);
clearsc;
oc:=7.0;
write('Damping form(1-5):');
readln(kk);
write('KEY NAME 1:');
readln(id_key1);
write('KEY NAME 2:');
readln(id_key2);
speed:=substr(id_key1, 2,2);
findk(f, 0, id_key1);
sum1:=0.0;
if not ubf(f) then
begin
  clearsc;
  writeln('file amp b1 b2 error');
  while (substr(f^id, 2,2)=speed) and (not ubf(f)) do
begin
  writeln(f^id,f^amp[1], f^b_eng[kk,1],
          f^b_eng[kk,2], f^b_eng[kk,3]);
  sum1:=sum1 + f^b_eng[kk,1];
  get(f);
end;
end;
else
  writeln('File 1 not found!');
speed:=substr(id_key2, 2,2);
findk(f, 0, id_key2);
sum2:=0.0;
if not ubf(f) then
begin
  clearsc;
  writeln('file amp b1 b2 error');
  while (substr(f^id, 2,2)=speed) and (not ubf(f)) do
begin
  writeln(f^id,f^amp[1], f^b_eng[kk,1],
          f^b_eng[kk,2], f^b_eng[kk,3]);
  sum2:=sum2 + f^b_eng[kk,1];
  get(f);
end;
end;
end
else
    writeln(’ File2 not found!’);

    writeln(’ Average difference: ’, (sum1-sum2)/no);
    close(f);
    readln(i);
end;

(Least square regression for a specific forward speed number)
procedure lsr:
var
    rpt_f : text;
    rpt_fn : packed array[1..10] of char;
    id_key : tkey;
    speed : packed array[1..2] of char;
    i, kk, no : integer;
    x, y : array[1..7] of real;
    xsum, ysum, xysum, xxsum, a, b: real;
    dd, err : real;
begi
    open(f, ’lab0801.dat’, history:=old,
         organization:=indexed, access_method:=keyed);
    resetk(f, 0);
    clearsc;
    write(’Damping form(1-5):’);
    readln(kk);
    write(’Output file name:’);
    readln(rpt_fn);
    write(’KEY NAME:’);
    readln(id_key);
    write(’ dd:’);
    readln(dd);
    write(’ initial angle:’);
    speed:=substr(id_key, 2,2);
findk(f, 0, id_key);

    if not ufb(f) then
    begin
        open(rpt_f, rpt_fn, history:=unknown);
        rewrite(rpt_f);
        clearsc;
        i:=0;
        while (substr(f^.id, 2,2)=speed) and (not ufb(f)) do
begin
    i:=i+1;
    x[i]:=(f^.amp[1]);
    y[i]:=f^.b_eng[kk,1] - dd;
    writeln(i, x[i], y[i]);
    get(f);
end;
no:=i;
xsum:=0;
ysum:=0;
xxsum:=0;
xxsum:=0;
for i:= 1 to no do
begin
  xsum := xsum + x[i];
  ysum := ysum + y[i];
  xysum := xysum + x[i]*y[i];
  xxsum := xxsum + x[i]*x[i];
end;
b := (no*xysum - xsum*ysum)/(no*xxsum - xsum*xsum);
a := (ysum - b*xsum)/no;
err := 0;
for i:=1 to no do
begin
  err := err + abs(y[i] - (a + b*x[i]));
  writeln(x[i], y[i], a+b*x[i]);
  writeln(rpt_f, x[i], y[i], a+b*x[i]);
end;
writeln('------');
writeln('a = ', a, ' b = ', b, ' error=', err);
end
else
  writeln(' File not found!');
close(f);
end;

{batch least square regression
results stored in LSR0801.DAT)
procedure lsr_bat;
type
tspeed = packed array[1..2] of char;
var
  f_rpt : text;
  f_name : text;
id_key : tkey;
speed : tspeed;
speed_a : array[1..8] of tspeed;
speed_v : array[1..8] of real;
i, il, kk, no : integer;
x, y : array[1..7] of real;
xsum, ysum, xysum, xxsum, a, b: real;
dd, err, gm : real;
exp_id : char;
begin
  speed_a[1] := '00';
  speed_a[2] := '03';
speed_a[3] := '05';
speed_a[4] := '07';
speed_a[5] := '09';
speed_a[7] := '13';
speed_a[8] := '15';
speed_V[1] := 0.0;
speed_V[2] := 0.3;
speed_V[3] := 0.5;
speed_V[4] := 0.7;
speed_V[5] := 0.9;
speed_V[6] := 1.1;
speed_V[7] := 1.3;
speed_V[8] := 1.5;

open(f_lsr, 'lsr0801.dat', history:=unknown,
    organization:=indexed, access_method:=keyed);
rewrite(f_lsr);
open(f_rpt, 'lsr0801.rpt', history:=unknown);
rewrite(f_rpt);
open(f_name, 'lsr_n.dat', history:=old);
reset(f_name);
open(f, 'lab0801.dat', history:=old,
    organization:=indexed, access_method:=keyed);
resetk(f, 0);
clearsc;
kk := 5;

while not eof(f_name) do
begin
  readln(f_name, exp_id);
  readln(f_name, dd);
  readln(f_name, gm);

  for i := 1 to 8 do
  begin
    id_key := exp_id + speed_a[i] + '01';
    writeln(id_key);
    speed:=substr(id_key, 2,2);
    findk(f, 0, id_key);

    if not ubr(f) then
    begin
      clearsc;
      i:=0;
      while (substr(f.id, 2,2)=speed) and (not ubr(f)) do
      begin
        i:=i+1;
      end
    end
  end
\[ x[i] := (f^\star .amp[1] + f^\star .amp[2] + f^\star .amp[3]) / 3.0; \]
\[ y[i] := f^\star .b_eng[kk, l] - dd; \]
\[ writeln(i, x[i], y[i]); \]
\[ get(f); \]
end;
no := i;
xsum := 0;
ysum := 0;
xysum := 0;
xxsum := 0;
for i := 1 to no do
begin
xsum := xsum + x[i];
ysum := ysum + y[i];
xysum := xysum + x[i]*y[i];
xxsum := xxsum + x[i]*x[i];
end;
b := (no*xysum - xsum*ysum)/(no*xxsum - xsum*xsum);
a := (ysum - b*xsum)/no;
err := 0;
for i := 1 to no do
begin
err := err + abs(y[i] - (a + b*x[i]));
end;
writeln(x[i], y[i], a+b*x[i]);
end;
writeln(id_key, a, b, err);
end;
end;
close(f);
end;
writeln(' File not found!');
end;
close(f_lsr);
end;

{Least square regression for one GM}
procedure lsr_gml;
type
tspeed = packed array[1..2] of char;
var
f_rpt_n : packed array[1..10] of char;
f_rpt : text;
id_key : tkey;
speed: real
speed_a: array[1..8] of real
speed_v: array[1..8] of real
i, il, kk, no: integer
x, y, dd: array[1..7] of real
xsum, ysum, xsxsum, a, b: real
err, gm, angle, len: real
exp_id: char

begin
speed_a[1] := '00';
speed_a[2] := '03';
speed_a[3] := '05';
speed_a[4] := '07';
speed_a[5] := '09';
speed_a[7] := '13';
speed_a[8] := '15';
speed_v[1] := 0.0;
speed_v[2] := 0.3;
speed_v[3] := 0.5;
speed_v[4] := 0.7;
speed_v[5] := 0.9;
speed_v[6] := 1.1;
speed_v[7] := 1.3;
speed_v[8] := 1.5;
write('Input len:');
readln(len);
write('Initial Angle:');
readln(angle);
angle := 3.1416*angle/180.0;
write('Input exp_id:');
readln(exp_id);
write('Input report name:');
readln(f_rpt_n);
open(f_rpt, f_rpt_n, history:=unknown);
rewrite(f_rpt);
open(f, 'lab0801.dat', history:=old,
    organization:=indexed, access_method:=keyed);
resetk(f, 0);
if ((exp_id='A') or (exp_id='B') or (exp_id='C')
or (exp_id='D') or (exp_id='E')) then
begin
    findk(f, 0, 'E6301');
    for il := 1 to 7 do
dd[il] := f^a.b_eng[5,1];
get(f);
findk(f, 0, exp_id+’0001’);
for il := 1 to 7 do
   dd[il] := f^a.b_eng[5,1] - dd[il];
   get(f);
end;

if ((exp_id=’H’) or (exp_id=’I’) or (exp_id=’J’) or (exp_id=’K’))
   then
begin
   findk(f, 0, exp_id+’6501’);
   for il := 1 to 7 do
      dd[il] := f^a.b_eng[5,1];
   get(f);
   findk(f, 0, exp_id+’0001’);
   for il := 1 to 7 do
      dd[il] := f^a.b_eng[5,1] - dd[il];
   get(f);
end;

if ((exp_id=’L’) or (exp_id=’M’) or (exp_id=’N’) or (exp_id=’O’)
   or (exp_id=’P’)) then
begin
   findk(f, 0, exp_id+’6601’);
   for il := 1 to 7 do
      dd[il] := f^a.b_eng[5,1];
   get(f);
   findk(f, 0, exp_id+’0001’);
   for il := 1 to 7 do
      dd[il] := f^a.b_eng[5,1] - dd[il];
   get(f);
end;

clearsc;
kk := 5;

for il := 1 to 8 do
begin
   id_key := exp_id + speed_a[il] + ’01’;
   writeln(id_key);

   speed := substr(id_key, 2, 2);
   findk(f, 0, id_key);

   if not ufb(f) then
   begin
      clearsc;
i := 0;
      while (substr(f^a.id, 2, 2)=speed) and (not ufb(f)) do
      begin
         i := i+1;
         x[i] := (abs(f^a.amp[1])+abs(f^a.amp[2])+abs(f^a.amp[3])) / 3.0;
      end;
   end;
end;
\[ y[i] = f^* . b \cdot \text{eng}(x[k], l) - dd[i]; \]
{ writeln(i, x[i], y[i]);
  get(f);
end;
no := i;

xsum := 0;
ysum := 0;
xysum := 0;
xxsum := 0;

for i := 1 to no do
begin
  xsum := xsum + x[i];
  ysum := ysum + y[i];
  xysum := xysum + x[i]*y[i];
  xxsum := xxsum + x[i]*x[i];
end;
b := (no*xysum - xsum*ysum)/(no*xxsum - xsum*xsum);
a := (ysum - b*xsum)/no;
err := 0;
for i := 1 to no do
begin
  err := err + abs(y[i] - (a + b*x[i]));
end;
writeln(f_rpt, speed_v[i1]/sqrt(9.8*len), ', ', a, ', ', b, ', ', a + b*angle, ', ', err);
end
else
  writeln(' File not found!');
end;
close(f);
close(f_rpt);
end;

{begin main program}
begin
while true do
begin
  writeln(' experimental data management and processing', ' suimin zhang sept. 1992');
  writeln(' main menu');
  writeln(' 1. data management');
  writeln(' 2. data analysis and report');
end
123
write ln(' 0. EXIT
Please Select

--- Data Management --->

1. create (or rewrite) database');
write ln(' 2. Update forwardspeed');
write ln(' 3. Update initial angle');
write ln(' 4. Append analytical result by E.M.F. Method');
write ln(' 5. Data examination (error finding)');
write ln(' 6. Update analytical result by E.M.F. Method');
write ln(' 7. List records in the Database');
write ln(' 0. Return to Main Menu');
write( ' Please select: ');
write ln;
write ln;
write ln;
write ln;
read (m_choice);
case m_choice of
 1: begin
  writeln(' All data in the database may be deleted! ');
  write (' Are you sure? (Y/N)');
  m_yn:= 'N';
  readln(m_yn);
  If((m_yn='Y') or (m_yn='y')) then
    cr_db
  else
    writeln(' Database not created (or rewrite)');
end;
2: updt_sp;
3: updt_agl0;
4: appe_db;
5: exam_db;
6: updt_db;
7: ls_db;
0: goto 13
end;
end;
end;
if m_select = 2 then
begin
while true do
begin
writeln;
writeln;
writeln;
writeln;
writeln;
writeln;
writeln(' <-- Data Analysis and Report -->');
writeln(' 1. output damping coef. of one speed');
writeln(' 2. compare two file');
writeln(' 3. single least square regression');
writeln(' 4. batch least square regression(LSR0801.DAT)');
writeln(' 5. least square regression for one GM');
writeln(' 6. output damping coef. of speed vie angle');
writeln(' 7. output damping coef. of l amplitude amp[1]');
writeln(' 8. output damping coef. of differencr OMEGA');
writeln(' 9. statistics natural frequency');
writeln(' 0. Return to Main Menu');
writeln;
writeln(' Please select:');
writeln;
writeln;
writeln;
writeln;
read(m_choice);
case m_choice of
 1: rpt_b;
 2: comp;
 3: lsr;
 4: lsr_bat;
 5: lsr_gml;
 6: rpt_va;
 7: rpt_ampl;
 8: rpt_freq;
 9: rpt_omega;
0: goto 13
end;
end;
end;
end;
end:
end.