9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE,
AUCKLAND, 8-12 DECEMBER 1986

A NOTE ON THE FLUID MEMORY EFFECTS AND NON LINEARITIES
INVOLVED IN OSCILLATORY SHIP MODEL MANOEUVRING EXPERIMENTS

A Note on the Fluid Memory Effects and Non Linearities Involved in Oscillatory Ship Model Manoeuvring Experiments

M. R. RENILSON

Australian Maritime College.

ABSTRACT

After a brief review of the theory of ship manoeuvring, the history and conventional analysis techniques involved in oscillatory model testing are discussed. It is shown that the conventional equations of motion use the zero frequency results which, although adequate for prediction of surface ship manoeuvres, cannot be obtained directly from oscillatory testing.

The problems involved with the conventional analysis techniques are discussed and a modified technique is presented. Experimental results extending to extremely low frequencies are given and analysed using the modified techniques.

Using this technique, it is possible to separate the Fluid Memory effects from the non-linearities and hence have greater confidence in the results. A comparison with a static test is given and seen to be good.

INTRODUCTION

The conventional equations of surface ship motion in the horizontal plane are based on a Taylor series expansion where it is assumed that:

$$\left.\begin{matrix} X \\ Y \\ N \end{matrix}\right\} = f(u, v, r, \dot u, \dot v, \dot r, \delta) \qquad \ldots(1)$$

and the coupling with roll is neglected (see figure 1 and Nomenclature). Neglecting surge, the non dimensionalised linear equations thus become (Mandel 1967):

$$-Y'_v v' + (m' - Y'_{\dot v})\dot v' - (Y'_r - m')r' - (Y'_{\dot r} - m'x'_G)\dot r' = Y'_\delta \delta'$$

$$-N'_v v' - (N'_{\dot v} - m'x'_G)\dot v' - (N'_r - m'x'_G)r' + (I'_z - N'_{\dot r})\dot r' = N'_\delta \delta' \qquad \ldots(2)$$

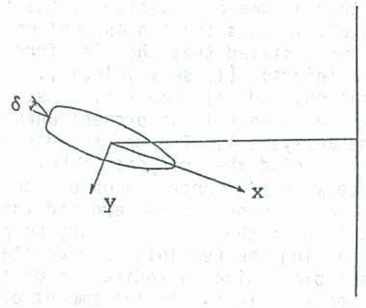


Fig 1: Body fixed co-ordinate system.

In order to describe the path of a ship in a tight turn these equations are inadequate, however, they can be used as a test for stability, for turning ability and for manual control ability which may form the basis of new IMO regulations (Clarke 1982). Unfortunately, due to the complexity of the flow, the hydrodynamic coefficients (or "derivatives"), $Y_{v'}$, $Y_{\dot v'}$, $Y_{r'}$, $Y_{\dot r'}$, $Y_{\delta'}$, $N_{v'}$, ... etc. cannot be obtained accurately from theory alone hence model experiments are required.

The coefficients $Y_{\delta'}$ and $N_{\delta'}$ can be readily obtained in a conventional towing tank using a captive model. The rudder is given a known deflection and the forces measured. The run is then repeated many times with various different deflections and a plot of force (or moment) against rudder angle is made, Y_δ and N_δ are obtained by measuring the slope of the line at the origin drawn through these points. Y'_δ and N'_δ are then obtained by non-dimensionalization. $Y_{v'}$ and $N_{v'}$ can be obtained in similar manner. This time there is no rudder deflection but the model will be orientated in such a way that there will be an angle, β, between it's centre line and direction of travel. v is then obtained from:

$$v = -U \sin \beta \qquad \ldots(3)$$

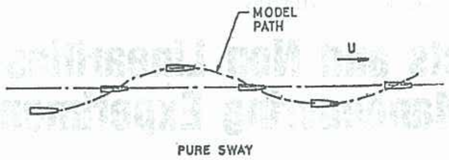
Again the slope at the origin on a plot of force (or moment) against v gives Y_v (or N_v) and Y'_v (or N'_v) can be obtained by non-dimensionalization.

The problem then was to obtain Y'_r and N'_r. For this a special facility had to be built which consisted of a large square or circular tank with a crane like structure in the middle. This supported a long arm to which a model could be attached. The whole structure could rotate with the model fixed at any given radius along the arm. The problem with this technique, in addition to the high cost, was that to get small values of r' (which were required for the linear co-efficients Y'_r and N'_r large radii were required since:

$$r' = \frac{L}{R} \qquad \ldots(4)$$

The rotating arm (as this facility is called) has the advantage of being able to obtain Y_v', N_v' Y_δ' and $N_{\delta'}$ in addition to Y'_r and N_r'. It can also be used to obtain the non-linear coefficients and the cross coupling coefficients, however, it is very costly and can not be used to obtain the acceleration coefficients ($Y'_{\dot v}$, $N'_{\dot v}$, $Y'_{\dot r}$, and $N'_{\dot r}$).

In order to obtain Y_r and N_r in a conventional towing tank, and in addition, to obtain the acceleration coefficients, a device known as a planar motion mechanism (or PMM) was invented by Goodman and Gertler in the late '50s Gertler 1959, Goodman 1960). This consisted of a mechanism which oscillated the model with simple harmonic motion whilst it travelled down the tank. By adjusting the phase angle between the oscillation of the bow and the stern it is possible to generate either pure sway (Y'_v, N'_v, $Y'_{\dot{v}}$, $N'_{\dot{v}}$), pure yaw (Y'_r, N'_r, $Y'_{\dot{r}}$, $N'_{\dot{r}}$) or a combination of these. (Figure 2).



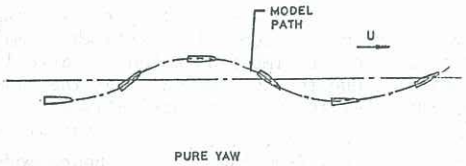


Fig 2: Path of Model during PMM Tests

Unfortunately, the results of the experiments with the first PMMs showed that the coefficients in equation (2) were functions of frequency. In other words the equations should be written:

$$-Y'_v(\omega)v'+(m'-Y'_{\dot{v}}(\omega))\dot{v}'-(Y'_r(\omega)-m')r'-(Y'_{\dot{r}}(\omega)-m'x'_G)\dot{r}' = Y'_\delta(\omega)\delta'$$

$$-N'_v(\omega)v'-(N'_{\dot{v}}(\omega)-m'x'_G)\dot{v}'-(N'_r(\omega)-m'x'_G)r'+(I'_z-N'_{\dot{r}}(\omega))\dot{r}' = N'_\delta(\omega)\delta' \quad \ldots (5)$$

In retrospect it is not surprising that the hydrodynamic coefficients of the manoeuvring equations should turn out to be frequency dependant, as it is well known that this is the case for the seakeeping equations. It is apparent that until the advent of PMMs the zero frequency values were used for path prediction. The obvious question to arise once the values are known as functions of frequency is how much difference to a path prediction would it make using the complete frequency range? Fujino (1975) and Loeser (1977) have carried out simulations using both the quasi steady assumption of eq. (2) and the frequency dependance of eq. (5) to find that there is essentially no difference in predicted path between the two approaches.
Assuming then that equations (2) are a good approximation to equations (5) for full scale ship manoeuvring and that the desired coefficient is the zero frequency coefficient, it is necessary to extrapolate the results of PMM tests (which must be carried out at non zero frequency) to zero frequency. Since the runs with low frequency will involve lower forces and hence greater error the extrapolation procedure causes great debate. (Gill and Price 1977, Burcher 1972, Renilson 1982 and Clarke 1981). An alternative approach is to test at a very low frequency and assume it is near enough to zero to give quasi steady conditions, and therefore the zero frequency values (Goodman, Gertler and Kohl 1976).

CONVENTIONAL PMM ANALYSIS

Considering the sway force only in the dynamic pure sway condition, the equations of motion are*

$$y = Y_0 \sin \omega t$$
$$v = Y_0 \omega \cos \omega t$$
$$\dot{v} = - Y_0 \omega^2 \sin \omega t \quad \ldots (6)$$

*The method for the sway force in the pure sway experiment is described, but the technique is similar for the other coefficients.

and the force equation is

$$Y = Y_v v + (Y_{\dot{v}} - m)\dot{v} \quad \ldots (7)$$

$$= (Y_v Y_0 \omega) \cos \omega t + (- (Y_{\dot{v}} - m) Y_0 \omega^2) \sin \omega t \quad \ldots (8)$$

which can be written

$$Y = Y_{out} \cos \omega t + Y_{in} \sin \omega t \quad \ldots (9)$$

where

$$Y_{out} = Y_v Y_0 \omega$$

and

$$Y_{in} = - (Y_{\dot{v}} - m) Y_0 \omega^2$$

From equation (9) it can be seen how, in principal, Y_v and $(Y_{\dot{v}} - m)$ can be obtained from the force record, $Y(t)$. However, Eq. 9 makes two very important assumptions: (1) the relation between side force and sway velocity or sway acceleration is linear, and (2) the force is entirely dependent on sway velocity and acceleration at the present moment and unaffected by their past history.

These assumptions imply that Y_v and $(Y_{\dot{v}} - m)$ are constants and should not vary with frequency (ω) or amplitude (Y_0). The results of PMM experiments show marked dependence on both ω and Y_0, however, and conventional analysis techniques cannot readily determine which of the assumptions made above is invalid. It is usual practice to plot the derivatives against a base of ω or ω^2 and extrapolate to zero frequency to obtain the "slow motion derivative" which is then used in the equations of motion. This procedure is not very accurate, particularly when using a conventional towing tank where the length of run is quite short and the frequency quite high.

MODIFIED ANALYSIS

The aim of the analysis presented here is to determine how accurate the two basic assumptions are for the range of amplitudes and frequencies tested and to provide a more reliable estimate of the coefficients to be used in the equations of motion.

The model was tested as normal and the force recorded as a function of time. Rather than using a conventional towing tank the tests were carried out in a circulating water channel (CWC) allowing virtually unlimited run length. This permitted lower frequencies to be used and more cycles to be obtained, reducing the extrapolation difficulties of the conventional method and increasing accuracy. (For details of the experimental set up see Renilson and Driscoll 1981 or Renilson 1982a).

Rather than assume an equation of the form 7, which immediately invokes the two assumptions to be tested, it is simply stated that the side force will be due to three things: (1) sway velocity, (2) sway acceleration, and (3) memory effects. The make-up of these components is at present unknown and that is what the analysis is directed to determine. The principle behind the analysis technique is to record the force when the contribution of one of the first two of these components is zero and then to vary the contribution of the third (by varying past history) whilst keeping the remaining one constant. The resultant plots give an indication of the importance of the memory effects and the amount of non-linearity separately.

From Equation (7) it can be seen that at time $t = 0$, $2\pi/\omega$, $4\pi/\omega$, ... the motion becomes

$$v = Y_0 \omega$$

$\dot{v} = 0 = y$

and at

$t = \pi/\omega,\ 3\pi/\omega,\ 5\pi/\omega,\ \ldots\ldots$ the motion becomes

$v = -\ Y_0\ \omega$

$\dot{v} = 0 = y$

Thus, any force acting on the model at these times must be due to (1) and (3) above, since there is no sway acceleration. The value of v is easily determined and it is possible to obtain the same value using various combinations of y_0 and ω, i.e. different past histories. Thus, if a plot of this force (denoted $Y^{(v)}$) is made against v ($\pm y_0\ \omega$) for the different amplitudes tested, then the difference between the curves is an indication of the memory effect. The deviation of these curves from a straight line shows the amount of non-linearity. In addition, for the sway velocity only, it is possible to plot the steady state results which have yet another past history. An example of this plot is given in Figure 3 where it can be seen that for this case the memory effect is negligible (at least for the low frequencies), but that non-linearities start to have influence above about v = 0.2 m/s. The coefficient, (Y_v), is obtained by taking the slope of the curve at the origin. The principal objection to this type of analysis is the fact that by using points much of the data is lost and the result is inaccurate. For the results presented here, the force curves were smoothed using neighbouring samples, reducing irregularities, and the long run time allowed sufficient cycles to be recorded to increase accuracy. If the assumptions discussed above were correct, all the points on Figure 3 would lie on the one straight line and $Y^{(v)}$ would equal y_{out}.

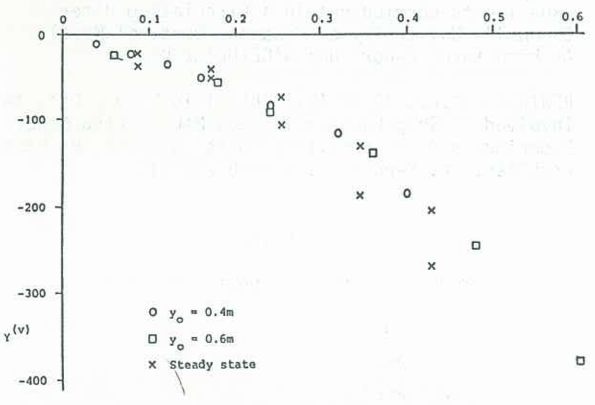


Fig 3: $Y^{(v)}$ for varying v.

It is possible to plot $Y^{(v)}/Y_0\ \omega$ against ω^2 as in Figure 4 which corresponds to $Y_{out}/y_0\ \omega$ in the conventional analysis and the difficulty of extrapolating to zero frequency can be seen.

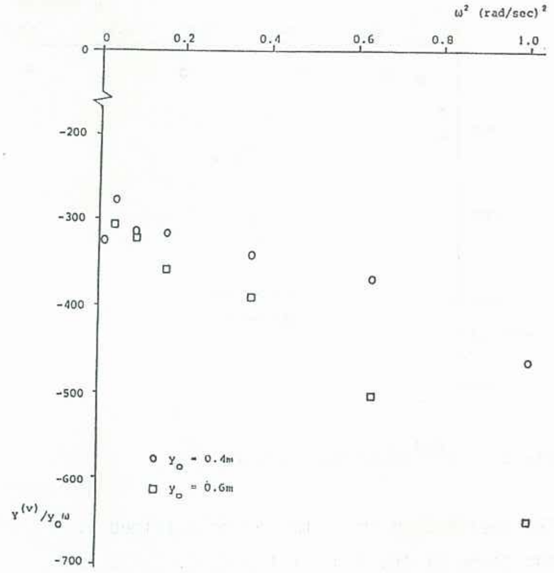


Fig. 4: $Y^{(v)}/Y_0\ \omega$ for varying ω^2

If a similar procedure is applied at time $t = 3\pi/2\omega$, $7\pi/2\omega$, $11\pi/2\omega$, ... and at $t = 5\pi/2\omega$, $9\pi/2\omega$, $13\pi/2\omega$, ..., then the curve of $Y^{(\dot{v})}$ against $\dot{v}$ can be obtain -ed in Figure 5.

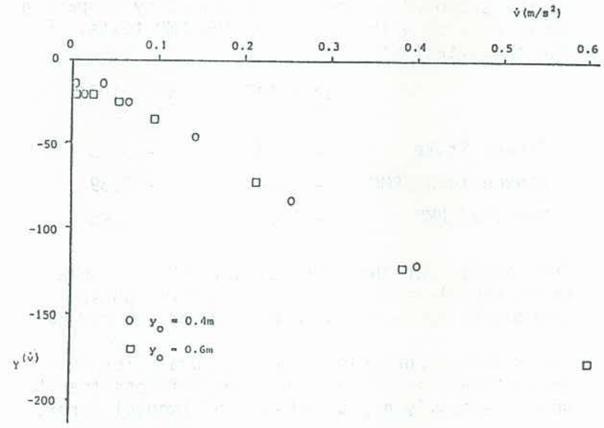


Fig 5. $Y^{(\dot{v})}$ for varying $\dot{v}$;

Here it can be seen that both non-linearity and memory effects are negligible over the range tested. This is because all the points lie on one straight line. The slight scatter at the low $\dot{v}$ values is due to the fact that the forces ar very small, resulting in a larger percentage error. This is much worse for the plot of $Y^{(\dot{v})}/Y_0\ \omega^2$ against ω^2, as the small force is divided by a small number ($Y_0\ \omega^2$), resulting in a large error. This is shown in Figure 6 where the difficulty of extrapolating the curve to zero frequency can be seen. However, for the more accurate higher frequencies there is a single straight line parallel to the x-axis, implying that the coefficient does not vary with frequency or amplitude, i.e. that the two assumptions are correct for this case.

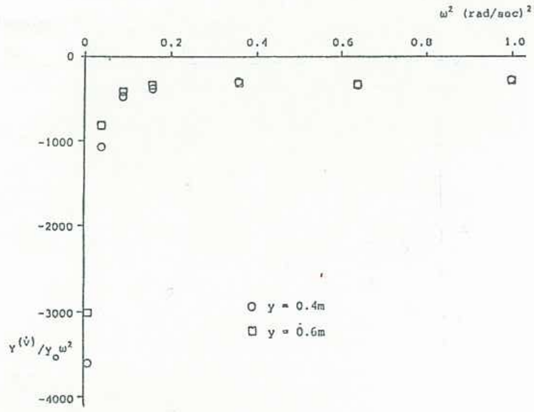


Fig 6. $Y^{(\dot{v})}/Y_0\omega^2$ for varying ω^2;

The coefficient $(Y_{\dot{v}} - m)$ can be obtained by taking the slope of the line in Figure 5. This line should pass through the origin and the slight offset is attributed to a small error in obtaining $Y^{(\dot{v})}$ from the force record.

RESULTS

It is the intention of the modified analysis technique to obtain the "slow motion derivatives" from PMM results. Since, by definition the "slow motion derivatives" Y_v and N_v can be obtained from oblique tow tests, an indication of the accuracy of the proposed method can be gained by comparing these results with those from the PMM tests. For the model tested:

	$Y'_v \times 10^{-3}$	$N'_v \times 10^{-3}$
Steady State	- 18.6	- 3.63
Conventional PMM	- 15.4	- 3.39
Modified PMM	- 18.7	- 3.45

The results for the conventional PMM were obtained using the plots of in-phase and out-of-phase components for ω = 0.4, 0.6, 0.8 and 1.0 rad/sec.

The modified analysis is more accurate for both derivatives, there being an error of less than 5%, which is easily explained as experimental error.

CONCLUSIONS

Difficulties can arise when trying to obtain "slow motion derivatives" from PMM results using the conventional analysis technique. A slightly modified technique has been presented which, when applied to the low frequency results obtained by oscillating a PMM in a CWC, can give a more accurate result.

An additional advantage of the modified method is its ability to separate memory effects from non-linearity between force and motion.

REFERENCES

CLARKE, D., 1981: Discussion to Renilson (1981)

CLARKE, D., 1982: "The Application of Manoeuvring Criteria in Hull Design Using Linear Theory". RINA Spring Meetings 1982.

FUJINO, M., 1975: "The Effect of Frequency Dependance of the Stability Derivatives on Manoeuvring Motion". Int. Ship Bld Prog Vol 22 No 256

GERTLER, M., 1959: "The DTMB Planar-Motion-Mechanism System" Proc of Symp on Towing Tank Facilities, Zagreb, Yugoslavia

GILL, A.D., PRICE, W.G., 1977: (a) "Determination of the Manoeuvring Derivatives of a Ship Model Using a Horizontal Planar Motion Mechanism in a Circulating Water Channel". Trans RINA

GILL, A.D., PRICE, W.G., 1977: (b) "Experimental Evaluation of the Effects of Water Depth and Speed on the Manoeuvring Derivatives of Ship Models". Trans RINA

GOODMAN, A., 1960: "Experimental Techniques and Meth -ods of Analysis Used in Submerged Body Research". Proc of the CNR 3rd Symp on Naval Hydrodynamics

GOODMAN, A., GERTLER, M., KOHL, R., 1976: "Experimental Techniques and Methods of Analysis Used at Hydronautics for Surface-ship Manoeuvring Predictions". Proc 11th ONR Symposium on Naval Hydrodynamics

LOESER, D.J., 1977: "Evaluation of Ship Motion Derivatives by Analytical and Experimental Methods". PhD Thesis, Uni. of California, Berekeley, Dept. of Naval Architecture.

MANDEL, P., 1967: "Ship Manoeuvring and Control". Chapter 8, Principles of Naval Architecture. SNAME pub.

RENILSON, M.R. and DRISCOLL, A., 1981: "Broaching - An Investigation into the Loss of Directional Control in Severe Following Seas". RINA Spring Meetings 1981

RENILSON, M.R., 1982: (a) "A Modified Technique for Analysing the Results from Planar Motion Mechanism Experiments carried out in a Circulating Water Channel" University of Glasgow, Dept. of Naval Architecture, Report No: NAOE/HL/82/01

RENILSON, M.R., 1982: (b) "The Fluid Memory Effects Involved in Ship Manoeuvring and Manoeuvring Model Experiments." University of Glasgow, Dept. of Naval Architecture, Report No. NAOE/HL/82/21

NOMENCLATURE

I_z	Moment of inertia about the z-axis
L	Ship length
m	Ship mass
N	Yaw moment
N_r	Yaw moment derivative with respect to angular velocity
$N_{\dot{r}}$	Yaw moment derivative with respect to angular acceleration
N_v	Yaw moment derivative with respect to sway velocity
$N_{\dot{v}}$	Yaw moment derivative with respect to sway acceleration
N_δ	Yaw moment derivative with respect to rudder angle
r	Angular velocity
$\dot{r}$	Angular acceleration
R	Radius of turn
t	Time
U	Ship speed
u	Surge velocity
$\dot{u}$	Surge acceleration

v	Sway velocity (in y direction)
$\dot{v}$	Sway accleration (in y direction)
X	Component of force along x-axis
x_G	x co-ordinate of the centre of gravity
Y	Component of force along y-axis
Y_r	Sway force derivative with respect to angular velocity
$Y_{\dot{r}}$	Sway force derivative with respect to acceleration
Y_v	Sway force derivative with respect to sway velocity
$Y_{\dot{v}}$	Sway force derivative with respect to sway acceleration
Y_δ	Sway force derivative with respect to rudder angle
Y_{in}	In phase component of measured sway force from PMM experiments
Y_{out}	Out of phase component of measured sway force from PMM experiments
$Y^{(v)}$	Measured sway force due to all sway velocity terms
$Y^{(\dot{v})}$	Measured sway force due to all sway acceleration terms
Y_0	Sway amplitude of PMM oscillation

Greek Symbols

β	Drift angle
δ	Rudder angle
ρ	Mass density of water
ω	Frequency

Superscript ' indicates that the quantity has been non-dimensionalised as follows:

Non-dimensional mass	$= m' = m/\frac{1}{2}\rho\, L^3$
Non-dimensional force	$= X' = X/\frac{1}{2}\, L^2U^2$
Non-dimensional velocity component	$= v' = v/U$
Non-dimensional angular velocity component	$= r' = r\, L/U$
Non-dimensional acceleration component	$= \dot{v}' = \dot{v}\, L/U^2$
Non-dimensional angular acceleration component	$= \dot{r}' = \dot{r}\, L^2/U^2$

Etc.