UNIVERSITY OF SOUTHAMPTON

DEPARTMENT OF SHIP SCIENCE

FACULTY OF ENGINEERING
AND APPLIED SCIENCE

PREDICTION OF THE MANOEUVRING FORCES ON A SLENDER SHIP USING SLENDER BODY THEORY

PART III: THE COMMISSIONING AND OPERATION OF A HORIZONTAL PLANAR MOTION MECHANISM

J.F. Wellicome, P.A. Wilson, X. Cheng

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Final Report on the Project

Prediction of the Manoeuvring Forces on a Slender Ship Using Slender Body Theory

Part III

The Commissioning and Operation of a Horizontal Planar Motion Mechanism

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1. INTRODUCTION

A series of towing tank tests has been carried out by the authors recently in the Southampton Institute Towing Tank using the Horizontal Planar Motion Mechanism (HPMM or PMM). This PMM was designed by a group of fourth year students in the University of Southampton in 1987 (Ref.1) for the purpose of measuring the hydrodynamic forces and derivatives of surface ship models in order to determine their manoeuvring characteristics.

During the test, the ship model is oscillated by the PMM in a small amplitude sinusoidal motion whilst being towed down the towing tank at constant speed. The generation of the required motion of the model and the measurement of the forces on the model are implemented by two sub-systems of the PMM: a mechanical system and a control system. The mechanical system contains a frame, suspensions which include forward and afterward struts and linkages, dynamometers, and tracks which constrain the struts to moving transversely. The control system consists of a personal computer, a CED-1400 A/D-D/A converter, an amplifier, two DC servo motors and motor controllers to drive the struts at required speed and to the required positions.

On the PMM, the following three dynamic motion modes can be generated by altering the phase difference between the motions of the forward and afterward struts: pure sway, pure yaw, and mixed sway and yaw. The static motion mode (oblique tow) can also be achieved by keeping the positions of the struts constant.

The present report will focus on the basic structures of the PMM, its operation procedure, and the data analysis methods.

2. THE PMM SYSTEM

2.1 Frame

The frame was designed to work as a rigid base upon which other components could be mounted and operate to convert the rotary motion of the motors into the translational motion of the struts. In the present PMM system, the conversion of motion was realized using toothed belts driven by the motors through an intermediate toothed belt and pulley arrangement. Each strut is mounted on a separate sub-frame on which the following components are mounted:

a. motors, toothed belts, and intermediate shafts
b. forward and afterward struts with suspension linkages
c. tracks
d. two moving plates which were driven by the toothed belts and onto which the struts were mounted
e. motor controllers

The forward sub-frame can be located in various positions on the main frame to enable the longitudinal separation of the struts to be adjusted to suit the model under test. The PMM is mounted behind the towing carriage of the Institute tank on two portable aluminium beams, which are bolted to the underside of the carriage as shown in Fig.1.

2.1.1 Frame Size

The main dimensions of the frame is as following

Length: 1575mm
Width: 1149mm
Depth: 610mm

The above dimensions are decided by the designed maximum struts separation (1000mm), the maximum oscillation amplitude (300mm), the space for drive motors and controllers, the dimensions of the carriage trailer, and the requirement on the rigidity of the frame.

2.1.2 Frame Materials

The frame was built with standard aluminium sections and plate. The frame members were made of 3" x 2" x 0.25" channel bar and all plate was 0.25" in thickness.

2.2 Dynamometers

The dynamometers were designed to measure the following three components of the forces and moment exerted by the model:

a. side force
b. yaw moment
c. drag force

There were two dynamometer units in the present design which were attached separately to each end of a base-plate, which would be fitted into the model, to ensure that they were perfectly aligned. The forward unit was a sway force dynamometer for measuring the sway force only and the rear unit consisted of a sway force dynamometer and a drag force dynamometer. The yaw moment could be calculated by taking the moment of the two measured sway forces about the centre of the two dynamometers. The forward dynamometer was not subjected to a drag force because of the design of the forward suspension linkage. Consequently the drag force would only be taken up by the rear dynamometer.

2.2.1 Designed Loads

The designed loads of the dynamometers were decided on the basis of the forces generated by a representative and reasonably large model executing harmonic motion. They were also the basis for the selection of the drive motors and the design of the suspension system.

Maximum Sway Force per Dynamometer = 50 N
Maximum Drag Force per Dynamometer = 18 N

2.2.2 Bridge Voltages

The dynamometers were to be used together with the existing facilities in the towing tank. The power supply to the bridge circuits in the dynamometers was at the recommended 5 volts.

2.3 Suspensions

The general arrangement of the linkage is shown in Fig. 2. The linkage is in two halves with each half connecting a dynamometer to the relevant strut. All the axles in the suspensions were made of stainless steel and the rest was made of aluminium.

The rear linkage consists of gimbal block 1 connected to the rear strut through horizontal link 1. The forward linkage consists of gimbal block 2 connected to the forward strut through horizontal link 3 and the vertical link 2.

Any vertical motion of the model is taken up by rotation of the horizontal links. Any increase in strut separation rotates the vertical link 2 in the forward linkage.

Each linkage is connected to the dynamometer base-plate by a post. The post forms the vertical pivot in the gimbal block which allows the rotation of the horizontal link about both vertical and horizontal axes.

The suspension linkages were designed to meet the following requirements:

a. To transmit a sway force of 80 N from the moving plates on the frame to the dynamometer through each linkage.
b. To apply a drag force of 18 N to the rear dynamometer.
c. To allow for ±40 mm vertical motion at each attachment point due to the pitch and heave of the model.
d. To allow for a maximum yaw angle of ±25 degs. This resulted in a forward and afterward movement of the forward strut of 80 mm along the model's centreline.
e. To attach to the moving plates and give 200 mm of vertical adjustment.

2.4 Motor Control and Transmission

The layout of the transmission and motor control system are shown in Fig.3. The following requirements should be met by this system:

a. To locate the struts over the range of ±300*mm* to an accuracy higher than 1%.

b. To transmit the rotary motion of the motor with suitable torque-speed characteristics to the linear motion of the struts with a peak force of 80N and a peak speed of 1.2m/s.

c. To provide an electrical measure of position for the feedback loop of the control system.

d. To follow the input signal to move the struts to the required position.

e. To follow the velocity within an accuracy of ±0.5%.

Two DC motors were used, each driving a strut through a double toothed belt drive. The first belt provides a speed reduction of 5:1 from the motor to an intermediate shaft and the second belt positions the strut. An electrical measure of the position of the strut is provided by a ten-turn potentiometer which is driven from the intermediate shaft.

The input voltage signal is produced in the range of ±5V using the CED 1401 A/D-D/A converter. The control system is effectively a DC servo-controller, it positions the strut in proportion to the input voltage using the potentiometer resistance as a position feedback signal. The input signals are generated by the controlling personal computer and are normally sinusoidal, but in principle non-sinusoidal signals could also be used.

2.5 Hardware and Software

The hardware used for the data acquisition consists of a CED 1401 A/D-D/A converter and a personal computer.

CED 1401 is a multi-channel device capable of converting 16 channels from analogue signals to digital signals and 4 channels from digital signals to analogue signals. The device has an internal memory of 64K Bytes of which approximately 55k Bytes is available for the storage of run data. The data can be collected (using timers built into the CED 1401) and stored into the memory of the A/D. When the experiment is complete, the data can be down loaded to the host computer for storage and analysis.

The host computer is currently a RM Nimbus PC running under MS-DOS operating system. This machine is capable of running a number of high level languages including Fortran, Basic, Pascal, Pro-Pascal.

The software used in the PMM test was written in Pro-Pascal because of the compatibility of this language with the input requirements of the CED 1401. It controls the

PMM motion and data acquisition. It can also carry out a part of the data analysis and display the collected data on the computer screen in graphic form using the graphic support library.

3. RUNNING THE TEST

3.1 Wiring

Before running the PMM test, appropriate connections between instruments should be made. Fig. 4 shows the schematic layout of the connections. The PMM panel which is attached to the PMM frame has four pairs of sockets. The CED 1401 converter has a DAC panel and a ADC panel, each having a number of channels. The connections are made in the following way:

a. PMM forward strut drive signal: from channel 1 on DAC to socket 1 on PMM panel.
b. PMM afterward strut drive signal: from channel 2 on DAC to socket 2 on PMM panel.
c. PMM forward strut motion feedback: from socket 3 on PMM panel to channel 1 on ADC.
d. PMM afterward strut motion feedback: from socket 4 on PMM panel to channel 2 on ADC.
e. Forward strut side force: from forward side force dynamometer to amplifier's input, from amplifier's output to channel 3 on ADC.
f. Aftward strut side force: from aft side force dynamometer to amplifier's input, from amplifier's output to channel 4 on ADC.
g. Drag force: from drag force dynamometer to amplifier's input, from amplifier's output to channel 5 on ADC.

3.2 Calibration of the Dynamometers

The calibration is carried out using the personal computer and each dynamometer is calibrated separately. In the original design gantries was used in the calibration for all the three dynamometers (one for drag and two for sway force). It was found that without using the gantry higher accuracy could be achieved in the sway force calibration. After making some modifications in the software, the gantry is no longer needed in the calibration of the two sway force dynamometers. However in the drag dynamometer calibration a gantry is still needed due to the difficulty in exerting the calibration load directly on the drag dynamometer.

3.2.1 Procedure for the Calibration of the Sway Force Dynamometers

The calibrations of the forward sway force dynamometer and the afterward one are carried out separately, but both follow the same procedure as following:

a. Adjust the amplifier's supply voltage to 5V for all the dynamometers.
b. Place the base-plate horizontally on a table or frame.
c. Select option 1 to run the experiment from the menu on the computer screen (see section 3.4.2 for how to get that menu on the screen), and then select the appropriate option for calibrating the dynamometer.
d. Select full scale load for the dynamometer.
e. Select calibration load.
f. Take the zero reading when the dynamometer is not loaded and the base-plate is placed horizontally. The zero reading can be adjusted if it is found to be too high.
g. Turn the base-plate 90 degrees into a vertical position to allow the calibration load to be applied towards the port side of the base-plate, attach the post and hook to the dynamometer, and then place the calibration load on the hook.
h. Use the voltmeter to check the output voltage from the amplifier to see if the gain is appropriately set. This is to make sure that the output voltage at full scale load will be equal to or slightly less than 5V. Adjust the gain if necessary.
i. Take the reading.
j. Remove the calibration load only and then take a reference reading.

The calibration coefficient is calculated by the computer using the calibration load and the difference between the two readings taken at stages i and j. It is important that after the calibration an experimental run be selected from the options on the screen so that the calibration coefficients can be recorded. For simplicity, this experimental run can be carried out at zero towing speed. After the run is complete, type "yes" when the computer asks "Are the data acceptable?" to store the data including the calibration coefficients onto the computer, otherwise they will all be lost.

3.2.2 Procedure for the Calibration of the Drag Force Dynamometer

A gantry is used in the calibration of the drag dynamometer as shown in Fig.5. Stages a to f are the same as those in section 3.2.1, and then

g. Place the gantry on the drag dynamometer, and then place the hook on the gantry, and place the load on the hook.

Stages h to j are the same as those in 3.2.1.

3.3 Attaching a Model to the PMM

A model is attached to the PMM by mounting the base-plate in the model. Since the dynamometers are attached to the base-plate and the struts can be connected to the dynamometers, the movement of the struts can thus be transmitted directly to the model. The following is the procedure of attaching a model to the PMM:

a. Loosening the two struts from their mounting plates by loosening the clamps.
b. Screw in the threaded lower struts into the dynamometers. The strut with the

extra linkage goes in the forward dynamometer.

c. Adjust the position of the after strut at the mounting plate to make the linkage horizontal. The upper section of the strut should be forward of the lower section.

d. Adjust the position of the forward motor axis so that when the forward strut is connected the upper linkage is vertical. This is done by removing the four attachment bolts (2 on each side of the frame) and sliding the axis. The bolts are replaced in the most appropriate set of holes.

e. Adjust the position of the forward strut at the mounting plate to make the lower linkage horizontal. The upper section of the strut should be aft of the lower section.

The model can be ballasted before it is attached to the PMM. However a part of the weight of the struts linkages (1.5 kg from the forward linkage and 1.7 kg from the aft linkage) will act on the model, which may slightly alter the draught of the model and therefore some adjustment to the ballast and the struts height may be needed after stage e.

3.4 Operation of the PMM

3.4.1 Switching on the System

The PMM system is controlled by the software. Before running the control software, the devices should be switched on. It is important that the CED 1401 is always switched on before the computer so that the CED 1401 can be recognised by the computer's operating system. When switching on the computer, an operating system disc should be inserted into drive A and a Propas disc into drive B, which creates a operation environment in which programs written in Pro-Pascal can be run. Once the operating system and the Propas disc have been loaded, both discs should be removed from the drives, and then insert a PMM control program disc into drive B and a data record disc into drive A. Before the data record disc can take in the test data, the following six files should be copied onto it from a previous data record disc.

(1) SHIPNAME
(2) SHIP* ("*" can be a number or characters given by the operator to identify the ship models)
(3) FBCONSTA
(4) PMM.SPR
(5) ADCMEMI.CMD
(6) MEMDACI.CMD

Note that every time a new disc is used to record the data, these six files on the previous data disc should be copied onto it.

3.4.2 Running the PMM Control Pragram

To run the PMM control program, simply type the name of the program (in drive B) and press RETURN. A menu of options will be displayed on the computer screen and the operation of PMM can be carried out by selecting the appropriate options from the menu.

Care should be taken in the test not to allow the run number of a model to reach 100, otherwise previous run data will be overwritten by the latest ones. If it is necessary to have 100 or more runs for a model, the model can be treated as a new one (when the run number is about to reach 100) by giving it a new name and the run number will start from 1 again.

4. DATA ANALYSIS

The data analysis is to determine the sway force, yaw moment, and their derivatives from the raw data. In the present analysis, up to third derivatives are considered.

At the end of each run, the acquired raw data can be displayed on the screen which include forward strut motion, after strut motion, sway force on the forward dynamometer, sway forward on the after dynamometer, and drag. Data analysis can also be carried out by the PMM control program and the calculated derivatives can be displayed on the screen. However in the PMM program the third derivatives, which are usually not accurately measured by the dynamometers, are used to calculate the first derivatives on a run by run basis and therefore the results are not as accurate as they can be if curve fitting methods are used. In the present experimental investigation, the derivatives were all worked out using the curve fitting methods. The PMM program was used to do the preliminary data analysis before the curve fitting methods were applied. The curve fitting methods require data from several runs and can only be used after the experimental programme is completed.

4.1 Preliminary Data Process

Before the curve fitting methods can be applied, the measured raw data should first be processed to separate different components which include in-phase terms and out-of-phase terms. For a ship hullform symmetric about the x-z plane, the out-phase terms contain first harmonic terms and third harmonic terms. These components can be separated from the raw data by expanding the data into a Fourier series. This series can be used to determined the coefficients in an analytical expression for the force which is also expanded into a series. This work is carried out by the PMM program (to do this select "Analyse Previous Runs" in the menu) and the following output file will be created:

for pure sway tests:	PSX*	PSY*	PSN*
for pure yaw tests:	PYX*	PYY*	PYN*

in which "*" stands for a number or characters used to identify the model being tested.

For the processed oblique tow test data, a HARDCOPY file can be created by selecting "Creat Print File" in the menu. This HARDCOPY file also contains the derivatives of pure sway and pure yaw tests calculated by the PMM program, but they are not used due to their unsatisfactory accuracy as mentioned before.

The format of each file above and the definitions of the data contained in the files are:

			FMDAT1	FMDAT2	FMDAT3	FMDAT4	FMDAT5
PSX*:	$\dot{v}$	v	X_o	$X1_{quad}$	$X2_{in}$	Dummy	Dummy
PSY*:	$\dot{v}$	v	Y_o	$Y1_{in}$	$Y1_{quad}$	$Y2_{in}$	$Y3_{quad}$
PSN*:	$\dot{v}$	v	N_o	$N1_{in}$	$N1_{quad}$	$N2_{in}$	$N3_{quad}$
PYX*:	$\dot{r}$	r	X_o	$X1_{quad}$	$X2_{in}$	$X2_{quad}$	$X4_{quad}$
PYY*:	$\dot{r}$	r	Y_o	$Y1_{in}$	$Y1_{quad}$	$Y2_{quad}$	$Y3_{quad}$
PYN*:	$\dot{r}$	r	N_o	$N1_{in}$	$N1_{quad}$	$N2_{quad}$	$N3_{quad}$

	Coeff1	Coeff2	Coeff3	Coeff4	Coeff5	Coeff6 ...	...Coeff10
HARDCOPY: (oblique tow)	u	v	X	Y	N	Dummy	Dummy

in which symbols are defined as

in pure sway case (all values are non-dimensional):

v=lateral speed
$\dot{v}$=lateral acceleration
Y_0=sway force at steady state (should be zero)
N_0=yaw moment at steady state (should be zero)
$Y1_{in}=-(m-Y_{\dot{v}})\ \dot{v}_o$
$Y1_{quad}=Y_v v_o + 3/4(1/6Y_{vvv})\ v_o^3$
$Y2_{in}$=second order acceleration terms (can be neglected)
$Y3_{quad}=-1/4\ (1/6Y_{vvv})\ v_o^3$
$N1_{in}=-(mx_G-N_{\dot{v}})\ \dot{v}_o$
$N1_{quad}=N_v v_o+3/4(1/6N_{vvv})\ v_o^3$
$N2_{in}$=second order acceleration terms (can be neglected)
$N3_{quad}=-1/4(1/6N_{vvv})\ v_o^3$

in pure yaw case (all values are non-dimensional):

r=angular speed
$\dot{r}$=angular acceleration
Y_o=sway force at steady state (should be zero)
N_o=yaw moment at steady state (should be zero)
$Y1_{in}=(mx_G-Y_{\dot{r}})\ \dot{r}_o$
$Y1_{quad}=(Y_r-m(1+c)U)\ r_o + 3/4(1/6Y_{rrr})\ r_o^3$
$Y2_{in}$=second order acceleration terms (can be neglected)
$Y3_{quad}=(mcU)\ r_o+1/4(1/6Y_{rrr})\ r_o^3$
$N1_{in}=(I_o-N_{\dot{r}})\ \dot{r}_o$
$N1_{quad}=(N_r-mx_G(1+c)U)\ r_o+3/4(1/6N_{rrr})\ r_o^3$
$N2_{in}$=second order acceleration terms (can be neglected)
$N3_{quad}=(mx_GcU)\ r_o+1/4(1/6N_{rrr})\ r_o^3$

in which

ω=circular frequency
v_o=maximum lateral speed which equals to $a\omega$ (a is the oscillation amplitude)
$\dot{v}_o=v_o\omega$, the maximum lateral acceleration
$\dot{r}_o=r_o\omega$, the maximum angular acceleration
x_G=the distance from the centre of the base-plate to the LCG of the model (x_G is negative if it is behind the base-plate centre)
I_o=dry moment of inertia of the ship model about the centre of the base-plate
$c=(a\omega\cos\varepsilon/U)^2/8$ (U is the towing speed and ε is ½ of the phase difference between the forward strut and aft strut motions)

in the case of oblique tow:

u=surge speed (in metres)
v=lateral speed (in metres)
X=drag force (in Newtons)
Y=sway force (in Newtons)
N=yaw moment (in Newton.metres)

It should be noted that in the above the yaw moment N is taken about the centre of the base-plate, which is also the centre of the two sway force dynamometers.

Although the third derivatives can be obtained directly from the third harmonic terms $Y3_{quad}$ and $N3_{quad}$, these data are inaccurate due to the smallness of the nonlinear components in the force and moment. It will also introduce undesirable error to the first derivatives if $Y3_{quad}$ and $N3_{quad}$ are used to determine the corresponding first derivatives. It is therefore more appropriate to use curve fitting methods to determine both the first and the third derivatives from the first harmonic terms $Y1_{quad}$ and $N1_{quad}$ which have larger values.

4.2 Curve Fitting Methods to Determine the Derivatives

The present curve fitting is to fit a straight line or a 3rd order polynomial to a set of data in the sense of least square, and to determine the slope of the straight line or the coefficients of the polynomial.

For sway or yaw tests, the set of data being fitted are from the tests at the same Froude number, same oscillation frequency but different amplitudes. This makes it possible to investigate the effects of Froude number and oscillation frequency on the results. In the case of oblique tow, the curve fitting is carried out to a set of data corresponding to the same Froude number but different drift angles.

It can be seen in section 4.1 that for the pure sway or pure yaw tests, the acceleration term $Y1_{in}$ is a linear function of $\dot{v}_0$ or $\dot{r}_0$. By fitting a straight line to a set of data, the slope of the line can be determined, and then the value of $-(m-Y_{\dot{v}})$ or $(mx_G-Y_{\dot{r}})$ is also determined which equals to the slope of the fitting line. For the damping terms $Y1_{quad}$ and $N1_{quad}$, a third order polynomial is used to fit the data, and the coefficients of v_0 and v_0^3 (or r_0 and r_0^3) can be determined by equating them to the corresponding coefficients in the polynomial. The derivatives can be worked out consequently after some simple calculations.

For oblique tow tests, the sway force Y and the yaw moment N are assumed to have the form

$$Y=Y_v v+Y_{vvv}v^3$$
$$N=N_v v+N_{vvv}v^3$$

The derivatives are determined by fitting the data with a third order polynomial.

It should be mentioned that in section 4.1 and in this section, the yaw moment is taken about the centre of the base-plate. This moment can be used to work out the moment about other reference point in a straight forward way.

As an example, the moment about the midships in the pure yaw test can be calculated using the following relations:

$$N=N_m+x_m Y$$
$$N_{\dot{r}}=N_{m\dot{r}}+x_m Y_{\dot{r}}$$
$$N_r=N_{mr}+x_m Y_r$$
$$N_{rrr}=N_{mrrr}+x_m Y_{rrr}$$

$$I_o=I_m+M(x_G^2-d_{mG}^2)$$

in which
N=yaw moment about the base-plate centre
N_m=yaw moment about the midships
x_m=distance from the base-plate centre to the midships (x_m is positive if it is in front of the base-plate centre and negative if it is after).
I_m=dry moment of inertia of the model about the midships
M=the mass of the model
x_G=distance from the centre of the base-plate to the LCG of the model.
d_{mG}=distance from the midships to the LCG of the model.

Again all the quantities above are non-dimensionalized.

5. CONCLUDING REMARKS

A Horizontal Planar Motion Mechanism was successfully commissioned and used to measure the forces and moments acting on three ship models executing pure sway and pure yaw motions as well as in yawed steady motion. The measured data for the "Mariner" and "British Bombardier" hulls were compared with the tests conducted by other organizations and generally satisfactory agreement was found (Ref.2). This can be seen as a validation of this PMM system being able to provide useful information about the hydrodynamic characteristics of a ship model. Future applications of this system can be envisaged in the research and teaching activities associated with ship hydrodynamics.

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Ship Science Report No.74, University of Southampton

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Revised Edition, Fifth Reprinting, August, 1980
Published by the Society of Naval Architects and Marine Engineers

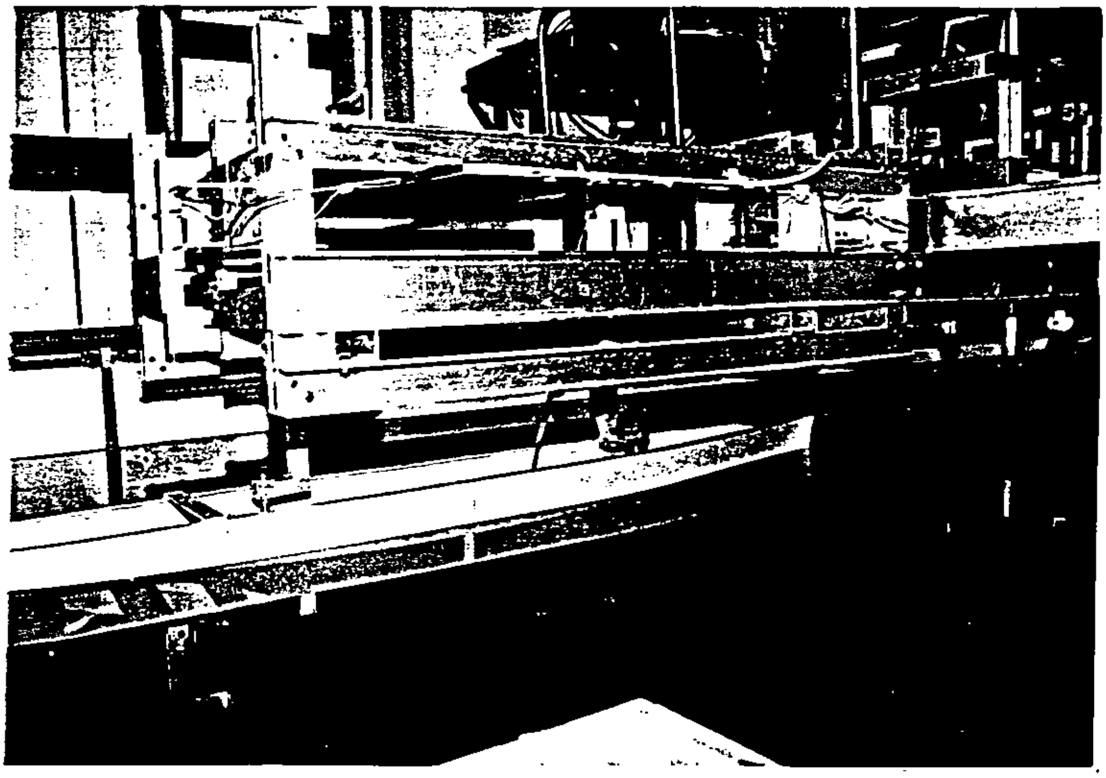


Fig.1 A Picture of the PMM Frame

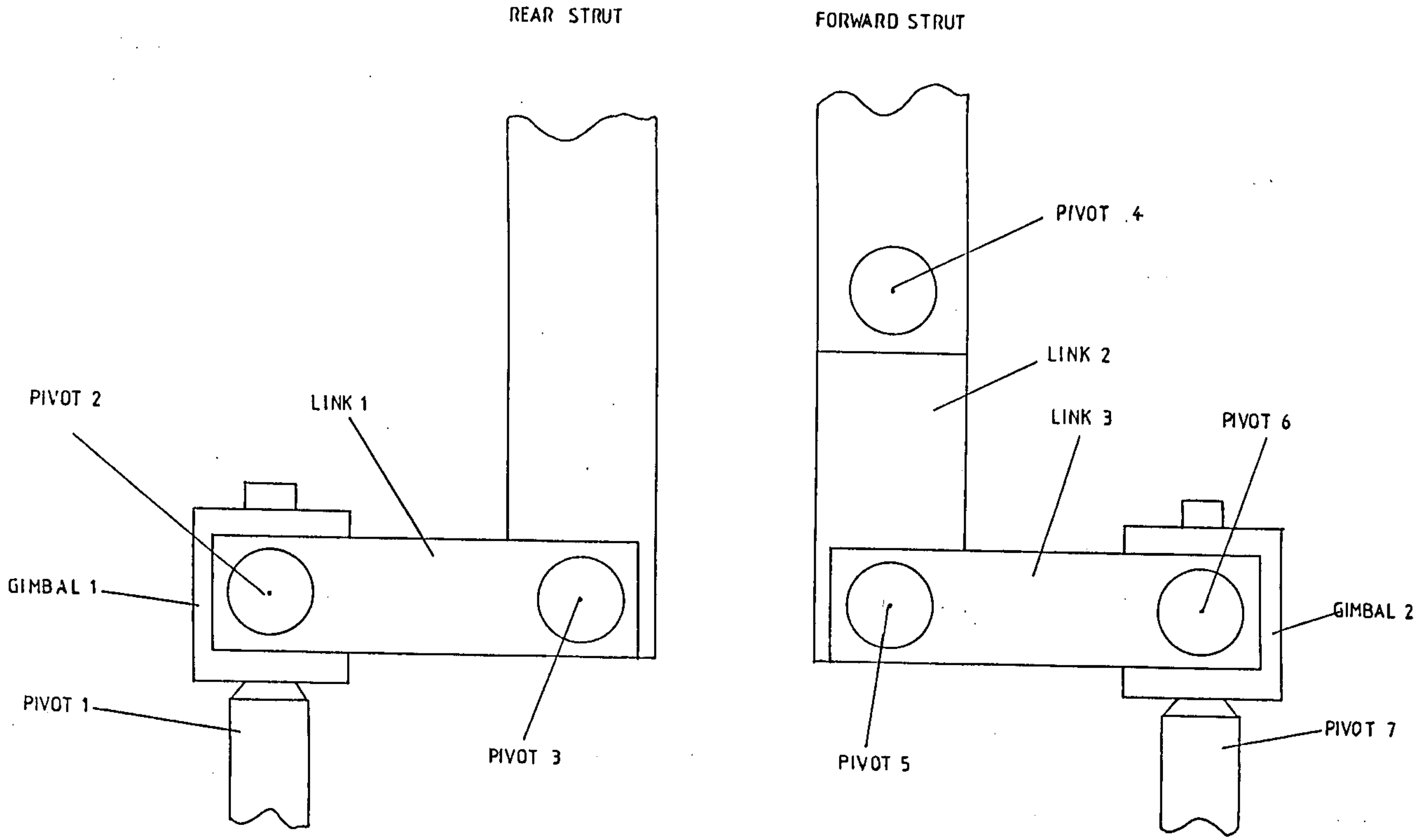
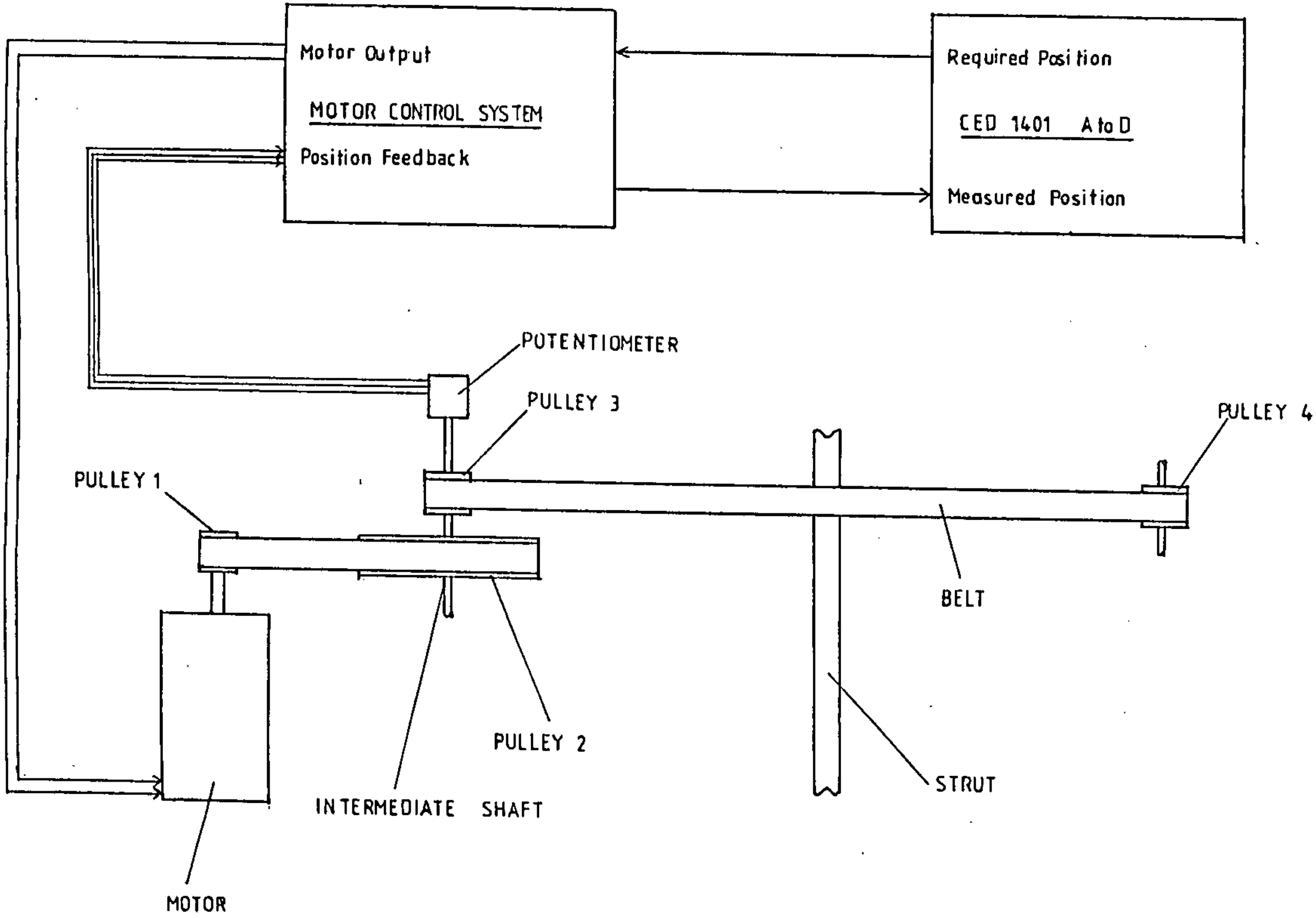


Fig.2 Suspension Linkage



ONLY ONE AXIS SHOWN

Fig.3 Motor Control and Transmission System

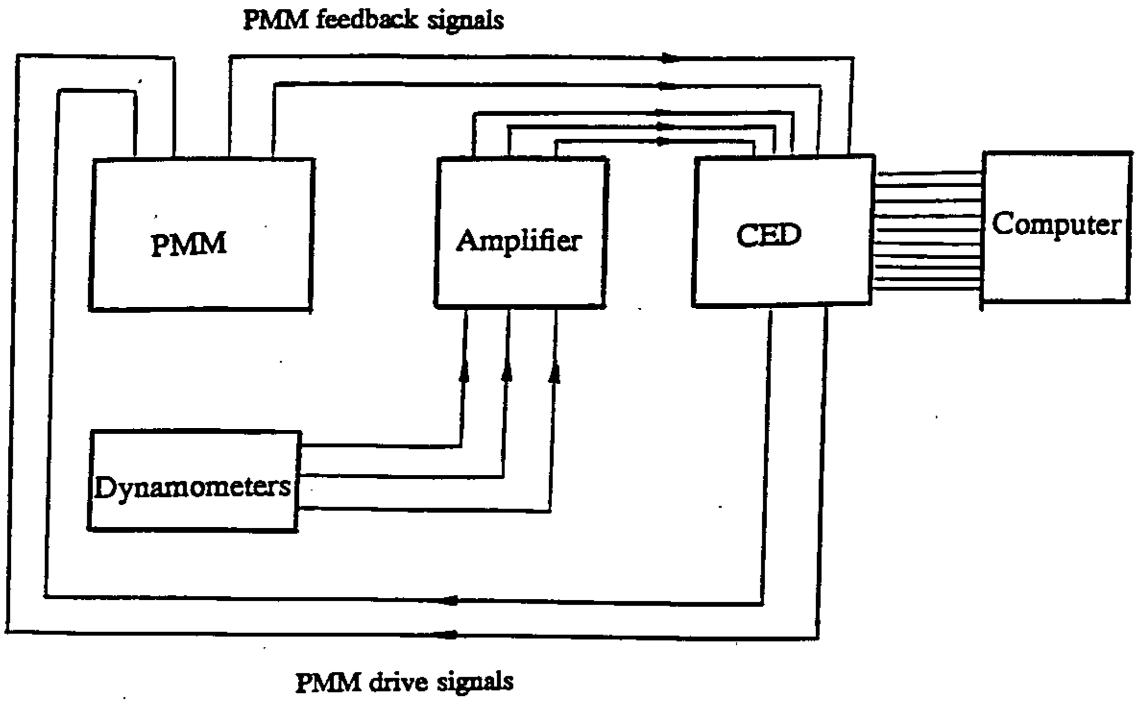


Fig.4 Layout of Control and Data Acquisition System

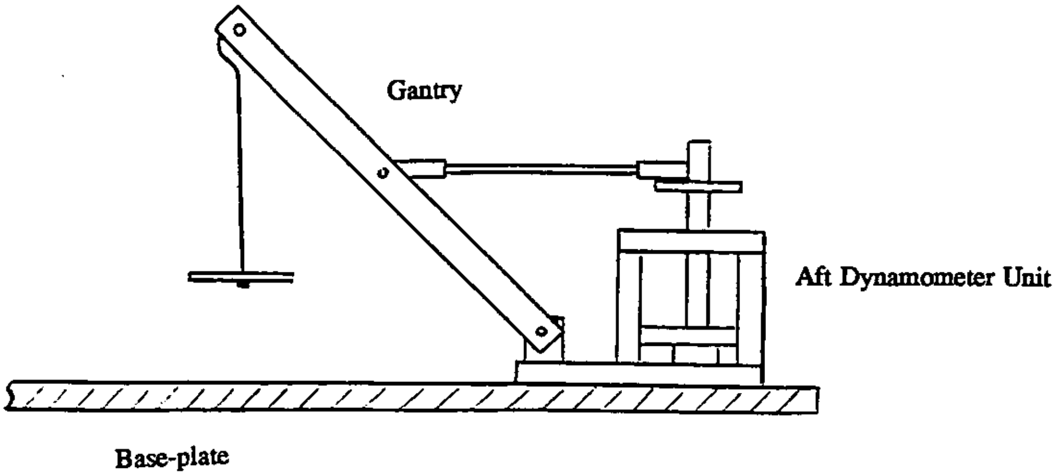


Fig.5 Calibration Gantry