ISSN 0140 3818
SSSU 74

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 II: TOWING TANK TESTS USING PLANAR MOTION MECHANISM

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

Ship Science Report No. 74
April 1994

Final Report on The Project

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

Part II

Towing Tank Tests Using Planar Motion Mechanism

by

J. F. Wellicome, P. A. Wilson

and

X. Cheng

Department of Ship Science
University of Southampton

April 1994

CONTENTS

NOTATION

a	Oscillation amplitude
Icg	Moment of inertia about LCG of the ballasted model
m	Mass of the ballasted model
LCG	Longitudinal centre of gravity of the ballasted model
N	Yaw moment acting on the hull of the model
N_D	Yaw moment acting on the dynamometers
r	Angular velocity
T	Oscillation period
v	Lateral velocity (in y direction)
v_o	Maximum lateral velocity
$\dot{v}$	Lateral acceleration
x,y	Coordinate system with the origin at the centre of the dynamometers, and x pointing to the bow and y to the starboard.
x_G	x coordinate of LCG
Y	Sway force acting on the hull of the model
Y_D	Sway force acting on the dynamometers
Yv, $Yvvv$	Lateral force derivatives with respect to v
Nv, $Nvvv$	Yaw moment derivatives with respect to v
$Y\dot{v}$	Lateral force derivatives with respect to $\dot{v}$
$N\dot{v}$	Yaw moment derivatives with respect to $\dot{v}$
Yr, $Yrrr$	Lateral force derivatives with respect to r
Nr, $Nrrr$	Yaw moment derivatives with respect to r
$Y\dot{r}$	Lateral force derivatives with respect to $\dot{r}$
$N\dot{r}$	Yaw moment derivatives with respect to $\dot{r}$
ω	Circular frequency
ϕ	Phase angle

1. INTRODUCTION

A series of PMM tests have been carried out as a part of the project to provide data for comparison with numerical computations. The tests, which consists 342 runs, were carried out with two models, a bulk carrier "Mariner" and a tanker "British Bombardier" (both without rudders) in various running conditions. The details of the test, the method of data analysis, and the test results will be presented in this report.

2. DESCRIPTION OF THE TEST SYSTEM

2.1 Planar Motion Mechanism

The Horizontal Planar Motion Mechanism used in the test was designed and built in the University of Southampton as part of a 4th year M.Eng. project (M. H. Cardases, et al., 1987). It was later tested and validated by Mr. D. Krishnan (1993), who conducted tests with the "Lord Nelson" model in the Austin Lamont Tank which is located in the University of Southampton.

The mechanism consists of the follwing main parts: a main frame, forward and afterward struts with suspension linkages, tracks on which the two struts can move which are in the direction perpendicular to the towing speed, two DC servo motors which drive the struts via toothed belt. The suspension linkages are designed to allow the model to pitch and heave (but not to roll) and to allow for the changing strut separation. The front linkage is designed not to transmit drag to ensure that the drag is only acted on the drag dynamometer connected to the rear suspension linkage.

The PMM can be operated in a) pure sway mode, b) pure yaw mode, c) mixed mode, by altering the phase between the two struts motions. In pure sway mode, the forward and aft struts are oscillated in phase resulting in pure sway velocity and acceleration of the model; in pure yaw mode, the forward and aft struts are oscillated with a specified phase difference, resulting in pure yaw velocity and acceleration; in mixed mode, the phase difference between the two strut motions is fixed at a non zero value which is different from that specified for the pure yaw condition, achieving a hybrid mode of operation in which the model is subjected to sinusoidal sway and yaw motions simultaneously. The PMM can also be operated in a static mode by keeping the strut positions constant to give the model a static drift angle during the run.

Fig.1 is a sketch which shows how the model is mounted on the PMM struts, and Fig.2 gives schematic definitions to the pure sway and pure yaw motions.

2.2 Dynamometers

The dynamometers are attached to a base-plate which will be mounted in the model during the test. The dynamometer connected to the front strut is for measuring the side force only, while the one connected to the rear strut can measure both side force and drag. The total side force acting on the two struts equals to the summation of the side forces measured by each dynamometer, and the yawing moment can be worked out by calculating the moment of each side force about the mid-point of the two side force dynamometers.

2.3 Towing Tank

The present PMM tests were conducted in the Southampton Institute Tank. In spite of some inconveniences in transportation of the equipment and travelling, conducting the test in the Institute Tank had following advantages: firstly the Institute Tank has a manned carriage which greatly facilitated the conduct of the experiment and visual observation of the model; secondly the rail and carriage suspension system gives much smoother ride resulting in less noise on the force signals associated with structural vibration; thirdly the Institute Tank has a length of about 61 m in contrast to 27.4 m of the Austin Lamomt tank, which, for the given models and oscillation periods, allows more oscillation cycles in the test; and finally the Insitute Tank is wider and deeper resulting in smaller blockage and wall interference.

2.4 Sub-carriage

To conduct the PMM test in the Institute Tank, a sub-carriage was needed to mount the PMM behind the existing carriage. This sub-carriage was designed by the Wolfson Unit engineers and constructed in the Southampton University's workshop. It was made of aluminium but with sufficient stiffness to prevent undesirable deflection. More details about the PMM and the sub-carriage can be seen in a separate report on PMM.

2.5 Control and Data Acquisition System

The control system consists of a micro-computer, a CED-1400 A/D-D/A converter, and motor controller for the struts' drive motors. A schematic hardware layout is shown in Fig.3. The experimental runs are entirely controlled by the computer software which is used for a) calibration of the dynamometers, b) generation of the drive signals for the motors, c) acquisition of the motion and force data and d) analysis of the acquired data.

3. DETERMINATION OF THE DRY MOMENT OF INERTIA Icg OF THE MODEL

Measurements of model's inertia were made for each model tested. For the measurement, each model was ballasted to the agreed weight and longitudinal centre of gravity to correspond to the test condition of the model. The ballast was stowed in the model amidships and moved to obtain the required LCG. No attempt was made to reproduce the ship radius of gyration as would have been necessary for free manoeuvring tests. Instead the ballast was disposed so as to minimise the 'tare' inertia to be subtracted from total measured moments to obtain hydrodynamic data.

As shown in Fig.4, the model was supported by two wooden frames placed at 0.45m forward of the LCG and 0.15m aft of LCG respectively. The frames were then suspended by two flexible steel wires attached to rigid supports at the top end. The model was then oscillated in sway and yaw, and the periods of the oscillations were measured. The effective length of the pendulum, i.e. the actual length of the wire plus the vertical distance from the suspending point on the frame to the VCG of the model, was determined from the measured sway period in the sway oscillation test. The moment of inertia in yaw was then determined from the following equation:

$$Icg = m\,(\frac{T}{2\pi})^2\,\frac{g}{l_e}\;x_a\,x_f$$

in which

T=yaw period
l_e = effective length of the pendulum
x_f= distance from LCG to forward frame
x_a= distance from LCG to aft frame
m = mass of the model

4. EXPERIMENT PROCEDURE

4.1 Dynamometer Calibration

The dynamometers were calibrated at the beginning of the experiment on every experiment day. In calibrating the sway force dynamometers, the base plate was placed vertically and the calibration weights were hung on a post connected to the sway force dynamometer. A gantry was used for the calibration of the drag dynamometer to avoid the awkward positioning of the base plate. Although the designed maximum load for each sway force dynamometer was 50 N and that for the drag dynamometer was 18 N, the full scale loads set in the calibration for each sway force dynamometer was about 25 N and that for the drag dynamometer was about 20 N, which were proved to be suitable levels to keep the highest loads measured in the tests within the range.

4.2 To Mount the Model on the PMM

The model was first fitted with the base plate, and the suspension linkages on the front and rear struts were then bolted into the front and rear dynamometers at both ends of the base plate. The original positions of the ballast weights were determined according to the original static trim (standard condition). The required change in static trim could be obtained by altering the positions of the ballast weights.

4.3 To Run the Test

All the run parameters are entered from the keyboard of the computer before the run, and the towing speed is set by entering an appropriate number to the speed controller. The PMM control system generates signals for the motors to drive the front and rear struts according to the required mode of motion. At the same time, the data acquisition system acquires the output signals from the three dynamometers and also the feedback signals from the PMM to updata the information on the current positions of the two struts. The acquired data are stored on the floppy disk at the end of each run for analysis.

5. DATA ANALYSIS

To illustrate the method used in the data analysis, let us take the pure sway mode as an example. The axis system and the sign convention are given in Fig.2a. Assume that the transverse motion of the struts is

$$y = a\cos(\omega t+\phi) \tag{1}$$

the transverse velocity and acceleration can then be expressed as

$$v = \dot{y} = -v_o \sin(\omega t+\phi) \tag{2}$$

$$\dot{v} = \ddot{y} = -v_o\omega \cos(\omega t+\phi) \tag{3}$$

in which $v_o = a\omega$.

It is also assumed that the hydrodynamic sway force and yaw moment acting on the model hull can be approximately expanded as

$$Y = Y_{\dot{v}}\dot{v} + Y_v v + 1/6\, Y_{vvv}v^3$$

$$N = N_{\dot{v}}\dot{v} + N_v v + 1/6\, N_{vvv}v^3$$

Note that in above it is assumed that the ship is symmetric about the x-z plane so that the sway force and yaw moment are odd functions of the sway velocity v. For this reason the second derivatives Yvv and Nvv do not appear in the above expressions. The assumption of linear relation between the force and acceleration is also adopted.

The sway force and yaw moment acting on the dynamometers can then be expressed as

$$Y_D = (m-Y_{\dot{v}})\,\dot{v} - Y_v v - 1/6\, Y_{vvv}v^3 \tag{4}$$

$$N_D = (m\,x_G-N_{\dot{v}})\,\dot{v} - N_v v - 1/6\, N_{vvv}v^3 \tag{5}$$

in which x_G is the x coordinate of LCG in the dynamometer's base plate coordinate system whose origin is at the mid-point between the two dynamometers and the positive x axis points toward the bow. The yaw moment N in expression (5) is taken about the origin of the coordinate system since, for the purposes of data acquisition and analysis, the software calculates the yaw moment about the origin. If it is required to use an alternative reference point (e.g. the midships) for the yaw moment, the derivative estimates should be adjusted accordingly. For instance, if the moment is to be taken about the midships, the N in expression (5) can be replaced by

$$N = N_m + Y\, x_m$$

where N and N_m are the moments about the origin and the midships respectively, Y is the sway force, and x_m is the x coordinate of the midships.

Replacing v and $\dot{v}$ in the above equations with expressions (2) and (3), and note that

$$\sin^3(\omega t+\phi) = 3/4\ \sin(\omega t+\phi)-1/4\ \sin3(\omega t+\phi)$$

we have

$$\begin{aligned} Y_D &= -(m-Y_{\dot{v}})v_o\omega\cos(\omega t+\phi)+Y_v v_o\sin(\omega t+\phi) \\ &+3/4\ (1/6Y_{vvv})v_o^3\sin(\omega t+\phi)-1/4\ (1/6Y_{vvv})v_o^3\sin3(\omega t+\phi) \end{aligned} \tag{6}$$

$$\begin{aligned} N_D &= -(mx_G-N_{\dot{v}})v_o\omega\cos(\omega t+\phi)+N_v v_o\sin(\omega t+\phi) \\ &+3/4\ (1/6N_{vvv})v_o^3\sin(\omega t+\phi)-1/4\ (1/6N_{vvv})v_o^3\sin3(\omega t+\phi) \end{aligned} \tag{7}$$

It can be seen that if the measured Y_D and N_D in the time domain are fitted with Fourier series, the derivatives in equations (6) and (7) can be determined by equating the Fourier series to the right hand side of the equations. After some simple mathematical manipulations, we can get

$$-(m-Y_{\dot{v}})\ v_o\omega = Y_{D1\ in} \tag{8}$$

$$Y_v v_o+3/4\ (1/6Y_{vvv})v_o^3 = Y_{D1\ quad} \tag{9}$$

$$-1/4\ (1/6Y_{vvv})v_o^3 = Y_{D3\ quad} \tag{10}$$

$$-(mx_G-N_{\dot{v}})\ v_o\omega = N_{D1\ in} \tag{11}$$

$$N_v v_0 + 3/4\ (1/6 N_{vvv}) v_0^3 = N_{D1\ quad} \qquad (12)$$

$$-1/4\ (1/6 N_{vvv}) v_0^3 = N_{D3\ quad} \qquad (13)$$

where the subscripts "1" and "3" designate the first and the third harmonics, while "in" and "quad" designate the in phase (cosine terms) and quadrature (sine terms) components.

Note that in deriving these equations, the Fourier series has been truncated in order to eliminate the unwanted noise in the raw data, only retaining up to the third harmonic terms.

The added mass $Y_{\dot{v}}$ can now be determined by fitting a straight line to the equation (8) as a function of v_0 using least square method, in which the slope of the line, which equals to $-(m-Y_{\dot{v}})$, is determined by minimizing the error of fitting. The damping coefficients Y_v, Y_{vvv} can be determined in three ways: a) to determine Y_{vvv} from the equation (10) and then to determine Y_v from the equation (9); b) to add the equation (10) to the equation (9), and then to fit the resultant equation with a cubic curve using least square method; c) to fit the equation (9) with a cubic curve. In this report the method c was used since it was found that the values of the third harmonic components were very small which made it difficult to achieve the desired accuracy in the measurement with the present dynamometers. The method b was only tried in a few cases for comparison with the method c. This procedure for determining the derivatives of side force Y was also adopted in determining the derivatives of yaw moment N.

6. TEST RESULTS

6.1 "Mariner" Model in Standard Condition

The particulars of the model:

Scale 1:64.36

LBP=2.5m
Breadth=0.36m
Draught=0.107m (forward)
0.126m (aft)
0.117m (mean)
Trim=0.43 deg. (bow up)
LCG=0.0388m (behind the midships)
Displacement=64.0 kg (ballasted)
Icg=8.021 kg m^2

in which Icg is the model's moment of inertia about LCG.

118 runs were carried out for this model which included oblique towing, pure sway and pure yaw. To investigate the effects of towing speed and oscillation frequency on the hydrodynamic coefficients, the model was run at three different Froude numbers and various oscillation frequencies. The details of each run condition are listed in Table 1.

The data of static towing test and the fitting curves are given in Fig.5 and Fig.6. The in-phase and quadrature components of the Fourier series of the measured forces and moments in pure sway and pure yaw modes, together with their fitting curves, are given in Fig.7 to Fig.18. These were plotted as a function of velocity/acceleration. As expected, the in-phase components of the forces show very good linearity, while the non-linearity in the first harmonic quadrature is also noticeable in most cases. The third harmonic quadrature components however, exhibit serious scatter, as can be seen in Fig.9, 12, 15, 18. For these data, the curve fitting was not carried out since it would not make much sense. The reason for the scatter is due to the small values of these components compared with the dynamometers' sensitivity. The derivatives obtained through curve fitting are presented in Table 2. Theoretically, the same coefficients obtained from static towing test and pure sway test should have the same values. Comparing Y_v and N_v values obtained from static towing and pure sway tests, we can see that the agreement is quite good. This is, to some extent, a validation of the test conducted. However, significant discrepancies are found when comparing the third derivatives obtained from the two different tests. Besides the small values of the higher order terms, the susceptibility of the third derivative to the data irregularity also contributes to the lack of consistency in the third derivative values.

The results also show that the effect of oscillation period on the force and moment is generally limited, but some exceptions can be found for the acceleration related force and moment as shown in Fig.10 and Fig.13. However it should be noted that the raw data in Fig.10a and Fig.13a are quite scattered, the results and conclusions derived from the analysis of these raw data may not always be genuine. The reason for the results not being strongly frequency dependent could be that the tests conducted were at frequencies below that at which serious frequency dependence seems likely according to G. Van Leeuwen (1964). On the other hand, the Froude number does influence the test results as can be seen in Fig.7,8,11,16,17, etc., which might be caused by the change in the draught of the model at different speeds since the suspension linkages allow the model to heave and pitch.

A comparison of the linear derivative data from the current tests with the values published from ITTC standard program show fairly good agreement for the static or sway derivatives Y_v , N_v and yaw derivative Y_r, N_r, but some discrepancy in relation to the acceleration terms.

The following table shows the comparisons

(values of derivatives must be multiplied by 0.001)

	Y_v	N_v	Y_r	N_r	$Y\dot{v}$	$N\dot{v}$	$Y\dot{r}$	$N\dot{r}$
Present Test (Fn=0.15,T=12.8)	-10.68	-4.74	2.02	-1.95	-9.20	-0.41	-0.86	-0.57
ITTC (Fn=0.19)	-10.73 to -13.10	-3.00 to -4.50	1.95 to 3.45	-1.70 to -2.65	-6.40	-0.30	-0.30	-0.30

Some derivatives in the above list have two values, which give the range of scatter of the derivatives obtained by different organizations with different test equipment (PMM, Rotating-arm, and straightline towing). It should be kept in mind that the condition of the present test is not identical to other PMM tests. As has been mentioned before, the model in the present test was free to pitch and heave, but was not allowed to roll. While in other PMM tests whose results were cited in the above table, the model was either fixed at designed draught and trim or was allowed to pitch, heave and roll. This difference was expected to cause some discrepancy to the test results.

6.2 "British Bombardier" Model

Scale 1:88.4

LBP=2.5m
Breadth=0.335m
Draught=0.141m (forward)
0.141m (aft)
0.141m (mean)
Trim=0.0 deg.
LCG=0.035m (in front of the midships)
Displacement=95.76 kg (ballasted)
Icg=12.818 kg m^2

For this model, 135 runs were conducted of which 88 runs were with the model fitted with turbulence stimulators. The present tests included oblique towing, pure sway, and pure yaw. The model was run at speeds U=0.495m/sec and 0.856m/sec which correspond to Fn=0.1 and 0.173. Table 3 is a list of all the run conditions for the "British Bombardier" model.

The first round tests were conducted with the bare model without turbulence studs. The raw data of the oblique towing tests and the fitting curves are shown in Fig.19 and Fig.20. These curves were plotted against the model's lateral speed v, which in the oblique towing case was related to the drift angle. Fig.21 and Fig.22 show the comparisons of the present oblique towing results with those of Haslar's. Quite good agreement can be seen in these figures. Fig.23 to Fig.30 show the in-phase and quadrature components of the measured forces in the pure sway and pure yaw tests. Since only three oscillation amplitudes (0.15m, 0.20m, 0.27m) were selected for each oscillation frequency, the number of data points was insufficient to do the curve fitting for each frequency, we therefore conducted curve fitting for all the data without separating them by frequencies. There was, in any case, little scatter in the data and no obvious indication that frequency influenced the results. The hydrodynamic derivatives obtained from the curve fitting are given in Table 4.

The second round tests were carried out with the model fitted with turbulence studs. In the pure sway and pure yaw tests, five oscillation amplitudes (from 0.15m to 0.30m) were selected, which enabled us to do the curve fitting for each oscillation frequency. Fig.31 and Fig.32 show the oblique towing test results. Comparing these two figures with Fig.19 and Fig.20, it is concluded that the turbulence studs only cause very little differences to the lateral force and moment as far as the oblique towing tests are concerned. The same conclusion can be derived by comparing the first derivatives obtained from the oblique towing tests with and without studs. Fig.33 to Fig.40 show the raw data and the fitting curves of the first harmonics. In the legends of these figures, T is oscillation period. The third harmonics were found to be too small to be measured accurately by the dynamometers and therefore were not plotted. In Table 4 it can be seen that the first derivatives are more or less consistent without drastic changes at various Froude numbers and oscillation frequencies; on the other hand, a great deal of scatter, some times even sign difference, can be found in some third derivatives. One reason for the inconsistencies is that the third derivatives are very sensitive to the irregularities in the raw data, especially when the curve fitting is applied to a small number of data. Another possible reason is that our sway and yaw tests were restricted to rather low frequencies for fear of damaging the dynamometers owing to the heavy weight of the ballasted model, which restricted the model's lateral speed to a small range within which the nonlinearity of the force and moment were not fully revealed. There was not only a upper limit for the frequency, the length of the towing tank also prevented the tests from being conducted at very low frequencies at desired towing speed. As a result, the band of frequencies of sway and yaw motion was quite narrow and relatively far away from zero frequency. For this reason, no attempt was made to extrapolate the coefficients backward to zero frequency.

6.3 "Mariner" Model in Trimmed Condition

The test with trimmed "Mariner" model is to investigate how the trim affects the hydrodynamic parameters. The model tested was the same as that discussed in section 6.1. By adjusting the positions of the ballast, different trim angles could be achieved. The required shift of ballast was calculated from the hydrostatic "moment to change trim" for the model. It should be noted that the trim angle was the one measured when the model was stationary. During the run, the trim would change due to the suspension linkages which allowed the model to ptich and heave. The tests were conducted at two different static trim angles, and the changed particulars of the model are as follows:

(1) Trim=-0.37 deg. (bow down)
LCG=-0.0148m (in front of the midships)
Icg=8.010 kg m^2

(2) Trim=1.50 deg. (bow up)
LCG=0.0924m (behind the midships)
Icg=8.175 kg m^2

53 runs were conducted for the first trim and 36 runs for the second trim which are listed in Table 5.

The curves in Fig.41 and Fig.42 show the comparisons of the sway forces and yaw moments measured in the oblique towing at different trims. Fig.43 to Fig.58 present the raw data and fitting curves of the sway and yaw tests at two different trim angles.

The increase in trim angle by stern seems to increase the sway force derivatives Yv and Yr as can be seen in Table 6. The centre of sway force due to damping can be determined by dividing Nv (or Nr) by Yv (or Yr). By doing this, a significant backward shift of the sway force centre at higher trim angle can be found, which explains why in spite of the increase in sway force, the yaw moment (about the midships) still becomes smaller as the trim by stern increases.

As for the acceleration terms, the results in sway case show that at higher trim angle, there is a obvious backward shift of the centre of the acceleration induced sway force, and that the increase in trim tends to reduce the added mass. These two factors cause a substantial reduction in the acceleration related yaw moment Nvdot.

Comparing the data at different frequencies, we can see that in most cases the effects of frequency are not very significant as far as the present frequency range is concerned. Frequency dependence is more obvious for acceleration related forces and moments especially for N1in in sway test and Y1in in yaw test as can be seen in Fig.45b and Fig.47b. The curve for T=16.0 sec. in Fig.45b does not seem to be in the right order, which may be caused by a great deal of scatter in the raw data.

The third diratives still present noticeable inconsistencies, which is believed to be caused mainly by the small number of data points (normally 5 to 6 points for each curve) in the curve fitting.

7. CONCLUDING REMARKS

A series of PMM tests have been conducted in the Southampton Institute Tank with a "Mariner" model and a "British Bombardier" model at various conditions. The test results of both "Mariner" model and "British Bombardier" model show good agreement in the oblique towing case with other researcher's tests. As for the sway and yaw tests, comparisons have been made with ITTC's data obtained from the tests with "Mariner" model. It showed reasonably good agreement for Yv, Nv, and Yr, Nr, but some discrepancy for other derivatives. Since the tests may not have been conducted in exactly the same condition, especially the way in which the model was mounted on the suspension linkages might differ from other tests, it is difficult to explain the real reason for the discrepancy. The third derivatives obtained in the present tests are not satisfactorily consistent. To improve their accuracy, larger number of data points are needed for each curve fitting, which will reduce the sensitivity of the third derivatives to the irregularity in the raw data. It is also desirable to conduct the test in a wider range of oscillation frequency and amplitude to allow the nonlinearity to be revealled more clearly. These of course should be within the capacity of the equipment and the tank time available.

In the authors' opinion, the present test equipment and method are sound. The measured data could be a useful reference for other researchers and for comparing with theoretical computations which is a part of the present contract.

REFERENCES

Cardases, M. H. et al. May 1987
The Design and Construction of A Horizontal Planar Motion Mechanism
Engineering Design Project Report, University of Southampton

Krishnan, D. 1993
Simulation of Manoeuvring and Control of Sailing Craft
Ph.D Thesis, Department of Ship Science, University of Southampton

Leeuwen, G. Van Dec. 1964
The Lateral Damping and Added Mass of A Horizontally Oscillating Ship Model
Report No. 65 S, Netherlands' Research Centre T.N.O. for Shipbuilding and Navigation

Table 1 RUNNING DETAILS OF PMM TESTS WITH MARINER MODEL IN STANDARD CONDITION

First Round Tests

	Oblique Towing	Pure Sway		Pure Yaw	
Fn	α (deg.) (drift angle)	T (sec.) (period)	A (m) (amplitude)	T (sec.)	A (m)
0.10	-8.0	12.8	0.071	12.8	0.079
0.10	-4.0	12.8	0.106	12.8	0.118
0.10	0.0	12.8	0.140	12.8	0.157
0.10	4.0	12.8	0.178	12.8	0.196
0.10	8.0	12.8	0.214	12.8	0.236
0.10	12.0	12.8	0.270	12.8	0.300
0.15	0.0	12.8	0.071	12.8	0.111
0.15	4.0	12.8	0.106	12.8	0.167
0.15	6.0	12.8	0.142	12.8	0.223
0.15	8.0	12.8	0.178	12.8	0.278
0.15	10.0	12.8	0.214		
0.15	12.0	12.8	0.270		
0.15		12.8	0.300		
0.15		8.0	0.071	8.0	0.075
0.15		8.0	0.106	8.0	0.112
0.15		8.0	0.142	8.0	0.149
0.15		8.0	0.178	8.0	0.186
0.15		8.0	0.214	8.0	0.224
0.15		8.0	0.270	8.0	0.280
0.15		8.0	0.300		
0.26	-8.0	8.0	0.071	6.4	0.098
0.26	0.0	8.0	0.106	6.4	0.147
0.26	4.0	8.0	0.142	6.4	0.196
0.26	8.0	8.0	0.178	6.4	0.245
0.26	10.0	8.0	0.214	6.4	0.294
0.26	12.0	8.0	0.270		
0.26		6.4	0.071	4.8	0.077
0.26		6.4	0.106	4.8	0.116
0.26		6.4	0.142	4.8	0.154
0.26		6.4	0.178	4.8	0.193

0.26		6.4	0.214	4.8	0.231
0.26		6.4	0.270	4.8	0.289

Second Round Tests

	Oblique Towing	Pure Sway		Pure Yaw	
Fn	α	T	A	T	A
0.26	-12.0	19.2	0.27	19.2	0.27
0.26	-8.0	19.2	0.20	19.2	0.20
0.26	-4.0	16.0	0.27	16.0	0.27
0.26	0.0	16.0	0.20	16.0	0.20
0.26	4.0	12.8	0.27	12.8	0.27
0.26	8.0	12.8	0.20	12.8	0.20
0.26	12.0	9.6	0.27	9.6	0.27
0.26		9.6	0.20	9.6	0.20
0.26		6.4	0.27	6.4	0.27
0.26		6.4	0.20	6.4	0.20
0.26		4.8	0.20	4.8	0.20
0.15		19.2	0.27	19.2	0.27
0.15		16.0	0.27	16.0	0.27
0.15		12.8	0.27	12.8	0.27
0.15		9.6	0.27	9.6	0.27
0.15		6.4	0.27	6.4	0.27
0.15		4.8	0.27	4.8	0.27

Table 2 DERIVATIVES OBTAINED FROM PMM TESTS WITH MARINER MODEL IN STANDARD CONDITION

1. OBLIQUE TOWING

Fn=0.10
Yv=-0.01142 1/6 Yvvv=-0.11484
Nv=-0.00444 1/6 Nvvv=0.01658

Fn=0.15
Yv=-0.01241 1/6 Yvvv=-0.11590
Nv=-0.00483 1/6 Nvvv= 0.02096

Fn=0.26
Yv=-0.01366 1/6 Yvvv=-0.13300
Nv=-0.00565 1/6 Nvvv=-0.00037

2. PURE SWAY

T=6.4 Fn=0.26
Yvdot=-0.01186 Nvdot=-0.00048
Yv=-0.01244 1/6 Yvvv=-0.18291
Nv=-0.00633 1/6 Nvvv=0.00405

T=8.0 Fn=0.15
Yvdot=-0.00951 Nvdot=-0.000380
Yv=-0.01086 1/6 Yvvv=-0.12338
Nv=-0.00468 1/6 Nvvv=0.00756

T=8.0 Fn=0.26
Yvdot=-0.01148 Nvdot=-0.00040
Yv=-0.01242 1/6 Yvvv=-0.18346
Nv=-0.00629 1/6 Nvvv=0.01966

T=12.8 Fn=0.10
Yvdot=-0.00877 Nvdot=-0.00038
Yv=-0.01009 1/6 Yvvv=-0.12375
Nv=-0.00440 1/6 Nvvv=0.01325

T=12.8 Fn=0.15
Yvdot=-0.00920 Nvdot=-0.00041
Yv=-0.01068 1/6 Yvvv=-0.15105
Nv=-0.00474 1/6 Nvvv=0.01763

3. PURE YAW

T=4.8 Fn=0.26
Yrdot=-0.00065 Nrdot=-0.00075
Yr=0.00194 1/6 Yrrr=0.00060
Nr=-0.00234 1/6 Nrrr=-0.00274

T=6.4 Fn=0.26
Yrdot=-0.00065 Nrdot=-0.00078
Yr=0.00165 1/6 Yrrr=0.00442
Nr=-0.00242 1/6 Nrrr=-0.00331

T=8.0 Fn=0.15
Yrdot=-0.00057 Nrdot=-0.00046
Yr=0.00177 1/6 Yrrr=0.00310
Nr=-0.00177 1/6 Nrrr=-0.00190

T=12.8 Fn=0.10
Yrdot=-0.00053 Nrdot=-0.00047
Yr=0.00190 1/6 Yrrr=0.00266
Nr=-0.00175 1/6 Nrrr=-0.00186

T=12.8 Fn=0.15
Yrdot=-0.00086 Nrdot=-0.00057
Yr=0.00202 1/6 Yrrr=0.00992
Nr=-0.00195 1/6 Nrrr=-0.00161

Note: the moments are taken about the midships.

Table 3 RUNNING DETAILS OF PMM TESTS WITH BRITISH BOMBARDIER MODEL

First Round Tests without Studs

	Oblique Towing	Pure Sway		Pure Yaw	
Fn	α (deg.) (drift angle)	T (sec.) (period)	A (m) (amplitude)	T (sec.)	A (m)
0.173	-12.0	19.2	0.27	19.2	0.27
0.173	-8.0	19.2	0.20	19.2	0.20
0.173	-4.0	19.2	0.15	19.2	0.15
0.173	-2.0	16.0	0.27	16.0	0.27
0.173	0.0	16.0	0.20	16.0	0.20
0.173	2.0	16.0	0.15	16.0	0.15
0.173	4.0	12.8	0.27	12.8	0.27
0.173	6.0	12.8	0.20	12.8	0.20
0.173	8.0	12.8	0.15	12.8	0.15
0.173	10.0	9.6	0.20	9.6	0.27
0.173	12.0	9.6	0.15	9.6	0.20
0.173	14.0			9.6	0.15
0.10	0.0	19.2	0.20	19.2	0.20
0.10	4.0	16.0	0.20	16.0	0.20
0.10	8.0	12.8	0.20	12.8	0.20
0.10	12.0			9.6	0.20
0.10	15.0				

Second Round Tests with Studs

	Oblique Towing	Pure Sway		Pure Yaw	
Fn	α (drift angle)	T (period)	A (amplitude)	T	A
0.173	-12.0	20.0	0.30	20.0	0.30
0.173	-8.0	20.0	0.27	20.0	0.27
0.173	-4.0	20.0	0.24	20.0	0.23
0.173	0.0	20.0	0.19	20.0	0.19
0.173	2.0	20.0	0.15	20.0	0.15
0.173	4.0				

Oblique Towing		Pure Sway		Pure Yaw	
Fn	α (drift angle)	T (period)	A (amplitude)	T	A
0.173	6.0	19.2	0.30	19.0	0.30
0.173	8.0	19.2	0.27	19.0	0.27
0.173	10.0	19.2	0.23	19.0	0.23
0.173	12.0	19.2	0.19	19.0	0.19
0.173	14.0	19.2	0.15	19.0	0.15
0.173		17.5	0.30	17.5	0.30
0.173		17.5	0.27	17.5	0.27
0.173		17.5	0.23	17.5	0.23
0.173		17.5	0.19	17.5	0.19
0.173		17.5	0.15	17.5	0.15
0.173		16.0	0.30	16.0	0.30
0.173		16.0	0.27	16.0	0.27
0.173		16.0	0.23	16.0	0.23
0.173		16.0	0.19	16.0	0.19
0.173		16.0	0.15	16.0	0.15
0.173		14.0	0.30	13.0	0.30
0.173		14.0	0.27	13.0	0.27
0.173		14.0	0.23	13.0	0.23
0.173		14.0	0.19	13.0	0.19
0.173		14.0	0.15	13.0	0.15
0.10	-12.0	20.0	0.30	20.0	0.30
0.10	-8.0	20.0	0.27	20.0	0.27
0.10	-4.0	20.0	0.23	20.0	0.23
0.10	0.0	20.0	0.19	20.0	0.19
0.10	4.0	20.0	0.15	20.0	0.15
0.10	8.0				
0.10	12.0	16.0	0.30	13.0	0.30
0.10		16.0	0.27	13.0	0.27
0.10		16.0	0.23	13.0	0.23
0.10		16.0	0.19	13.0	0.19
0.10		16.0	0.15	13.0	0.15

Table 4 DERIVATIVES OBTAINED FROM THE PMM TEST WITH THE BRITISH BOMBARDIER

1. OBLIQUE TOWING TEST

without turbulence stimulators:

Fn=0.173 Yv=-0.01747 1/6 Yvvv=-0.14715
Nv=-0.00735 1/6 Nvvv=-0.00156

Fn=0.100 Yv=-0.01910 1/6 Yvvv=-0.12724
Nv=-0.00705 1/6 Nvvv=0.00670

with turbulence stimulators:

Fn=0.173 Yv=-0.01700 1/6 Yvvv=-0.09725
Nv=-0.00751 1/6 Nvvv=0.00051

Fn=0.100 Yv=-0.01900 1/6 Yvvv=-0.09733
Nv=-0.00717 1/6 Nvvv=0.01318

2. PURE SWAY TEST

without turbulence stimulators:

Fn=0.173 Yvdot=-0.01101 Nvdot=-0.00072
Yv=-0.01587 1/6 Yvvv=-0.18156
Nv=-0.00759 1/6 Nvvv=0.02438

with turbulence stimulators:

Fn=0.173 T=19.2 Yvdot=-0.01236 Nvdot=-0.000810
Yv=-0.01488 1/6 Yvvv=-0.21351
Nv=-0.00758 1/6 Nvvv=0.01335

T=17.5 Yvdot=-0.01312 Nvdot=-0.00080
Yv=-0.01430 1/6 Yvvv=-0.22783
Nv=-0.00739 1/6 Nvvv=0.00290

T=16.0 Yvdot=-0.01168 Nvdot=-0.00075
Yv=-0.01500 1/6 Yvvv=-0.17269
Nv=-0.00765 1/6 Nvvv=0.02127

T=14.0 Yvdot=-0.01282 Nvdot=-0.00076
Yv=-0.01506 1/6 Yvvv=-0.16757
Nv=-0.00769 1/6 Nvvv=0.02086

3. PURE YAW TEST

without turbulence stimulators:

Fn=0.173 Yrdot=-0.00080 Nrdot=-0.00063
Yr=0.00342 1/6 Yrrr=0.00207
Nr=-0.00259 1/6 Nrrr=-0.00059

with turbulence stimulators:

Fn=0.173 T=20.0 Yrdot=-0.00156 Nrdot=-0.00078
Yr=0.00428 1/6 Yrrr=-0.10315
Nr=-0.00219 1/6 Nrrr=-0.04160

T=17.5 Yrdot=-0.00164 Nrdot=-0.00085
Yr=0.00279 1/6 Yrrr=0.02279
Nr=-0.00271 1/6 Nrrr=0.00141

T=16.0 Yrdot=-0.00134 Nrdot=-0.00076
Yr=0.00224 1/6 Yrrr=0.03704
Nr=-0.00279 1/6 Nrrr=0.00406

T=13.0 Yrdot=-0.00086 Nrdot=-0.00066
Yr=0.00331 1/6 Yrrr=-0.00198
Nr=-0.00250 1/6 Nrrr=-0.00338

Note: The moments are taken about the midships.

Table 5 RUNNING DETAILS OF PMM TESTS WITH TRIMMED MARINER MODEL

First Round Tests (trim=-0.37 deg., bow down)

	Oblique Towing	Pure Sway		Pure Yaw	
Fn	α (deg.) (drift angle)	T (sec.) (period)	A (m) (amplitude)	T (sec.)	A (m)
0.26	-8.0	16.0	0.106	16.0	0.106
0.26	-6.0	16.0	0.142	16.0	0.142
0.26	-4.0	16.0	0.214	16.0	0.214
0.26	-2.0	16.0	0.270	16.0	0.270
0.26	0.0	16.0	0.300	16.0	0.300
0.26	2.0				
0.26	4.0	12.8	0.071	12.8	0.106
0.26	6.0	12.8	0.106	12.8	0.142
0.26	8.0	12.8	0.142	12.8	0.214
0.26	10.0	12.8	0.214	12.8	0.270
0.26		12.8	0.270	12.8	0.300
0.26		8.0	0.071	8.0	0.071
0.26		8.0	0.106	8.0	0.106
0.26		8.0	0.142	8.0	0.142
0.26		8.0	0.214	8.0	0.214
0.26		8.0	0.270	8.0	0.270
0.26		8.0	0.300	8.0	0.300
0.26		6.4	0.071	6.4	0.071
0.26		6.4	0.106	6.4	0.106
0.26		6.4	0.142	6.4	0.142
0.26		6.4	0.170	6.4	0.214
0.26		6.4	0.200	6.4	0.270
				6.4	0.300

Second Round Tests (trim=1.5 deg., bow up)

	Oblique Towing	Pure Sway		Pure Yaw	
Fn	α	T	A	T	A
0.26	-6.0	16.0	0.106	16.0	0.270
0.26	-4.0	16.0	0.142	16.0	0.300
0.26	-2.0	16.0	0.214		
0.26	0.0	16.0	0.270	12.8	0.300
0.26	2.0	16.0	0.300		
0.26	4.0			8.0	0.106
0.26	6.0	12.8	0.106	8.0	0.142
0.26	8.0	12.8	0.142	8.0	0.214
0.26	10.0	12.8	0.214	8.0	0.270
0.26		12.8	0.270	8.0	0.300
0.26		12.8	0.300		
				6.4	0.142
0.26		8.0	0.106	6.4	0.214
0.26		8.0	0.142		
0.26		8.0	0.214		
0.26		8.0	0.270		
0.26		8.0	0.300		
0.26		6.4	0.142		
0.26		6.4	0.214		

Table 6 DERIVATIVES OBTAINED FROM PMM TESTS WITH TRIMMED MARINER MODEL
(Fn=0.26)

1. OBLIQUE TOWING

Trim=-0.37 deg. (bow down)
Yv=-0.010886 1/6 Yvvv=-0.077001
Nv=-0.006192 1/6 Nvvv=-0.004043

Trim=1.50 degs. (bow up)
Yv=-0.013107 1/6 Yvvv=-0.144481
Nv=-0.003544 1/6 Nvvv= 0.022209

2. PURE SWAY

TRIM=-0.37 deg. (bow down)

T=6.4 sec.
Yvdot=-0.008302 Nvdot=-0.000545
Yv=-0.009482 1/6 Yvvv=-0.083420
Nv=-0.006814 1/6 Nvvv=0.013053

T=8.0 sec.
Yvdot=-0.008405 Nvdot=-0.000525
Yv=-0.009505 1/6 Yvvv=-0.074563
Nv=-0.006531 1/6 Nvvv=0.011427

T=12.8 sec.
Yvdot=-0.008867 Nvdot=-0.000512
Yv=-0.009981 1/6 Yvvv=-0.046093
Nv=-0.006216 1/6 Nvvv=-0.006964

T=16.0 sec.
Yvdot=-0.008830 Nvdot=-0.00064
Yv=-0.010153 1/6 Yvvv=-0.001225
Nv=-0.006062 1/6 Nvvv=-0.010380

TRIM=1.5 deg. (bow up)

T=8.0 sec.
Yvdot=-0.007418 Nvdot=-0.000027
Yv=-0.011042 1/6 Yvvv=-0.133943
Nv=-0.003828 1/6 Nvvv=0.015642

T=12.8 sec.

Yvdot=-0.007448 Nvdot=0.000042
Yv=-0.011281 1/6 Yvvv=-0.137672
Nv=-0.004003 1/6 Nvvv=0.046783

T=16.0 sec.

Yvdot=-0.007708 Nvdot=0.000088
Yv=-0.011624 1/6 Yvvv=-0.137901
Nv=-0.004121 1/6 Nvvv=0.075517

3. PURE YAW

TRIM=-0.37 deg. (bow down)

T=6.4 sec.

Yrdot=-0.000739 Nrdot=-0.000600
Yr=0.001496 1/6 Yrrr=0.006883
Nr=-0.002155 1/6 Nrrr=-0.001572

T=8.0 sec.

Yrdot=-0.000912 Nrdot=-0.000544
Yr=0.001810 1/6 Yrrr=0.003134
Nr=-0.002008 1/6 Nrrr=-0.004213

T=12.8 sec.

Yrdot=-0.001146 Nrdot=-0.000529
Yr=0.001605 1/6 Yrrr=0.004413
Nr=-0.002333 1/6 Nrrr=0.012015

T=16.0 sec.

Yrdot=-0.001278 Nrdot=-0.000553
Yr=0.001521 1/6 Yrrr=-0.045812
Nr=-0.002095 1/6 Nrrr=-0.052588

TRIM=1.5 deg. (bow up)

T=8.0 sec.

Yrdot=-0.000107 Nrdot=-0.000464
Yr=0.003684 1/6 Yrrr=0.008901
Nr=-0.001888 1/6 Nrrr=-0.002078

Note: the moments are taken about the midships.

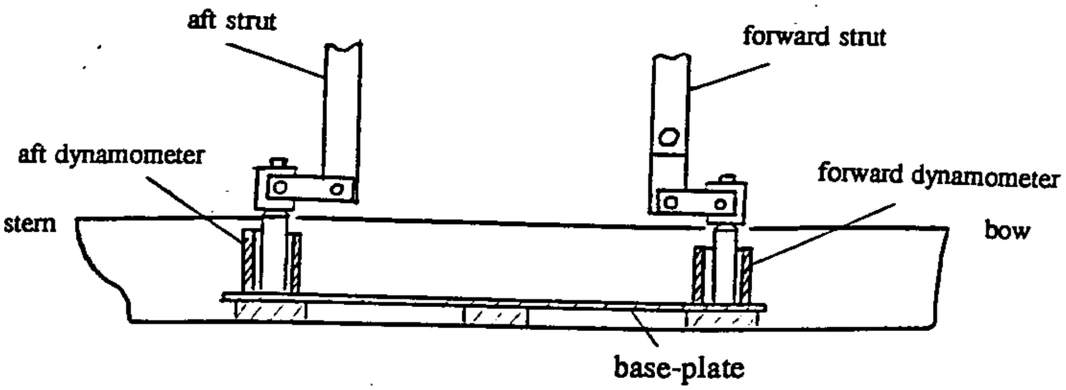


Fig.1 The Model Mounted on the PMM Struts

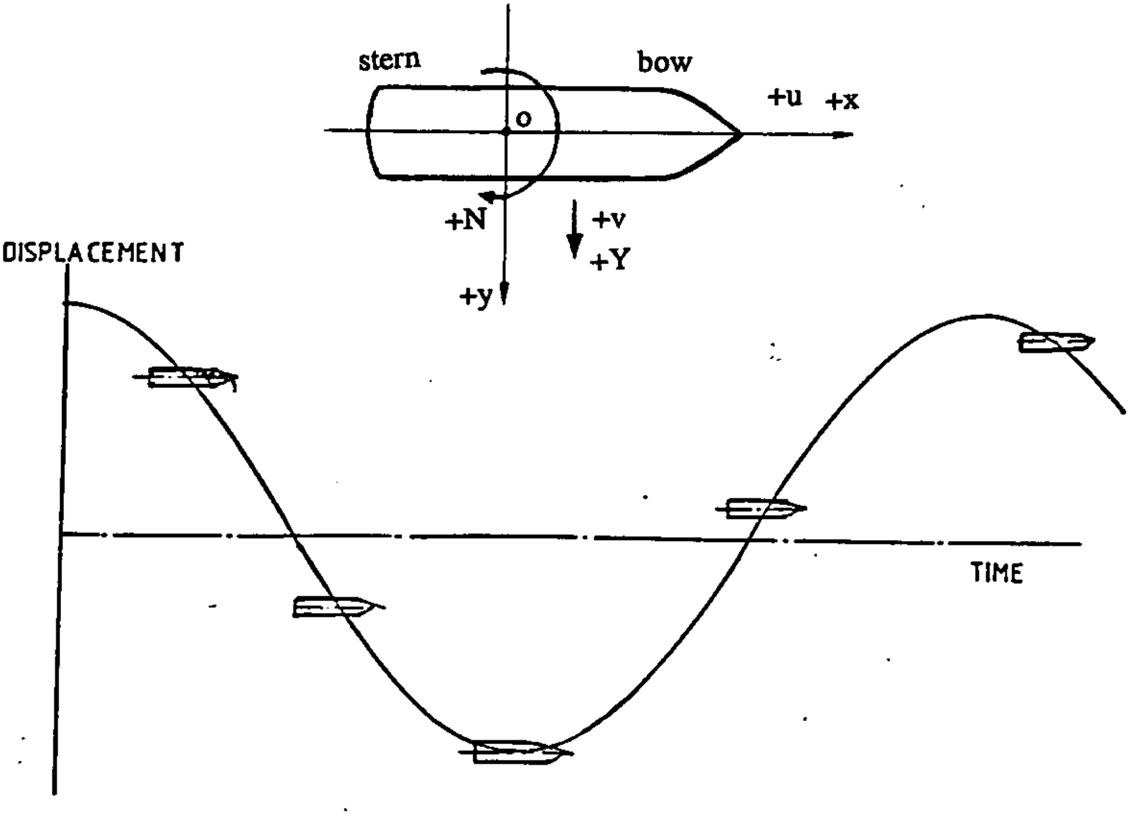


Fig.2a Pure Sway Motion and Sign Convention

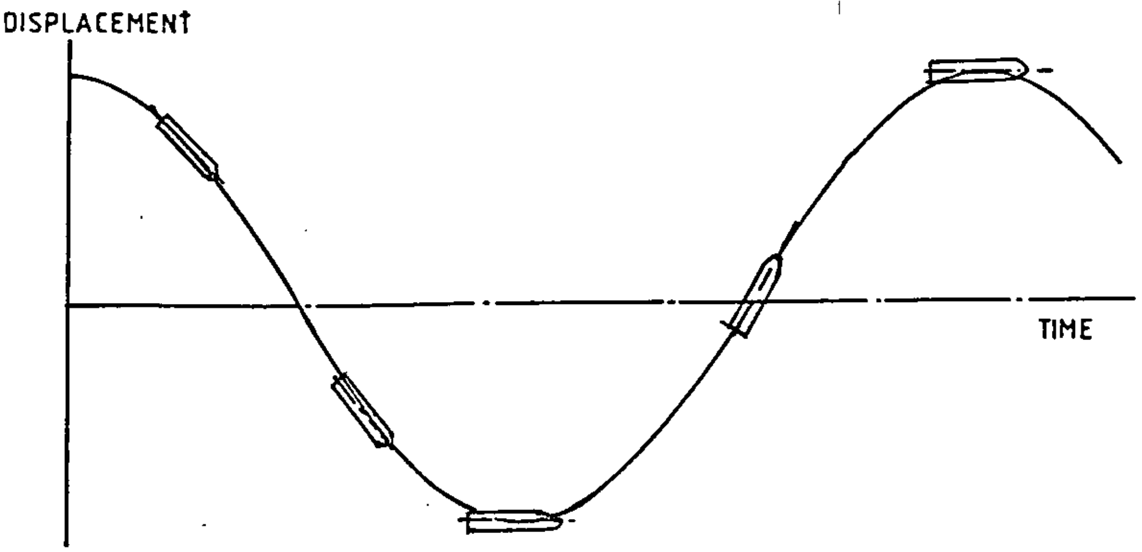


Fig.2b Pure Yaw Motion

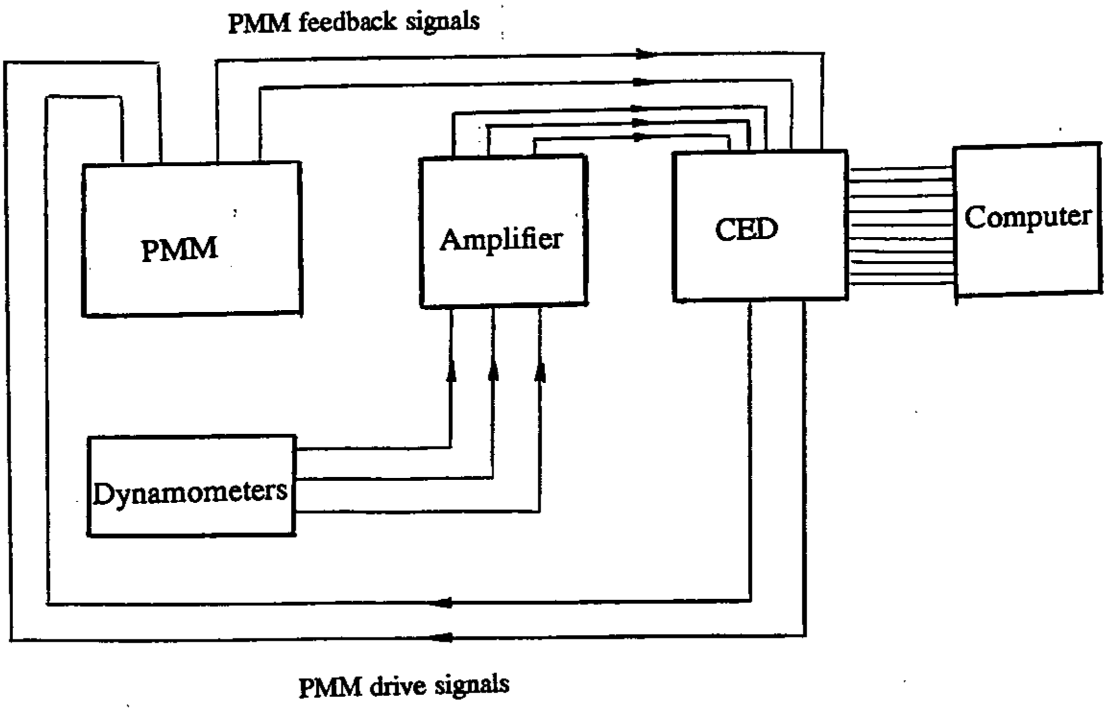


Fig.3 Layout of Control and Data acquisition System

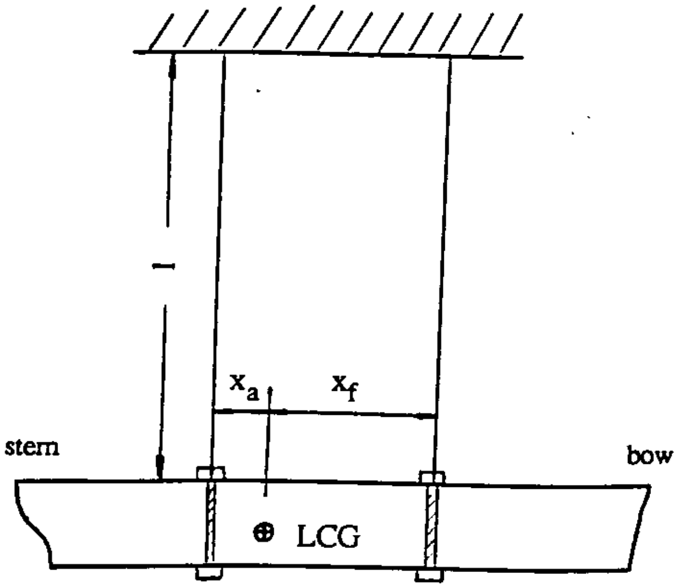


Fig.4 The Set-up for Determining the Moment Of Inertia of the Model

Fig.5 Sway force of Oblique Towing Test with Mariner Model

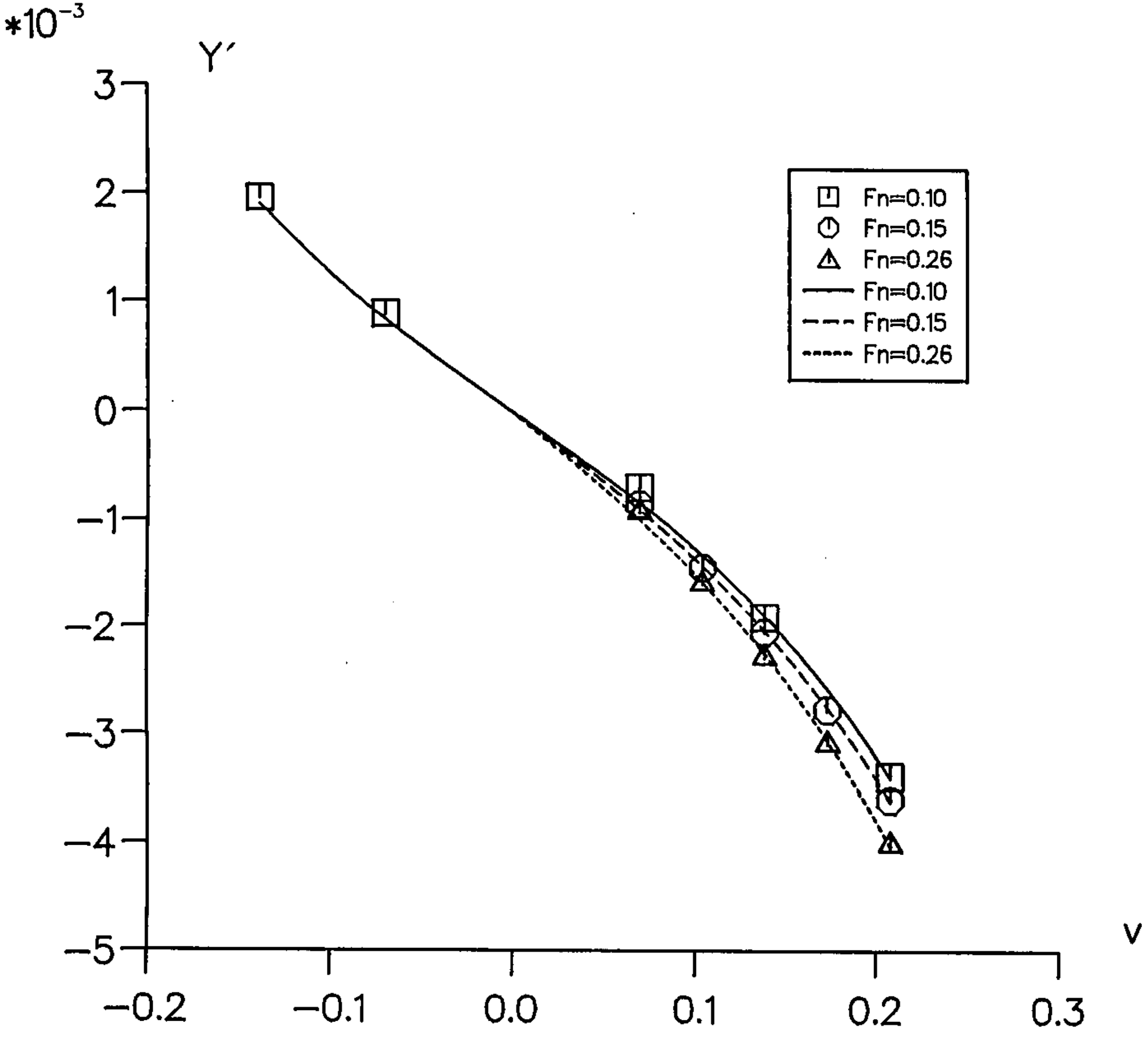
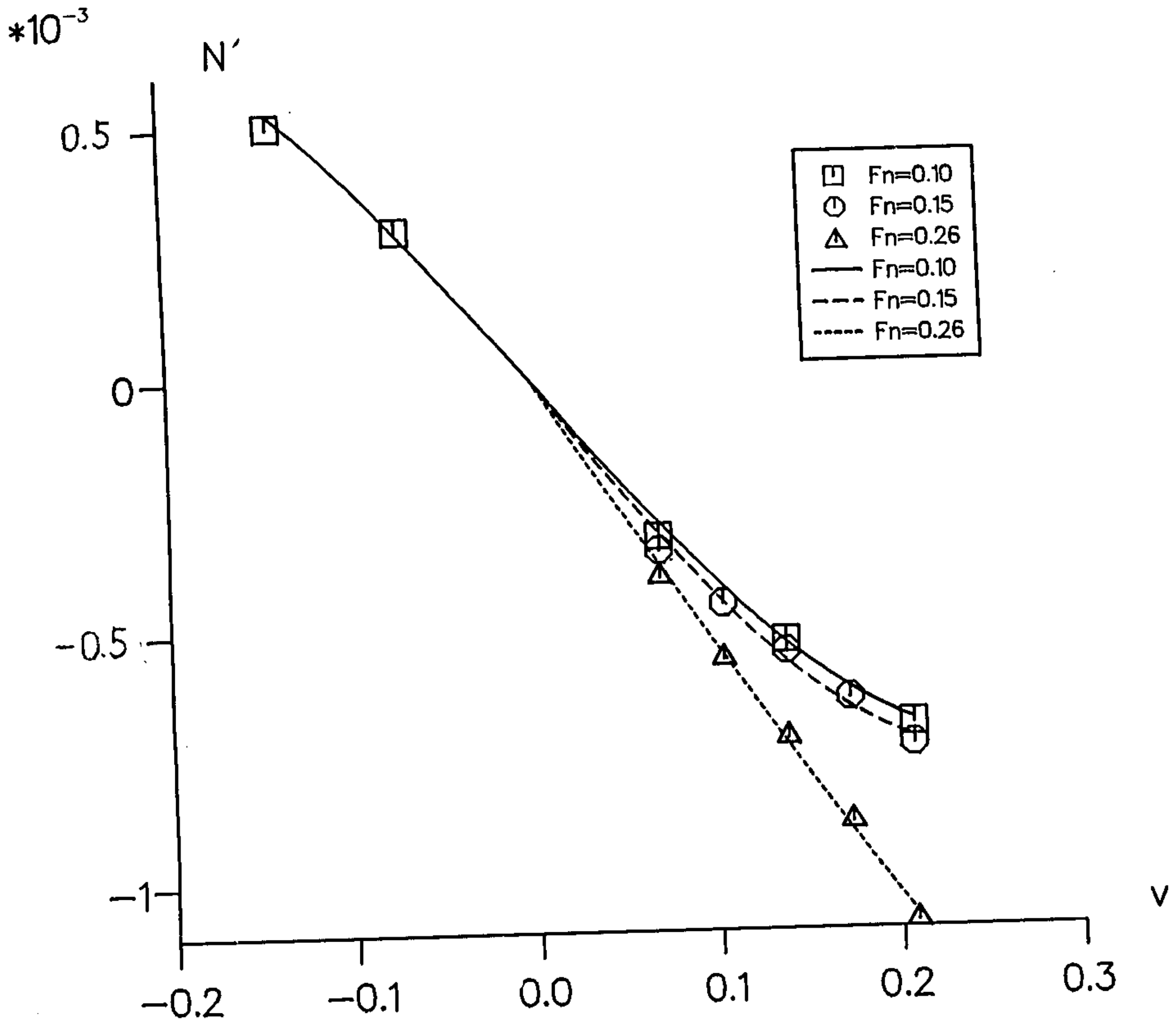


Fig.6 Yaw Moment of Oblique Towing Test with Mariner Model



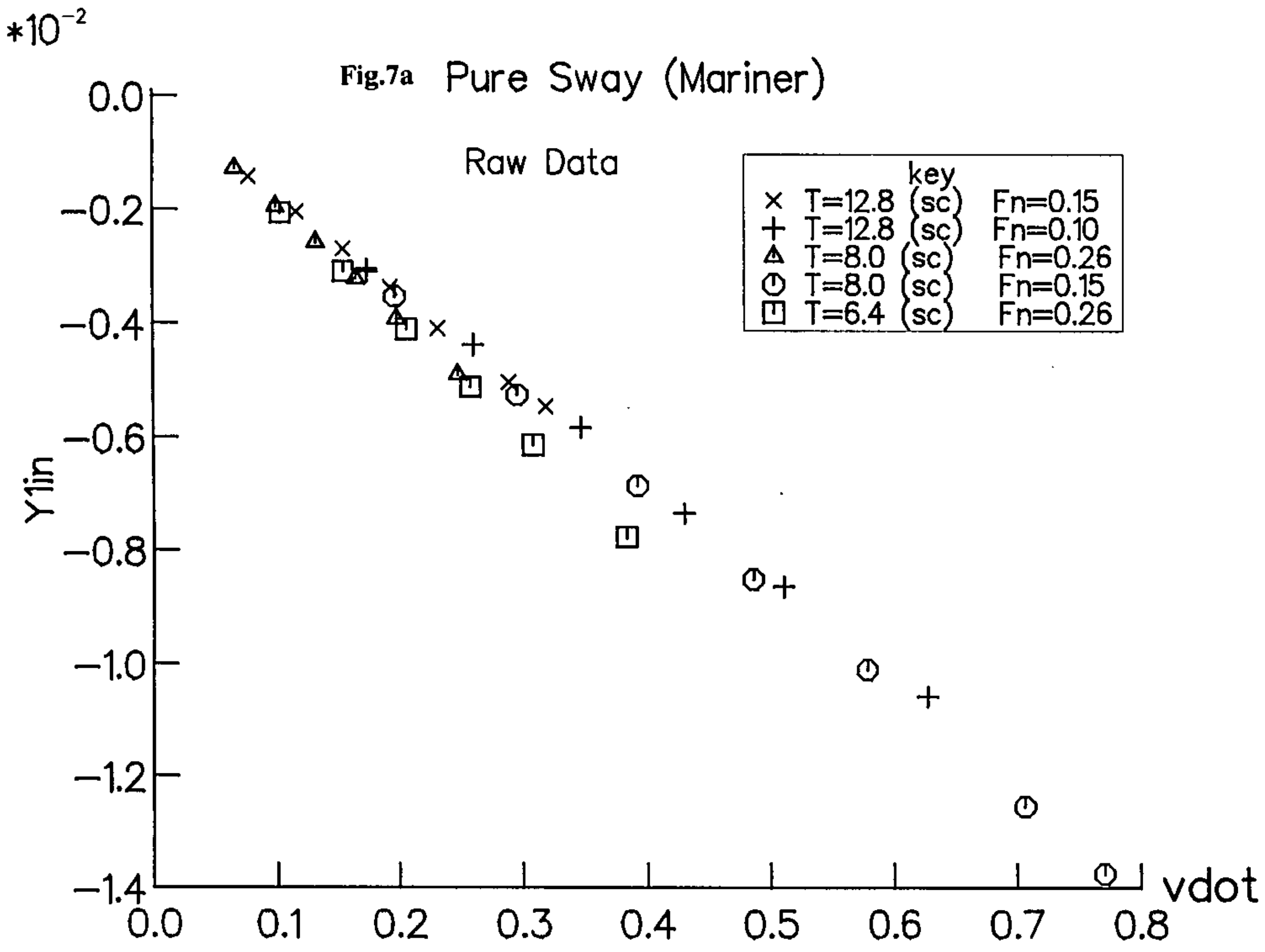
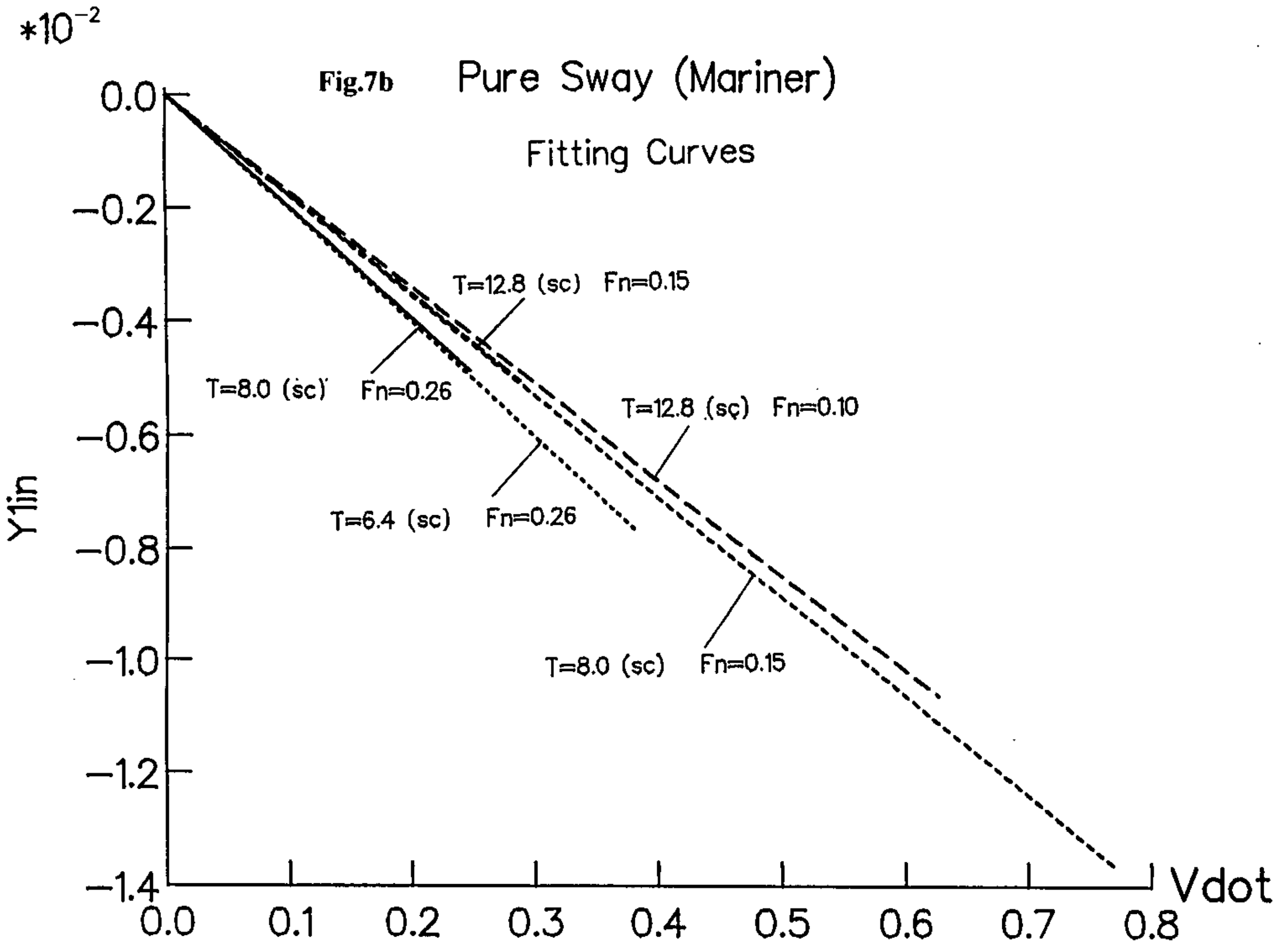


Fig.7a Pure Sway (Mariner)

Fig.7b


Pure Sway (Mariner)
Fitting Curves
*10^-2
Y1in
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
Vdot
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
T=12.8 (sc) Fn=0.15
T=8.0 (sc) Fn=0.26
T=12.8 (sc) Fn=0.10
T=6.4 (sc) Fn=0.26
T=8.0 (sc) Fn=0.15

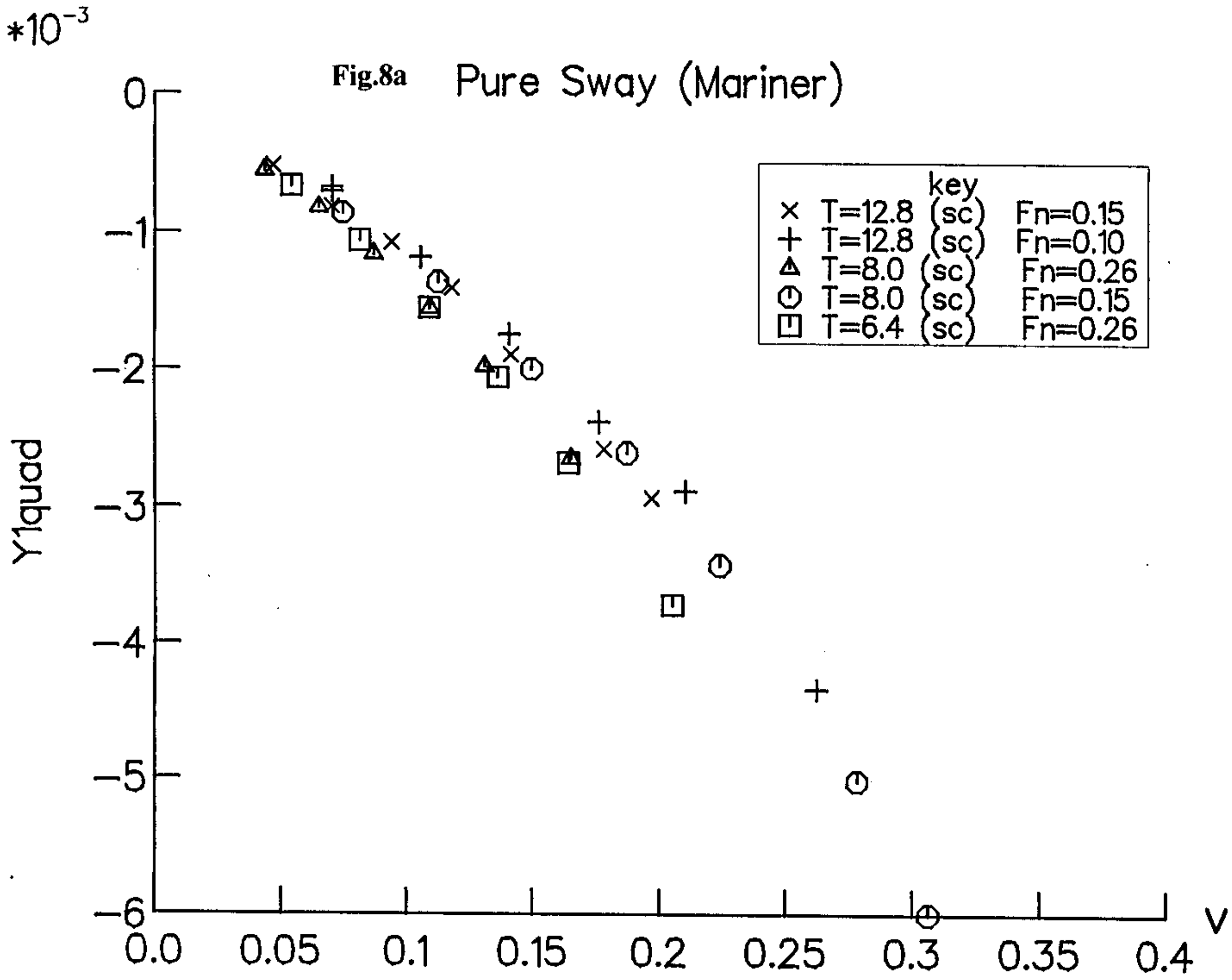


Fig.8a

*10^-3
Pure Sway (Mariner)
Y1quad
0
−1
−2
−3
−4
−5
−6
0.0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
V
key
× T=12.8 (sc) Fn=0.15
+ T=12.8 (sc) Fn=0.10
△ T=8.0 (sc) Fn=0.26
○ T=8.0 (sc) Fn=0.15
□ T=6.4 (sc) Fn=0.26

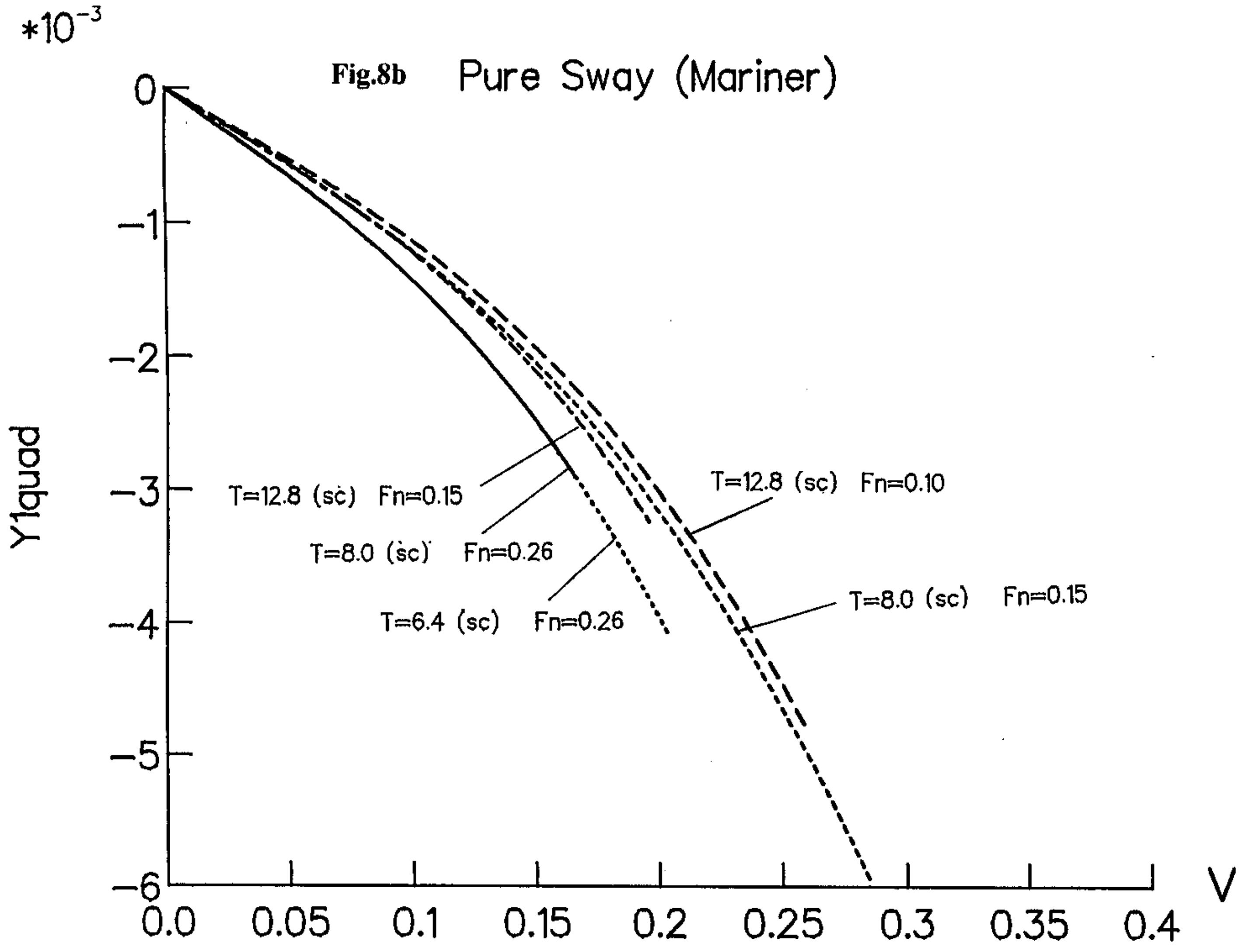
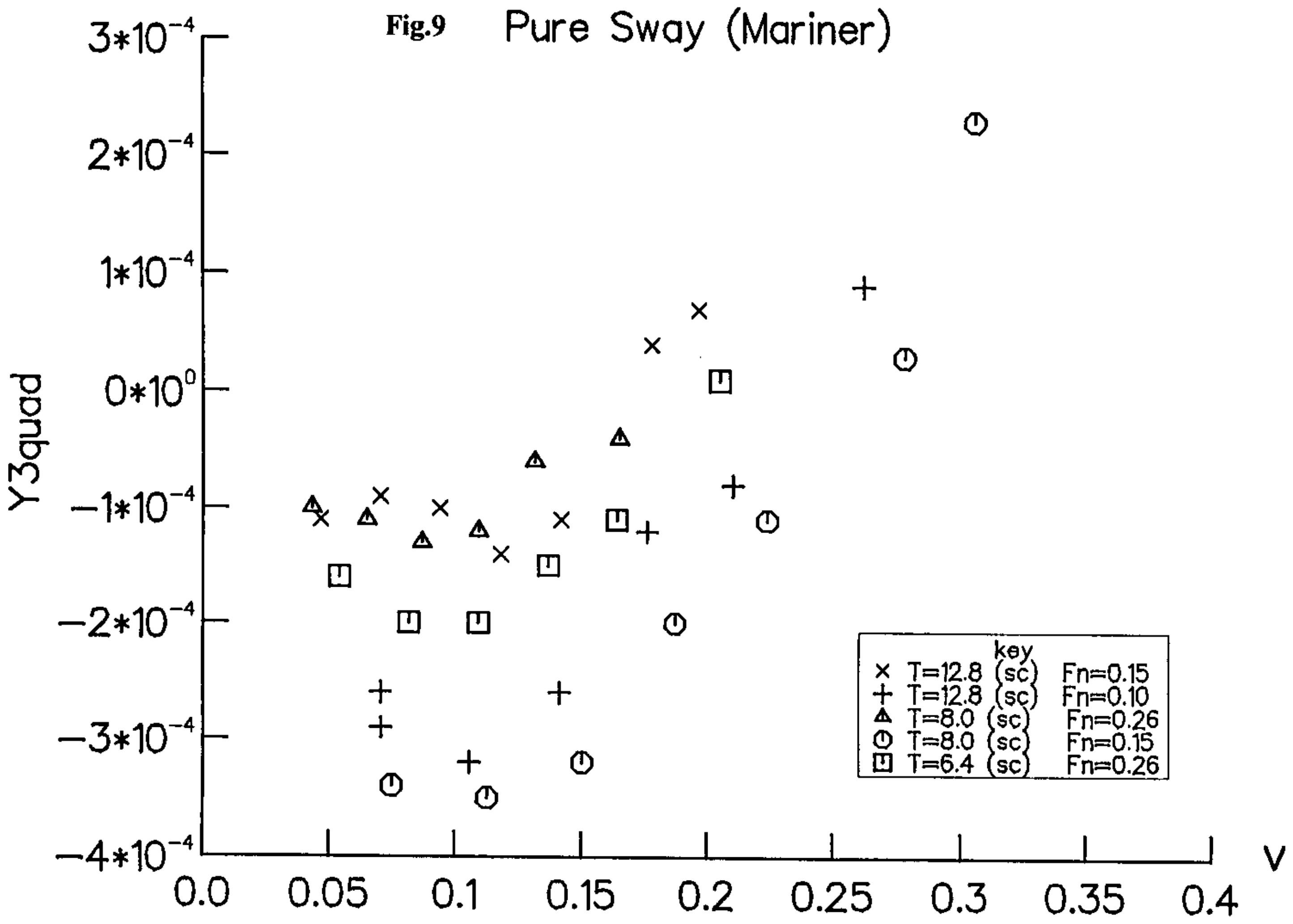


Fig.8b Pure Sway (Mariner)

Fig.9


Pure Sway (Mariner)
Y3quad
3*10^-4
2*10^-4
1*10^-4
0*10^0
−1*10^-4
−2*10^-4
−3*10^-4
−4*10^-4
0.0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
V
key
× T=12.8 (sc) Fn=0.15
+ T=12.8 (sc) Fn=0.10
Δ T=8.0 (sc) Fn=0.26
Θ T=8.0 (sc) Fn=0.15
⊡ T=6.4 (sc) Fn=0.26

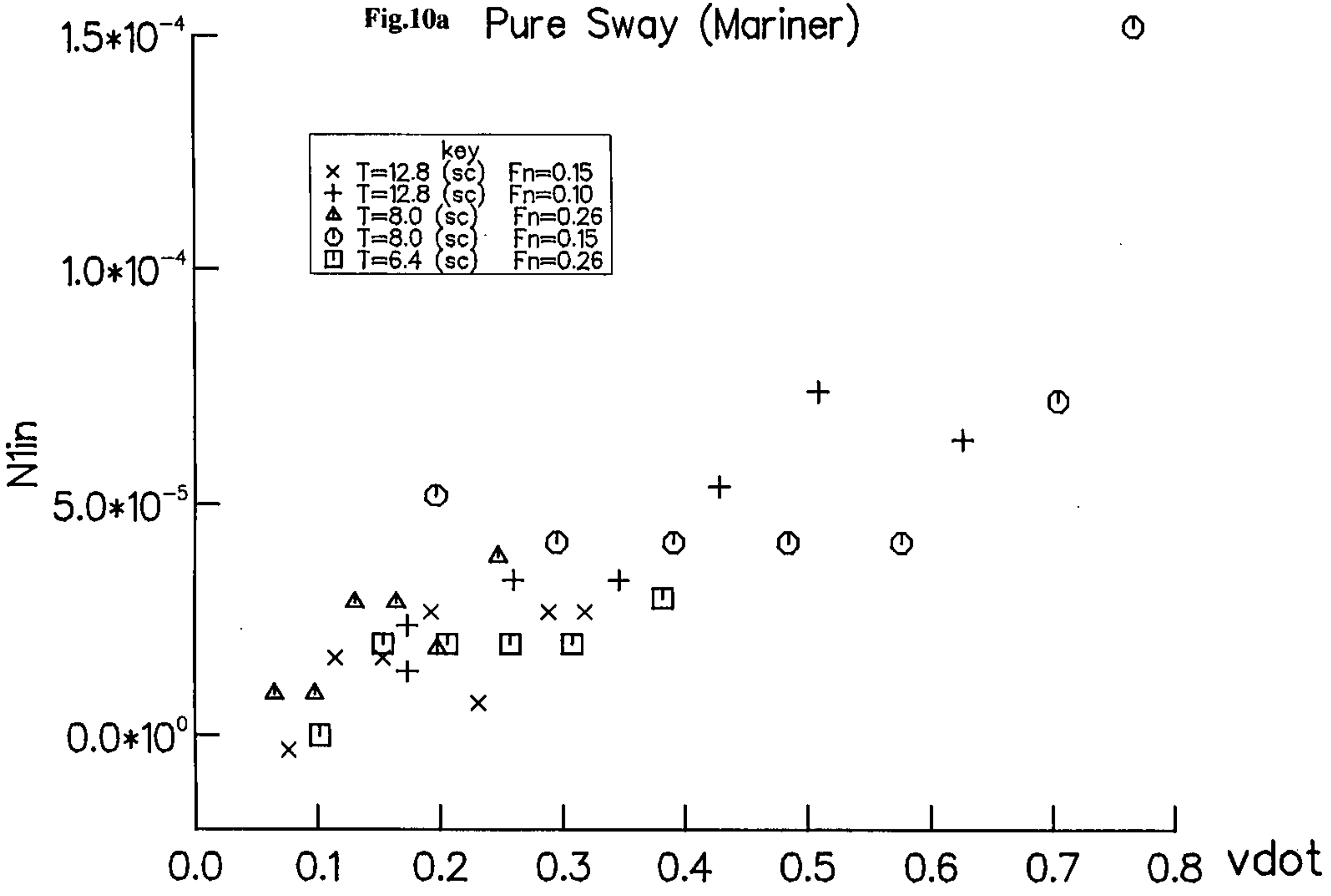


Fig.10a Pure Sway (Mariner)

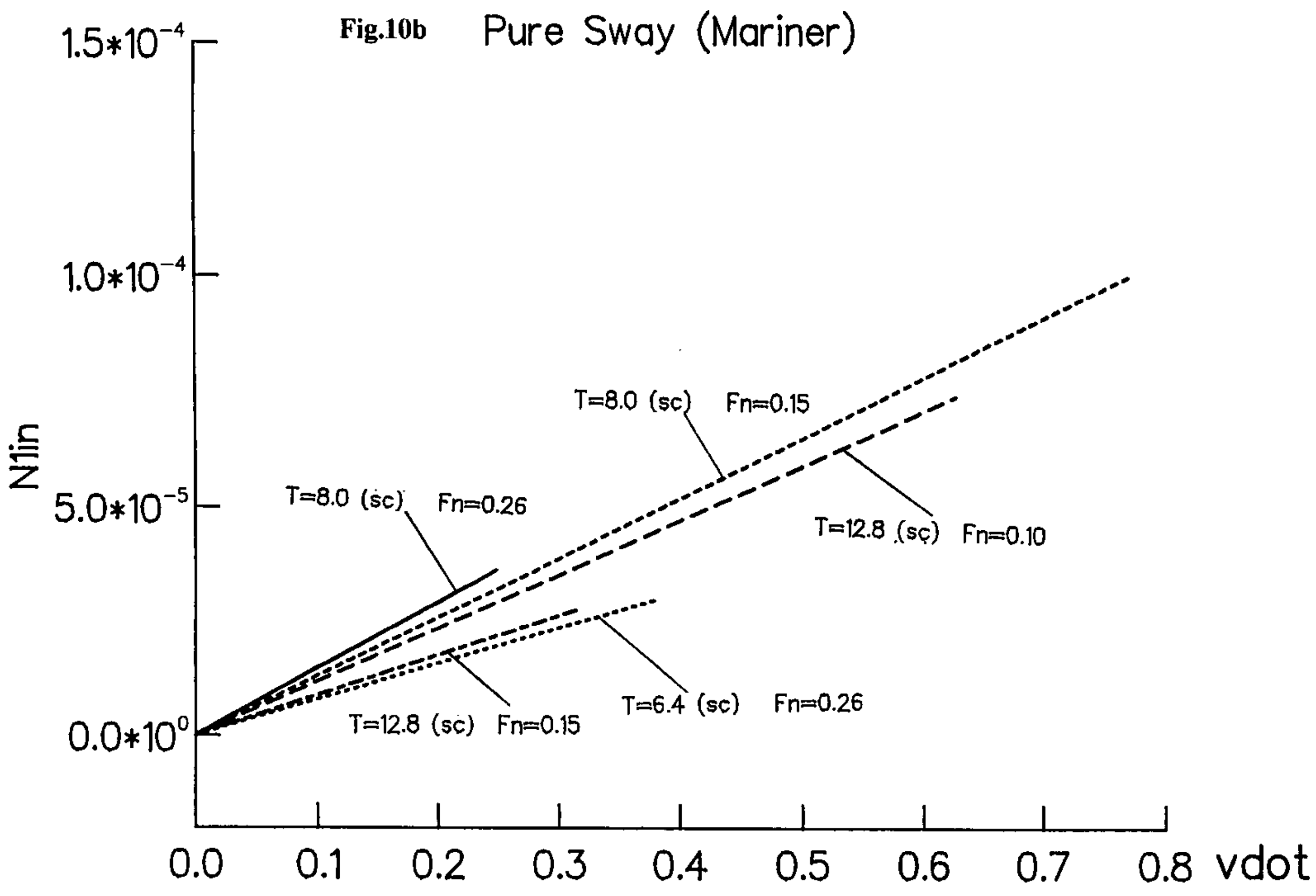


Fig.10b Pure Sway (Mariner)

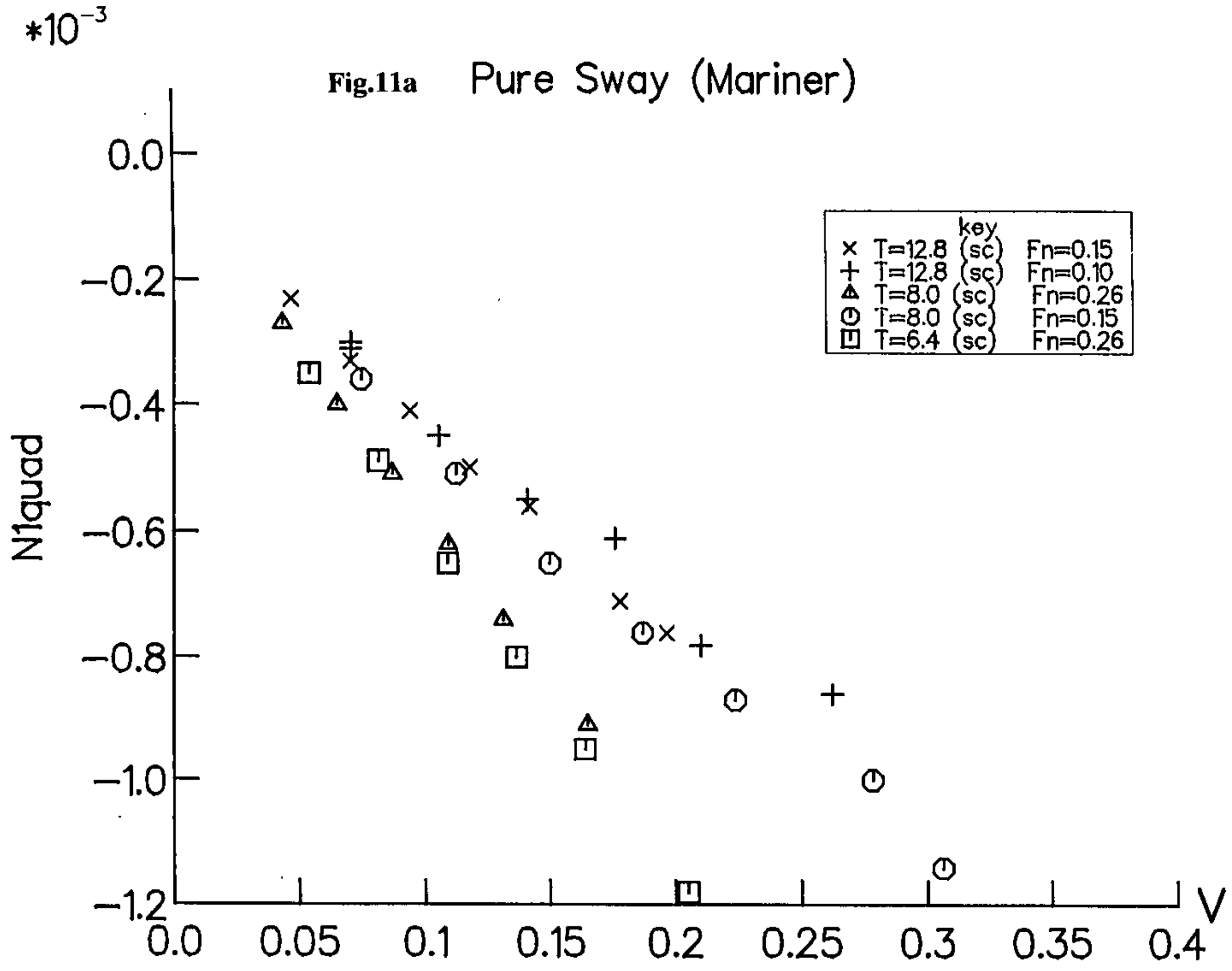


Fig.11a Pure Sway (Mariner)

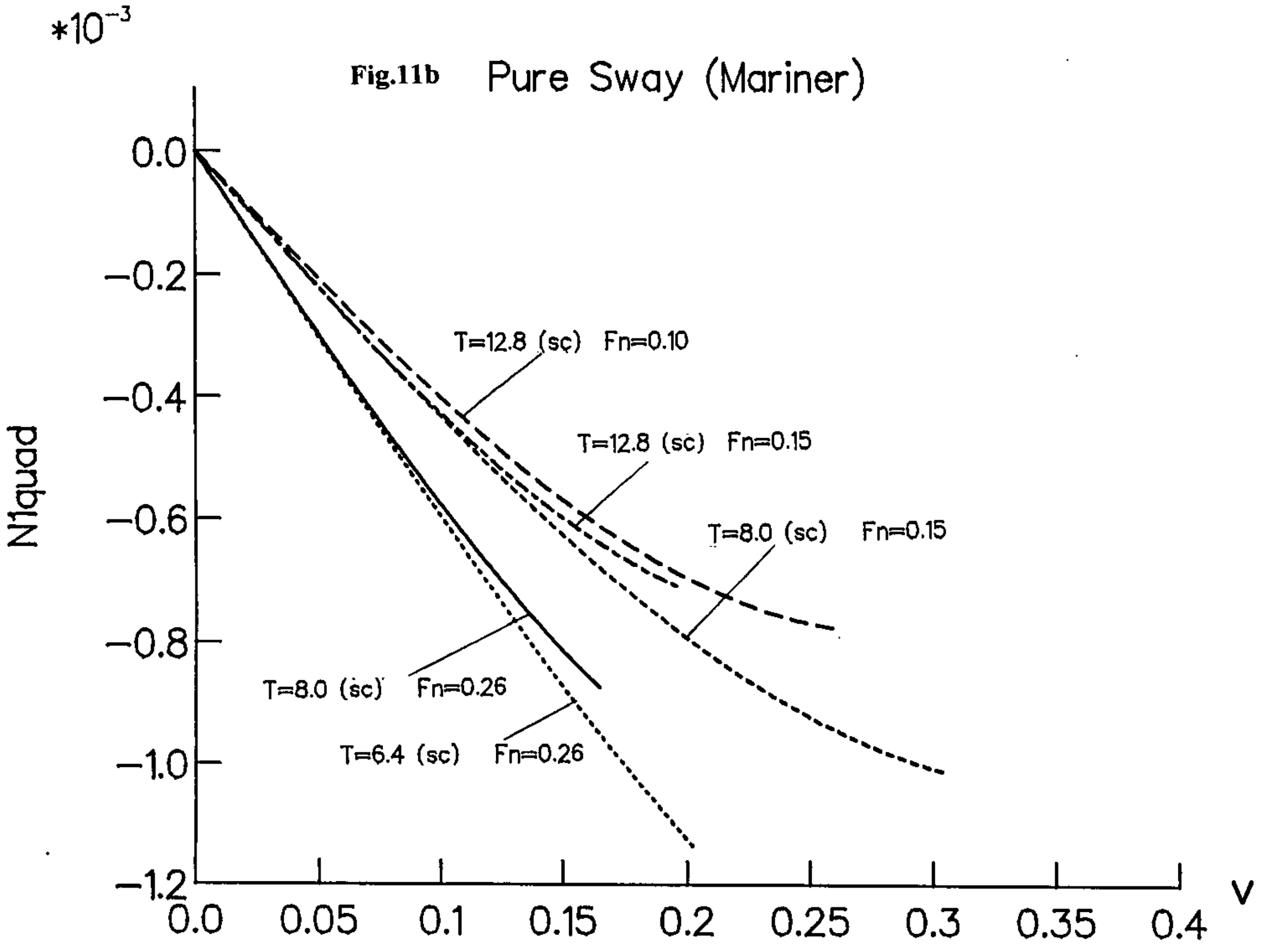


Fig.11b Pure Sway (Mariner)

Fig.12 Pure Sway (Mariner)

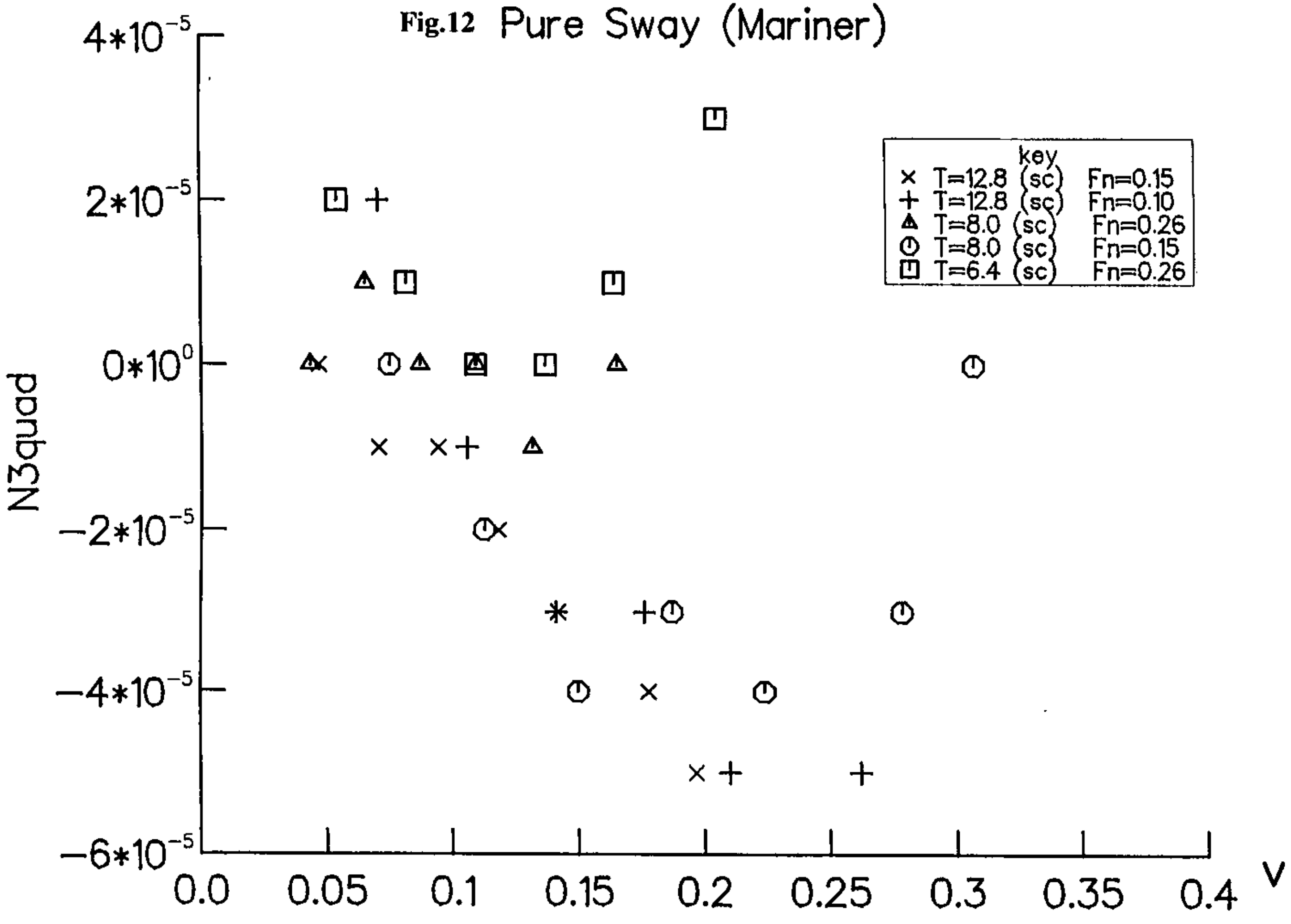


Fig.13a

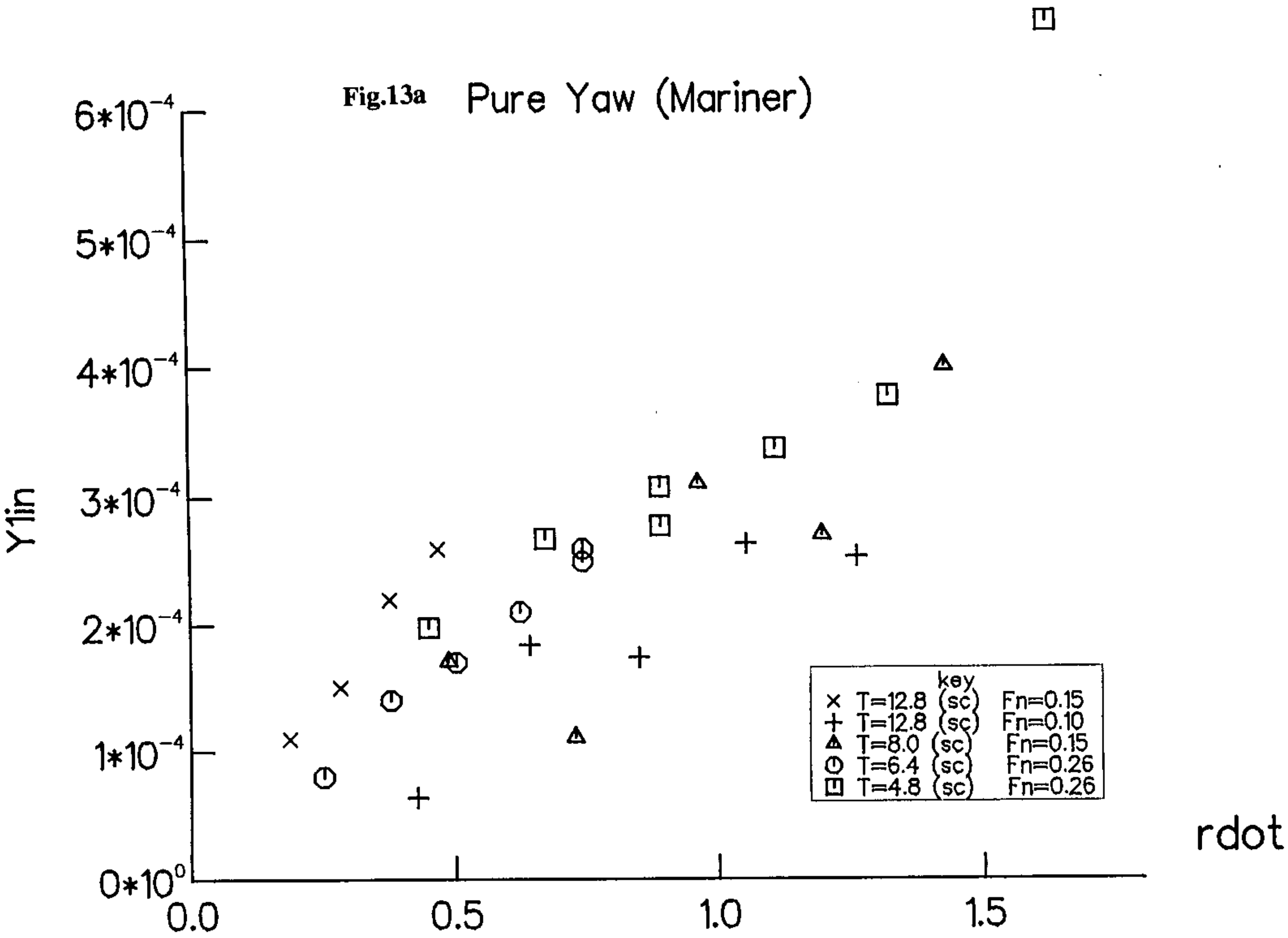
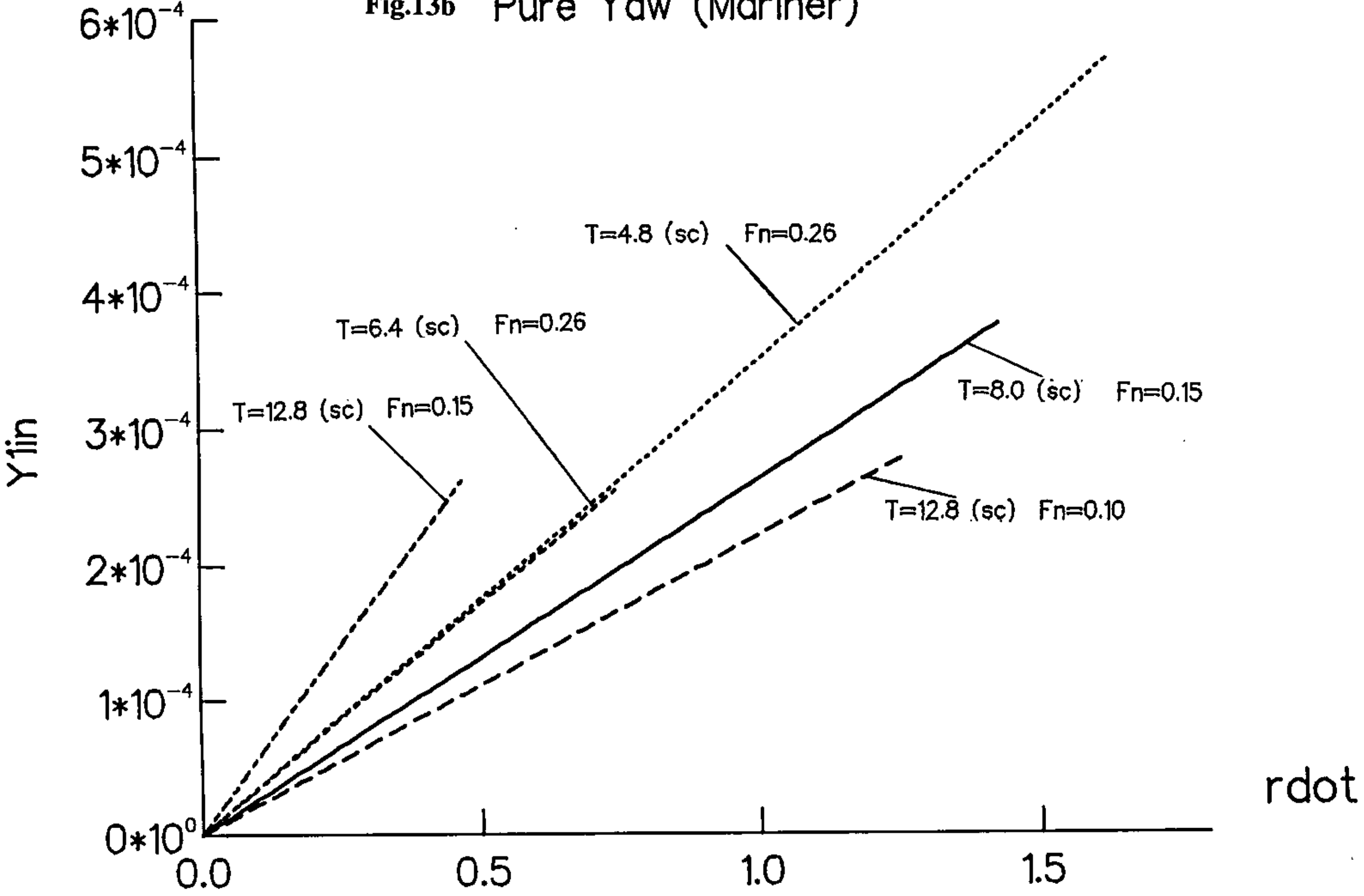

Pure Yaw (Mariner)
Y1in
6*10^-4
5*10^-4
4*10^-4
3*10^-4
2*10^-4
1*10^-4
0*10^0
0.0
0.5
1.0
1.5
rdot
key
× T=12.8 (sc) Fn=0.15
+ T=12.8 (sc) Fn=0.10
▲ T=8.0 (sc) Fn=0.15
⊖ T=6.4 (sc) Fn=0.26
⊟ T=4.8 (sc) Fn=0.26

Fig.13b Pure Yaw (Mariner)



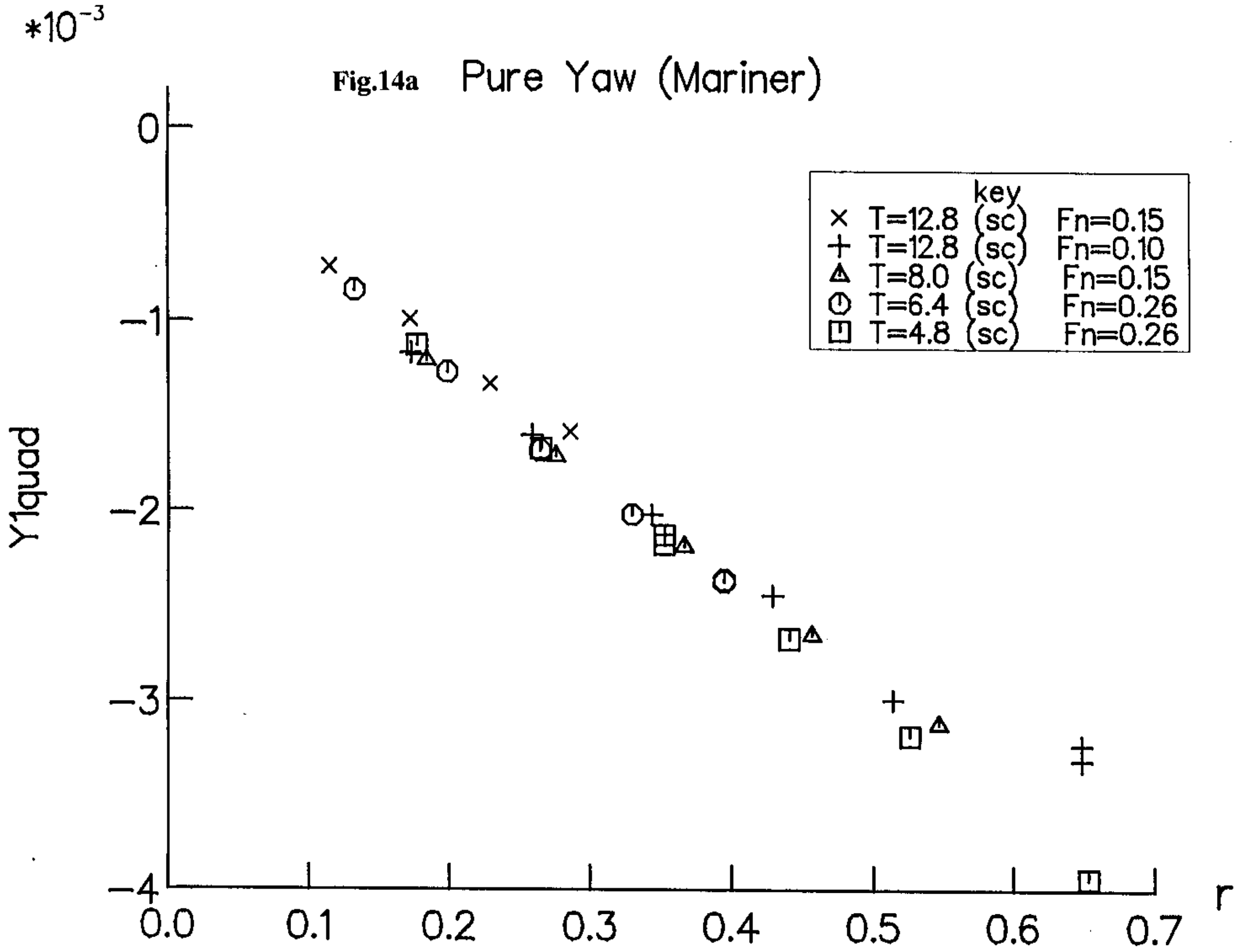

Pure Yaw (Mariner)
*10^-3
Y1quad
0
−1
−2
−3
−4
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
r
key
× T=12.8 (sc) Fn=0.15
+ T=12.8 (sc) Fn=0.10
△ T=8.0 (sc) Fn=0.15
○ T=6.4 (sc) Fn=0.26
□ T=4.8 (sc) Fn=0.26

Fig.14a

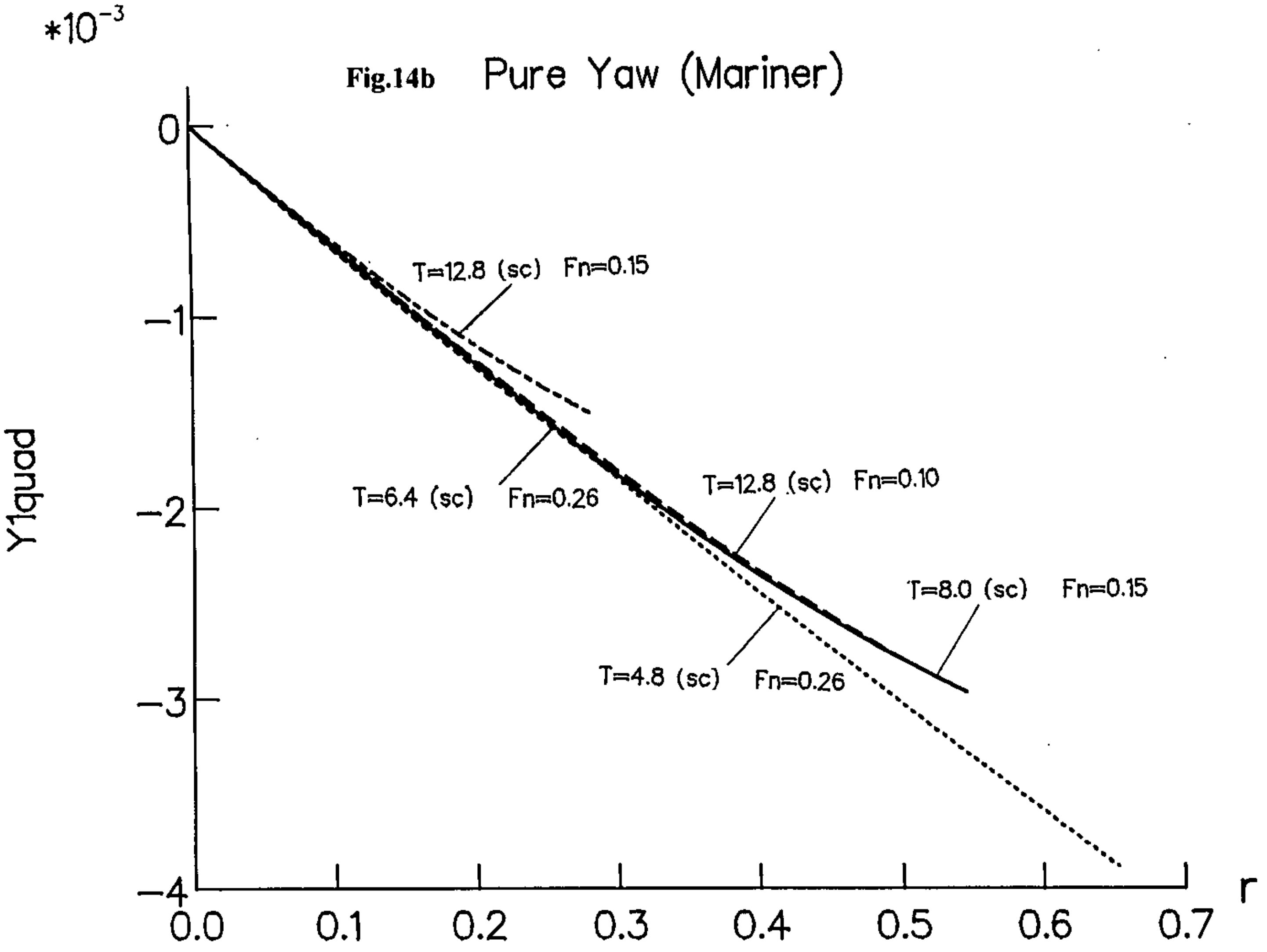
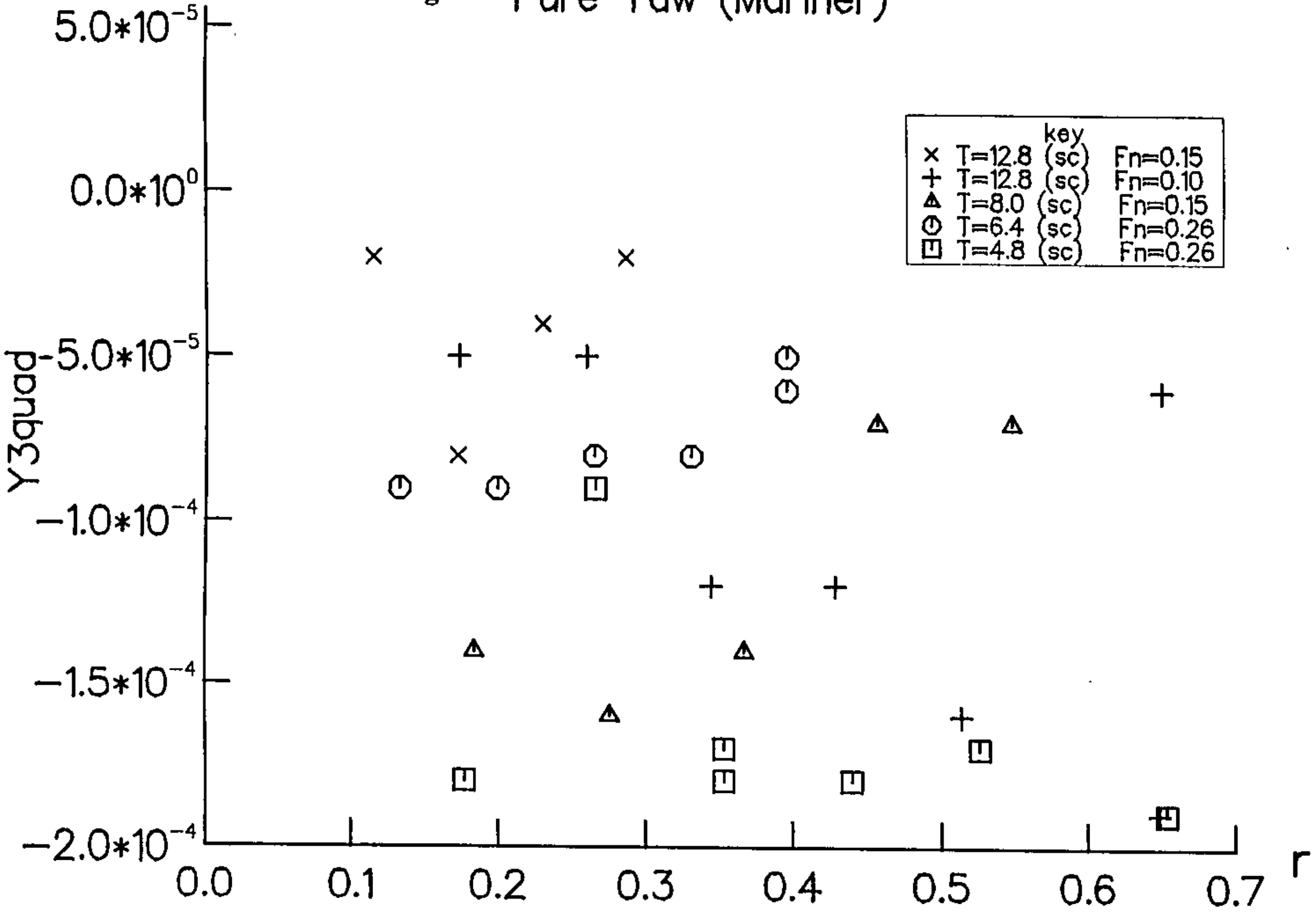


Fig.14b Pure Yaw (Mariner)

Fig.15 Pure Yaw (Mariner)



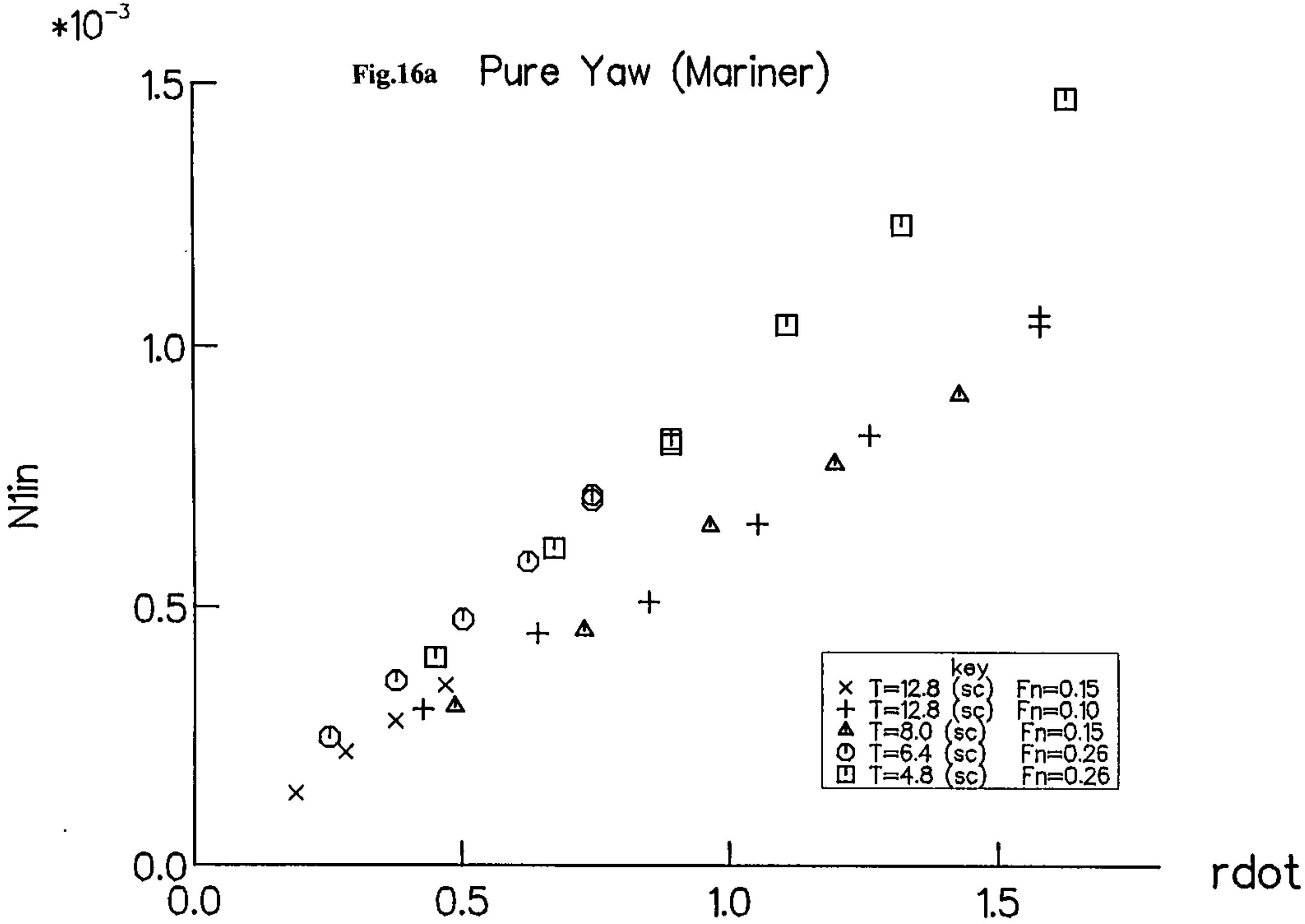


Fig.16a Pure Yaw (Mariner)

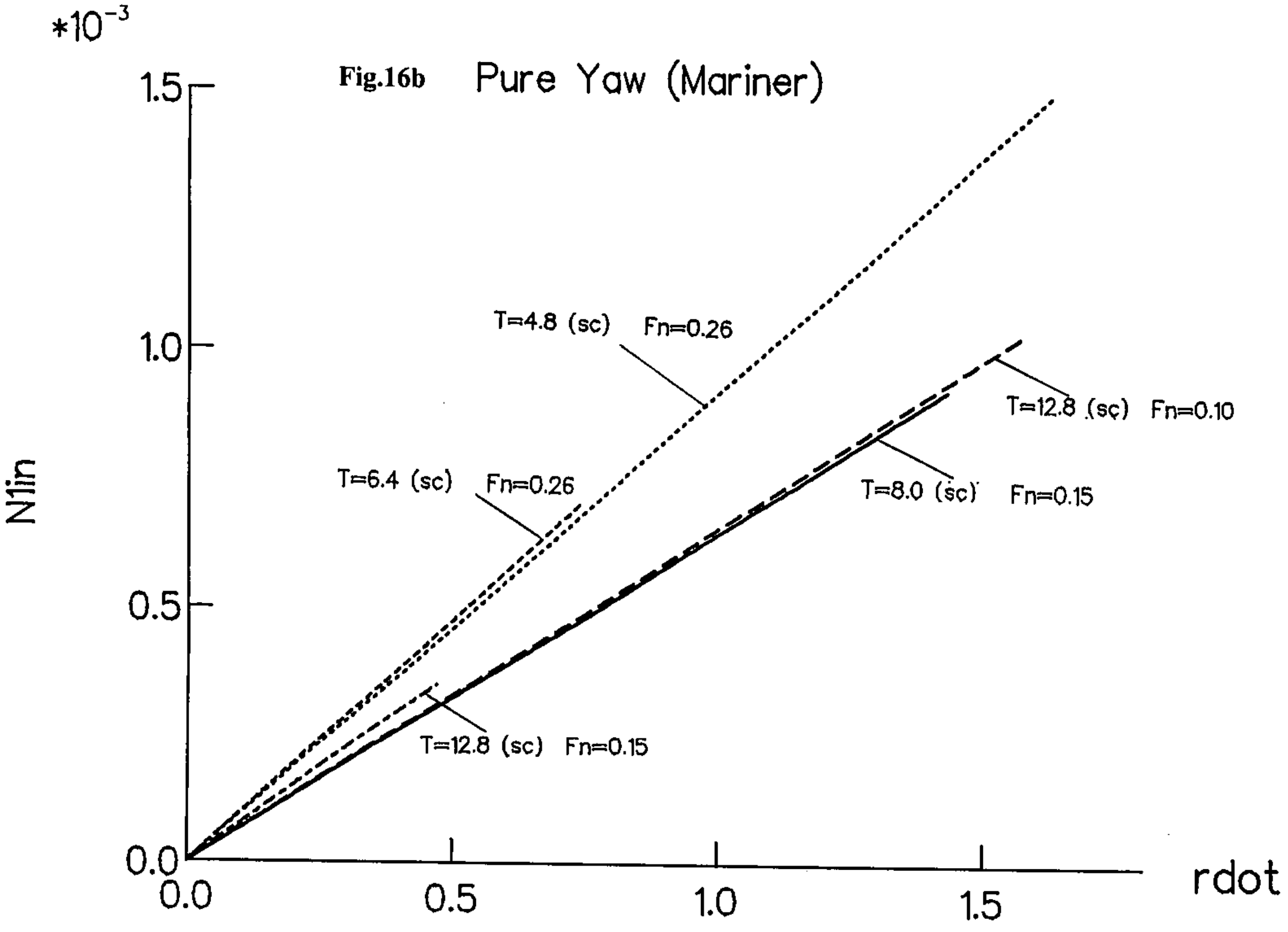


Fig.16b Pure Yaw (Mariner)

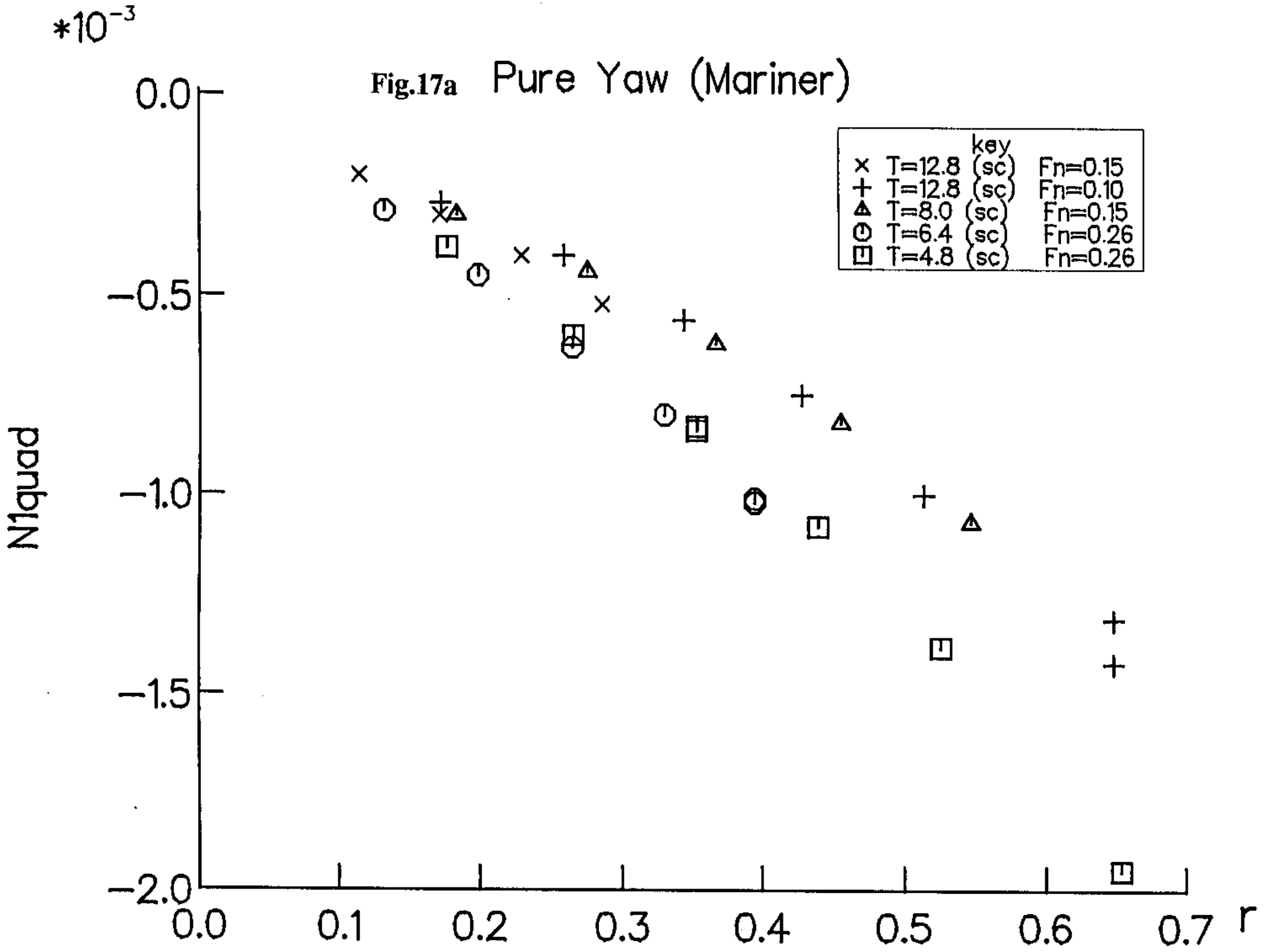


Fig.17a

Pure Yaw (Mariner)
*10^-3
N1quad
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
r
key
× T=12.8 (sc) Fn=0.15
+ T=12.8 (sc) Fn=0.10
△ T=8.0 (sc) Fn=0.15
⊖ T=6.4 (sc) Fn=0.26
⊟ T=4.8 (sc) Fn=0.26

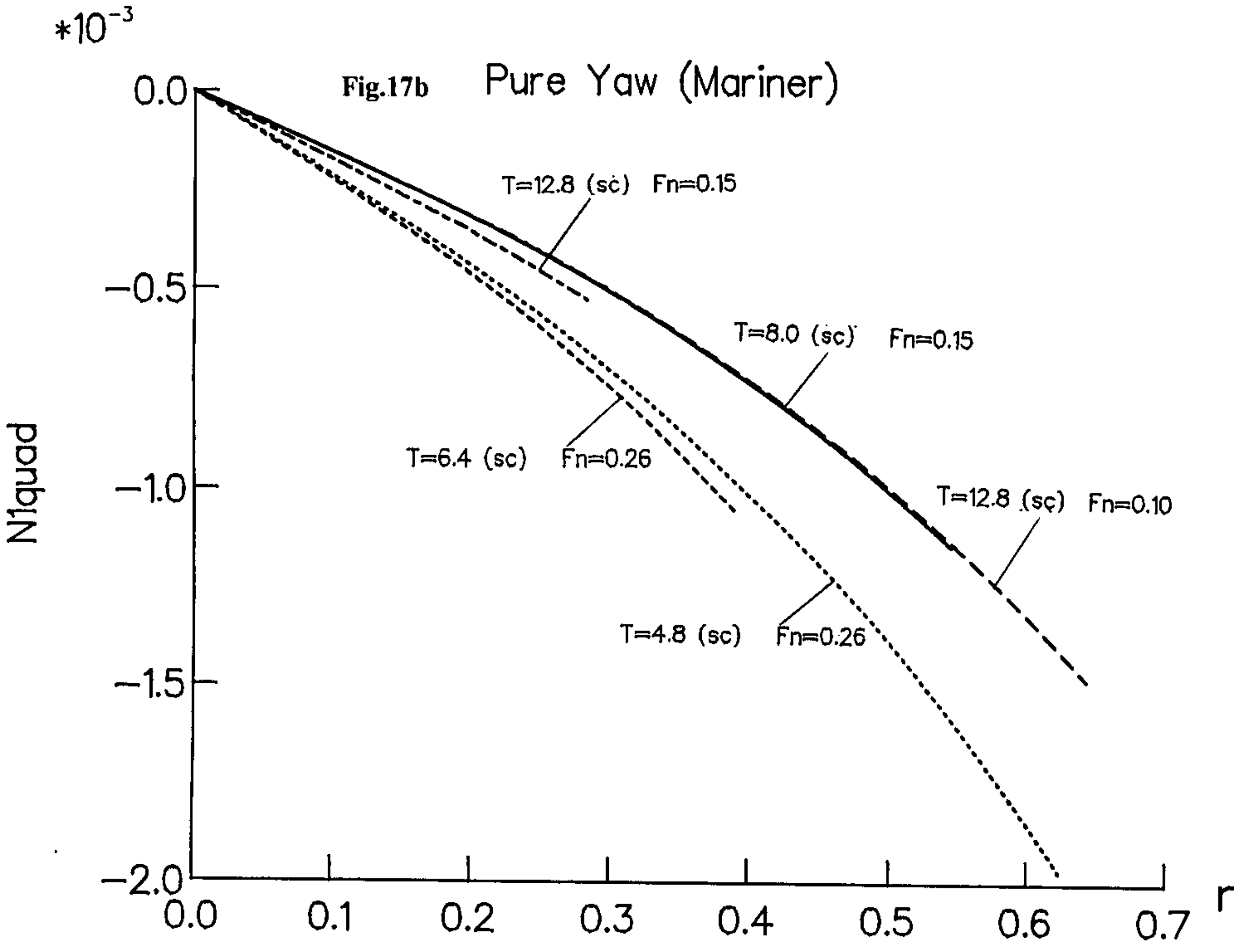


Fig.17b Pure Yaw (Mariner)

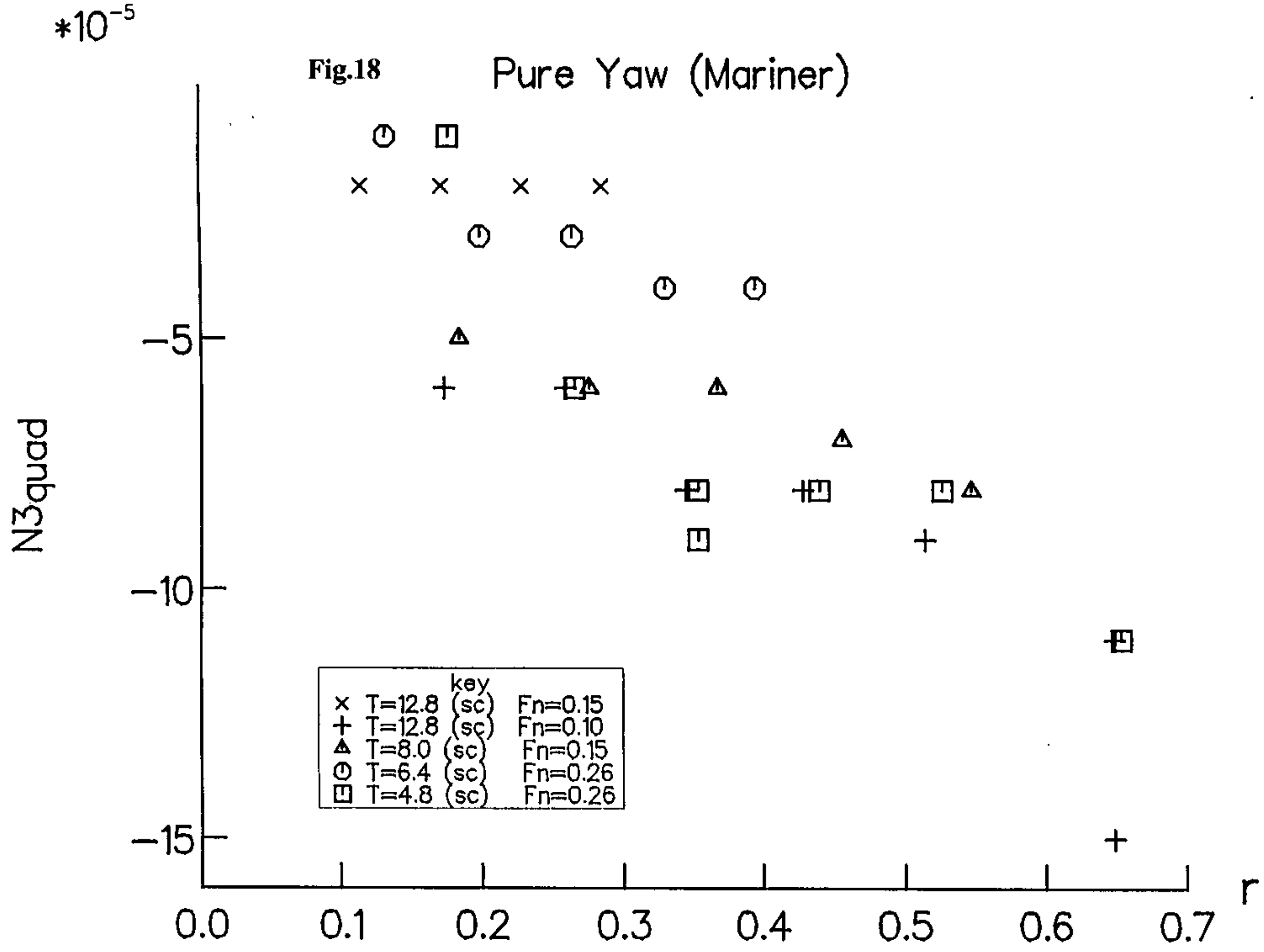
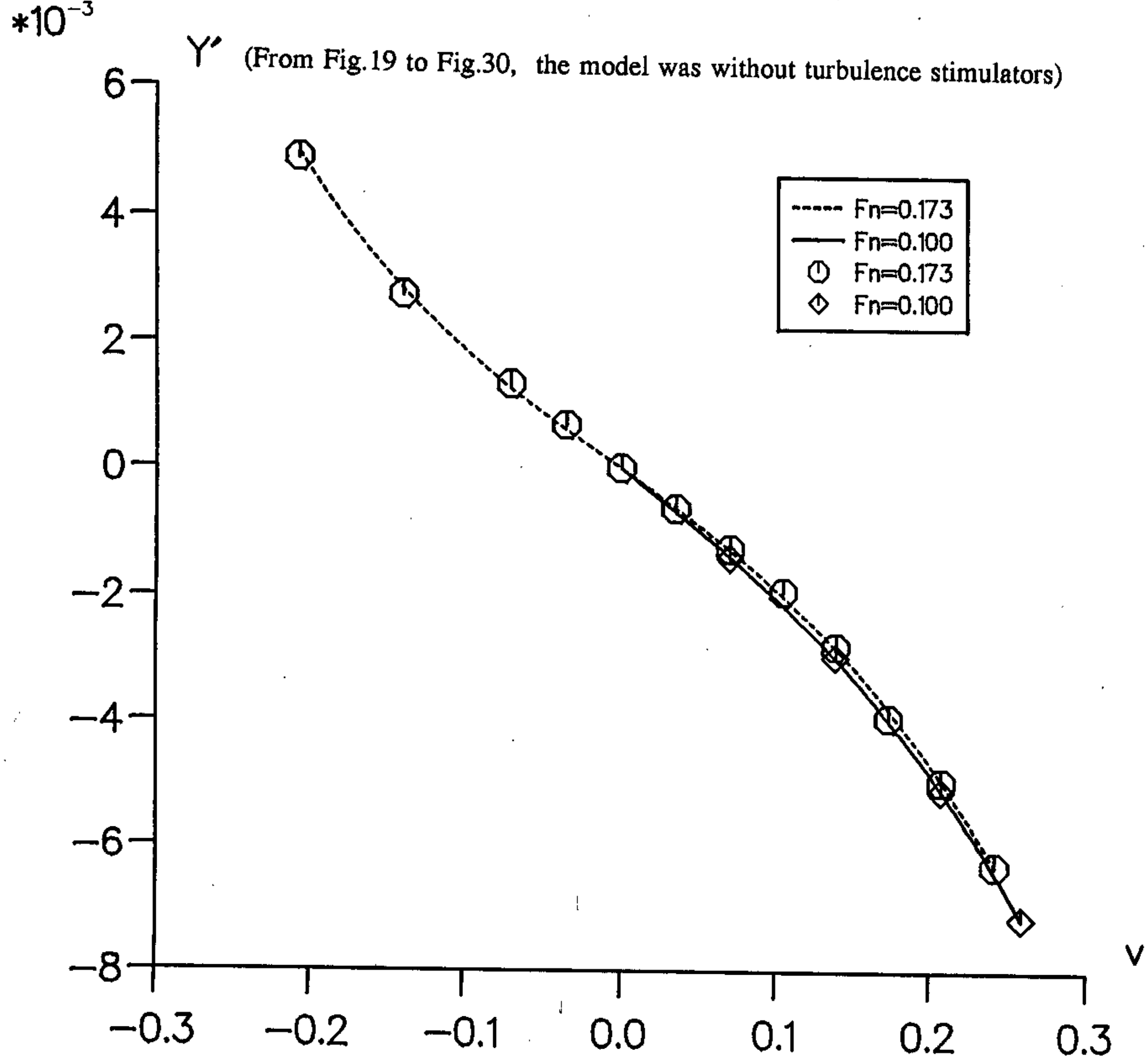


Fig.18

*10^-5
Pure Yaw (Mariner)
N3quad
−5
−10
−15
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
r
key
× T=12.8 (sc) Fn=0.15
+ T=12.8 (sc) Fn=0.10
△ T=8.0 (sc) Fn=0.15
⊖ T=6.4 (sc) Fn=0.26
⊟ T=4.8 (sc) Fn=0.26

Fig.19 Static (British Bombardier)



(From Fig.19 to Fig.30, the model was without turbulence stimulators)

Fig.20 Static (British Bombardier)

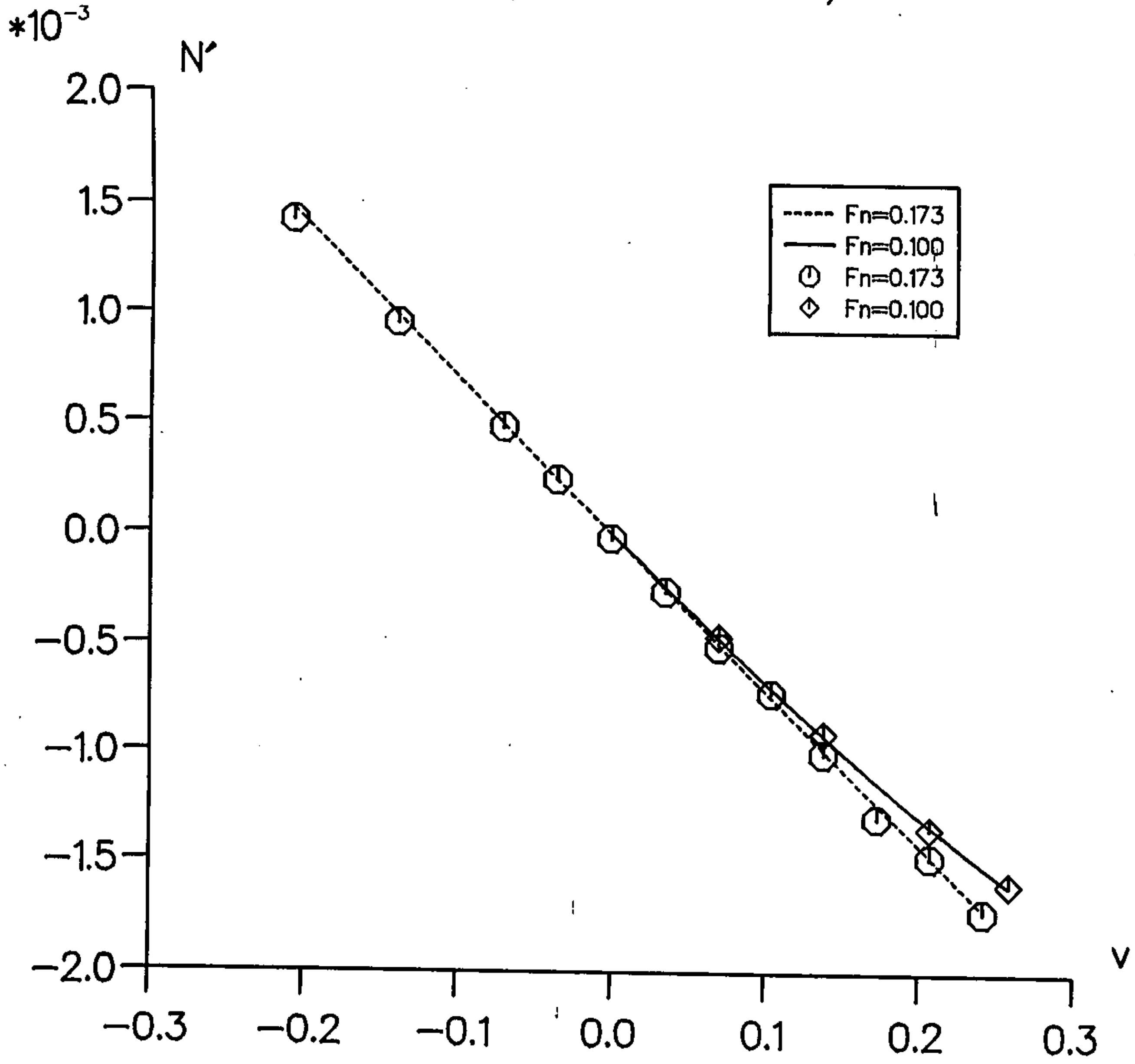


Fig.21 Oblique Towing Tests with British Bombardier

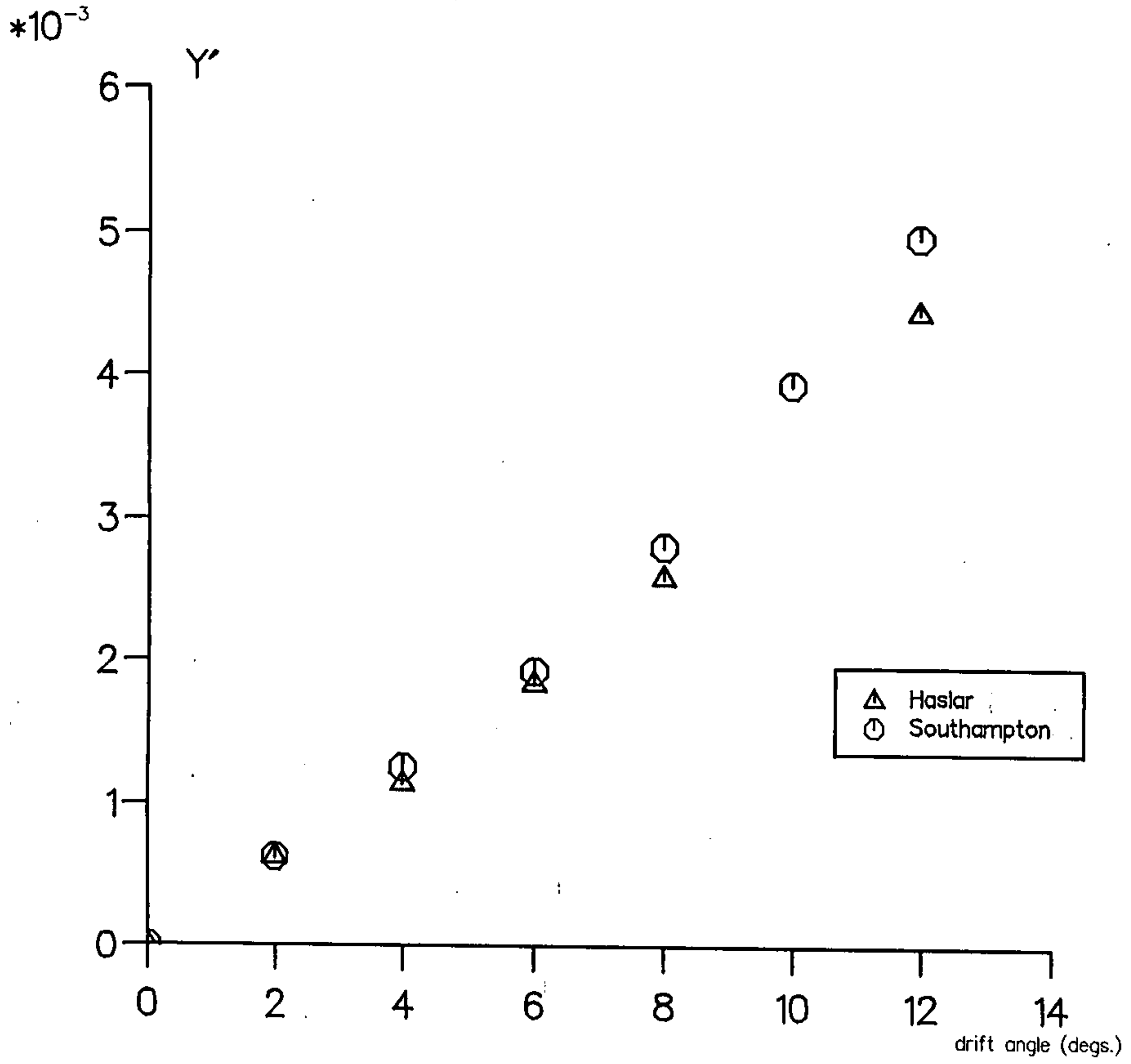


Fig.22 Oblique Towing Tests with British Bombardier

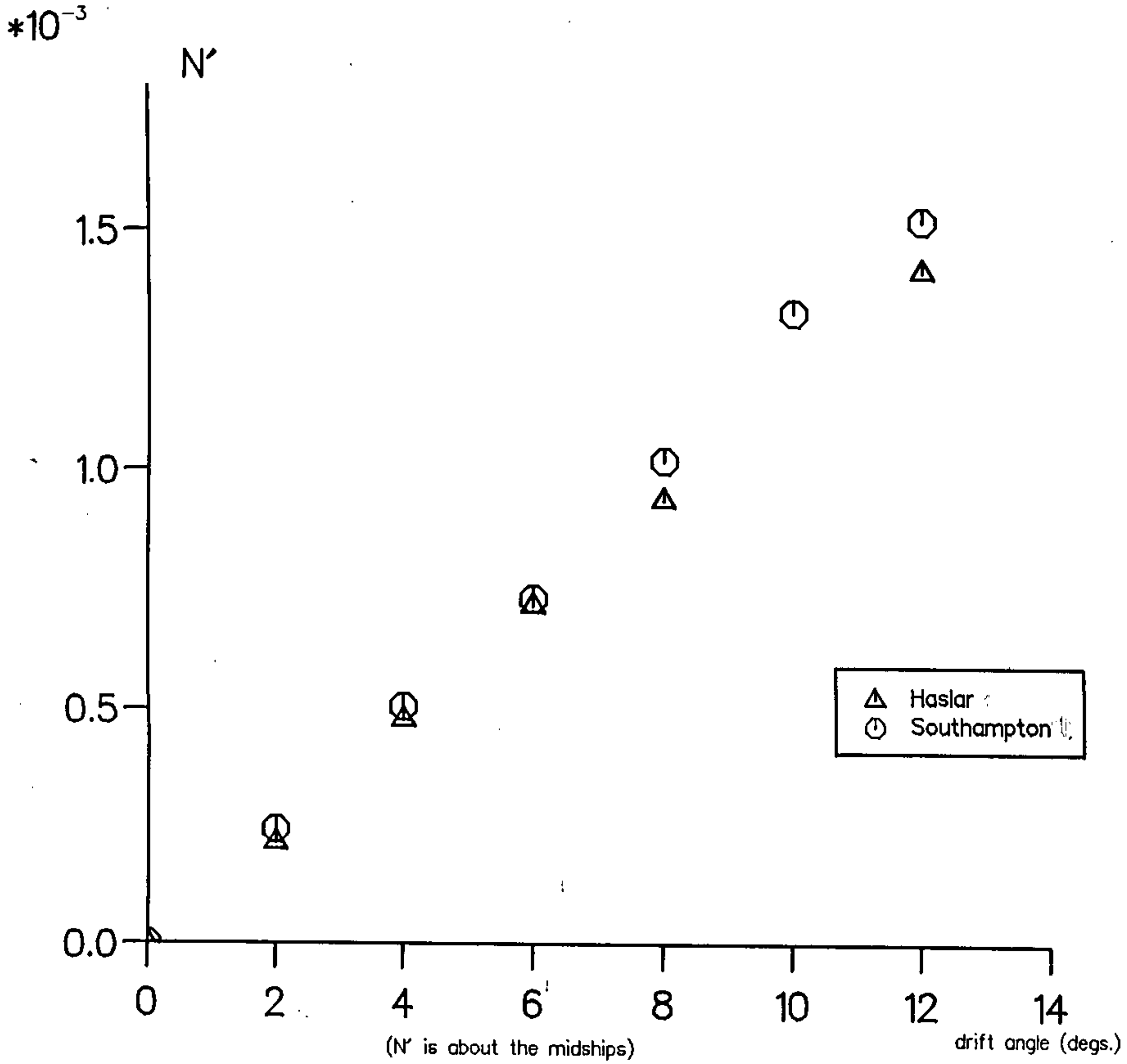


Fig.23 Pure Sway (British Bombardier)

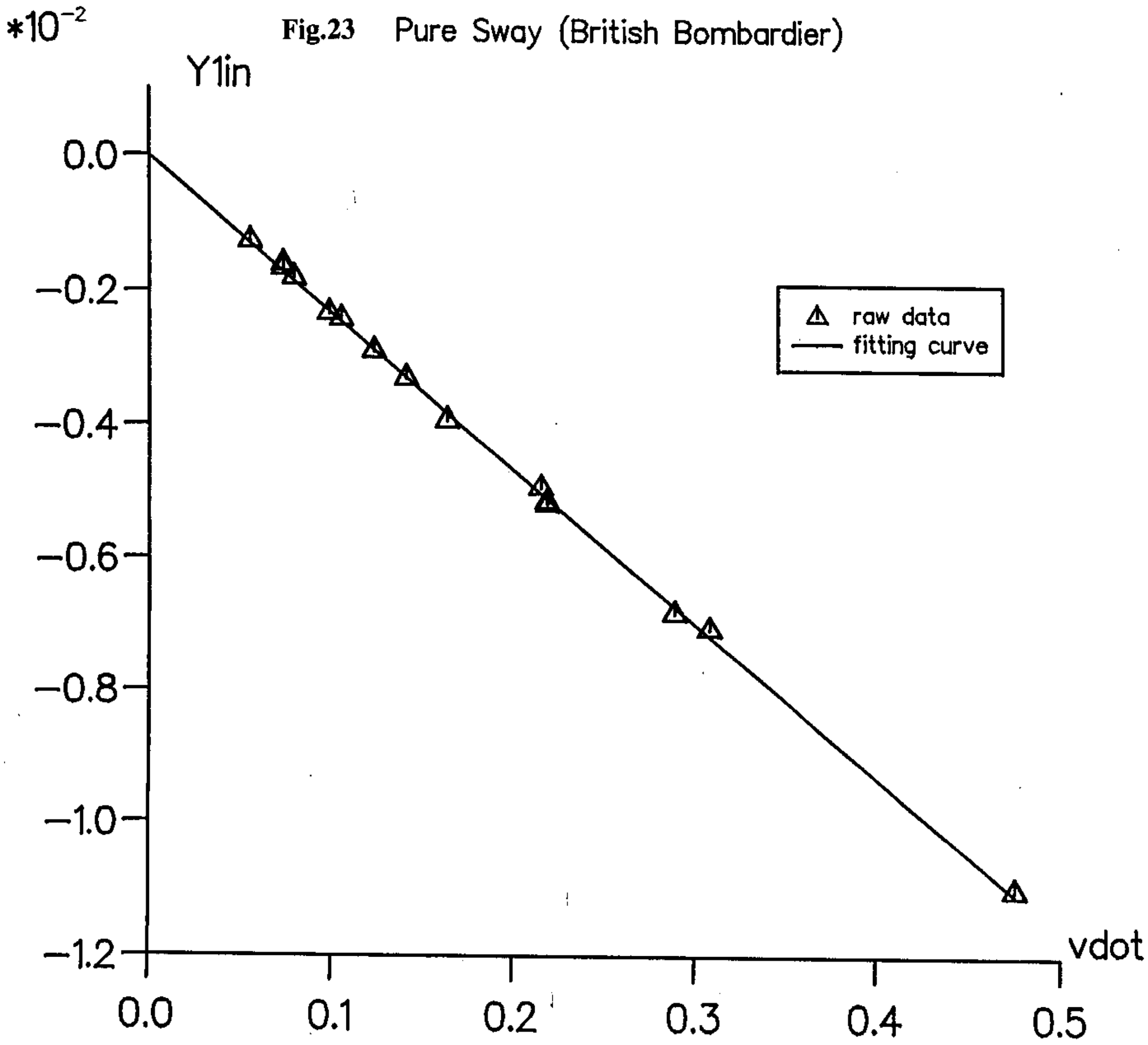


Fig.24 Pure Sway (British Bombardier)

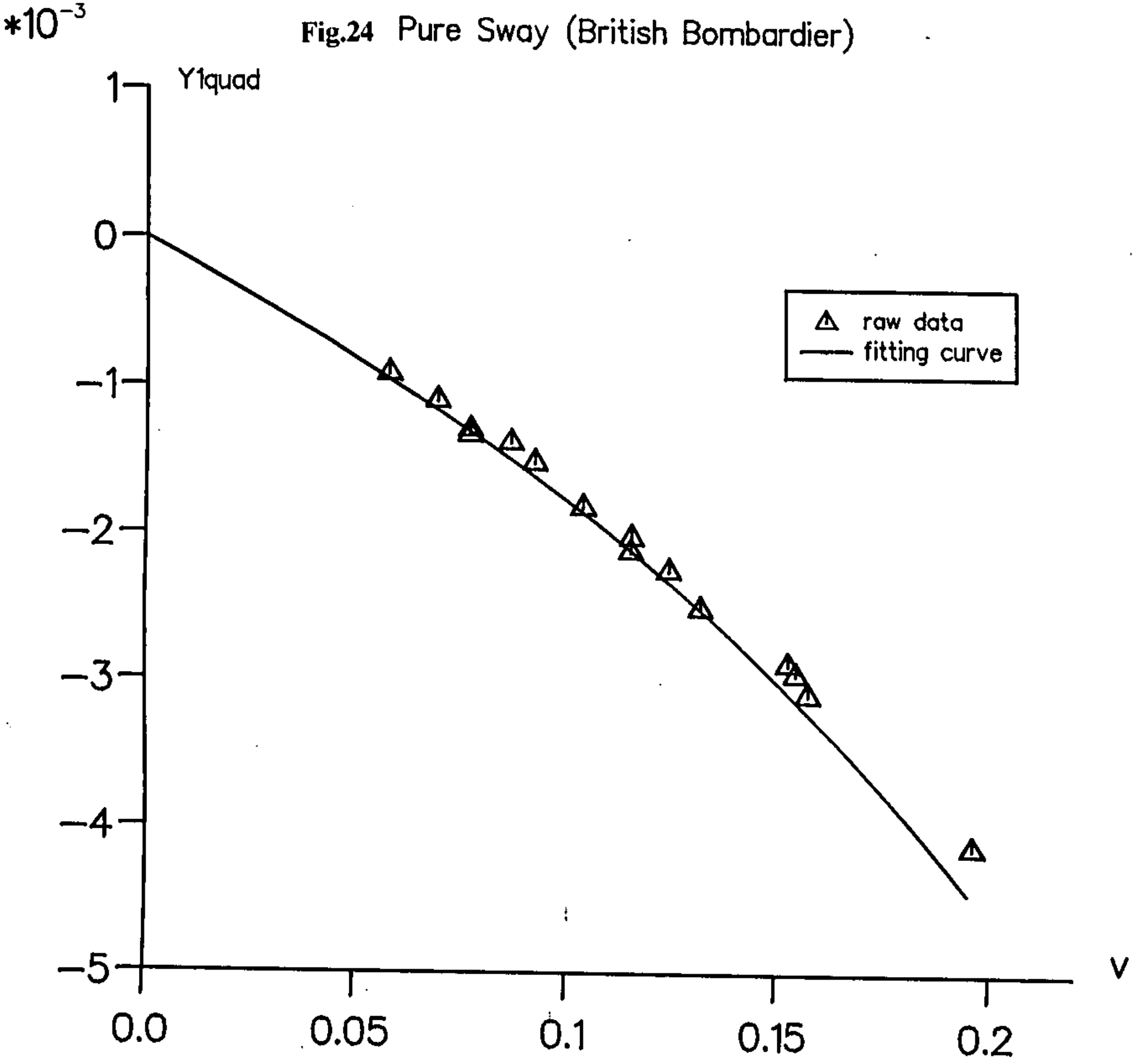
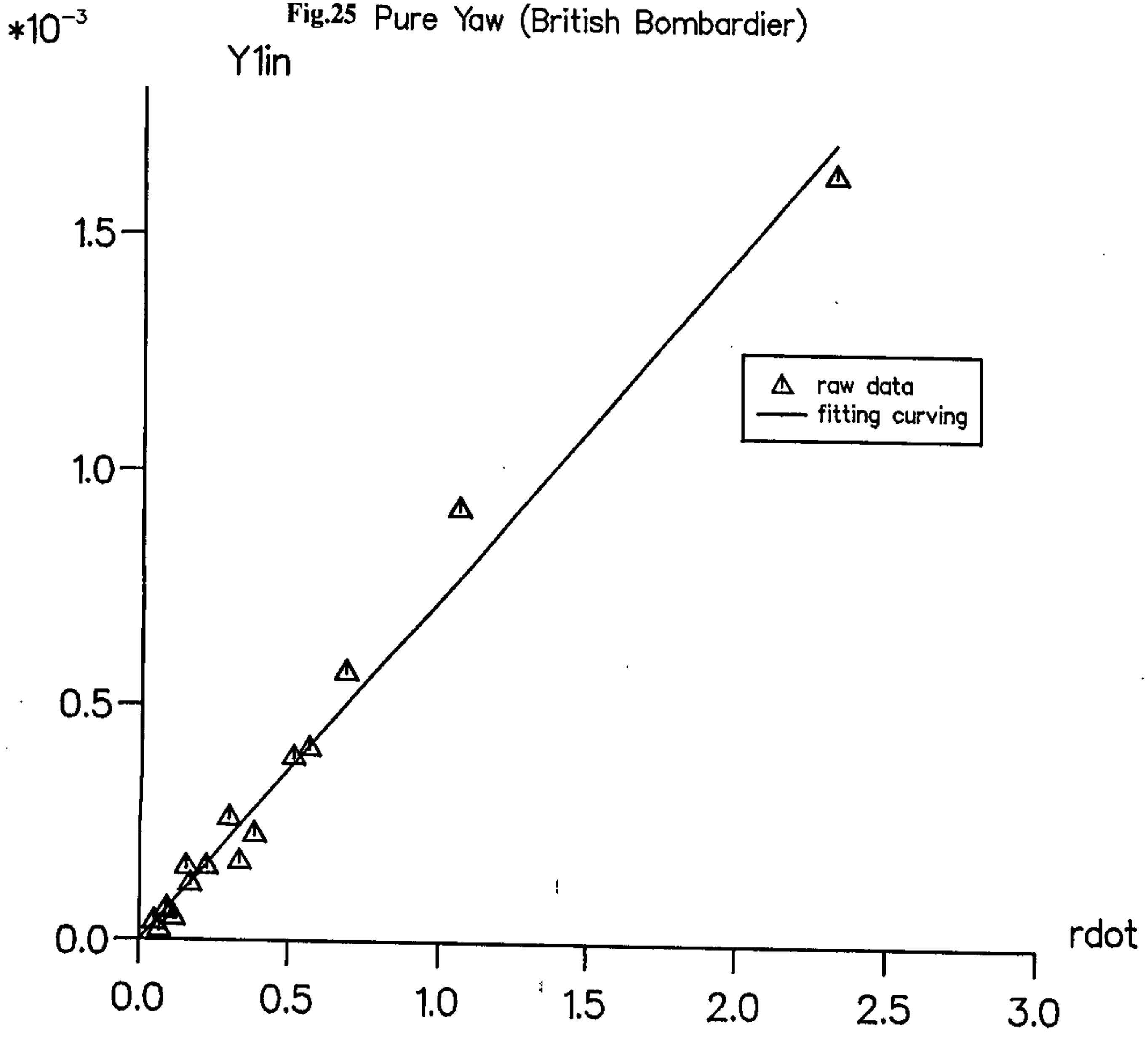


Fig.25 Pure Yaw (British Bombardier)



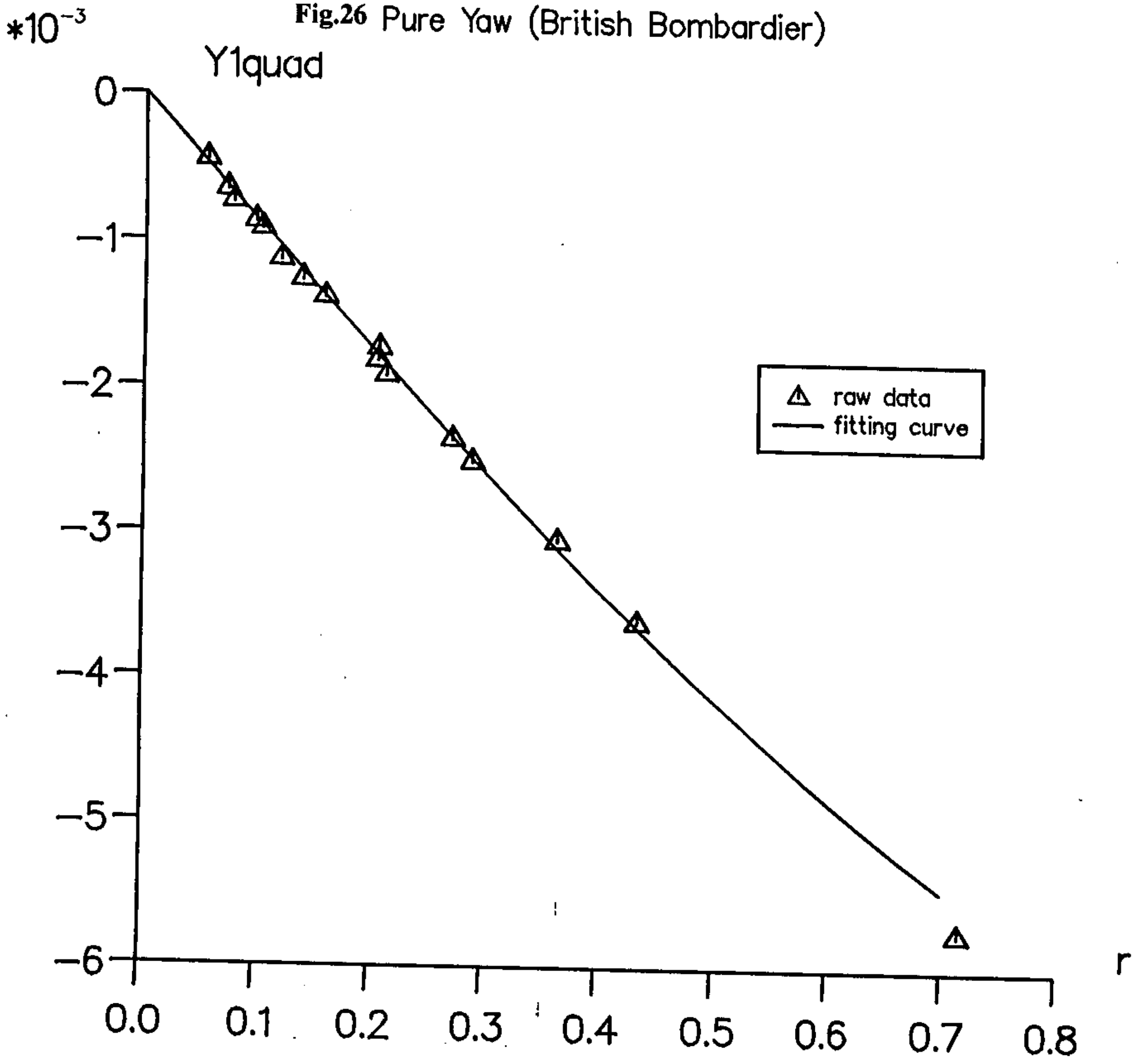


Fig.26 Pure Yaw (British Bombardier)

Fig.27 Pure Sway (British Bombardier)

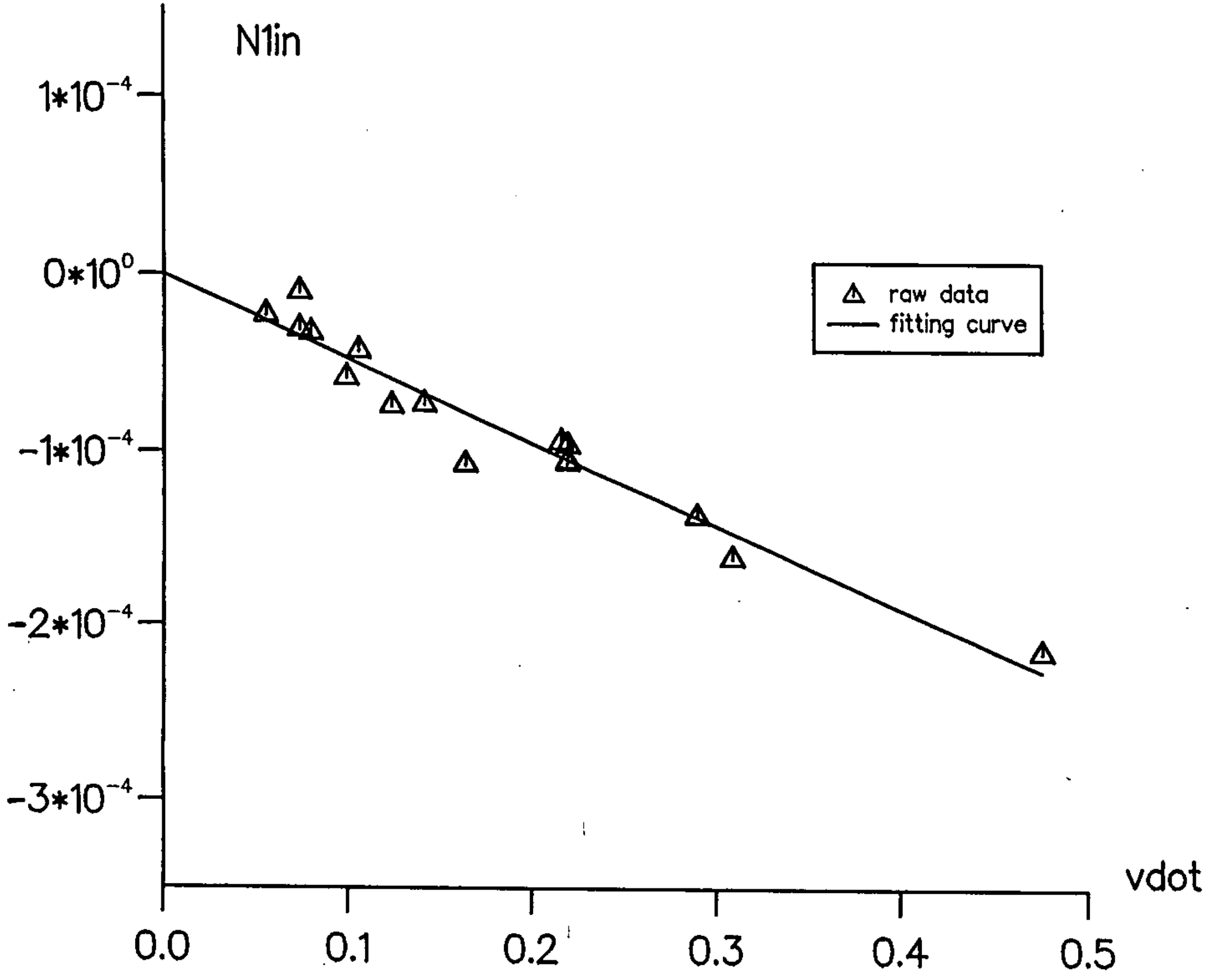
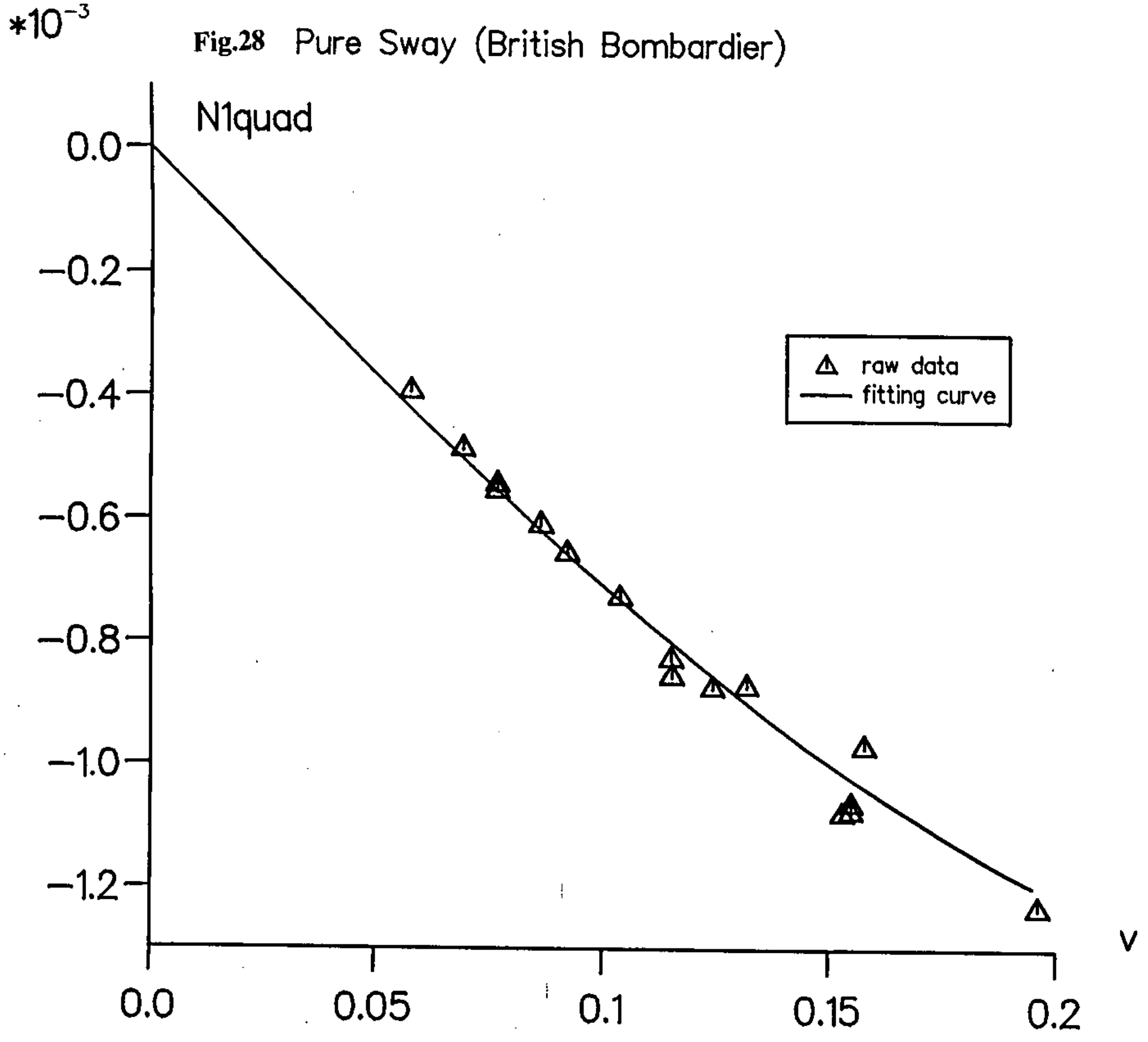


Fig.28 Pure Sway (British Bombardier)



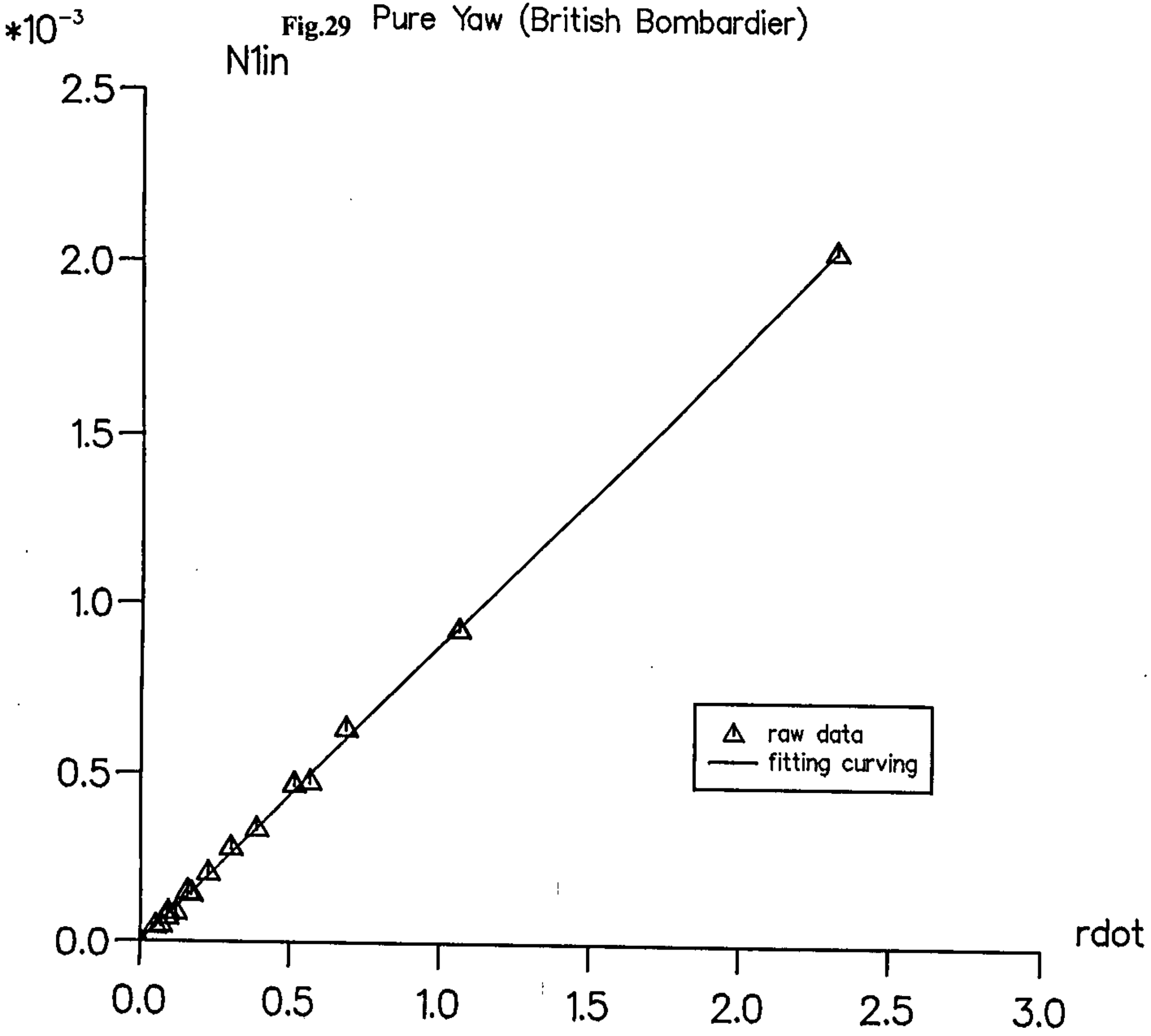
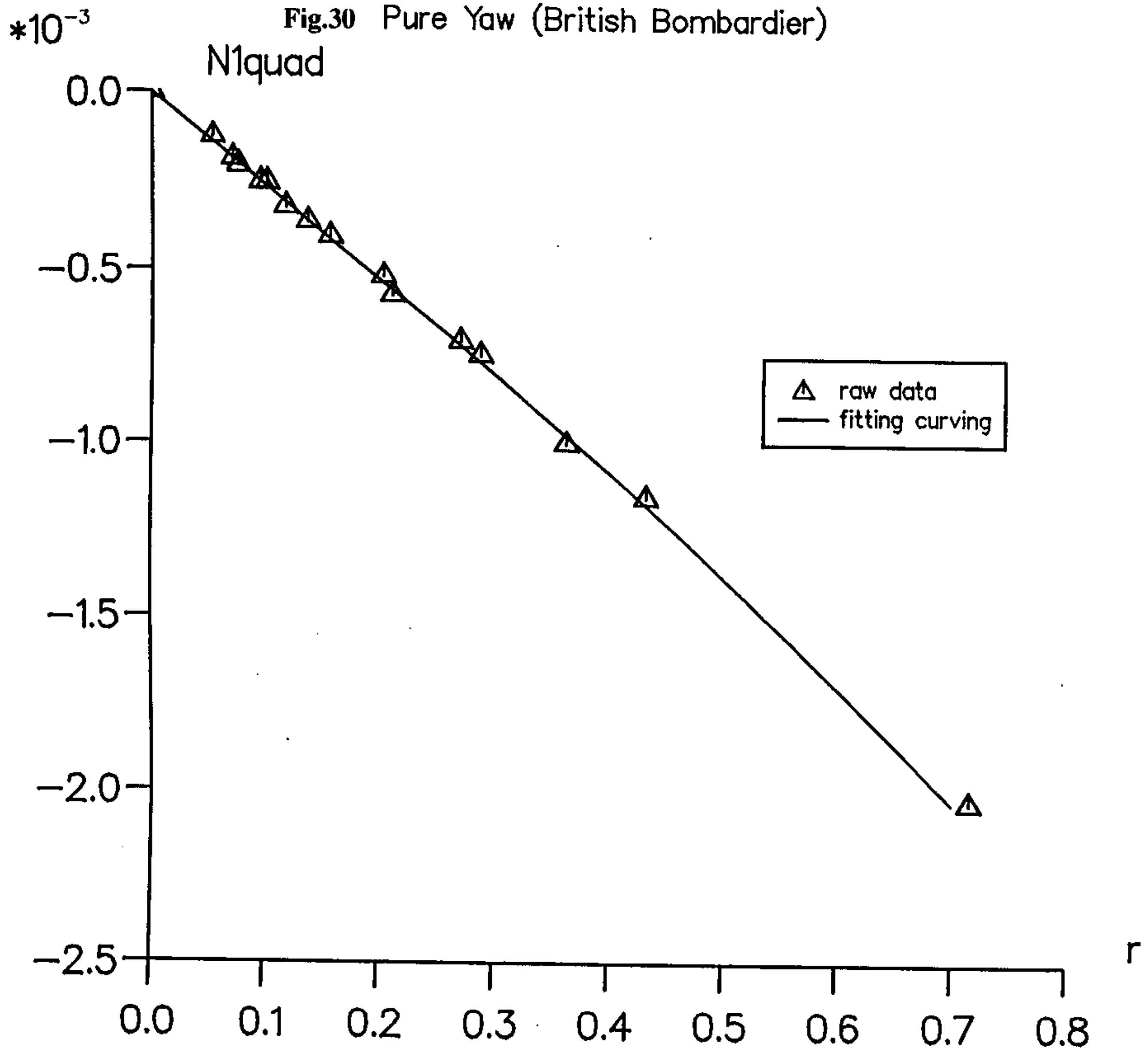


Fig.29 Pure Yaw (British Bombardier)

Fig.30 Pure Yaw (British Bombardier)



(From Fig.31 to Fig.40, the model was fitted with turbulence stimulators)

Fig.31

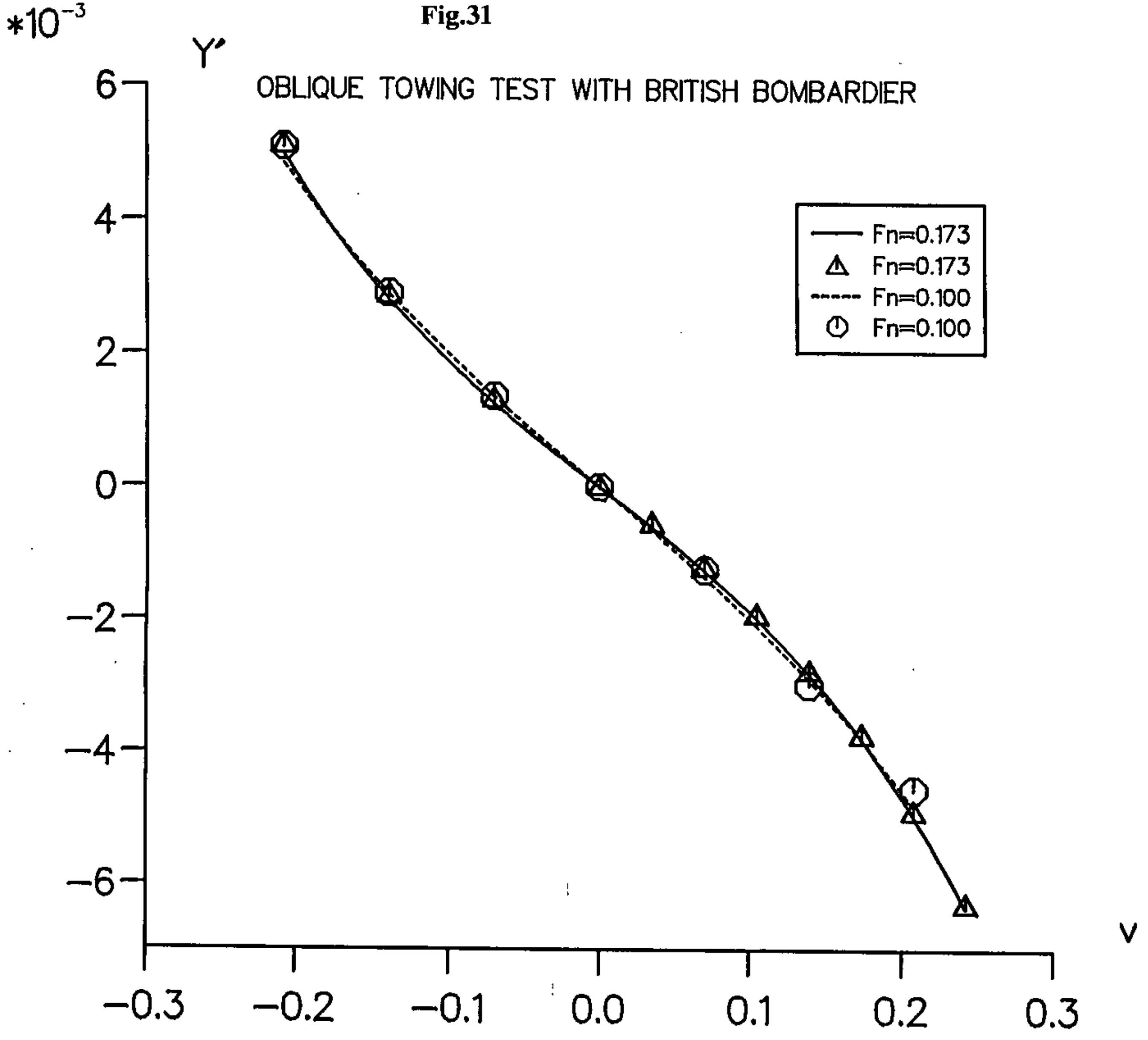


Fig.32

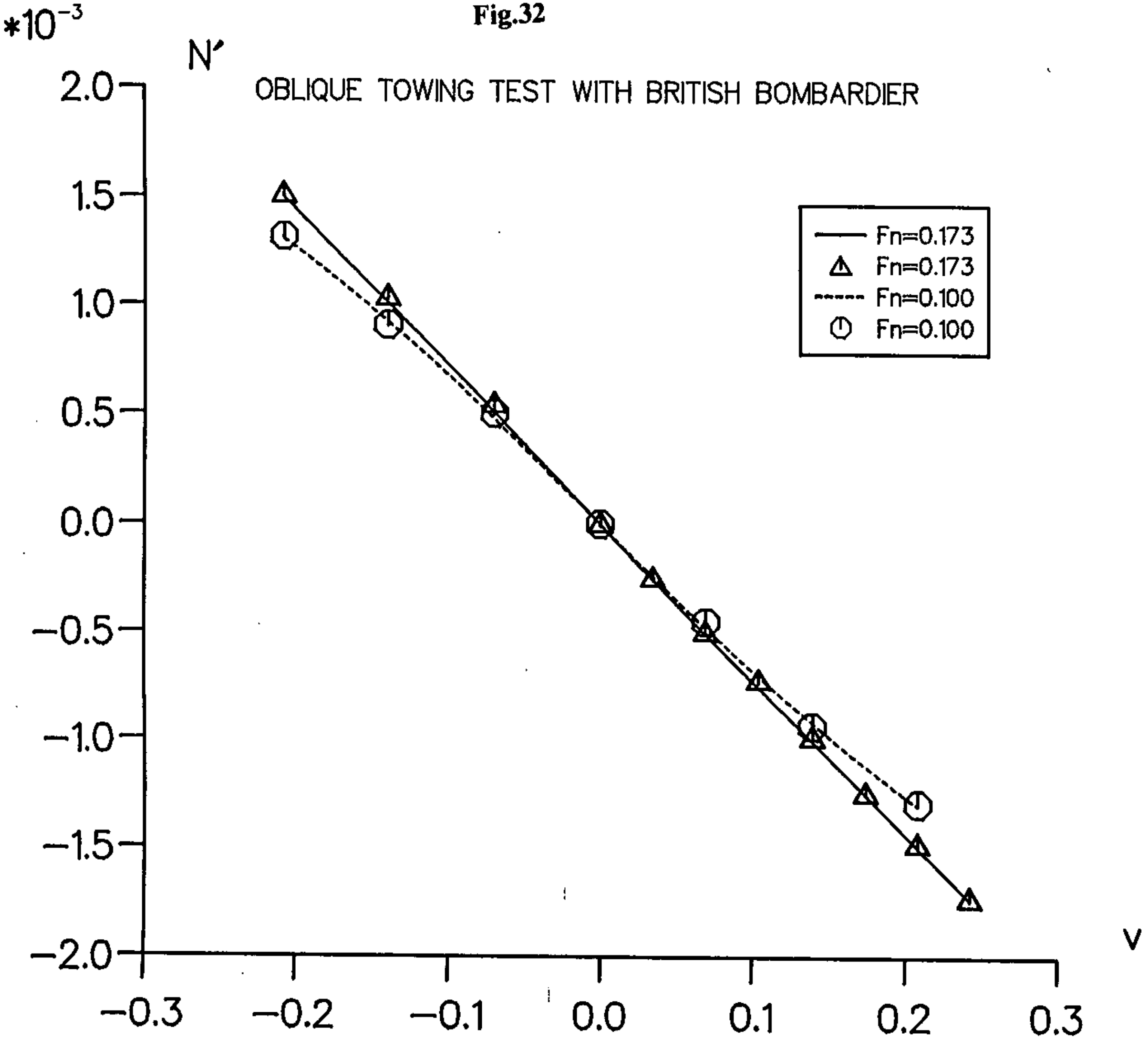

*10^{-3}
N′
OBLIQUE TOWING TEST WITH BRITISH BOMBARDIER
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
v
Fn=0.173
Fn=0.173
Fn=0.100
Fn=0.100

Fig.33a

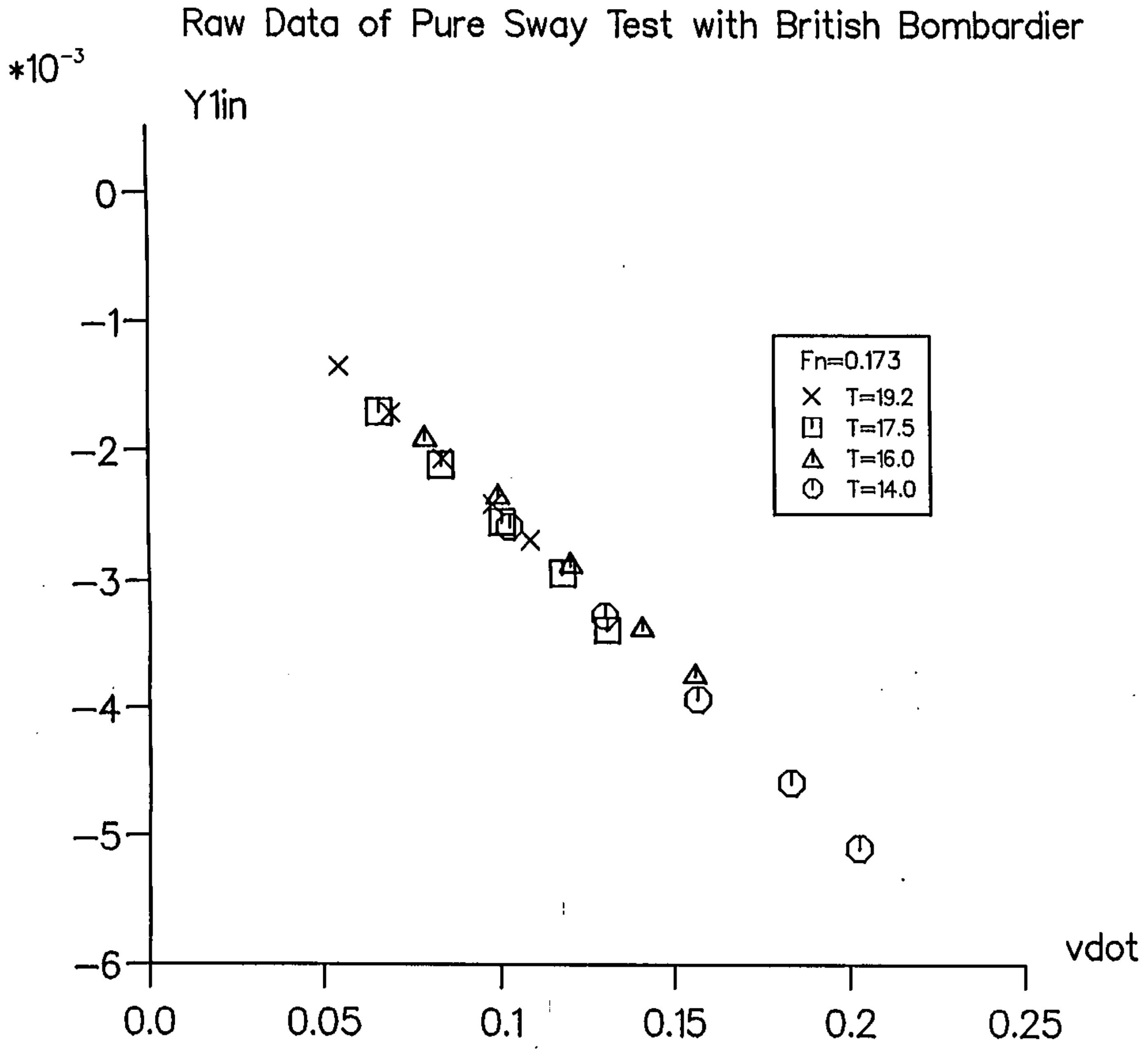

Raw Data of Pure Sway Test with British Bombardier
*10^-3
Y1in
0
−1
−2
−3
−4
−5
−6
0.0
0.05
0.1
0.15
0.2
0.25
vdot
Fn=0.173
T=19.2
T=17.5
T=16.0
T=14.0

Fig.33b Fitting Curves of Pure Sway Test Data

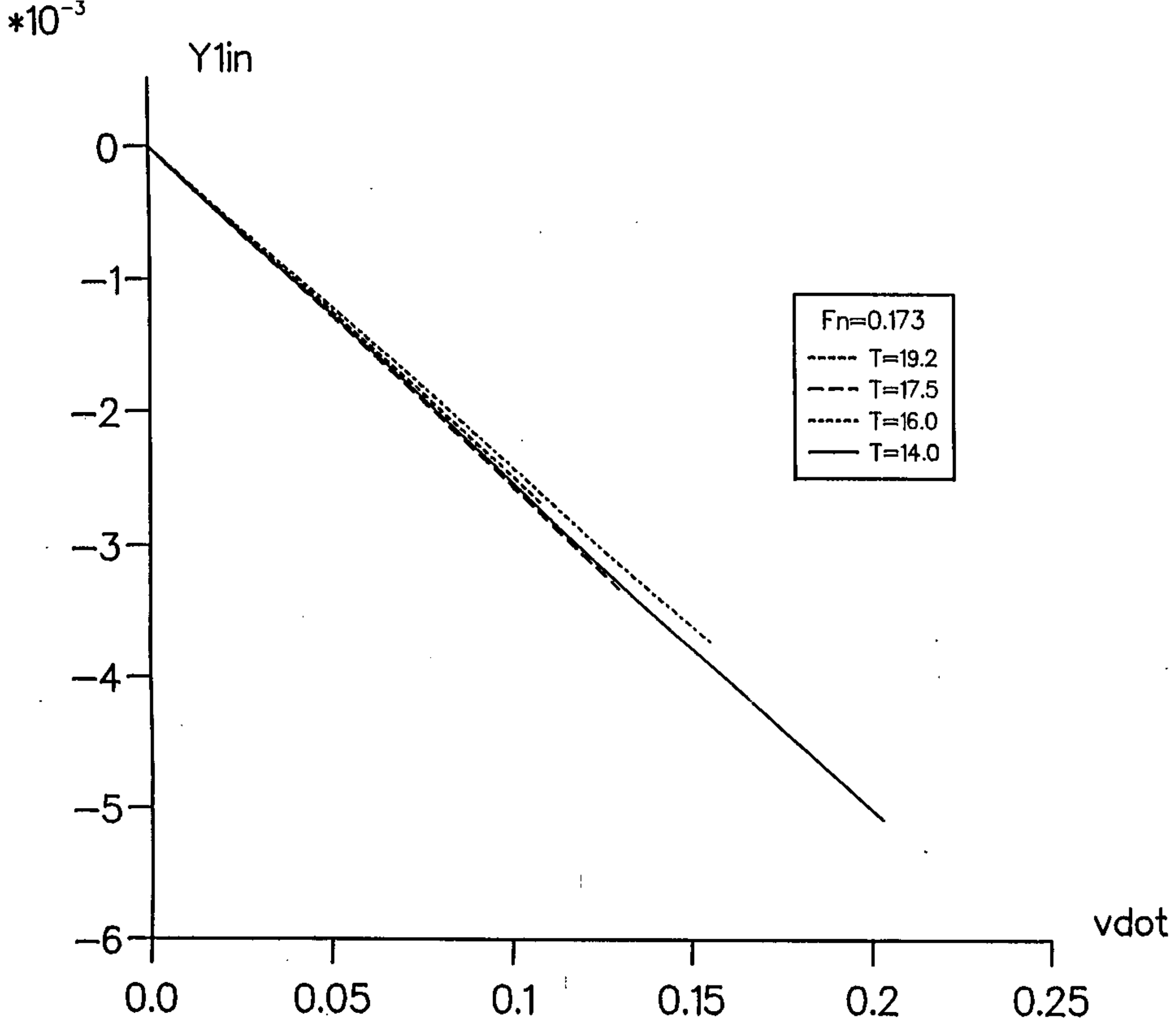


Fig.34a

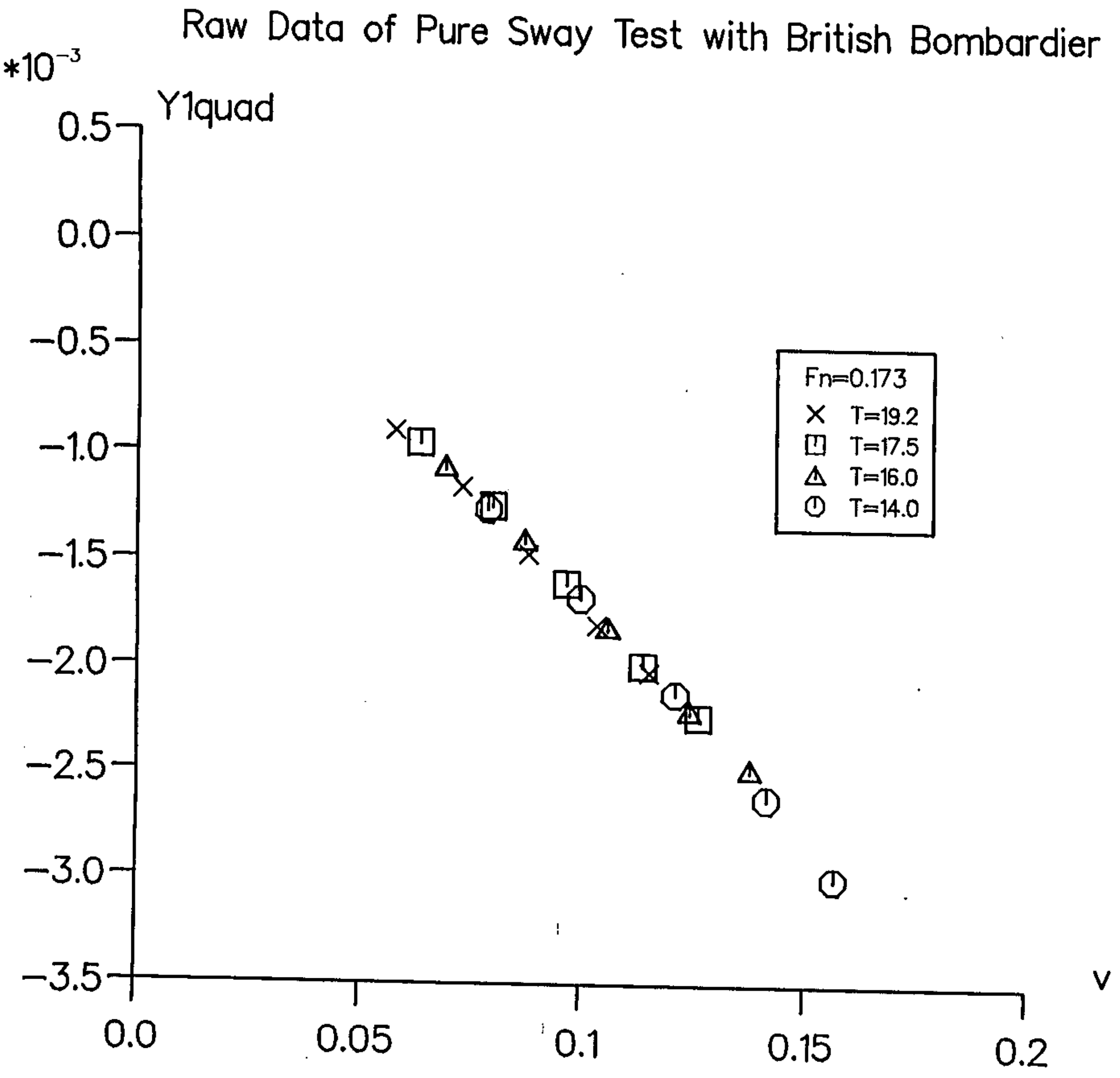

Raw Data of Pure Sway Test with British Bombardier

Fig.34b Fitting Curves of Pure Sway Test Data

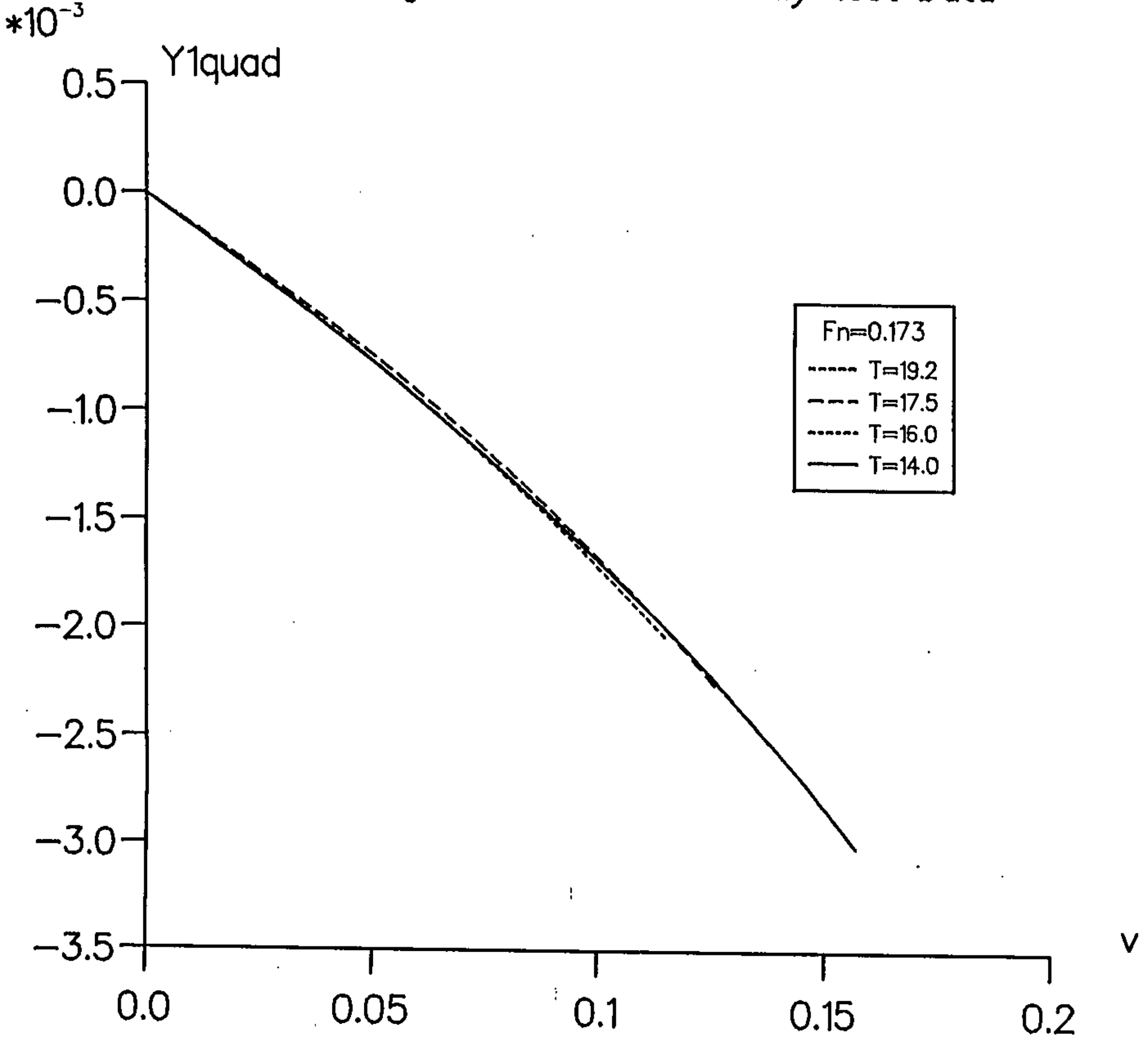


Fig.35a

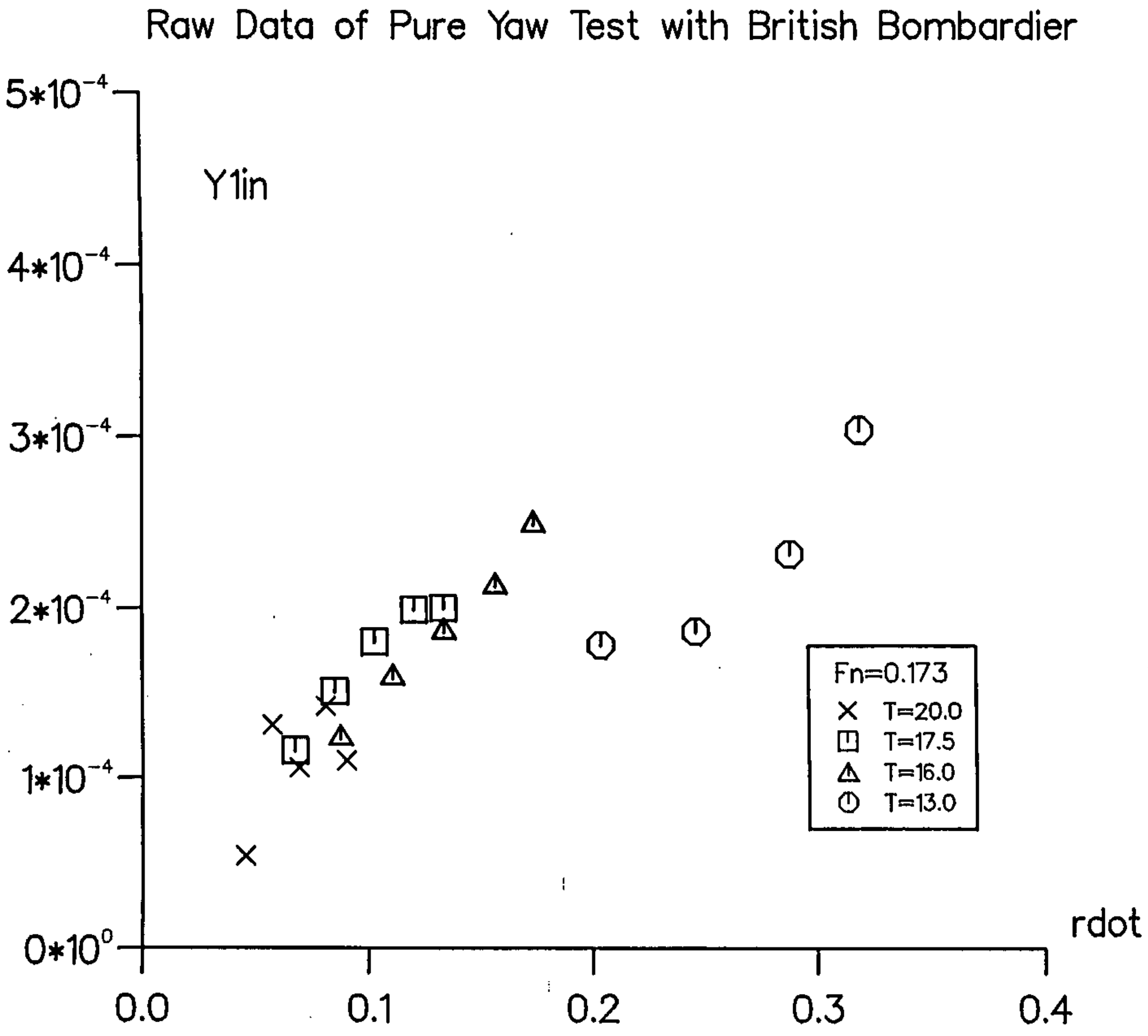

Raw Data of Pure Yaw Test with British Bombardier

Fig.35b Fitting Curves of Pure Yaw Test Data

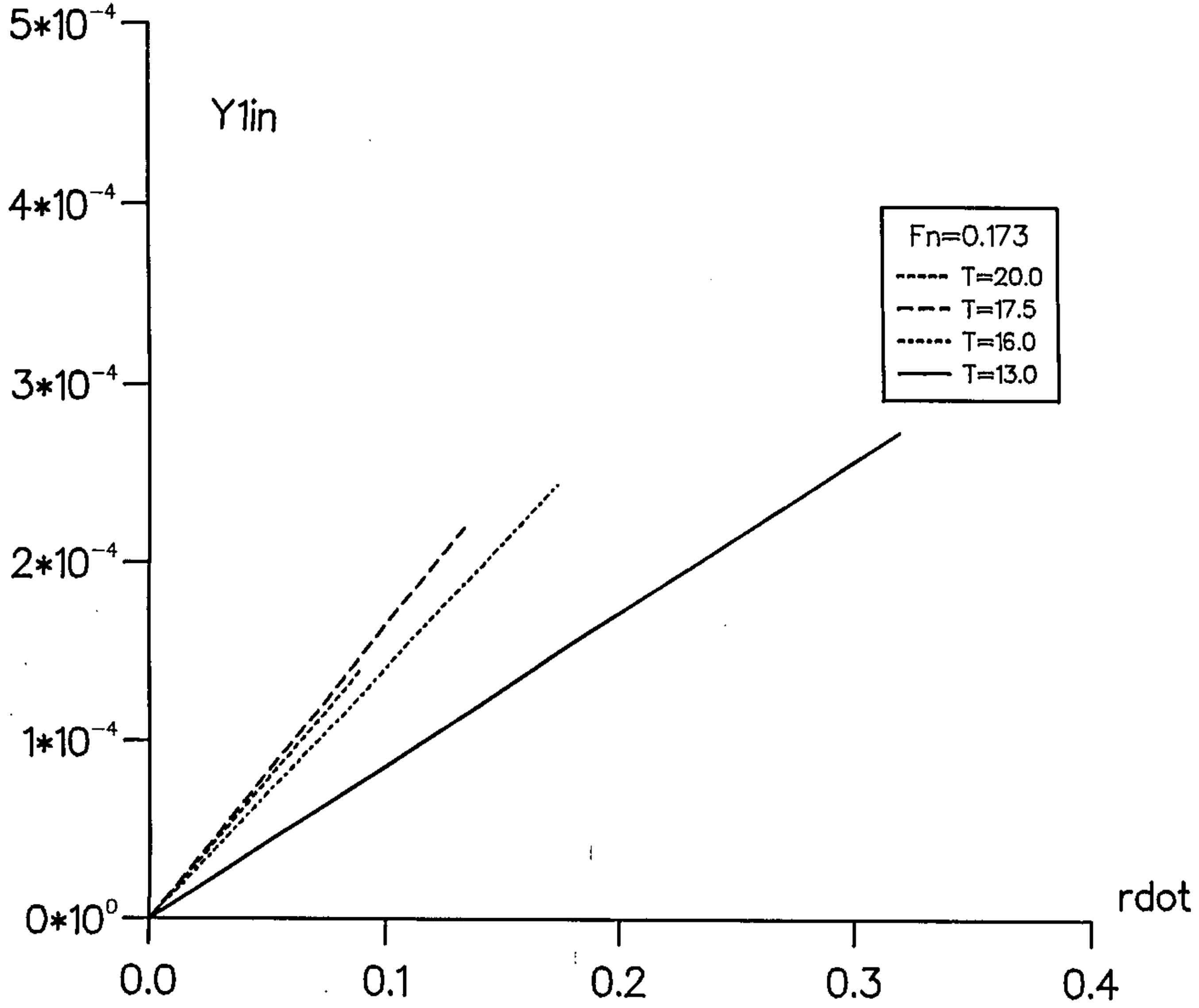


Fig.36a

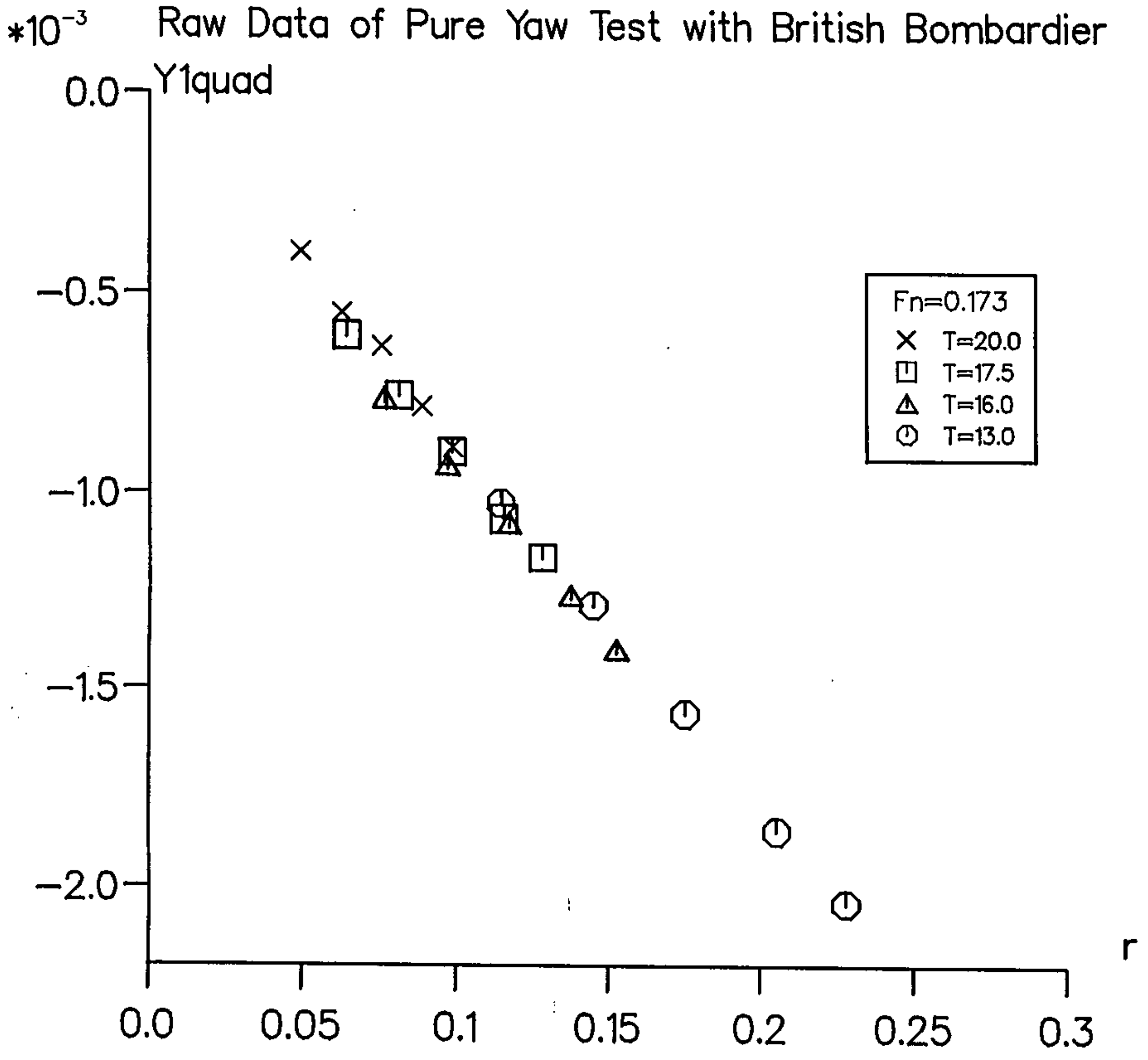

Raw Data of Pure Yaw Test with British Bombardier
*10⁻³
Y1quad
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.05
0.1
0.15
0.2
0.25
0.3
r
Fn=0.173
× T=20.0
□ T=17.5
△ T=16.0
○ T=13.0

Fig.36b

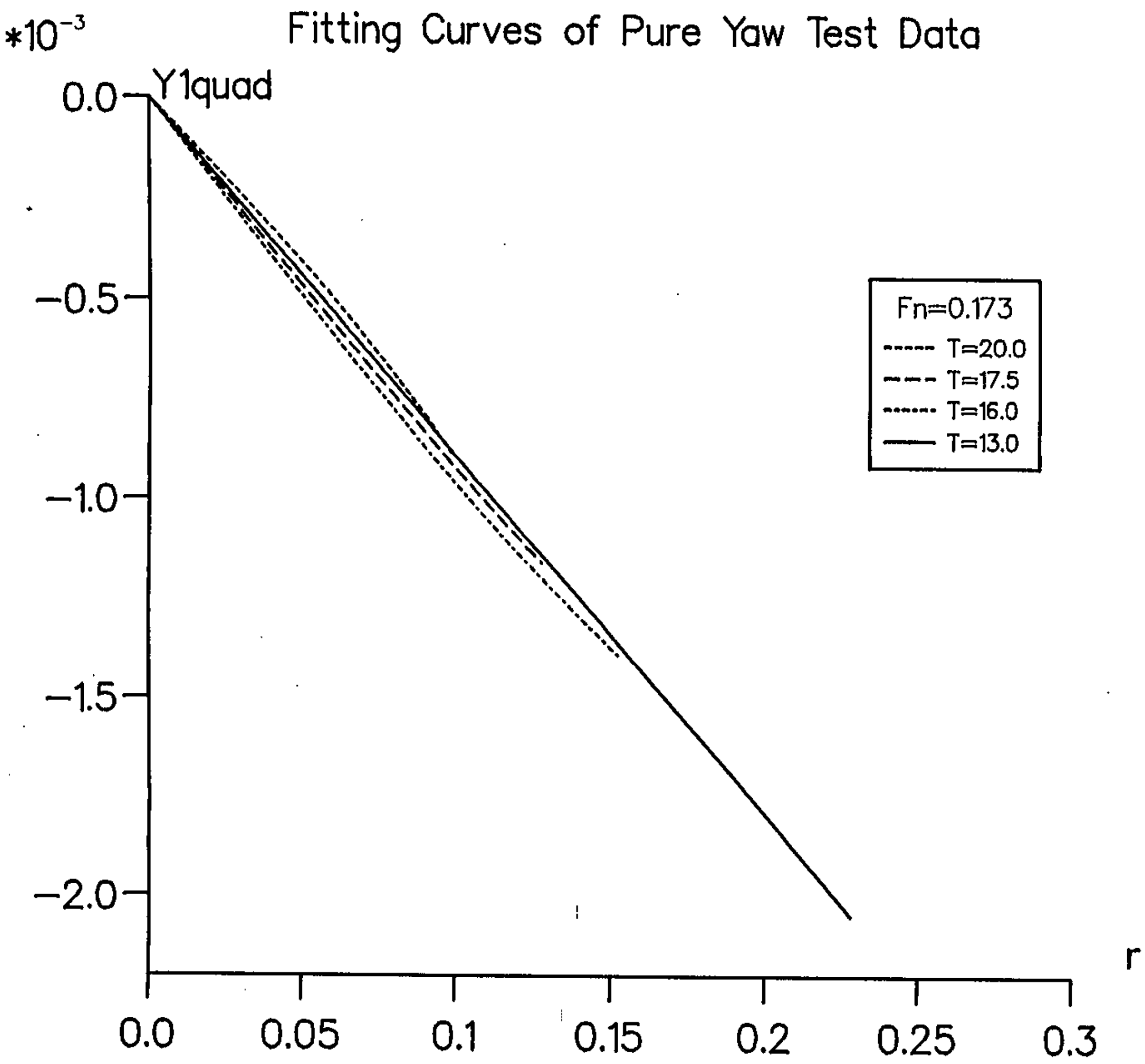
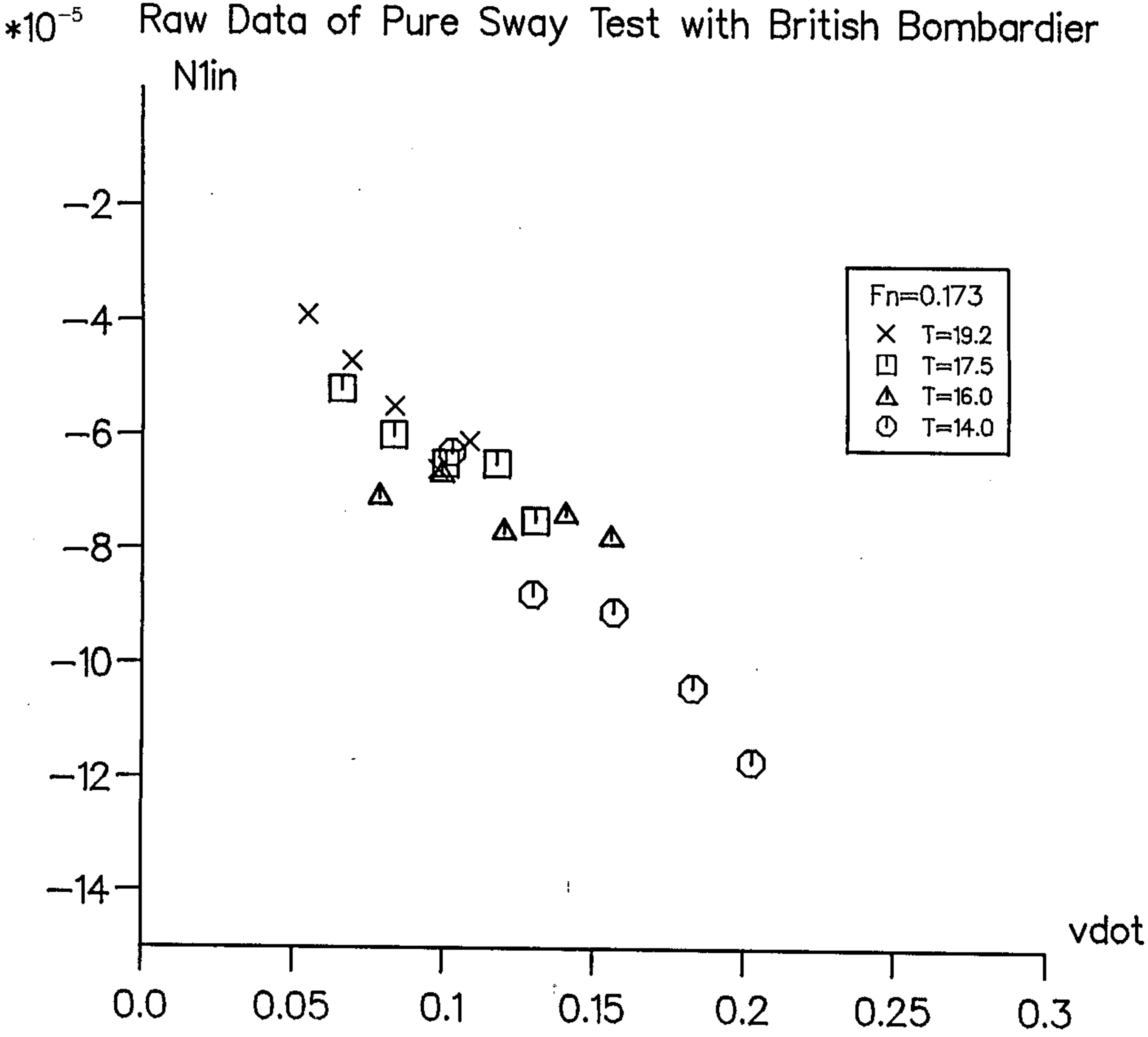

Fitting Curves of Pure Yaw Test Data
*10⁻³
Y1quad
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.05
0.1
0.15
0.2
0.25
0.3
r
Fn=0.173
T=20.0
T=17.5
T=16.0
T=13.0

Fig.37a



Raw Data of Pure Sway Test with British Bombardier

Fig.37b

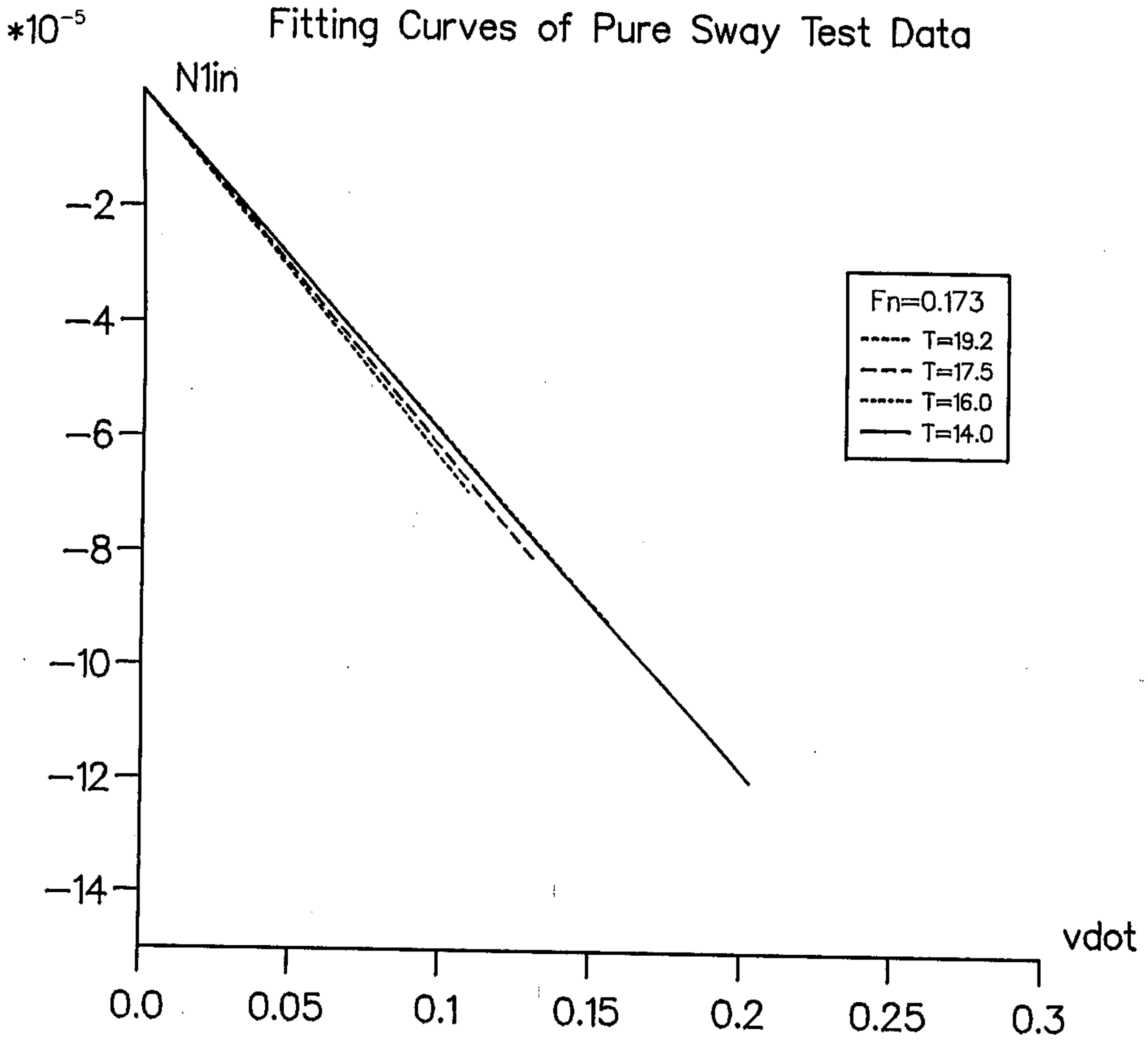

Fitting Curves of Pure Sway Test Data
*10^-5
N1in
-2
-4
-6
-8
-10
-12
-14
0.0
0.05
0.1
0.15
0.2
0.25
0.3
vdot
Fn=0.173
T=19.2
T=17.5
T=16.0
T=14.0

Fig.38a

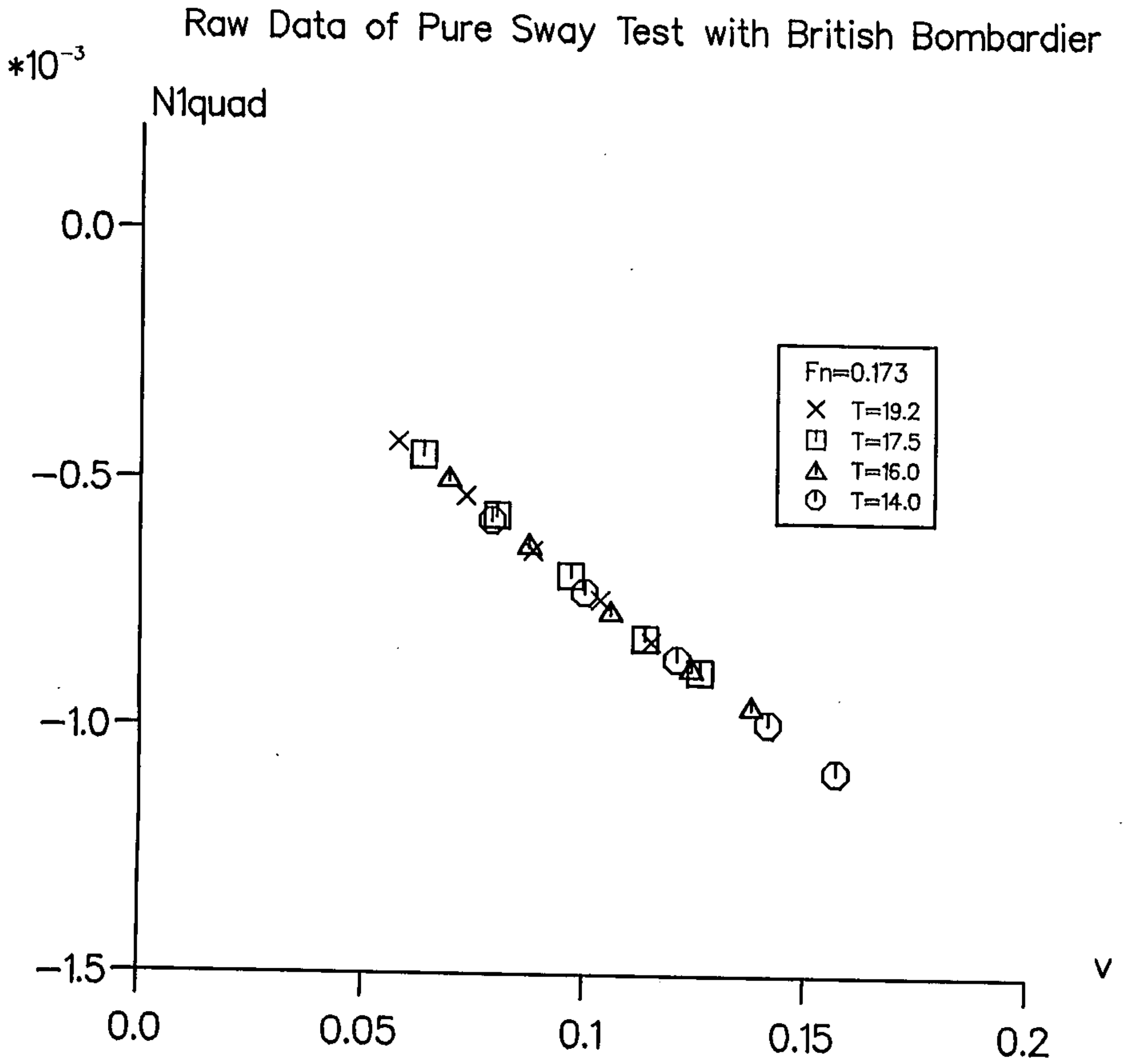

Raw Data of Pure Sway Test with British Bombardier
*10^{-3}
N1quad
0.0
−0.5
−1.0
−1.5
0.0
0.05
0.1
0.15
0.2
v
Fn=0.173
× T=19.2
□ T=17.5
△ T=16.0
○ T=14.0

Fig.38b Fitting Curves of Pure Sway Test Data

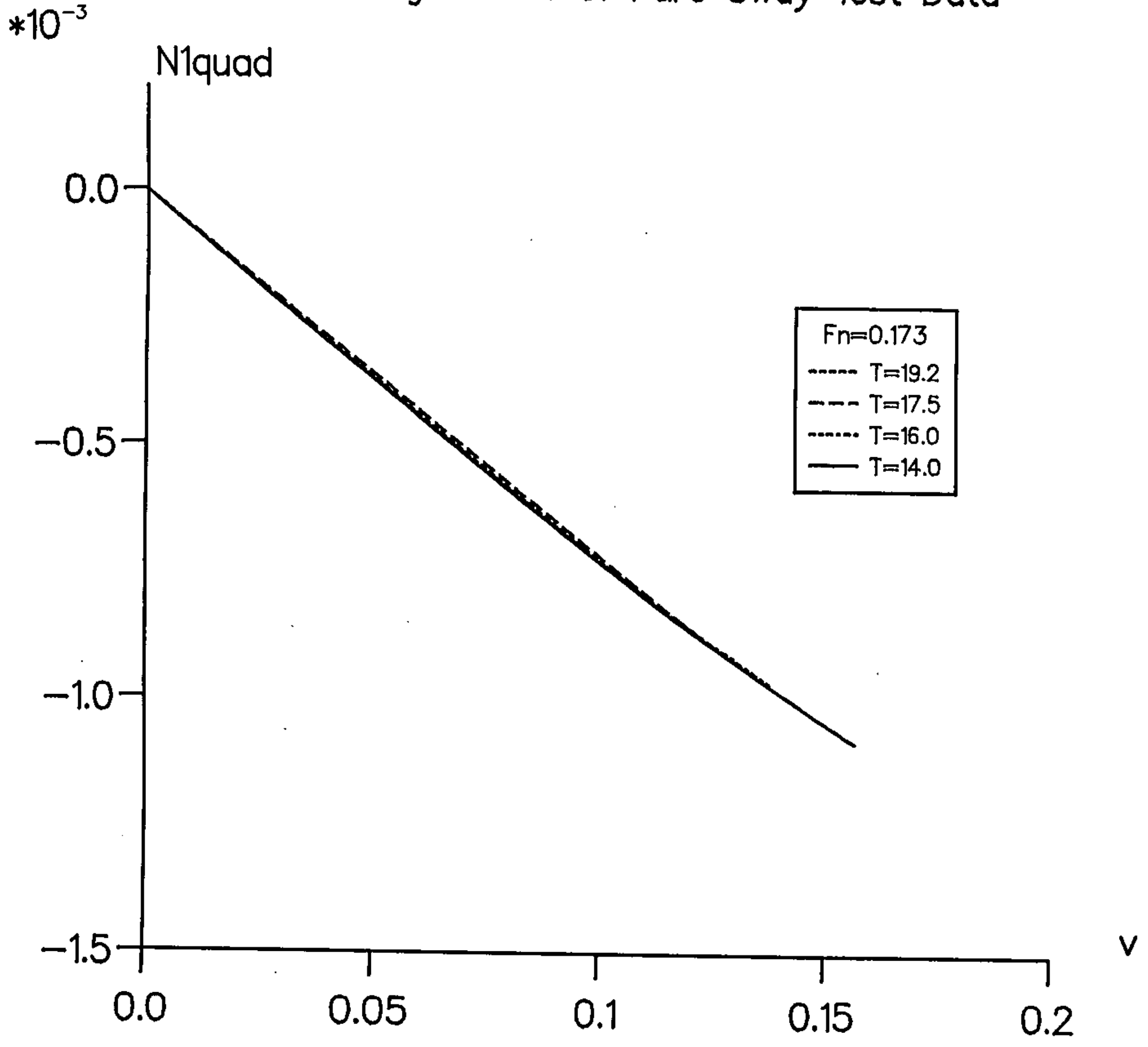


Fig.39a

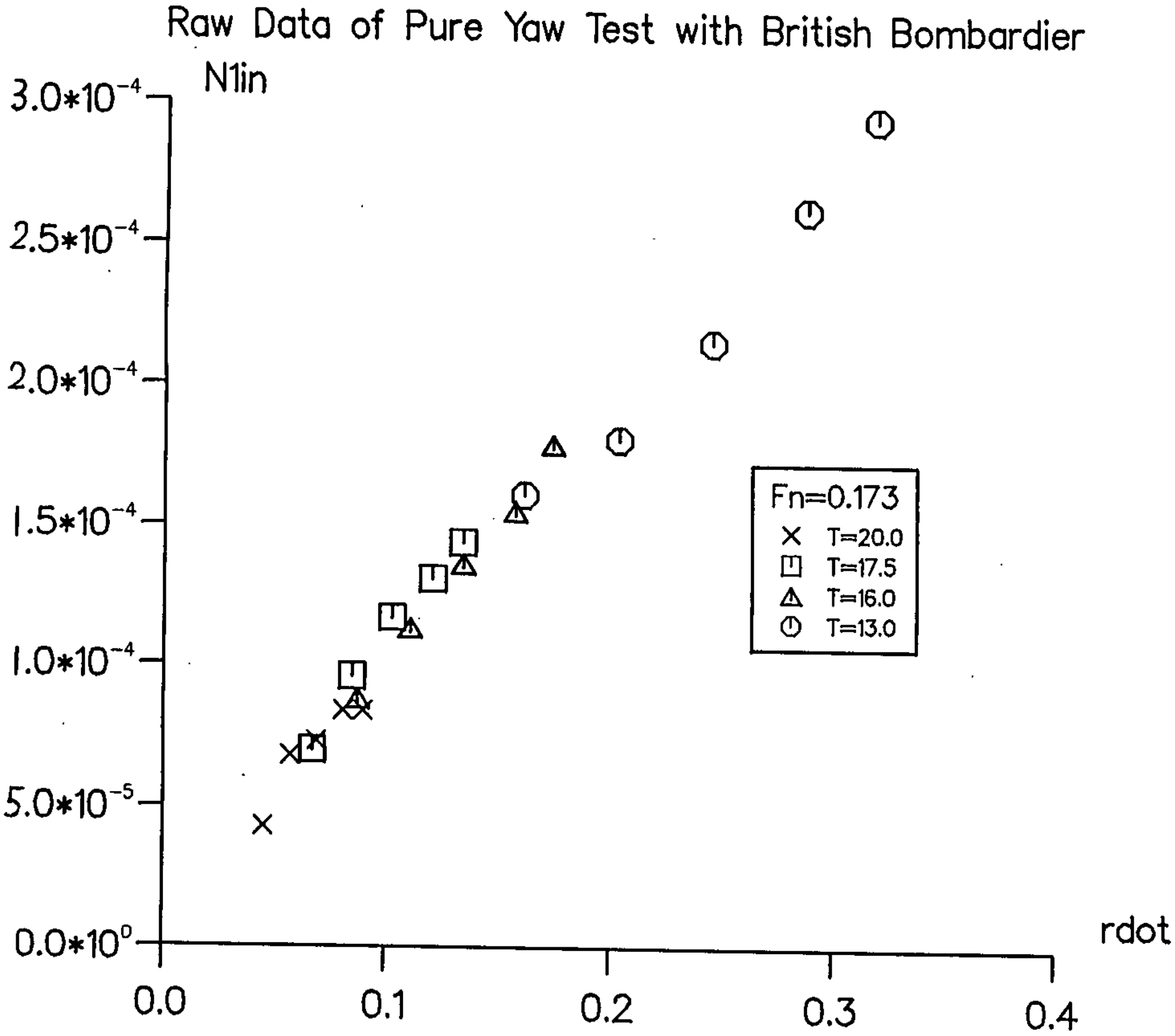

Raw Data of Pure Yaw Test with British Bombardier
N1in
3.0*10^-4
2.5*10^-4
2.0*10^-4
1.5*10^-4
1.0*10^-4
5.0*10^-5
0.0*10^0
0.0
0.1
0.2
0.3
0.4
rdot
Fn=0.173
× T=20.0
□ T=17.5
△ T=16.0
○ T=13.0

Fig.39b

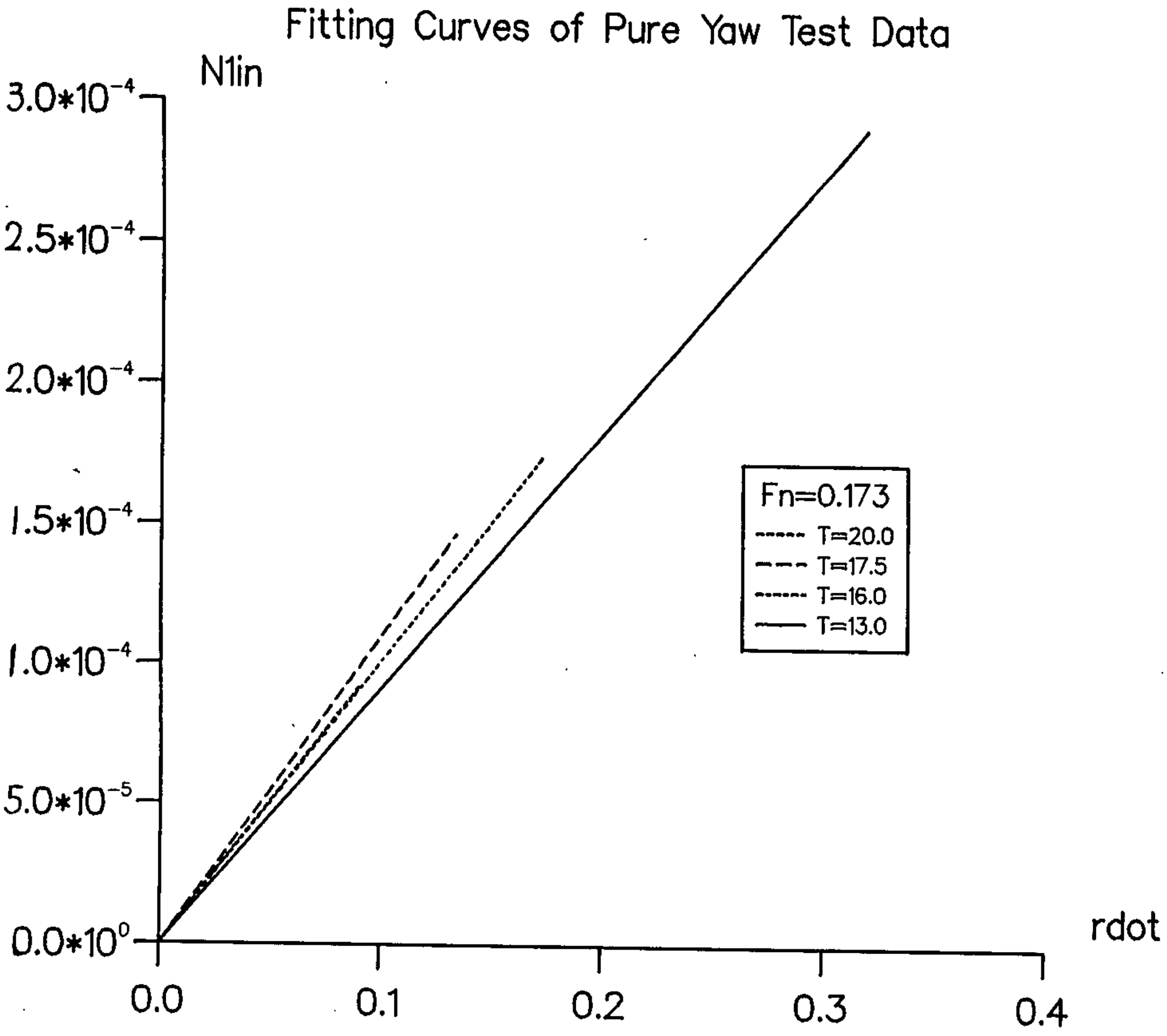

Fitting Curves of Pure Yaw Test Data
N1in
3.0*10^{-4}
2.5*10^{-4}
2.0*10^{-4}
1.5*10^{-4}
1.0*10^{-4}
5.0*10^{-5}
0.0*10^{0}
0.0
0.1
0.2
0.3
0.4
rdot
Fn=0.173
T=20.0
T=17.5
T=16.0
T=13.0

Fig.40a

Raw Data of Pure Yaw Test with British Bombardier

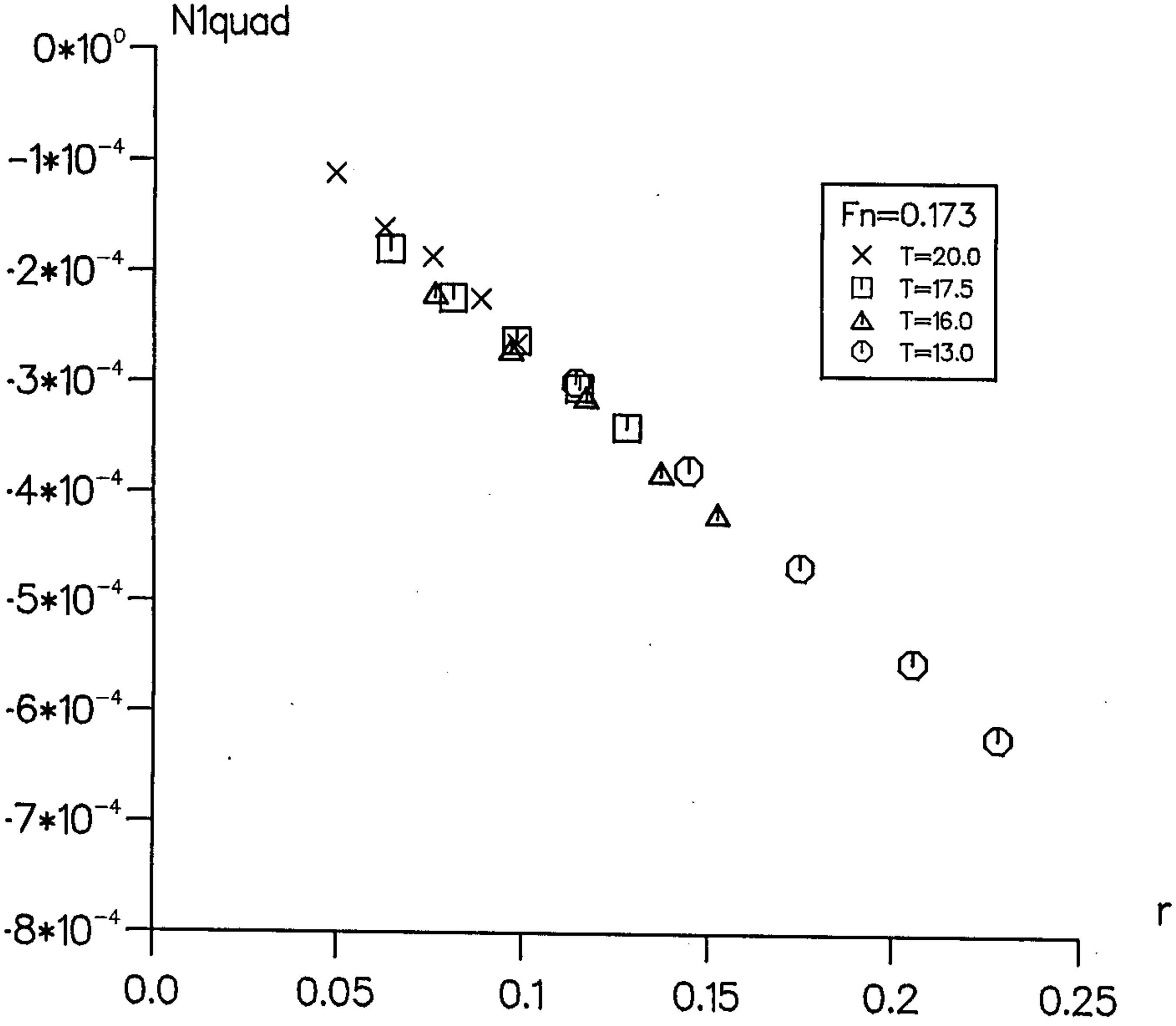


Fig.40b

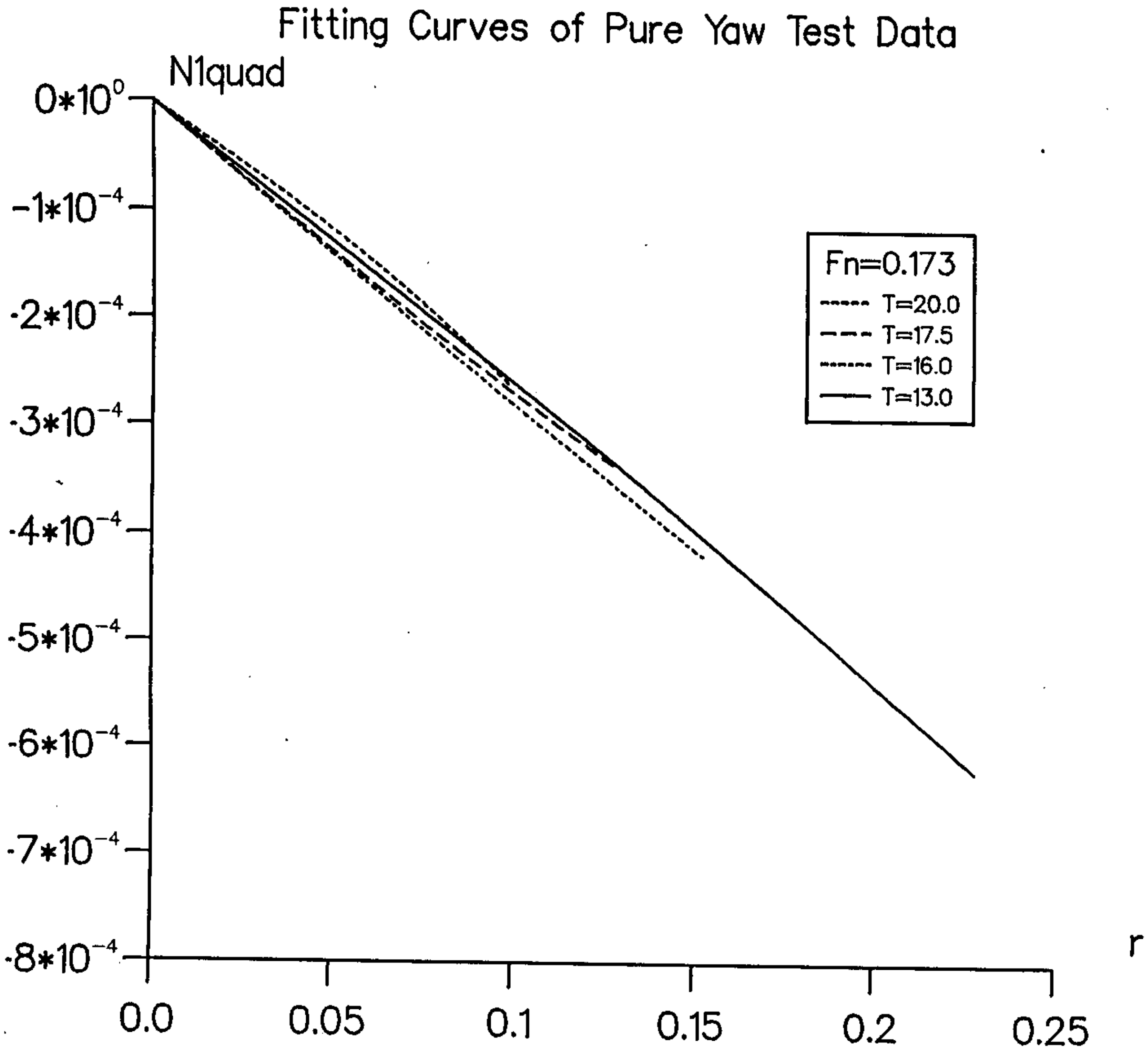

Fitting Curves of Pure Yaw Test Data
N1quad
0*10^0
-1*10^-4
-2*10^-4
-3*10^-4
-4*10^-4
-5*10^-4
-6*10^-4
-7*10^-4
-8*10^-4
0.0
0.05
0.1
0.15
0.2
0.25
r
Fn=0.173
T=20.0
T=17.5
T=16.0
T=13.0

Fig.41

Side Force in
Oblique Towing withTrimmedMariner Model

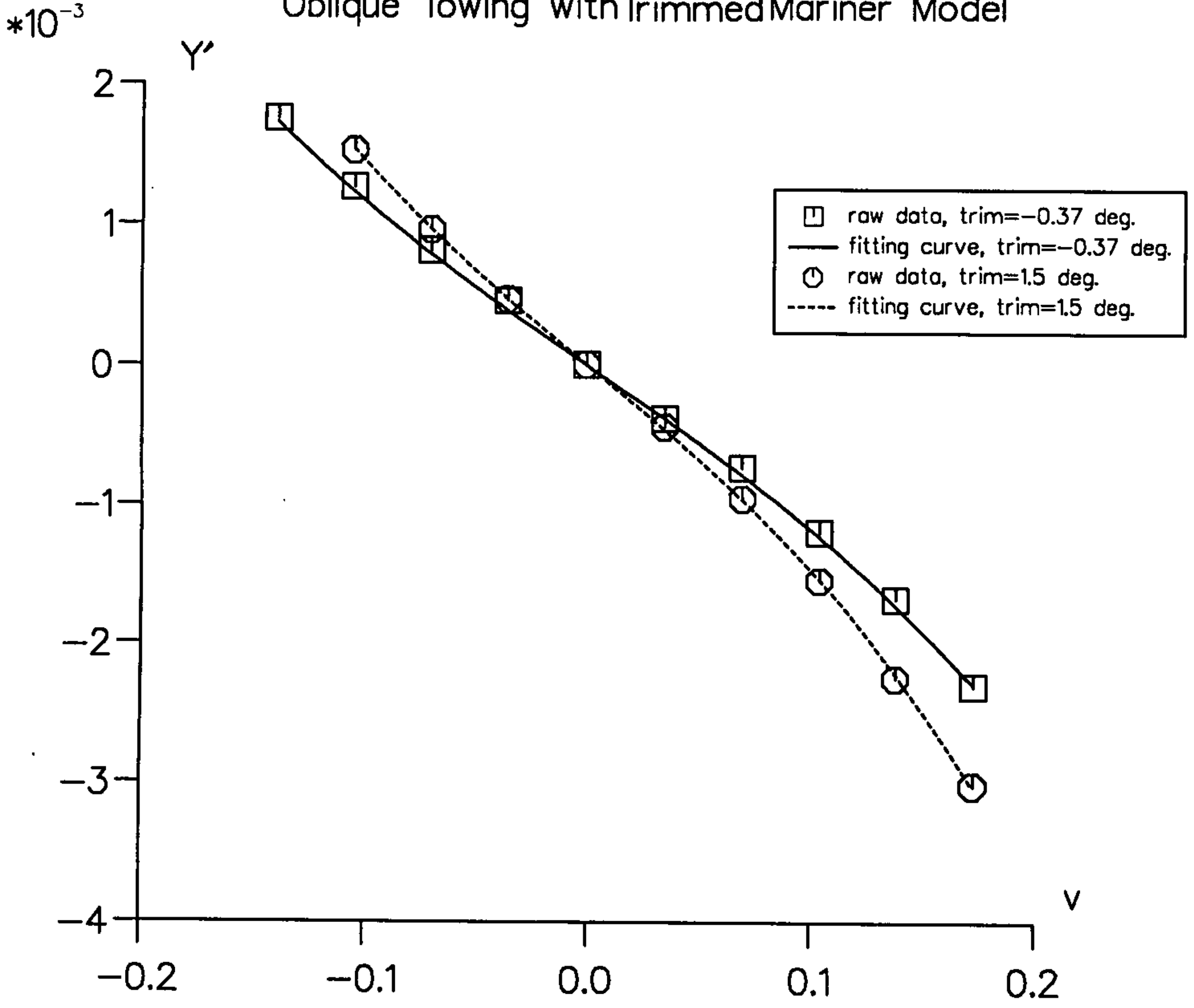
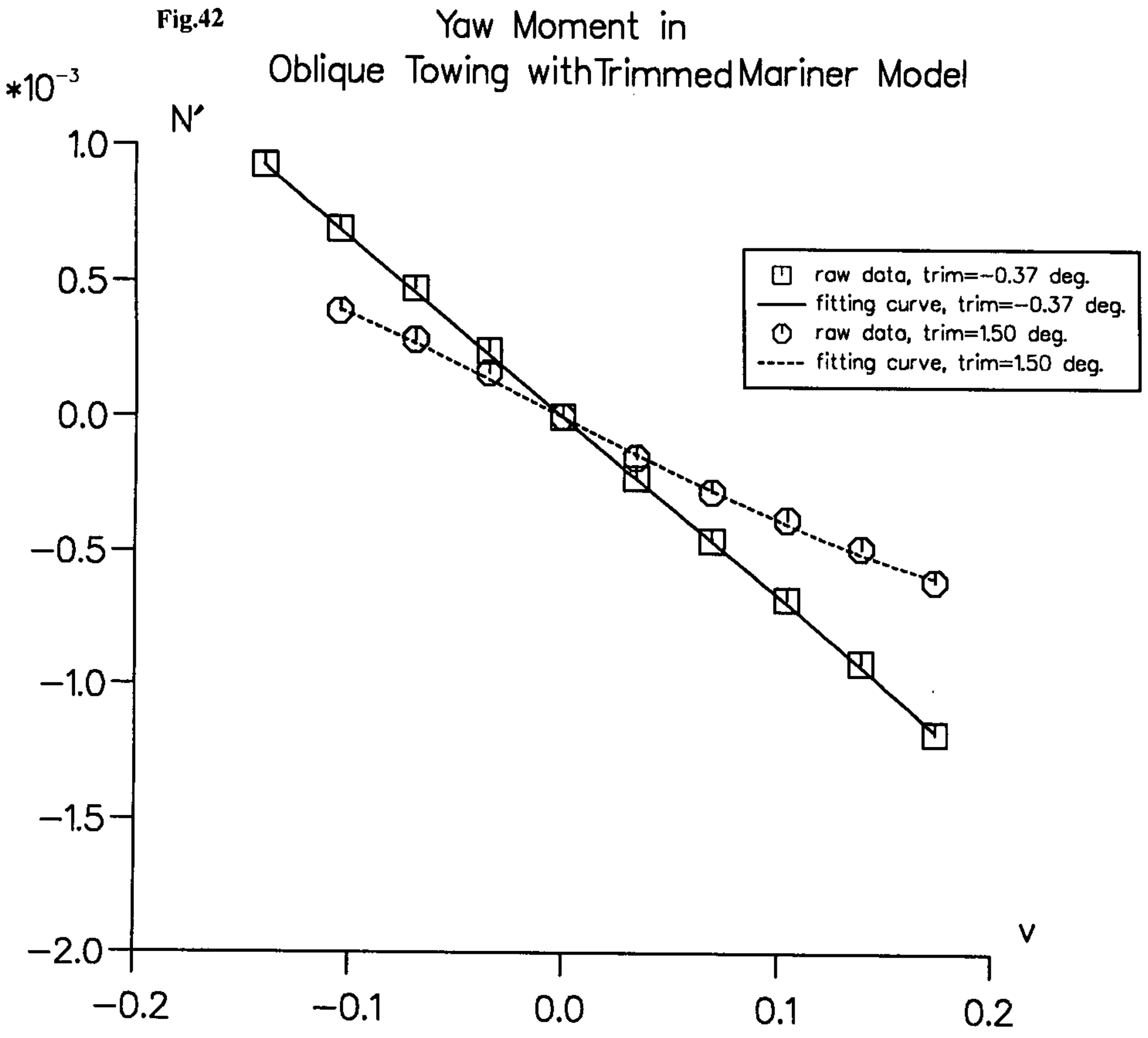
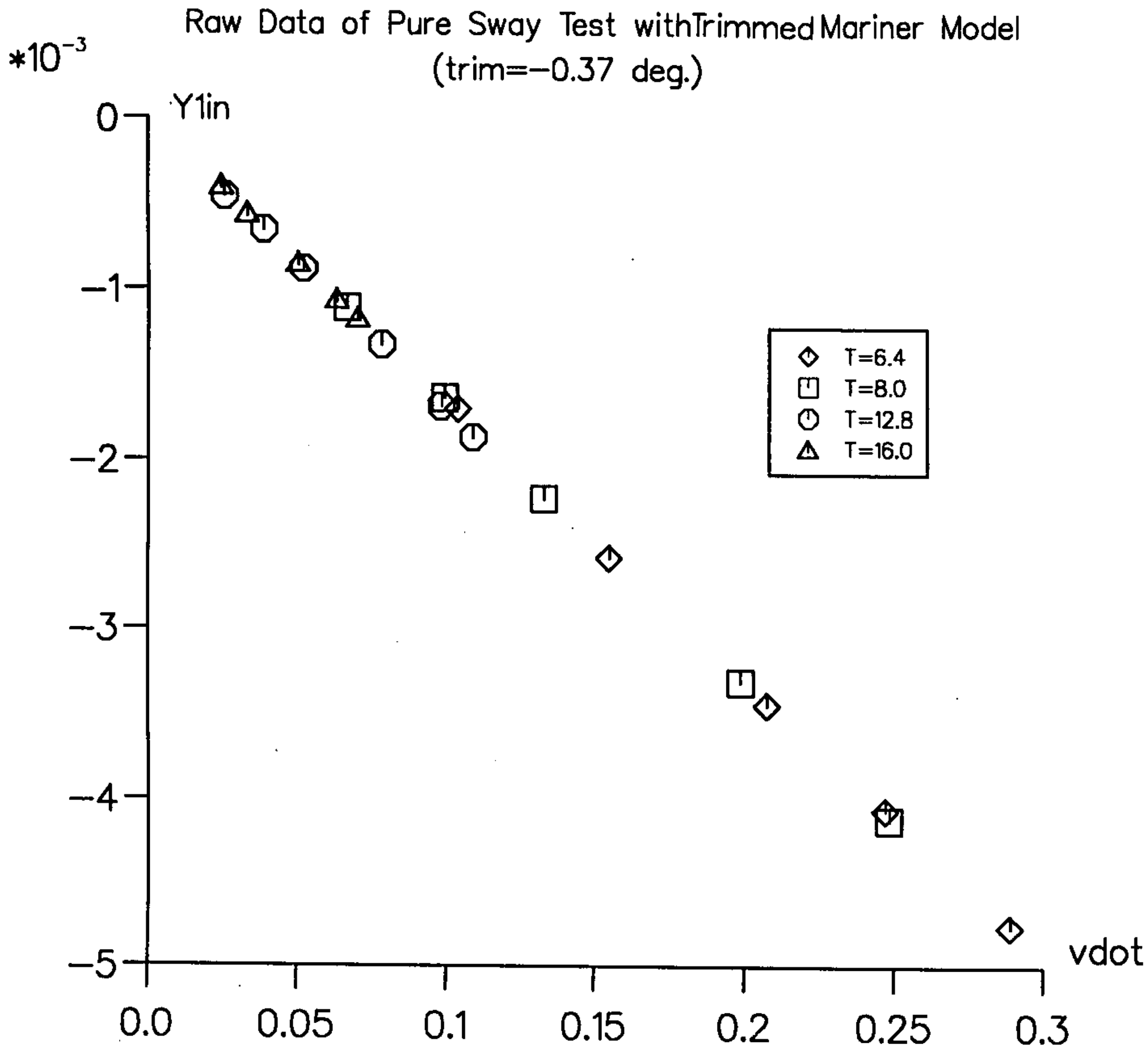


Fig.42



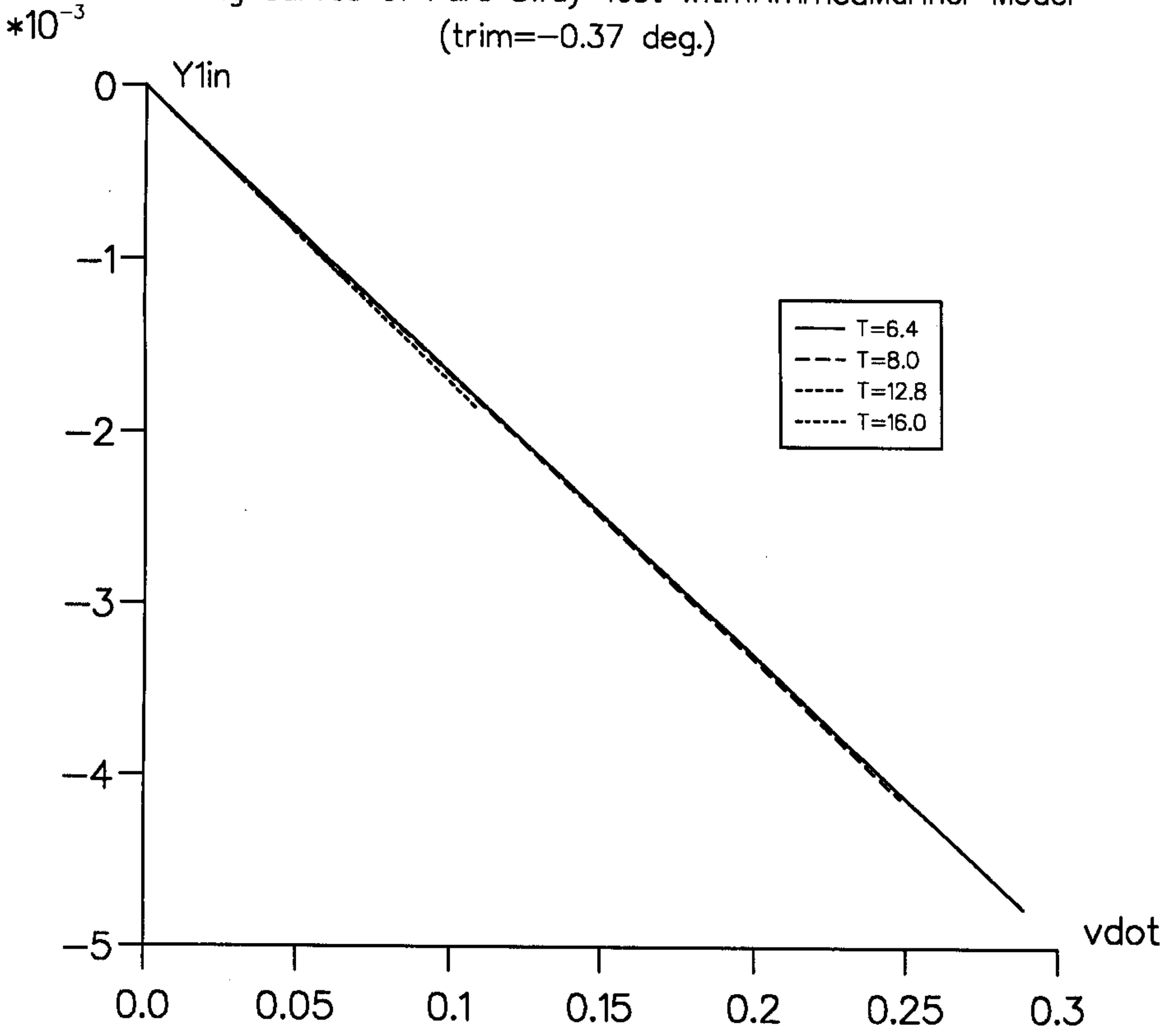
Yaw Moment in Oblique Towing withTrimmedMariner Model

Fig.43a



Raw Data of Pure Sway Test withTrimmedMariner Model
(trim=−0.37 deg.)

Fig.43b



Fitting Curves of Pure Sway Test withTrimmedMariner Model (trim=−0.37 deg.)

Fig.44a

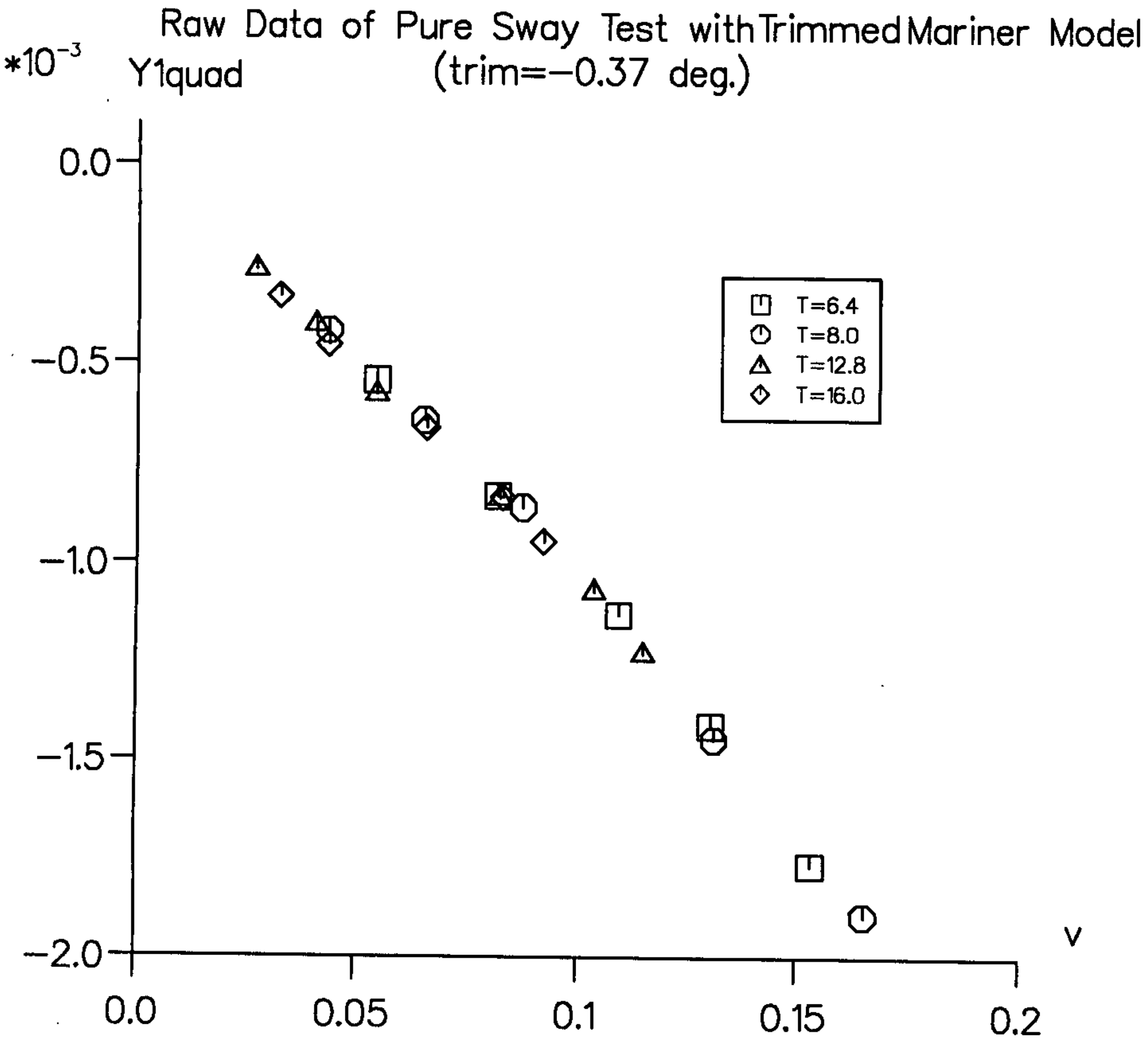
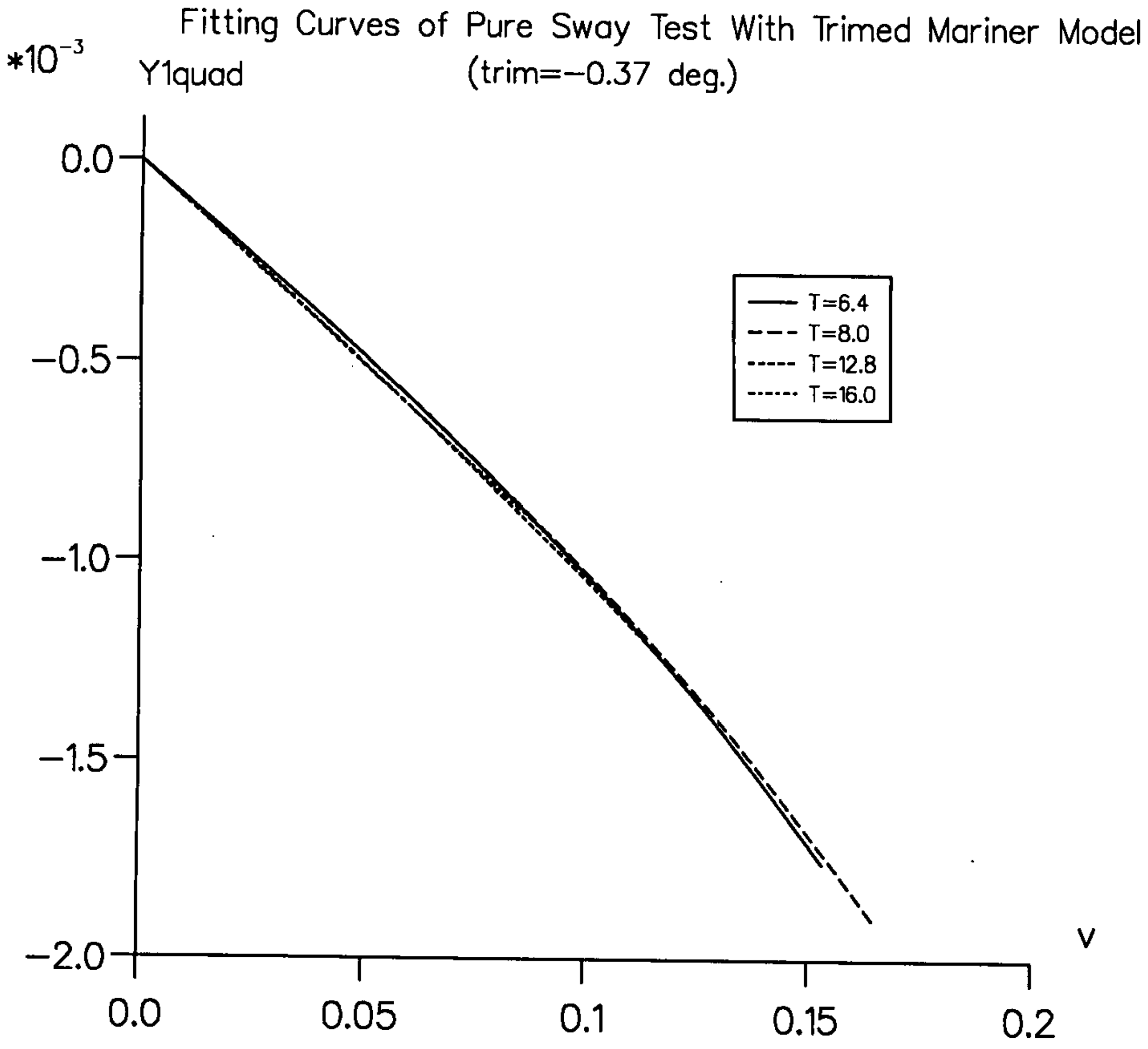

Raw Data of Pure Sway Test with Trimmed Mariner Model
(trim=−0.37 deg.)
*10^−3
Y1quad
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.05
0.1
0.15
0.2
v
T=6.4
T=8.0
T=12.8
T=16.0

Fig.44b



Fitting Curves of Pure Sway Test With Trimed Mariner Model
(trim=−0.37 deg.)

Fig.45a

Raw Data of Pure Sway Test with Trimed Mariner Model
(trim=–0.37 deg.)

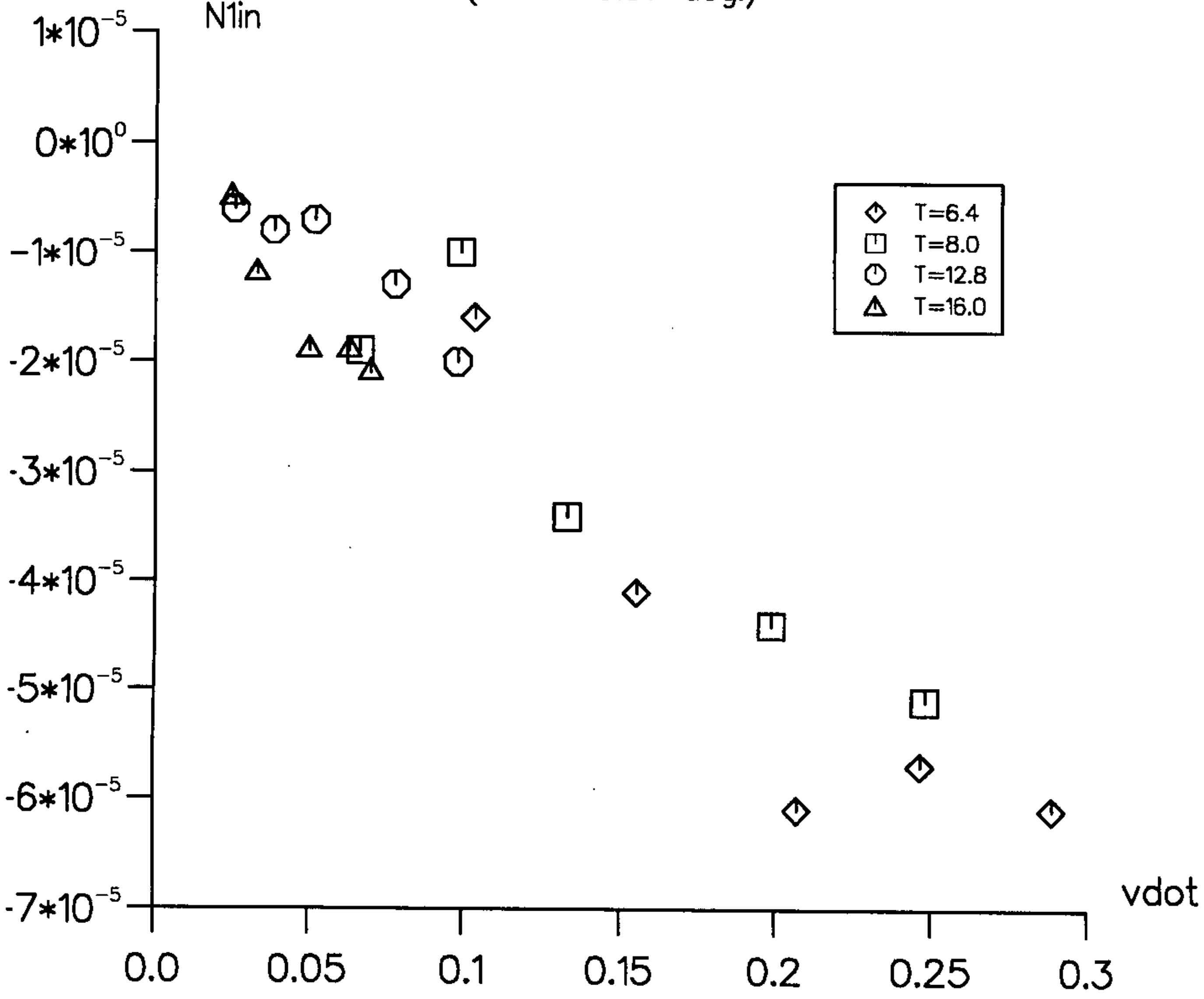


Fig.45b

Fitting Curves of Pure Sway Test with Trimed Mariner Model
(trim=−0.37 deg.)

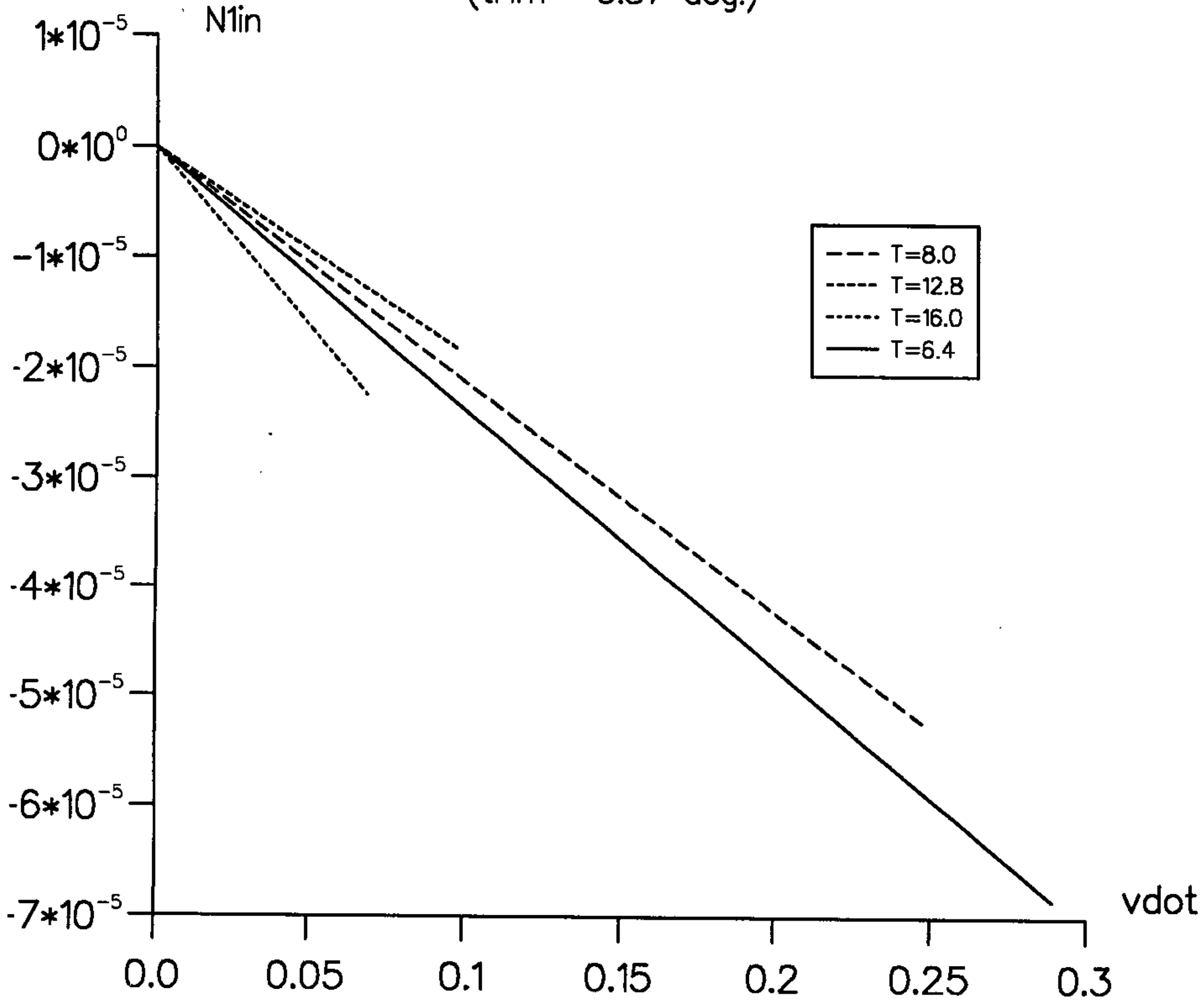
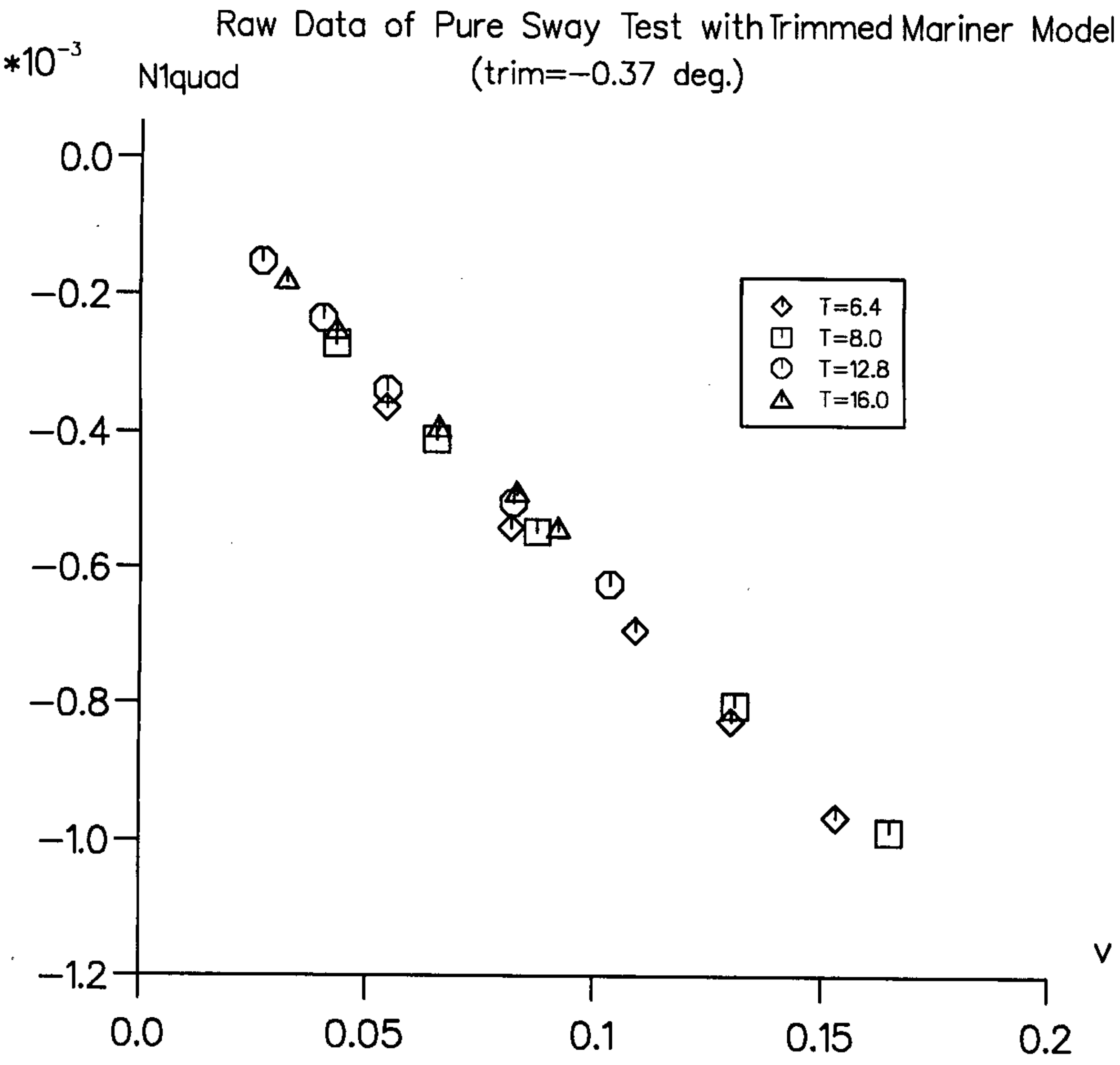
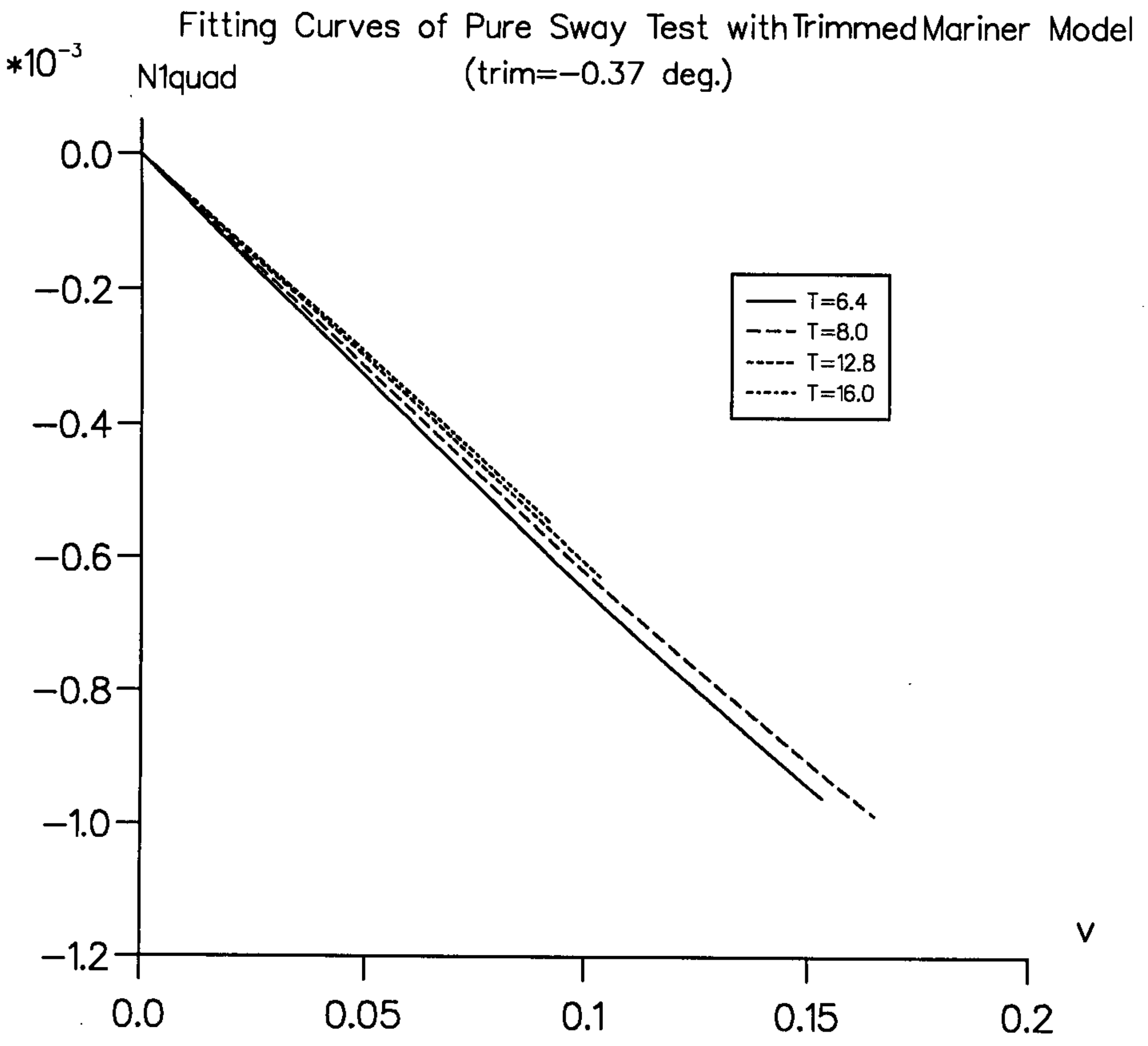


Fig.46a



Raw Data of Pure Sway Test with Trimmed Mariner Model
(trim=-0.37 deg.)

Fig.46b



Fitting Curves of Pure Sway Test with Trimmed Mariner Model
(trim=−0.37 deg.)

Fig.47a

Raw Data of Pure Yaw Test with Trimmed Mariner Model
(trim=−0.37 deg.)

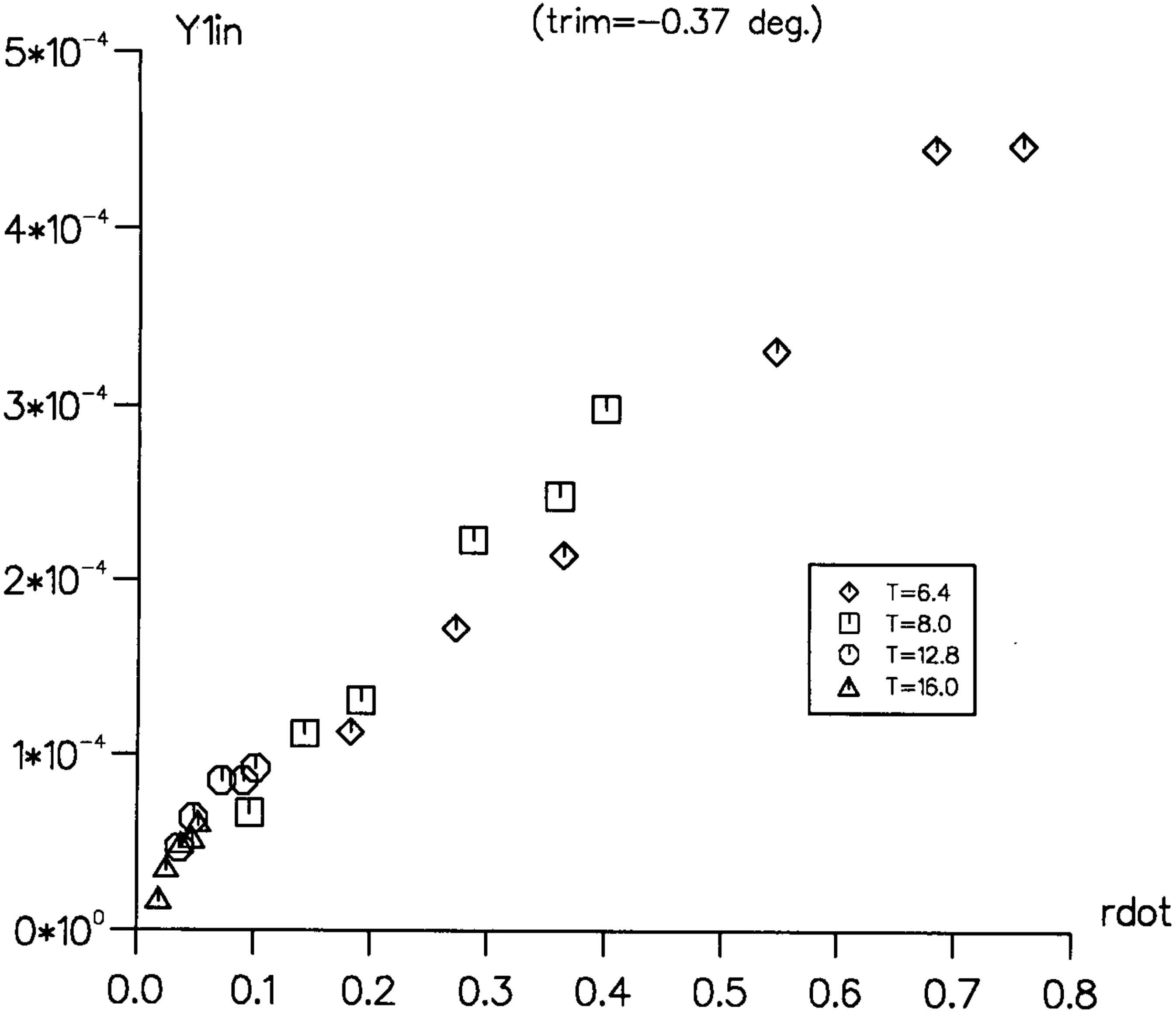


Fig.47b

Fitting Curves of Pure Sway Test with Trimmed Mariner Model

(trim=−0.37 deg.)

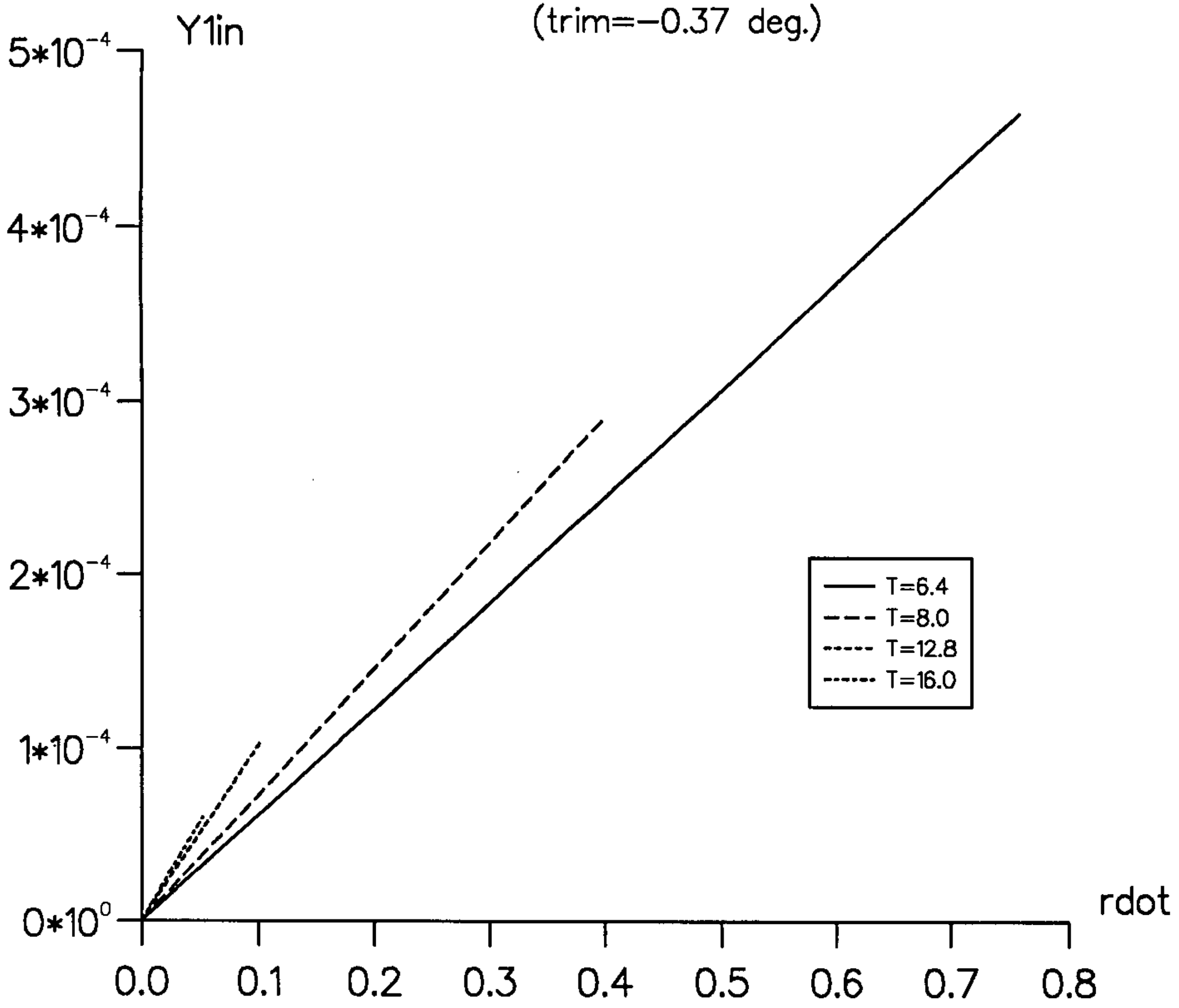


Fig.48a

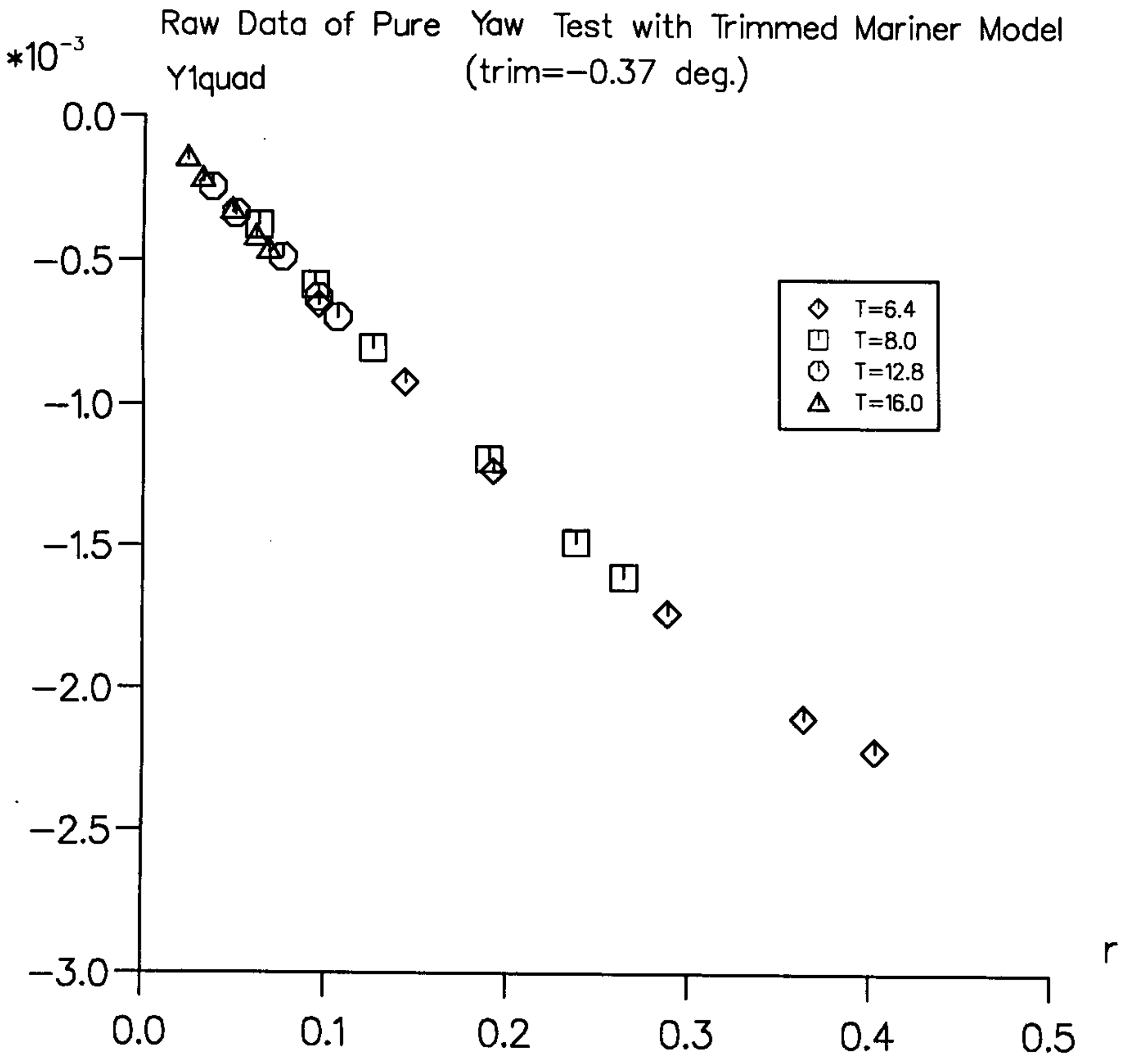

Raw Data of Pure Yaw Test with Trimmed Mariner Model
Y1quad
(trim=−0.37 deg.)
*10^-3
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
0.0
0.1
0.2
0.3
0.4
0.5
r
T=6.4
T=8.0
T=12.8
T=16.0

Fig.48b

Fitting Curves of Pure Yaw Test with Trimmed Mariner Model
(trim=−0.37 deg.)

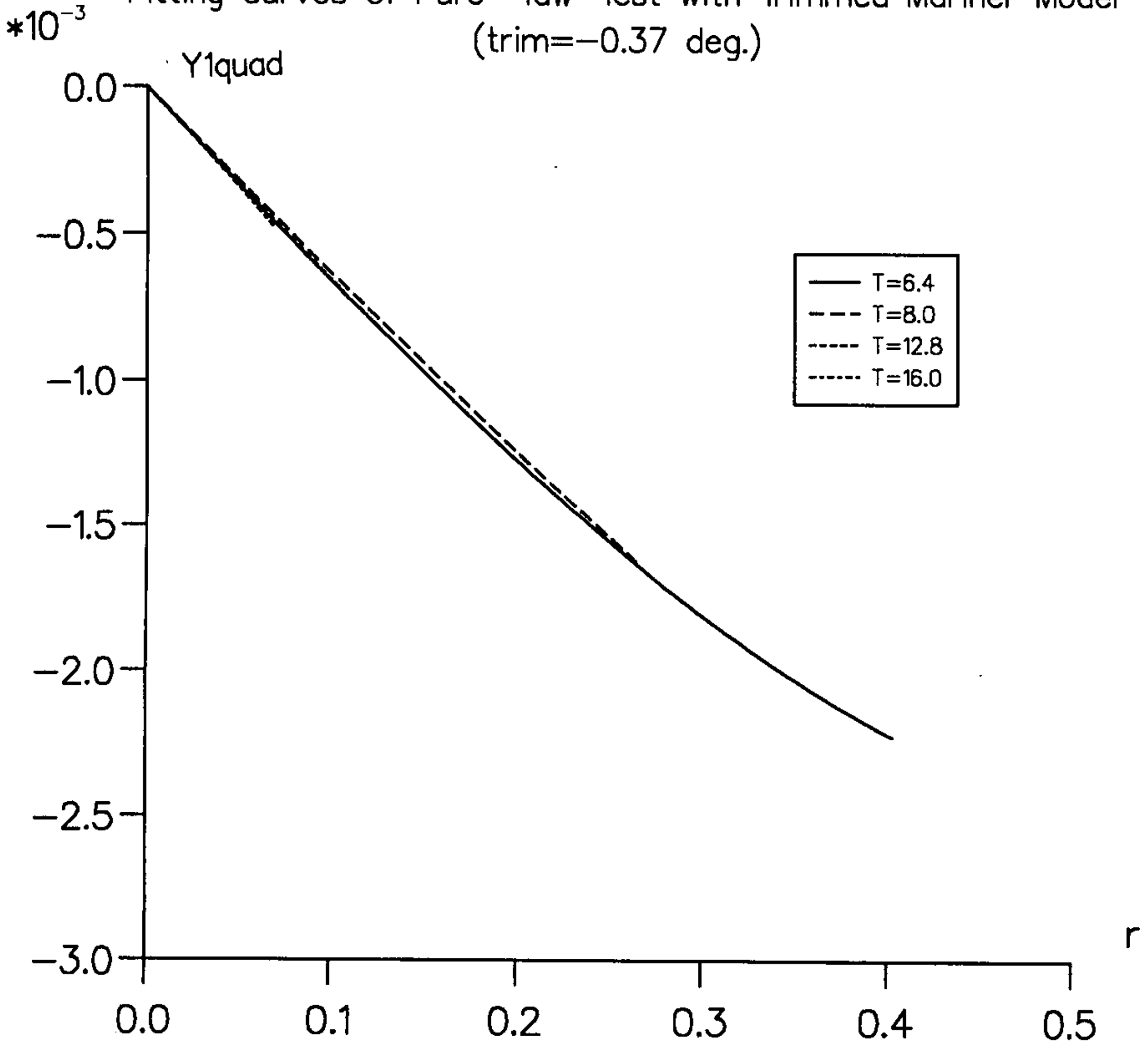
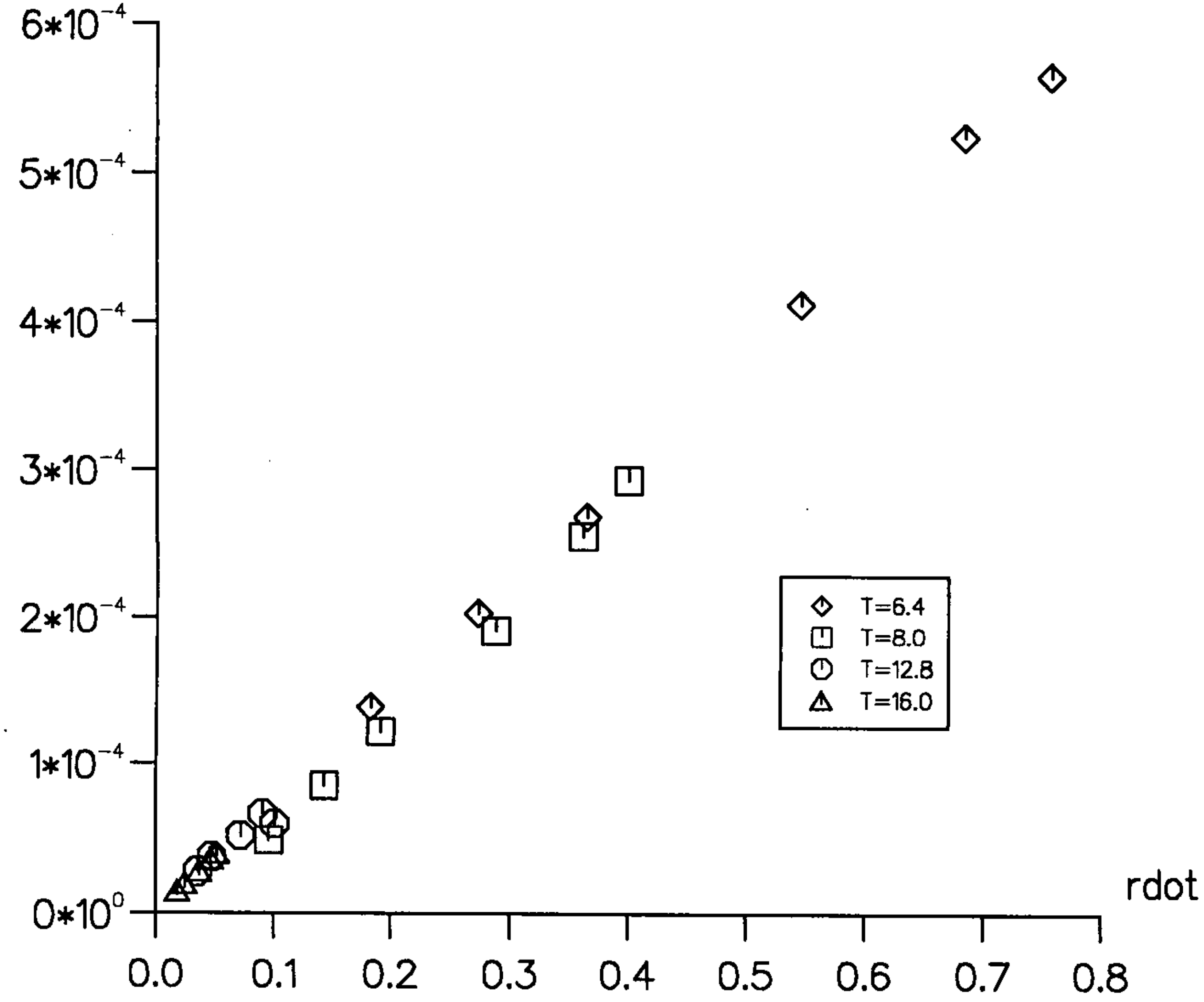


Fig.49a



Raw Data of Pure Yaw Test with Trimmed Mariner Model
(trim=−0.37 deg.)

Fig.49b

Fitting Curves of Pure Yaw Test with Trimmed Mariner Model
(trim=−0.37 deg.)

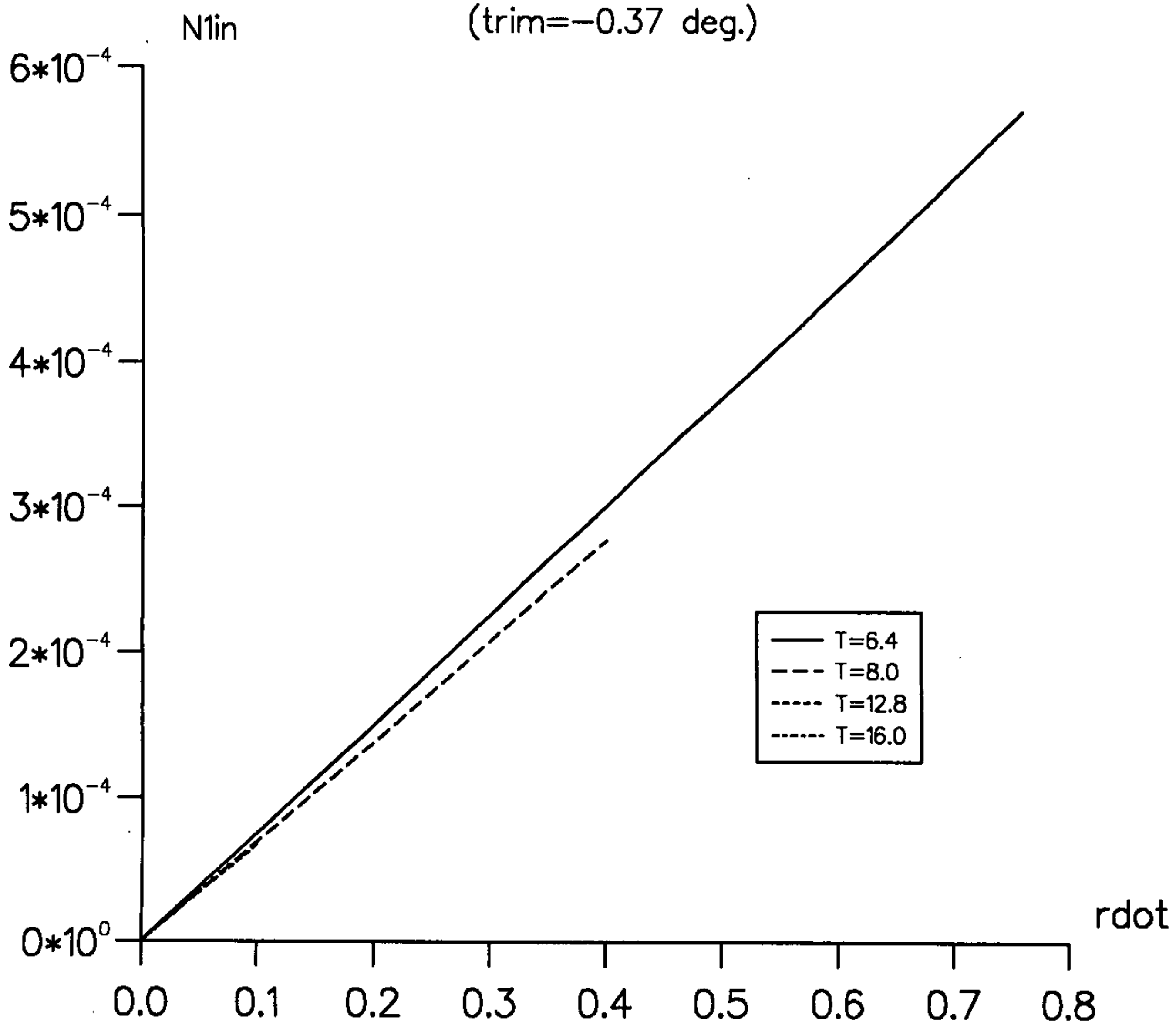


Fig.50a

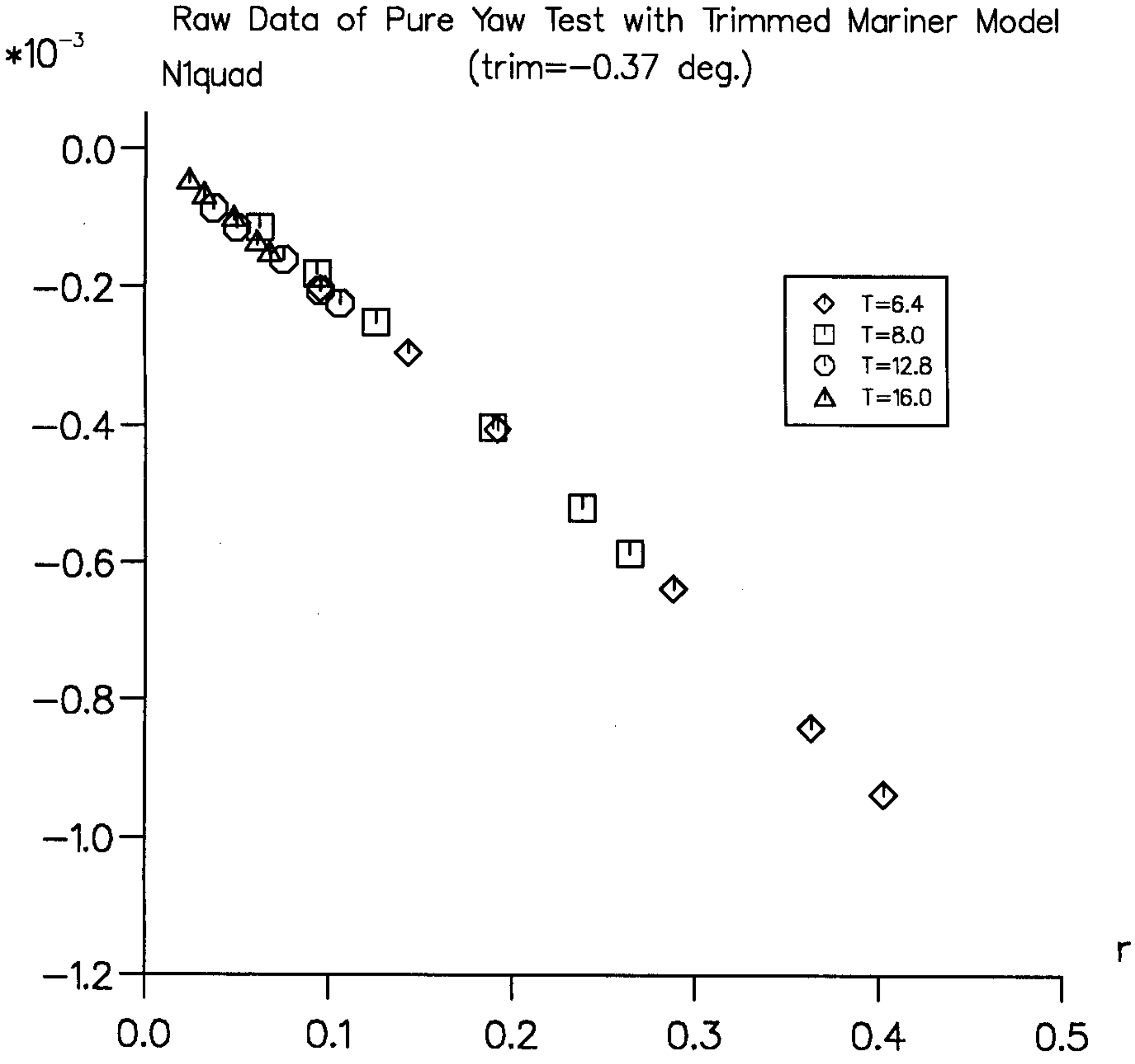

Raw Data of Pure Yaw Test with Trimmed Mariner Model
(trim=−0.37 deg.)
*10^−3
N1quad
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
0.0
0.1
0.2
0.3
0.4
0.5
r
T=6.4
T=8.0
T=12.8
T=16.0

Fig.50b

Fitting Curves of Pure Yaw Test with Trimmed Mariner Model
(trim=−0.37 deg.)

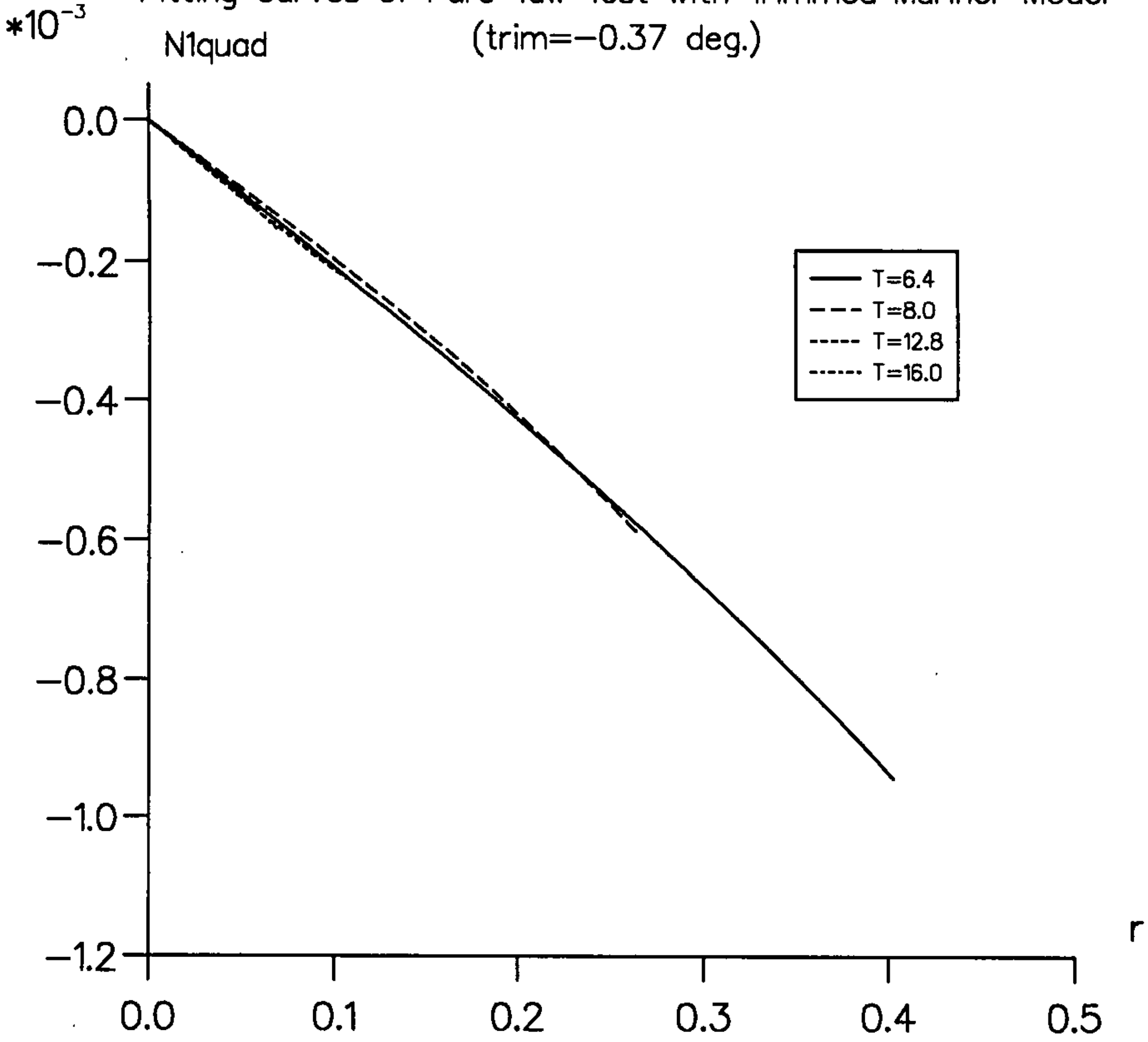


Fig.51a

Raw Data of Pure Sway Test withTrimmedMariner Model
(trim=1.5 deg.)

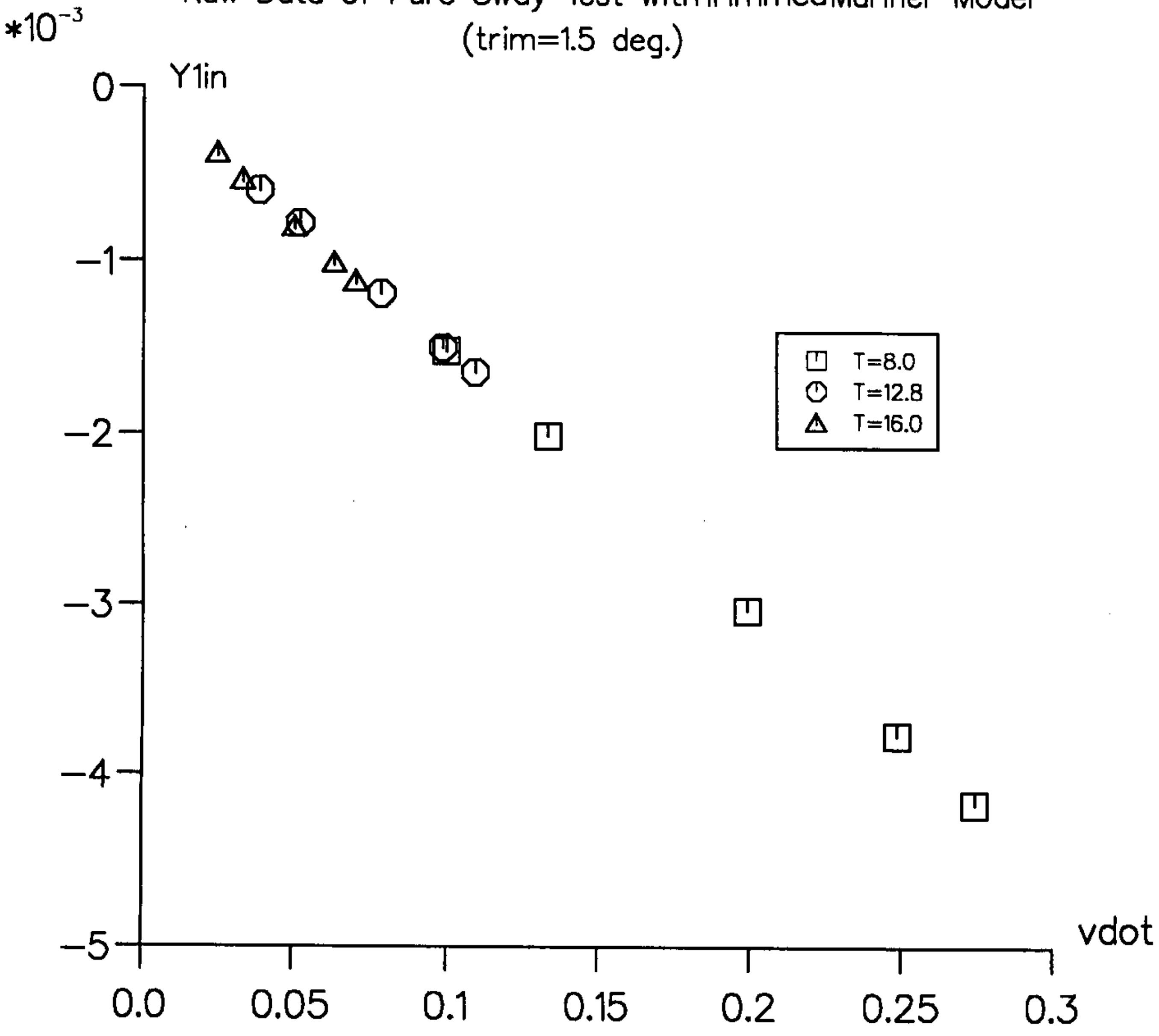


Fig.51b

Fitting Curves of Pure Sway Test withTrimmedMariner Model
(trim=1.5 deg.)

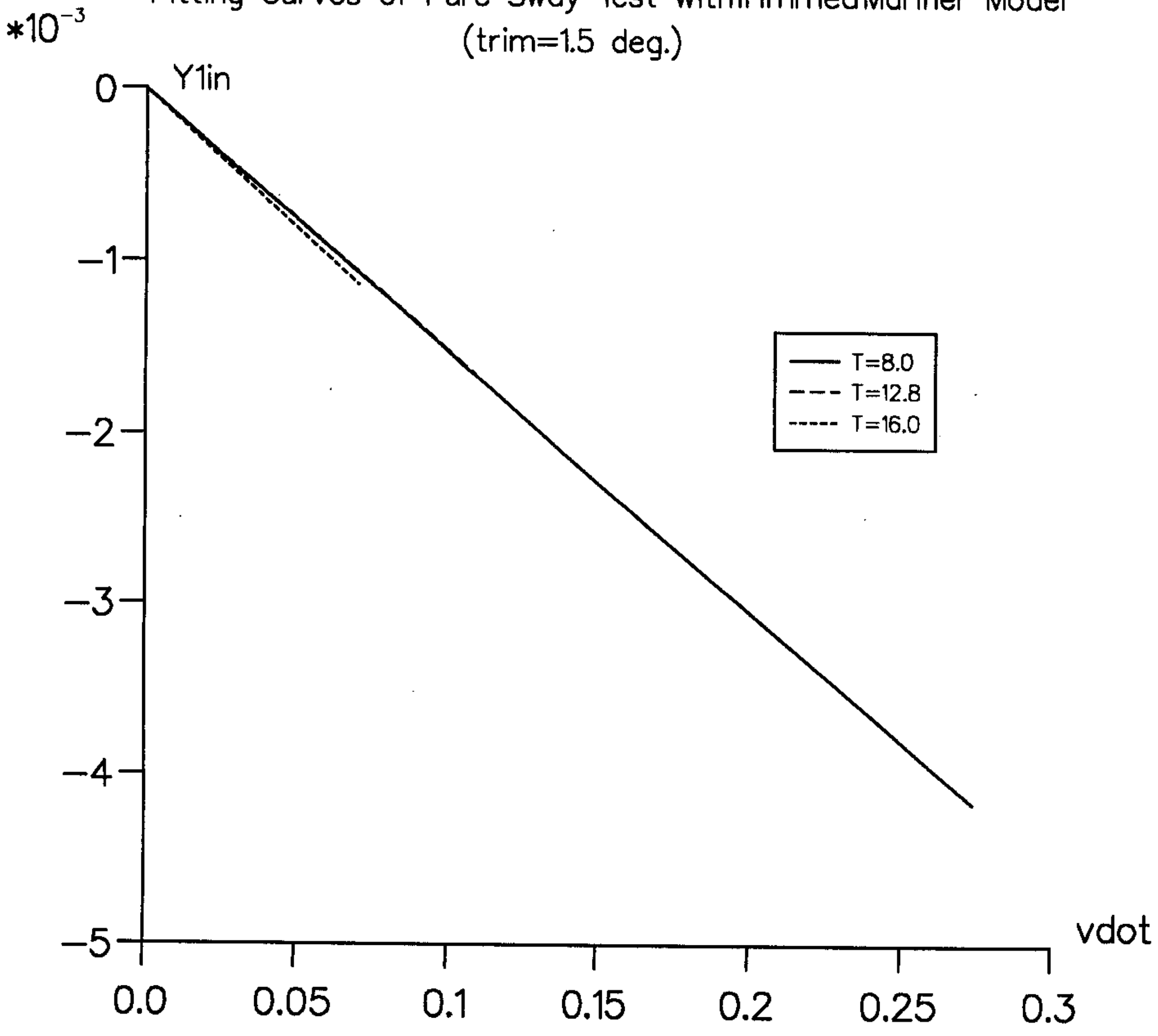


Fig.52a

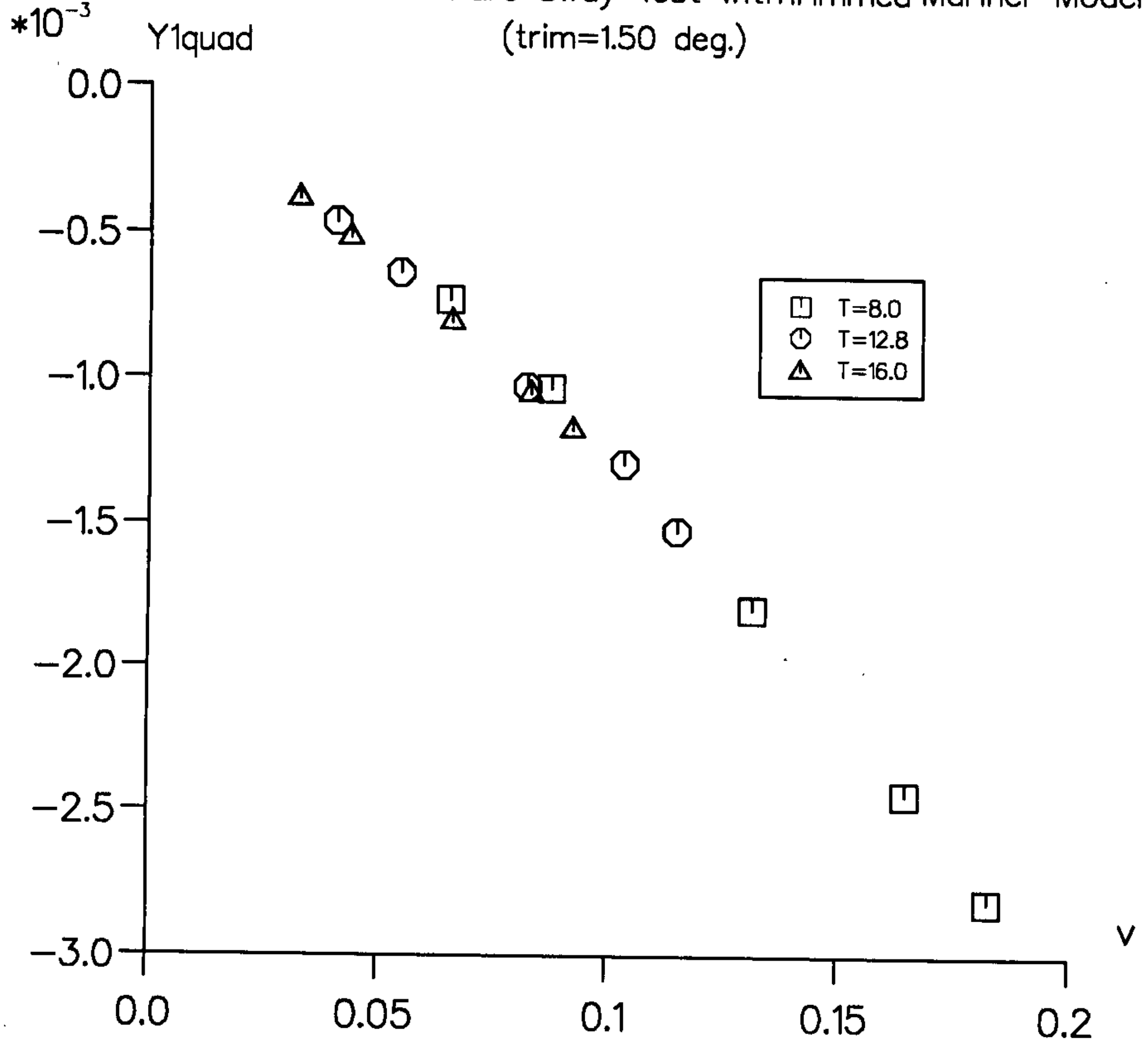

Raw Data of Pure Sway Test withTrimmed Mariner Model
(trim=1.50 deg.)

Fig.52b

Fitting Curves of Pure Sway Test With Trimmed Mariner Model

(trim=1.50 deg.)

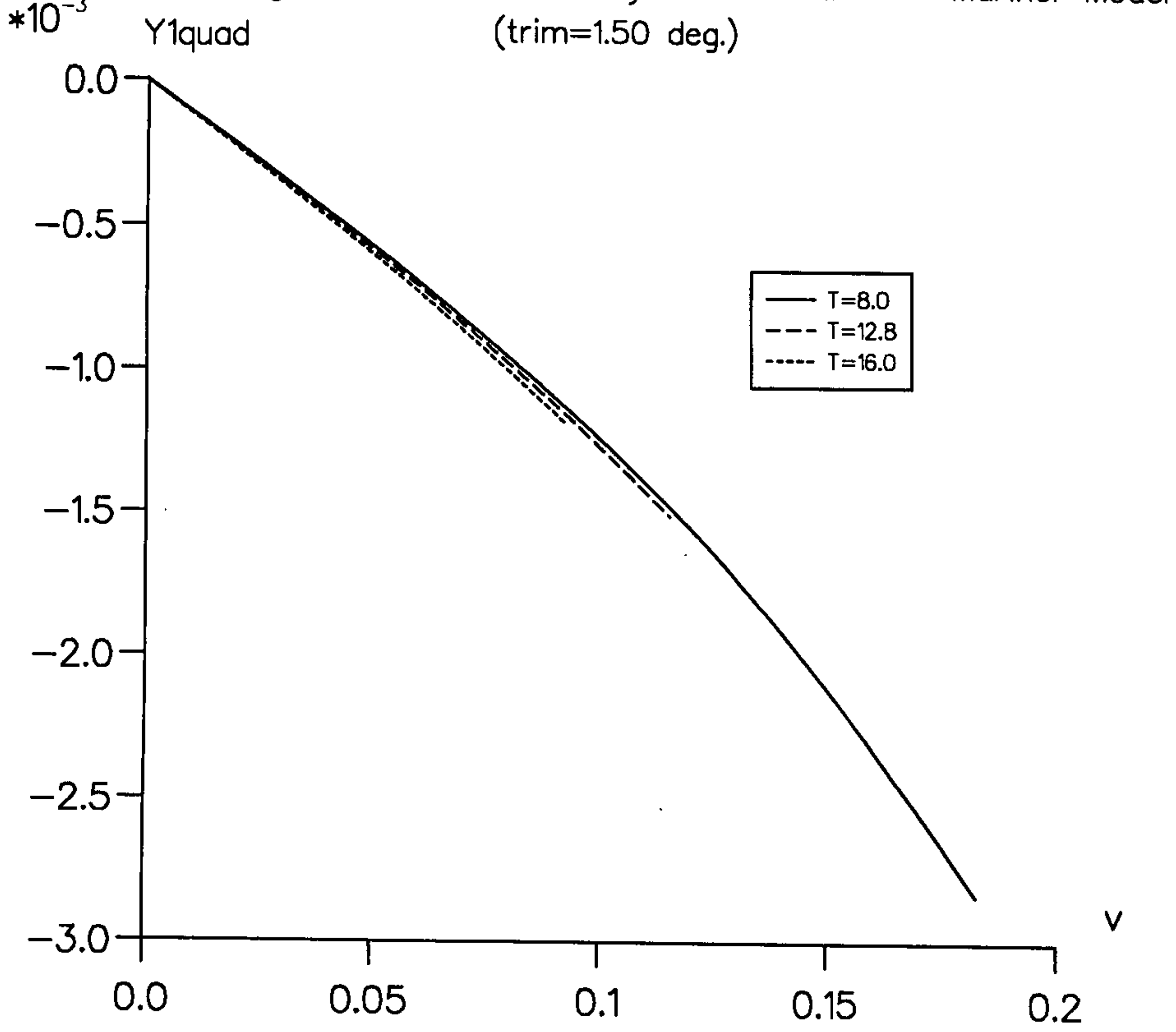
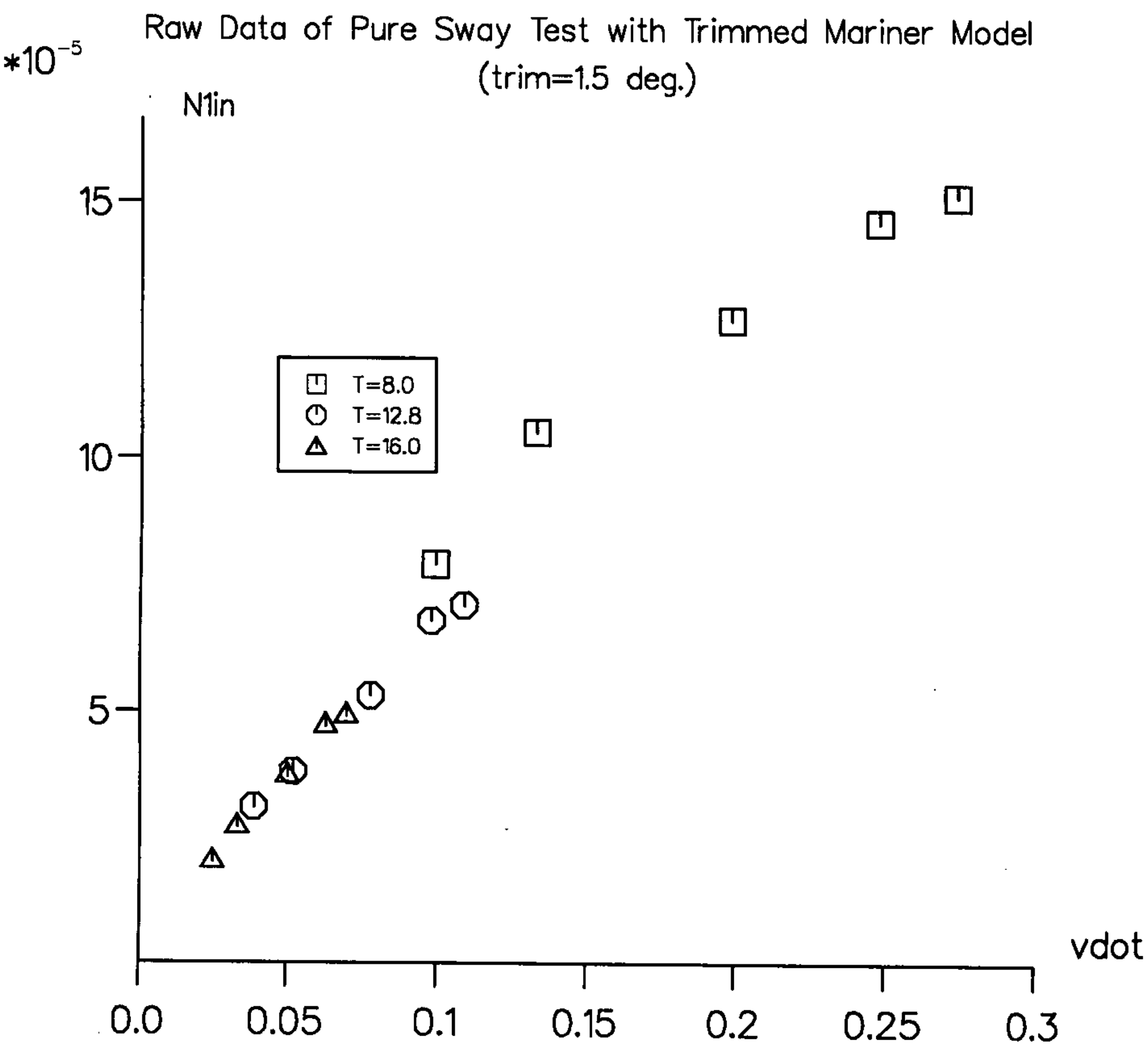


Fig.53a



Raw Data of Pure Sway Test with Trimmed Mariner Model
(trim=1.5 deg.)

Fig.53b

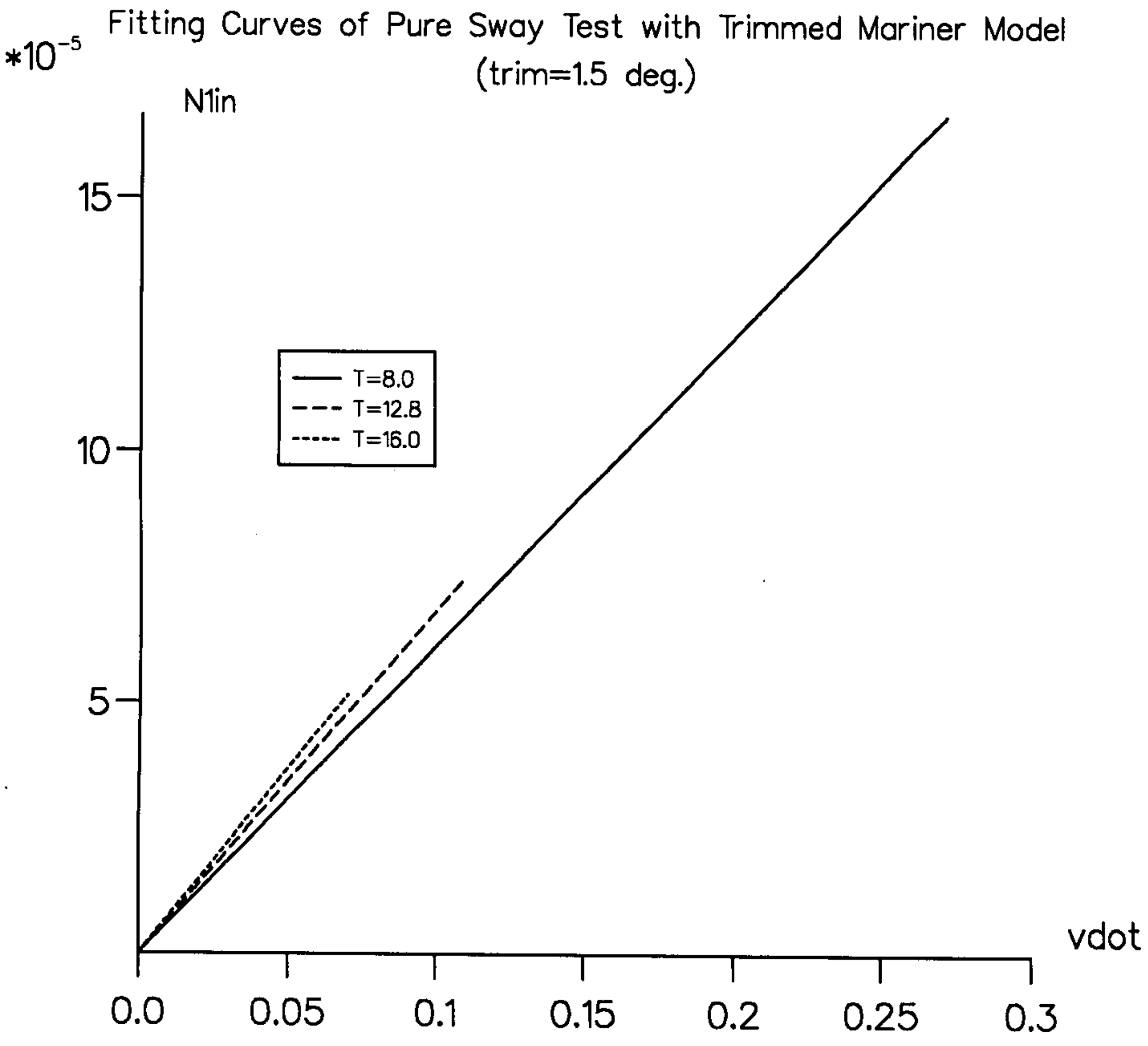

Fitting Curves of Pure Sway Test with Trimmed Mariner Model
(trim=1.5 deg.)

Fig.54a

Raw Data of Pure Sway Test with Trimed Mariner Model
(trim=1.50 deg.)

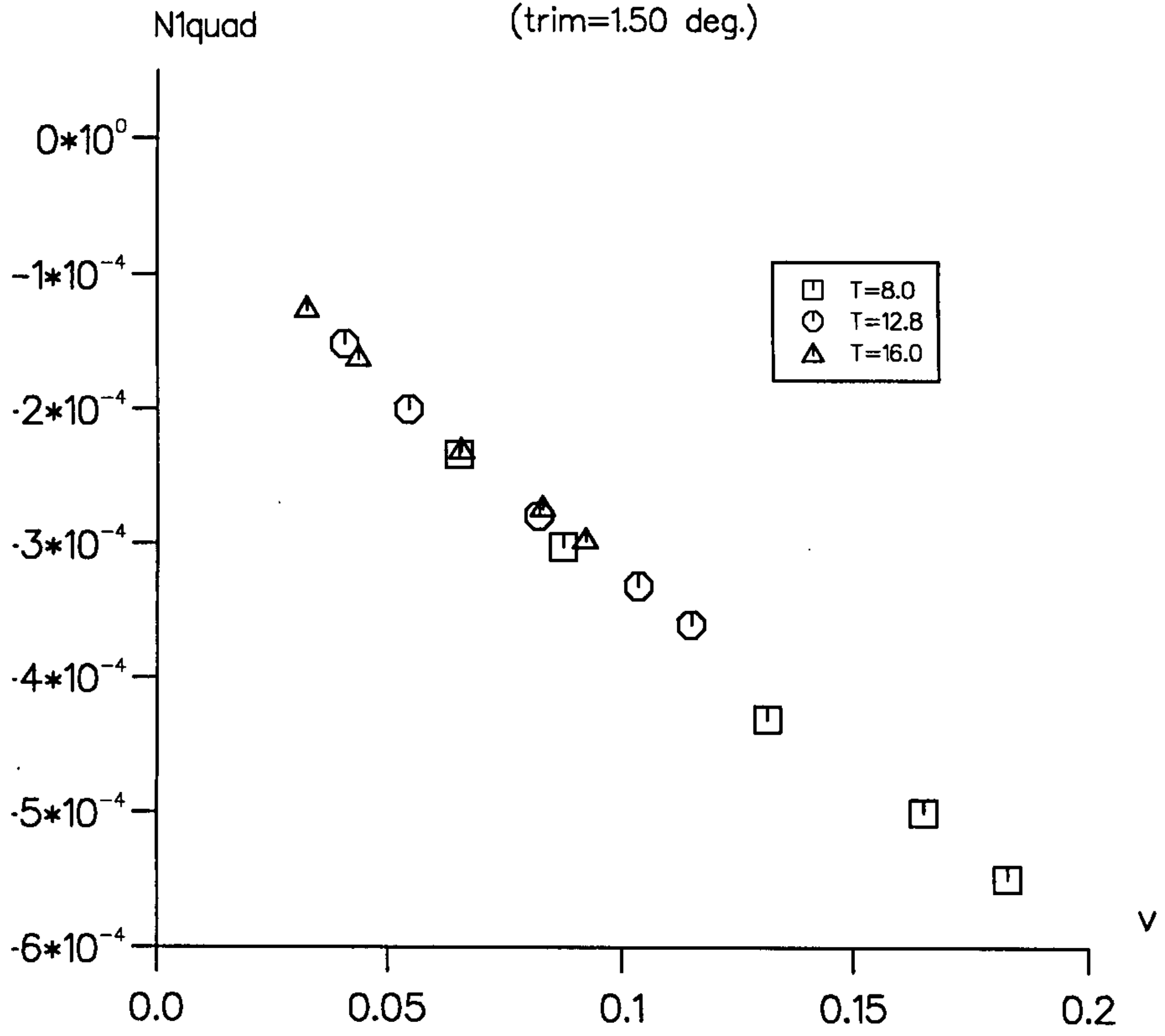


Fig.54b

Fitting Curves of Pure Sway Test with Trimed Mariner Model

(trim=1.50 deg.)

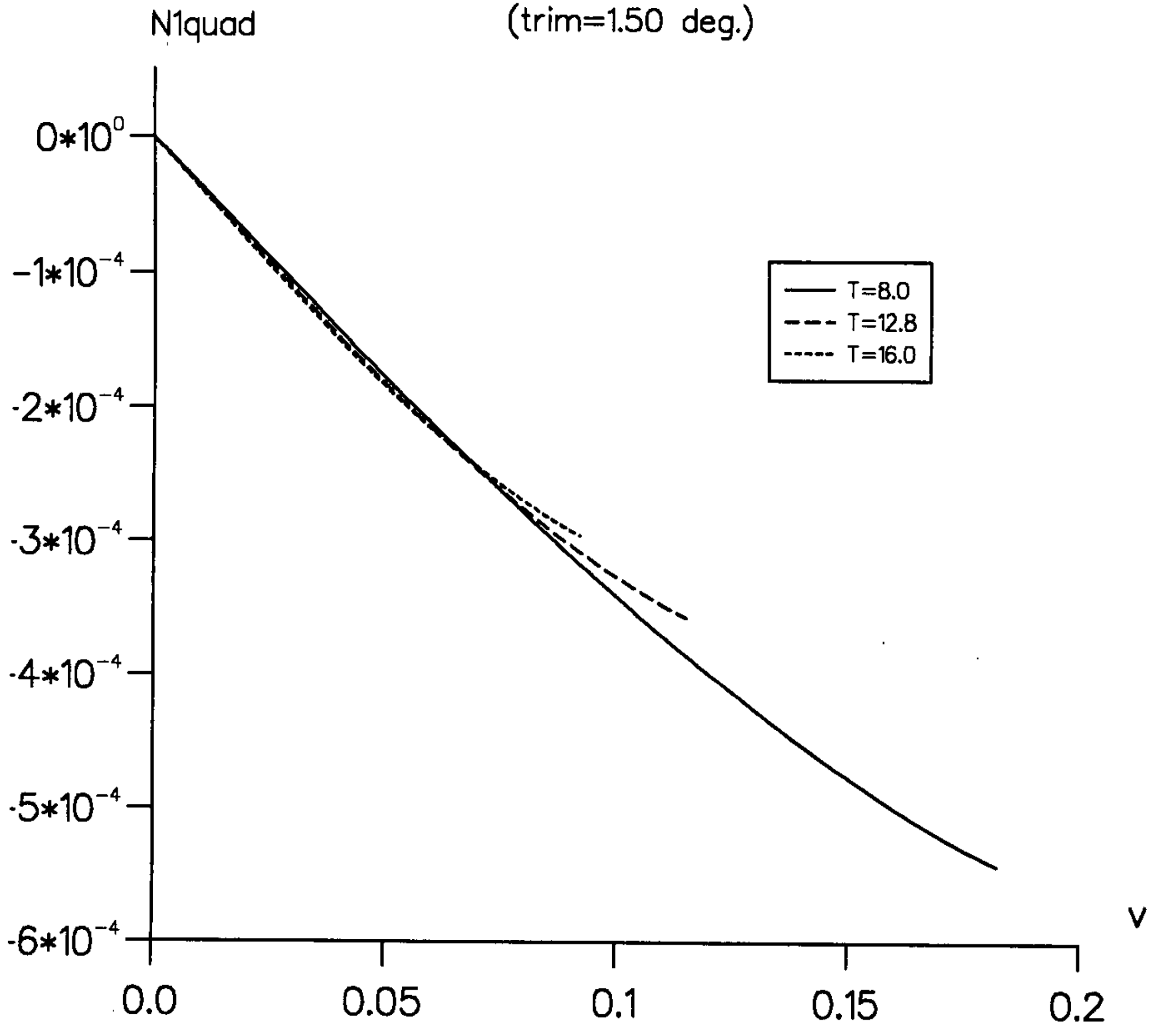
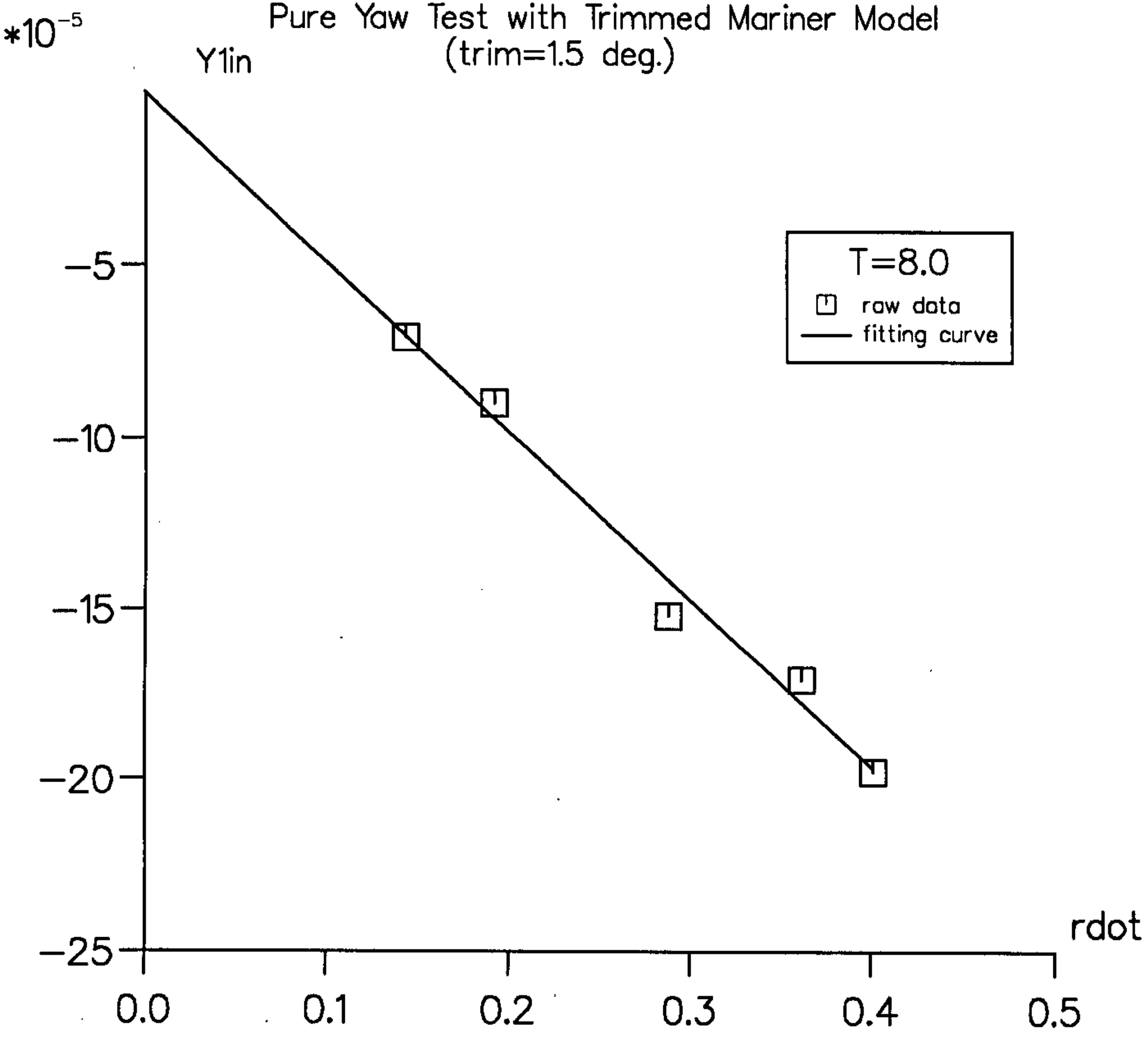


Fig.55



Pure Yaw Test with Trimmed Mariner Model
(trim=1.5 deg.)

Fig.56

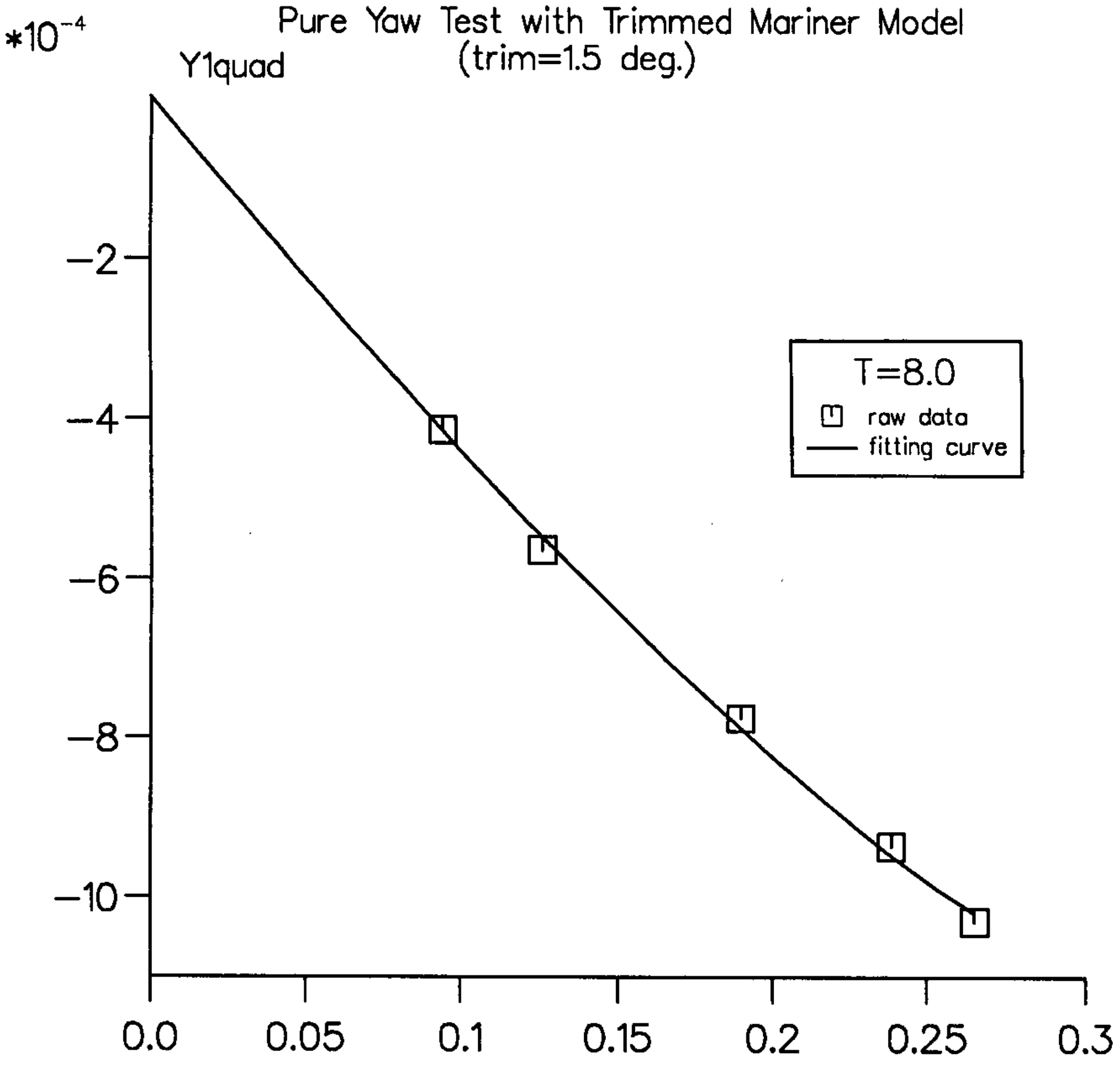

Pure Yaw Test with Trimmed Mariner Model
(trim=1.5 deg.)
$*10^{-4}$
Y1quad
−2
−4
−6
−8
−10
0.0
0.05
0.1
0.15
0.2
0.25
0.3
r
T=8.0
raw data
fitting curve

Fig.57

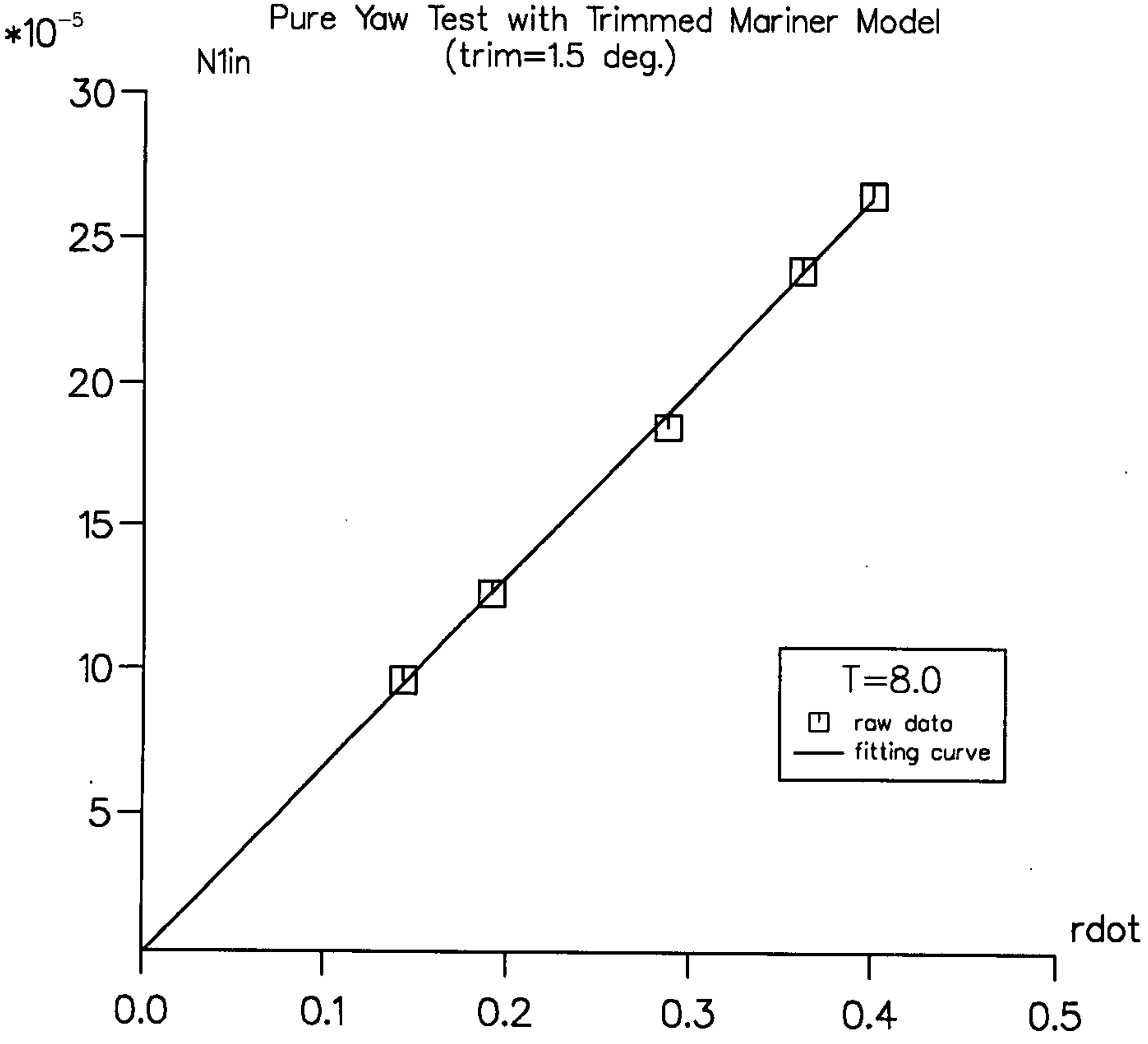
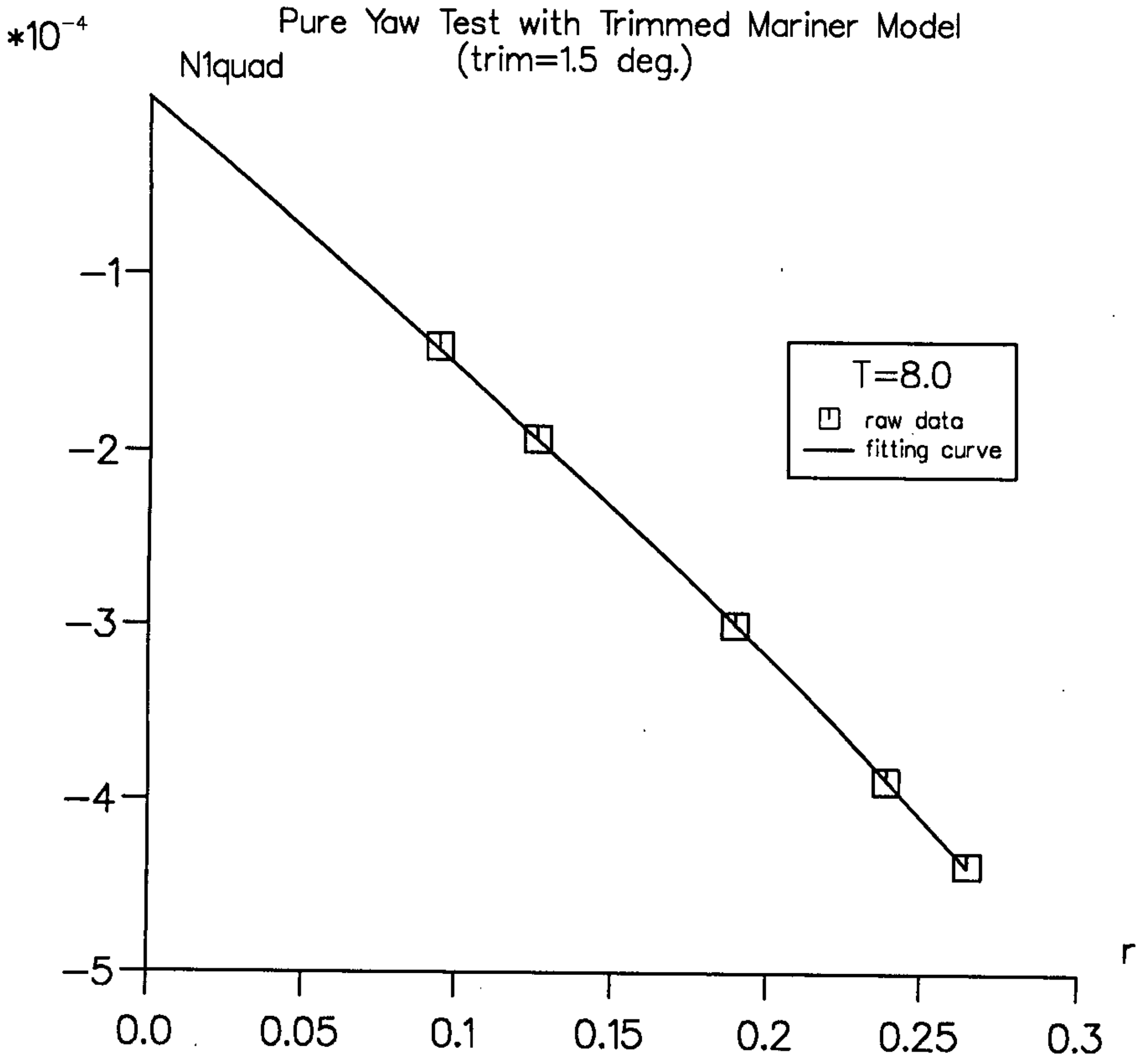

Pure Yaw Test with Trimmed Mariner Model
(trim=1.5 deg.)
*10⁻⁵
N1in
30
25
20
15
10
5
0.0
0.1
0.2
0.3
0.4
0.5
rdot
T=8.0
raw data
fitting curve

Fig.58


Pure Yaw Test with Trimmed Mariner Model
(trim=1.5 deg.)
*10⁻⁴
N1quad
−1
−2
−3
−4
−5
0.0
0.05
0.1
0.15
0.2
0.25
0.3
r
T=8.0
raw data
fitting curve