Wake and Thrust Deduction from Quasisteady Ship Model Propulsion Tests Alone

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Abstract

After continued theoretical and experimental studies extending over the last eight years a procedure has been developed permitting the determination of the interaction between ship hull, propeller, and duct, if any, from relatively short measurements taken during quasisteady propulsion tests, i. e. at small deviations from the service conditions. This systems identification procedure based on a few necessary and carefully selected axioms, i. e. conventions, may be the only meaningful, as e. g. for partially integrated ducts, and/or may be the only practical, as e. g. for full scale ships in operation.

The feasibility of this procedure has been proven in model tests using the standard measuring techniques available and has been finally developed for routine applications in towing tanks and circulating tunnels. After the previous fundamental work only the problems of reliable measurements of the acceleration and extrapolations to the equivalent states of vanishing thrust and vanishing advance ratio had remained to be solved. Where possible parallel evaluation of the measurements according to the traditional procedure is performed, as shown in the results of the model tests reported.

As expected the procedure provides much broader, more reliable, and more relevant information, even if the traditional procedure fails, and it can be performed faster and more cheaply as compared to the traditional technique based on propulsion tests at steady conditions and requiring extra hull towing and propeller open water tests, although these may provide rather meaningless results as e. g. open water tests with wake-adapted propellers.

As long as only few results are available judging the model results and predicting full scale performance remain of course major problems. One possible and in some cases, e. g. of ducted propellers, necessary step towards better simulation of the flow around the ship, boundary layer suction at the model, has been successfully tested in a preceding project. The necessity of turbulence stimulation at the propeller is being investigated.

Not only for research into the scale effects, the present knowledge of which is based on very scarce data, it is imperative that the new technique be tested and utilized on board of full scale ships as soon as possible. It may then be used for research into and monitoring of the daily operation, e. g. determination of effects of loading, water way, weather conditions, and fouling on all relevant efficiencies and factors of merit.

In view of its far-reaching impact on all aspects of performance analysis and prediction it is hoped that the community concerned will consider and test the procedure proposed and explore its potential, maybe under the auspicies of the ITTC Powering Performance Committee as has been the case 50 years ago with Horn's proposal, an early forerunner of the present work.

1. Introduction

Traditionally propulsion tests with ship models are performed at steady conditions. After the phase of model acceleration by the towing carriage the model is released and its speed is adjusted to the constant carriage speed. After steady conditions have been established the model speed, frequency of shaft revolution, propeller thrust, and propeller torque are being measured. For a detailed analysis of the propulsive performance additional towing tests with the hull alone and open water tests with the propeller alone have to be performed.

For many hull-propeller configurations this traditional procedure is quite inadequate due to the different flow conditions in propulsion, towing, and open water tests. The traditional procedure may be even impossible, as e. g. for full scale ships. Consequently a procedure is in urgent need permitting adequate propulsion analysis in any case under service conditions at model as well as full scale.

A procedure taylored to suit exactly the problem outlined has been developed on the basis of sets of axioms, principles, or conventions, i. e. three coherent and adequate mathematical models of hull-propeller interaction, namely the equivalent conditions of vanishing displacement wake, vanishing total wake, and vanishing thrust (Schmiechen 1984, 1985). The data necessary are propeller thrust and torque as well as the necessary towing force at a given constant speed for various frequencies of shaft revolution, i. e. overload tests according to the British method.

Applying and measuring towing forces and adjusting steady conditions at model as well as full scale may be difficult if not practically impossible. In towing tanks the application of towing forces introduces unnecessary disturbances into the systems under investigation, while at full scale ships under service conditions towing forces cannot be realized.

Consequently it has been proposed to replace steady testing by quasisteady testing at small quasisteady, but else arbitrary variations of the frequency of shaft revolution around its service condition. In this case the inertial forces replace the external towing forces. In principle this technique has been tested successfully some time ago with a set-up developed for a different purpose (Schmiechen, 1984).

At this state of affairs the goal of the present project was to develop a technique for routine application in towing tanks and in circulating tunnels, where the problems are somewhat different as will be discussed in due course. In order to save testing time and money and stick to steady testing at the same time the original idea was to use the control phase after release of the model for data acquisition only. In view of the range and quality of data this idea was given up in favour of quasisteady oscillatory changes of the frequency of propeller revolutions.

After the preceding fundamental experimental and theoretical developments which have been carefully documented and discussed (s. 8. References) only two problems remained to be solved, which had not been addressed thoroughly before. The first problem was the reliable measurement of model accelerations in the range of less than ± 1/1000 g with a simple technique. The second problem was the meaningful, practical extrapolation to the states of vanishing thrust and vanishing advance ratio, respectively.

The plan of this report is to describe the test technique, the model tests, and, last but not least, the test results evaluated according to the rational procedure proposed and according to the traditional procedure for comparison. Theories will be presented only as far as necessary to link up with the basic reference in English (Schmiechen, 1984). The paper will conclude with an outlook on future projects and prospects.

It is of historical interest that as early as 1937 at the 4th ITTC in Berlin member organisations reported experience with an early forerunner of the present method proposed by Horn and Dickmann (Weitbrecht, 1937). The tests had been carried out following a recommendation of the 3rd ITTC in Paris 1935. The present work is the result of a new attempt to solve the old problem in the spirit of Horn using more powerful tools of philosophy than available in the early days of ship theory.

2. Test technique and data acquisition

The analysis of the propulsion performance of a ship model in a towing tank is based on

$$i = 1 \ldots n$$

sampled sets of measured values of the carriage speed V_i^f, the frequency of propeller revolutions N_i, the propeller thrust T_i, the propeller torque Q_{Pi}, maybe towing forces F_i^T, and the model displacement S_i relative to the carriage.

Differentiation of the displacement results in values of the relative model speed V_i^r and further differentiation in values of the relative model acceleration A_i^r. If the small oscillations of the carriage speed at the tests are of higher frequencies than the changes of the relative model speed caused by the quasisteady changes of the frequency of revolutions the total model speed is

$$V_i = \bar{V}^f + V_i^r$$

and the total towing force is

$$F_i = F_i^T - m\ A_i^r \quad .$$

This simple filter technique can be applied e. g. in the deep water tank of VWS, while in the shallow water tank low frequency oscillations of the carriage had to be accounted for in later tests according to the complete equations of the total speed

$$V_i = V_i^f + V_i^r$$

and the total force

$$F_i = F_i^T - m\ A_i$$

with the total acceleration

$$A_i = A_i^f + A_i^r .$$

In the circulating tunnels the equations to be applied are simply

$$V_i = \overline{V}$$

and

$$F_i = F_i^T .$$

The differentiations necessary are simply performed via Fourier analysis with subsequent synthesis, the noise being suppressed by ignoring orders beyond the range of interest. At the tests reported 200 sets of samples have been taken in about 2 minutes covering about 4 periods. Consequently harmonic components up to the 15 order have been considered to be relevant. Small drifts have been accounted for separately. The first set of figures shows the basic data of a randomly chosen test run without any correction.

In the range of interest of less than ± 1/1000 g measurement of the acceleration cannot be performed by an accelerometer on the model. Although an attempt to keep the accelerometer free of the small pitch motions of the model was successful the noise introduced by the model drive did upset the measurement. Finally a simple potentiometer was used to measure the relative displacement of the model in the range of about ± 0.3 m relative to the carriage and two consecutive differentiations were performed without problem as described.

The inertia or mass m of the model may be derived from its desplacement volume ∇ and the density ρ of the water and the inertial effects of the surrounding water, i. e.

$$m = \rho\nabla + m_x^h .$$

In the present study a constant ratio

$$m_x^h/\rho\nabla = 0.05$$

has been used for the model ratios

$$L/B = 6.589$$

and

$$B/T = 3.917$$

based on the idea of an equivalent ellipsoid.

To directly measure towing forces acting on a model rigidly connected to the carriage by a balance is impossible due to carriage control. As already mentioned the situation is different in circulating tunnels. In full scale tests the technique described for tests in towing tanks can be applied without change. The solution of the various measuring problems will be subject of a research and development project funded by the German Federal Ministry of Research and Technology.

3. Data reduction and extrapolation

The basic data obtained in quasi-steady propulsion tests as described before have to be reduced before a performance analysis can be undertaken. Following the arguments of the theory of similarity any quasisteady state may be uniquely described by

the thrust ratio

$$K_T \equiv T/(\rho D^4 N^2) = k_T (J_H, F_n, R_n)$$

the torque ratio

$$K_{QP} \equiv Q_P/(\rho D^5 N^2) = k_{QP} (J_H, F_n, R_n)$$

and the force ratio

$$K_F \equiv F /(\rho D^4 N^2) = k_F (J_H, F_n, R_n)$$

as function of the hull advance ratio

$$J_H \equiv V/(DN)$$

the Froude and the Reynolds numbers F_n and R_n, respectively.

The thrust, torque, and force functions k are a complete description of the quasisteady dynamics of the hull-propeller system in the range investigated at the average Froude number

$$\overline{Fn} \equiv \overline{V}/(g\ L)^{1/2}$$

under consideration. As indicated the dynamic functions k are further depending on the normalized viscosity, i. e. the Reynolds number

$$R_n \equiv VL/\nu$$

or the ratio of Reynolds and Froude numbers

$$r \equiv R_n/F_n = g^{1/2}\ L^{3/2}/\nu$$

or the scale factor

$$s \equiv (R_n/F_n)^{2/3} = L\, g^{1/3}/\nu^{2/3} ,$$

the latter two being constant for a given model at a given water condition.

Extensive investigations have shown that in the present tests the small deviations of the Froude number from the average had no detectable explicite influence on the dynamic functions. In view of the omnipresent noise it can be safely assumed that this situation will be the same in general. Consequently the axiom or convention

$$K = k_{(s,\overline{Fn})}(J_H)$$

may be stipulated.

In view of the excellent test conditions in the deep water tank of VWS the noise in the measurements was felt to be somewhat large. As the cross correlation of the torque and force ratios with the thrust ratio indicate this noise was due to the resolution of the frequency of revolution being too poor for the purpose at hand. Further the torque data of the run selected show that there has been some systematic problem at higher propeller loadings which was not observed at other runs.

In view of the noise, which will be larger in most cases, e. g. in circulating tunnels and at full scale, and the extreme range of extrapolation it was found after much deliberation and experimentation that the only way to obtain a meaningful set of faired propulsion data, were linear fits to the functions

$$K_T = k_{TH}(J_H) = K_{T0} + K_{TH}^{(1)} J_H$$

and

$$K_{QP} = k_{QT}(K_T) = K_{QP0} + K_{QPT}^{(1)} K_T .$$

Again these linear laws have to be agreed upon as axioms, i. e. as adequate principles under the conditions given, and the way of fairing may have to be standardized in addition, i. e. agreed upon as well.

In the present case fits have been performed according to the procedure described in the basic reference, for numerical reasons after normalisation of the range of investigation to

$$-1 \leq x \leq +1 \ ,$$

where

$$x = (J_H - J_{HC})/J_{HR} \ ,$$

J_{HC} denoting the centre and J_{HR} the radius of the range. The two linear functions so obtained may of course be combined to derive the linear relation

$$K_{QP} = K_{QP0} + K_{QPH}^{(1)} J_H$$

between the torque and the hull advance ratio.

The purpose of the extrapolations will be explained in detail in the next chapter. They are certainly not intended to predict the performance of the propeller outside the range of observation. Quite to the contrary the purpose is to continue the tendencies observed in the vicinity of the service condition. As can be seen from the data presented and as can be concluded by theoretical arguments a linear fit to the force data is not adequate. This problem will be addressed after the elaboration on the determination of the total wake and the various performance parameters of the propeller which can be evaluated as soon as the wake is known.

6. Conclusions

The present study has shown by way of example that based on the ideas promoted now for eight years an adequate and effective systems identification procedure for testing and analysing the propulsive performance of ship models in towing tanks and circulating tunnels can be derived. As expected the procedure provides much broader, more reliable, and more relevant information, even if the traditional procedure fails, and it can be performed faster and more cheaply as compared to the traditional technique based on propulsion tests at steady conditions and requiring extra hull towing and propeller open water tests, although these may provide results of rather doubtful value as e. g. open water tests with wake-adapted propellers.

The technique of quasisteady testing can be performed with the standard measuring techniques available in every towing tank. And the technique of analysis is based on the conceptual frame work familiar to every naval architect with the addition of only a few carefully selected axioms permitting an analysis on the basis of only one coherent set of data obtained under service conditions.

It is important to note here that the axioms are conventions to be agreed upon by the parties interested. The rational method advocated is therefor a conventional method as is the traditional method. The difference is that the axioms of the rational method are explicitely stated and more or less plausible, constituting coherent mathematical models, while the traditional conventions and their implications are hard to grasp.

As long as only few results are available judging the model results and predicting full scale performance remain of course major problems. One possible and in some cases, e. g. of ducted propellers, necessary step towards better simulation of the flow around the ship, boundary layer suction at the model, has been successfully tested in a preceding project. The necessity of turbulence stimulation at the propeller is being investigated.

Not only for research into the scale effects, the present knowledge of which is based on very scarce data, it is imperative that the new technique be tested and utilized on board of full scale ships as soon as possible. It may then eventually be used for research into and monitoring of the daily operation, e. g. determination of effects of loading, water way, weather conditions, and fouling on all relevant efficiencies and factors of merit. As has been mentioned a project to this effect funded by the German Ministry of Research and Technology is well under way.

In view of its far-reaching impact on all aspects of performance analysis and prediction it is hoped that the community concerned will consider and test the procedure proposed and explore its potential, maybe under the auspicies of the ITTC Powering Performance Committee as has been the case 50 years ago with Horn's proposal, an early forerunner of the present work.

It is important that the normative aspect of the whole procedure proposed be fully understood and appreciated. Further, standardisation of procedures for measurement and analysis will have to be agreed upon. This is absolutely mandatory in view of the measurement noise and the sensitivity of the analysis.

The present report is a preliminary version of the final report on a project administered by the Forschungszentrum des Deutschen Schiffbaus in Hamburg. Funding derived from the European Recovery Program and made available by the Senator für Wirtschaft und Arbeit in Berlin is gratefully acknowledged.

The impact of the present work and its underlying philosophy on the design of propellers has not been mentioned in this report. Work has been done in this field (Schmiechen and Zhou, 1987) along the lines indicated in a speculative reconstruction of the problem (Schmiechen, 1983).

8. References

Schmiechen, M. (1968): Performance Criteria for Pulse-Jet Propellers. Proc. 7th Symp. on Naval Hydrodynamics, pp. 1085-1104.

Schmiechen, M. (1970): Über die Bewertung hydromechanischer Propulsionssysteme. Schiffstechnik Vol. 17, No. 89, pp. 91-94.

Schmiechen, M. (1980a): Eine axiomatische Theorie der Wechselwirkungen zwischen Schiffsrumpf und -propeller. Schiffstechnik, Vol. 27, No. 2, pp. 67-99.

Schmiechen, M. (1980b): Nachstrom und Sog aus Propulsionsversuchen allein. Eine rationale Theorie der Wechselwirkungen zwischen Schiffsrumpf und -propeller. Jb. STG, Vol. 74, pp. 333-351.

Schmiechen, M. (1982): Über Weiterentwicklung des Vorschlages "Nachstrom und Sog aus Propulsionsversuchen allein". Schiff & Hafen, Vol. 34, No. 1, pp. 91-92.

Schmiechen, M. (1984): Wake and Thrust Deduction from Propulsion Tests Alone. A rational theory of ship hull-propeller interaction. Proc. 15th Symp. on Naval Hydrodynamics, pp. 481-500.

Schmiechen, M. (1985): Schiffsmodellversuche mit Grenzschichtbeeinflussung durch Absaugung. VWS-Bericht Nr. 1021/85; FDS-Bericht Nr. 163/85.

Schmiechen M. (1986): Ship Model Tests with Boundary Layer Suction. VWS Report No. 1071/86.

Schmiechen, M. (1983): On Optimal Ducted Propellers for Bodies of Revolution. Proc. Int. Symp. on Ship Hydrodynamics and Energy Saving (El Pardo), No. VI, 2, pp. 1-7.

Schmiechen M. and Zhou, Lian-di (1987): An Advanced Method for the Design of Optimal Ducted Propellers Behind Bodies of Revolution. VWS Report No. 1083/87; Final report on a Partnership in Engineering Sciences sponsored by Stiftung Volkswagenwerk.

Weitbrecht, H.M. (Ed) (1937): Proc. 4th ITTC: Internationale Tagung der Leiter der Schleppversuchsanstalten. Berichte, Beiträge und Entschliessungen. Berlin: Preussische Versuchsanstalt für Wasserbau und Schiffbau.

9. Notation

The symbols of concepts introduced in the sections indicated correspond as far as possible to the ITTC Standard Symbols 1976, but have a slightly different meaning, which may not be inferred from the names of the concepts, but only from the formal contexts and the operational interpretations developed in preceding publications, the basic reference in particular, and the present report. S. also Appendix 7.2

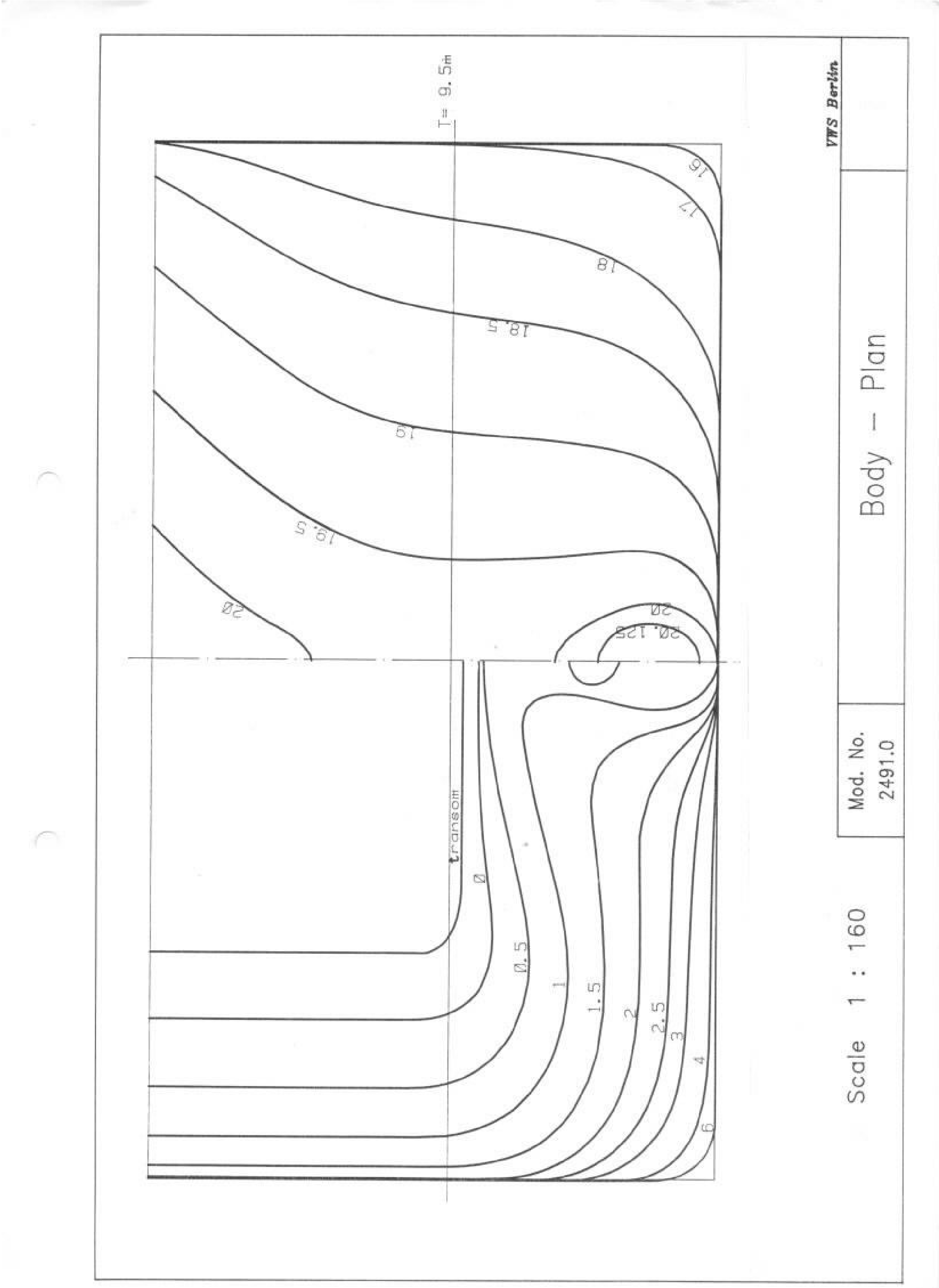
9.1 Quantities

Symbol	Section	Name
A	2	acceleration
B	2	breadth of model
C_F	5	force coefficient
C_R	10	resistance coefficient
D	3	diameter of propeller
E	10	efficiencies, factors of merit explanations s. 10 definitions s. Schmiechen, 1984
F	2	force
F_n	3	Froude number
J_H	3	hull advance ratio
J_P	4	propeller advance ratio
k	3	dynamic functions
K_F	3	force ratio
K_{PL}	4	lost power ratio
K_{PP}	4	propeller power ratio
K_{QL}	4	lost torque ratio
K_{QP}	3	torque ratio
K_R	5	resistance ratio
K_T	3	thrust ratio
L	2	length of model
L_{PP}	10	length of model
m	2	mass, inertia
n	2	number of samples

N	2	frequency, alias number, of revolutions
R	5	resistance
R_n	3	Reynolds number
s	3	scale factor
S	2	relative shift
T	2	draught of model
T_A	10	draught aft
T_F	10	draught forward
w	4	total wake fraction
w_E	5	energy, alias frictional, wake fraction
ν	3	kinematic viscosity
ρ	2	density
ω	5	wake ratio
∇	2	displacement volume

9.2 Indices

Γ	2	basic, carriage
F	3	force
i	2	current sample
L	4	loss
P	3	power, propeller
Q	3	torque
r	2	relative
r	4,10	rational
t	4,10	traditional
tQ	4,10	torque identity
tT	4,10	thrust identity
T	2	towing
T	3	thrust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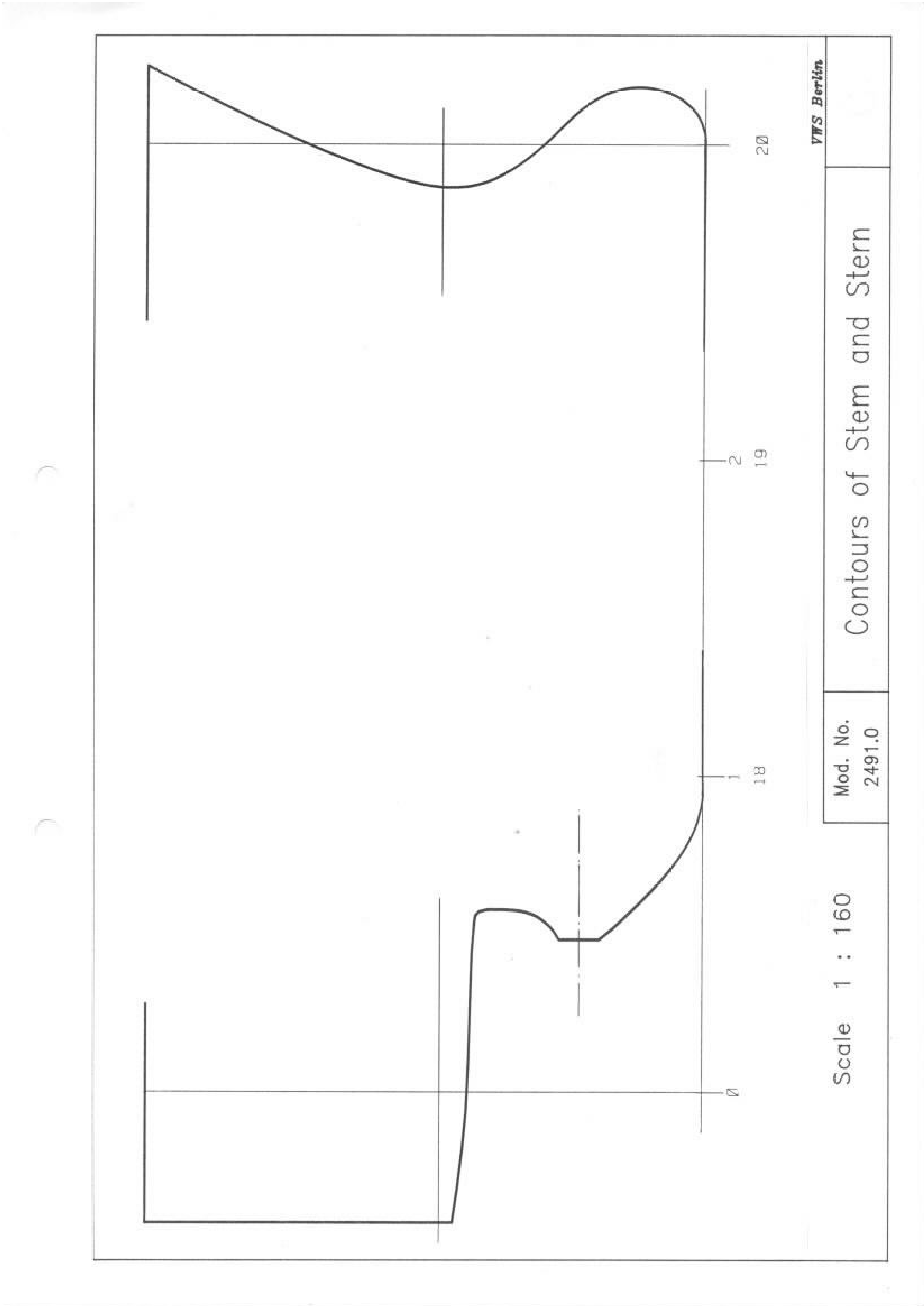
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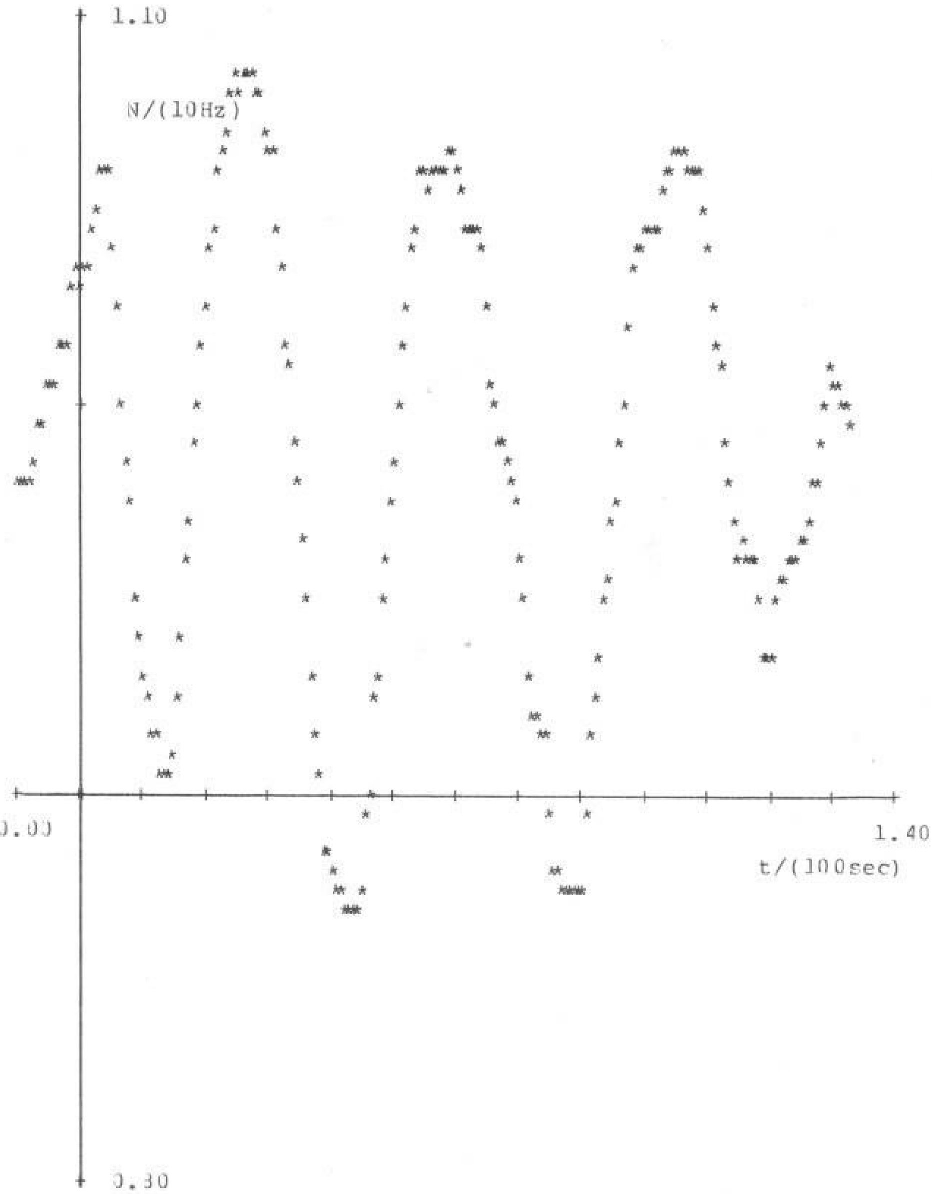

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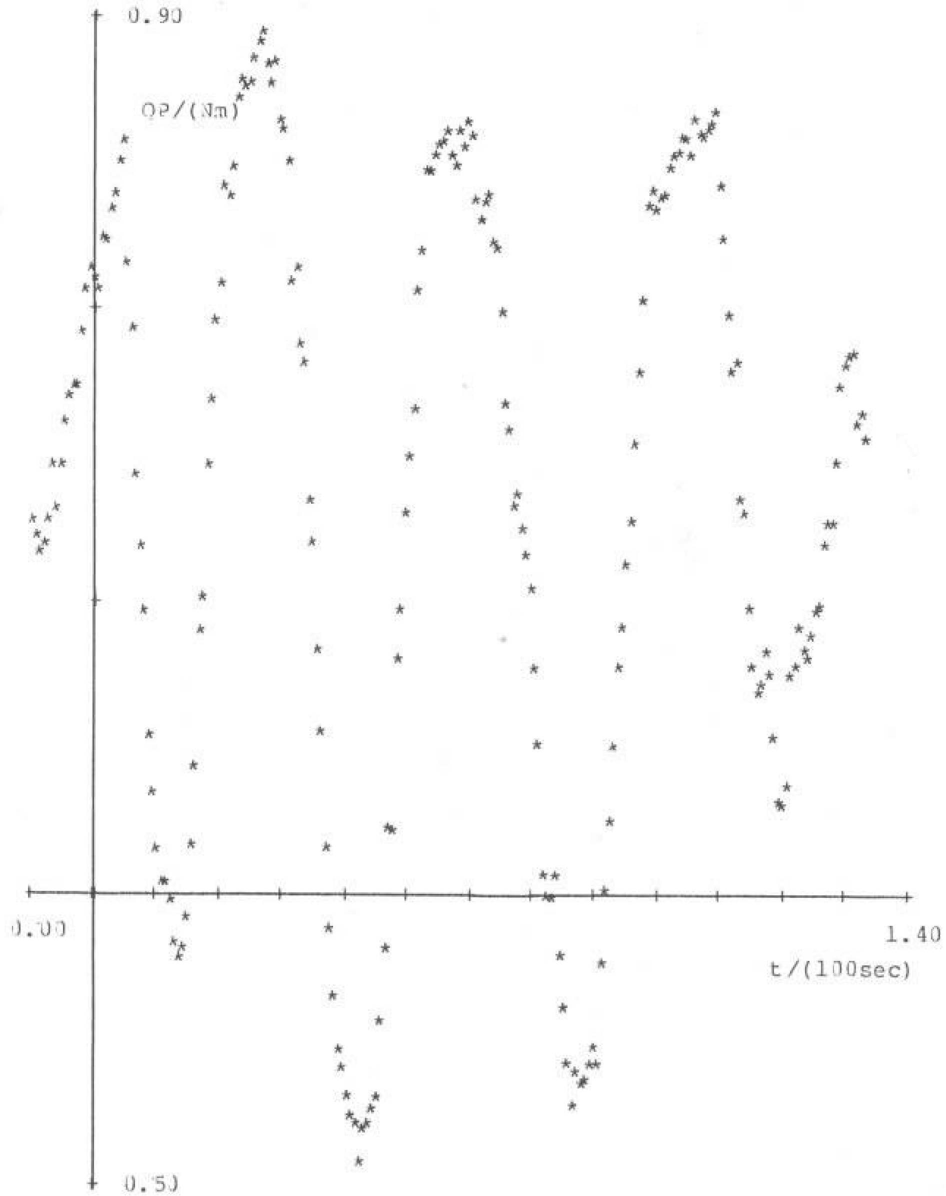

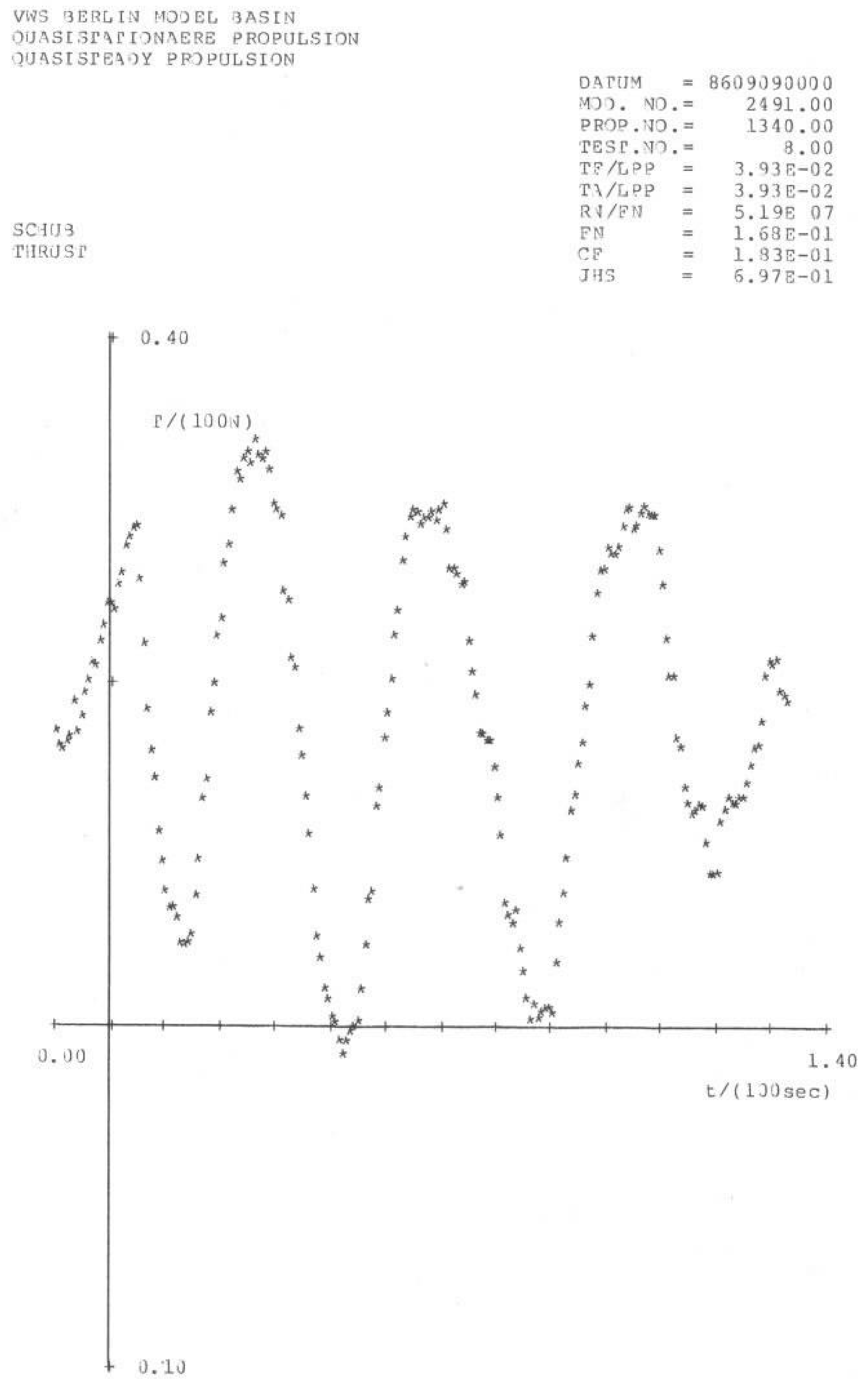
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RELATIVE VERSCHIEBUNG
RELATIVE SHIFT