FULL SCALE TORQUE AND THRUST MEASUREMENTS ON BOARD THE SES CORSAIR / MEKAT

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ABSTRACT

The full scale measurements reported are part of a project to determine the scale effects of a SES with reference to corresponding model tests. In a roughly historical account the present paper describes the details of the shaft calibration, of the measurements on board the CORSAIR, of the first results of their evaluation, and of the identification of the propulsion parameters based on data observed at periodic quasi-steady changes of the rates of shaft revolutions. In the meantime the corresponding model tests have been performed in the large circulating tunnel of VWS and preliminary evaluations already confirm observations made during the full scale tests.

1. INTRODUCTION

The prediction of the powering performance of displacement ships with fully submerged propellers is traditionally based on the hull-propeller interactions derived from the separate model tests with the hull, the propeller, and the total hull-propeller system, and a large mass of data on scale effects accumulated over the last hundred years.

The same procedure of separate tests with hulls and propellers may not be meaningful or applicable for many advanced hull propeller configurations, e. g. for full scale high speed craft with semi-submerged propellers considered in the ongoing present project. The reason is that the flow around the hull in the towing condition is no longer similar to the flow in the propulsion condition and the inflows to the propeller are certainly different in the open and behind conditions, even if the submergence could be defined.

Consequently the methodology of quasi-steady testing developed in the METEOR project, Schmiechen (1991a, b), was selected for the new project on scale effects in SES. The goal is to develop the methodologies of quasi-steady testing and of parameter identification for application at high speed craft with semi-submerged propellers. They are to be applied on full scale and model scale thus permitting to determine the scale effects as directly as possible.

The paper deals with the problems of measuring torques and thrusts in the propeller shafts under service conditions on the CORSAIR, an SES fitted with two controllable pitch propellers; Schlichthorst et al. (1991). In particular it describes the calibration necessary due to the considerable cross-talk of the torques on the strain gauges for the thrust measurements. The calibration rig is being described that has been constructed to provide the necessary precision.

Further the paper gives details of the measurements and the test procedure using quasi-steadily varying rates of revolutions of the propellers. The first results of the evaluation of measurements as well as the first results of the identification of the propulsion parameters are being reported. In the meantime the corresponding model tests have been performed in the large circulating tunnel of VWS and preliminary evaluations already confirm observations made during the full scale tests.

2. CALIBRATIONS

2.1 Shaft calibration

The discussion in this chapter is restricted to the calibration of thrust and torque only though of course calibrations have been performed for the other physical quantities of interest too. Especially the precision of thrust measurements is of utmost importance for the application of the identification procedure for propulsion parameters intended. In order to provide for the necessary precision of the thrust and torque measurements, strain gauge configurations have to be calibrated as will again be shown by the following results.

In the case of the METEOR a new hollow shaft was manufactured and, before it was installed on board of the single screw ship, it was calibrated as a six component balance at VWS using a specially designed six component calibration rig. In case of the CORSAIR the shafts of the two adjustable pitch propellers could not be replaced with new shafts calibrated outside the craft. Consequently a special rig had to be designed, which could be installed on board on both shafts.

2.2 Requirements

According to the special task the most important conditions and restrictions for the design and construction of the calibration device have been:

- combined loads at at least two different ratios to be applied in order to permit precise calibration including cross talk effects,
- the large forces necessary for the calibration not be introduced into the hull in view of the glass fiber reinforced plastic construction of the CORSAIR,
- the geometrical dimensions of the unit to be compatible with the very restricted space inside of the SES-demihulls,
- the mounting and calibration procedure to be performed without docking of the ship in view of the time and costs,
- subsequent mounting of the device on each of the propeller shafts to be possible within reasonable time for the same reason.

2.3 Description

The final design realised (Fig. 1) to meet these requirements is in principle an arrangement of two flanges (1) fixed to the shaft by friction using conical ring elements, and three load units (2) connected to the flanges by low friction ball joints with skew relative to the shaft axis.

Fig. 1: Scheme of the calibration rig

Each of the load units is equipped with a hydraulic cylinder for the generation of the calibration loads and a load cell to measure these loads. The application of loads at two different ratios of torque and thrust is accomplished by an uniform axial shift of the connection points at one flange resulting in a distinct variation of the skew of the load units.

An important feature for practical application of the calibration device is that provisions have been made that all individual parts can be handeled and mounted easily so as to reduce the difficult and time consuming work on board. In order to permit the mounting of the flanges on the respective propeller shaft, it was necessary to design them in sections which can be assembled by screwing them together. The same holds for the conical ring elements for the transmission of the loads to the shafts.

The schematic drawing (Fig. 1) showing one of the three load units gives an impression of the extreme compactness of the rig. The whole device is designed for 80 kN thrust and 20 kNm torque and was only possible with steel of high tensile strength.

The reference torque and thrust for calibration purposes are defined by the three forces measured and the coordinates of the joints taking into account the elastic deformations at the specific load condition. Calibration torque and thrust loads applied roughly corresponding to the actual relation of both have already been successfully applied at the METEOR shaft. The rationale and experience behind this technique is that ‘any’ system to be calibrated is slightly nonlinear and consequently linearisations have to be made around the service conditions.

2.4 Procedure

The calibrations have been performed in three steps: calibration of a reference load cell at the Berlin division of the Physikalisch-Technische Bundesanstalt (PTB), calibrations of the the load cells of the load units themselves in a special calibration rig at VWS before integrating them into the calibration rig and, finally, calibration of strain gauge configurations on the shafts on board the CORSAIR.

Prior to transportation to the ship the calibration rig was mounted on a hollow shaft section in a mock-up of one of the afterbodies under realistic conditions. The shaft was made of the same steel, which was available by chance, and permitted realistic testing and precalibration. The final calibrations have been performed repeatedly at various angular positions of the shafts and the evaluations have been based on all data.

2.5 Results

The torque calibration factors were nearly the same for both shafts. The corresponding calibration based on the shaft geometry, the modulus and the data of the strain gauge configuration resulted in 3% smaller values. Without calibration the torque, and correspondingly the power, would have been underestimated by that amount. The relative 95% confidence level of the calibration factors were 0.5% for the starboard and 2.2% for the port shaft, respectively.

The thrust calibration provided values different by 3% for both shafts with the same relative 95% confidence level of 0.8%. The corresponding calibration factor based on shaft and strain gauge data is about 8% higher than calculated. Consequently the thrust based on this value would have been overestimated by that value.

More interesting in this connection are the calibration factors for the cross talk of the torque on the thrust. Both values ‘happened’ to be of very nearly the same magnitude and negative in sign. For typical ratios of 2 for the signals of torque and thrust the cross talk accounts for nearly 7% of the thrust, in this case nearly doubling the overestimation based on the ‘theoretical’ calibration. The relative 95% confidence level of about 12.5% for the calibration factors is of course much larger than that for the dominant factors, but does not change the overall confidence level.

Although the rig as designed would have permitted calibration in the right direction the port shaft was calibrated in the same way as the starboard one. Subsequently the problem arose how to handle the sign of the corresponding calibration factor for the cross talk. Assuming the cross talk to depend on the magnitude of the torque the calibration matrix was used as determined.

3. MEASUREMENTS

3.1 Total set-up

A schematic sketch of the measuring arrangement for the quantities related to the propeller shafts is shown in Fig. 2.

Thrust and torque measurements are based on the well known strain gauge technique, which consists in the measuring of the elastic deformations of the material under load and relating them to the loads itself by special calibration or by calculation from the ‘known’ mechanical properties of the material, the geometrical dimensions of the shaft section, and the electrical resistance of the strain configurations on the shafts. In principle mechanical deformations are translated into changes of the electrical resistance in a Wheatstone bridge and in turn transformed into a voltage proportional to thrust and torque respectively.

The voltages together with the output of a thermo-couple for monitoring of the shaft temperature are amplified and transformed into frequencies which in turn, taking in account a well defined offset, are proportional to the original voltages. The frequencies in question are transmitted wirelessly after highfrequency modulation to a receiver mounted in about 10 millimeters radial distance from the rotating propeller shafts.

Fig. 2: Scheme of the measuring system

From there transmission is accomplished by wires to the central data station on the ship. The pulses received are connected to an electronic counter unit with counting time intervalls contolled by the rate of revolutions of the shaft concerned in such a manner that the pulses for thrust, torque, and temperature are counted over even multiples of shaft revolutions resulting in readings exactly proportional to the meanvalues of the quantities over the interval of observation.

Pulses for revolutions have been inductively picked up close to the shafts, lead by wire to the central data station, and used for the triggering mentioned as well as for another counter fed with a calibrated constant 10 000 Hz pulse frequency in order to measure the rates of revolutions of the shafts.

3.2 Procedure

Installation of the whole measuring system, including the equipment for operational and environmental quantities mentioned in short later, was followed by test runs and a first series of tests, the successive calibrations of the propeller shafts, and another series of tests on the Baltic Sea in September and October 1994. The fact that calibrations of the shafts were not performed at the very beginning of the tests proved to be inevitable due to considerable problems arising during the design and manufacturing of the calibration rig.

Care was taken as far as possible to identify electrical and mechanical disturbances of the measuring signals caused by auxiliary bord devices, incomplete separation of shaft couplings in disengaged position, incorrect groundings etc. Each test series started and ended with measurements for zero conditions.

3.3 Other parameters

In addition to the physical quantities already mentioned, a number of operational and environmental parameters have been measured and recorded. During the preparations it became evident that most of them could not be taken from the existing instruments on board due to incompatibilities of data interfaces.

Of dominant importance for the intended application of the results are measurements of the craft's velocity, which were performed with a calibrated electromagnetic log and with a GPS unit. The existing calibration of the log was reconfirmed during measured mile tests. A special problem in the evaluation will be the correct coordination of the signals from the separate GPS unit, occasionally dominating the sample time interval.

3.4 Results

The raw data resulting from the measurements were not only stored on the basic HP A 400 system used as central computer, but were transfered to a PC system and underwent preliminary checks and evaluations as far as possible under the conditions of the tests. Particularly helpful for the rapidly varying tasks was the MathCAD+5.0 system, which is being used in the following evaluations with great advantage as well.

4. IDENTIFICATION

4.1 Test procedure

As mentioned in the introduction the identification of the propulsive performance of high speed craft under service conditions is possible only on the basis of propulsion tests alone. This is certainly true for full scale craft, for which no hull towing and propeller open water tests can be performed at the conditions of interest. In order to provide the data necessary for a detailed analysis small excursions from the steady states under investigation have to be performed as usual in systems identification.

The excursions may be due to artificial manoeuvres, e. g. changes of the frequencies of revolutions according to a pre-determined programme, or just any moderate changes of speed taking place during the mission, e. g. changes from one steady test speed to the other. Any severe manoeuvres would disturb the service conditions and the flow conditions to be investigated.

Due to the inherent low pass behaviour of ships and craft the limitation to quasi-steady manoeuvres does of course at the same time limit the number of parameters to be identified reliably as has been confirmed by the sample evaluation and identification and will be discussed later.

4.2 Physical data

The basic physical data for the following discussion of the principles are assumed to be a number of sampled values of the prescribed reference rate of revolutions Nr, the velocity V, the rate of revolutions N, and the thrust T and the torque Q of the propellers measured at equidistant instances in time t during the manoeuvres. From the values of the velocity V the values of the acceleration A may be determined. As examples Figure 3 shows the rate of revolution and the thrust of the starboard propeller as well as the velocity of the craft as measured with the differential GPS unit, just to show the quality of the data at a mild sea state.

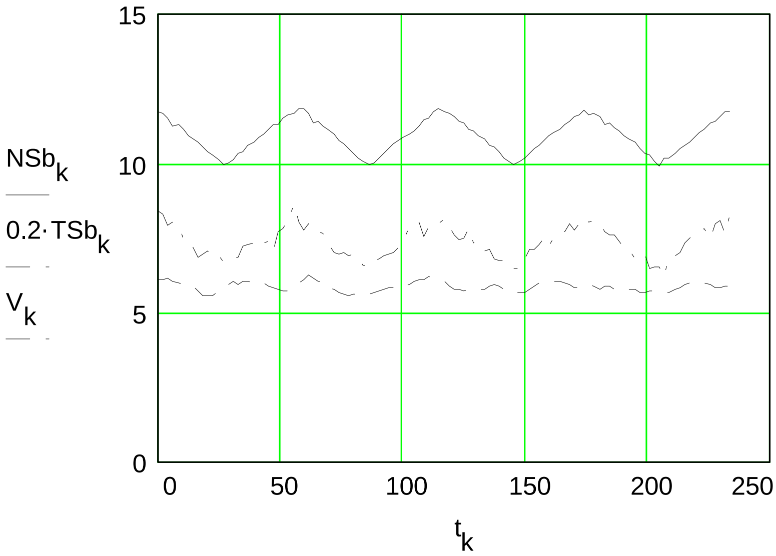

Fig. 3: Test 1330.199: Sample physical data

In reality it has to be taken into account that the values of the rates of revolutions of both propellers as well as of their thrusts and torques may not only be different but are in fact more or less different due to small asymmetries of inflows. The situation is complicated by the fact that the two propellers may change to partial ventilation with a dramatic change of torque and thrust at different rates of revolutions. For the following discussion it is assumed that both propellers are always in the fully ventilated condition as was mostly the case at the test 1330.199 evaluated.

4.3 Feed back of noise

As has been discussed at length in the METEOR report and the Proceedings of the 2nd INTERACTION, Schmiechen (1991), problems arise in identification due to the feed back of noise in the various feed back loops. The only way to avoid systematic errors due to this phenomenon is the cross-correlation of the noisy data V, N, T, Q with the reference data, which are independent of the noise; see e. g. Solodownikow (1963), pp. 276/277.

In the simplest case of periodic manoeuvres considered here the resulting co-variance functions are periodic as was the case at test 1330.199. Due to the inherent low pass behaviour of the craft in this case the co-variance functions are even harmonic. Figure 4 shows the co-variance functions of the quantities displayed in Figure 3.

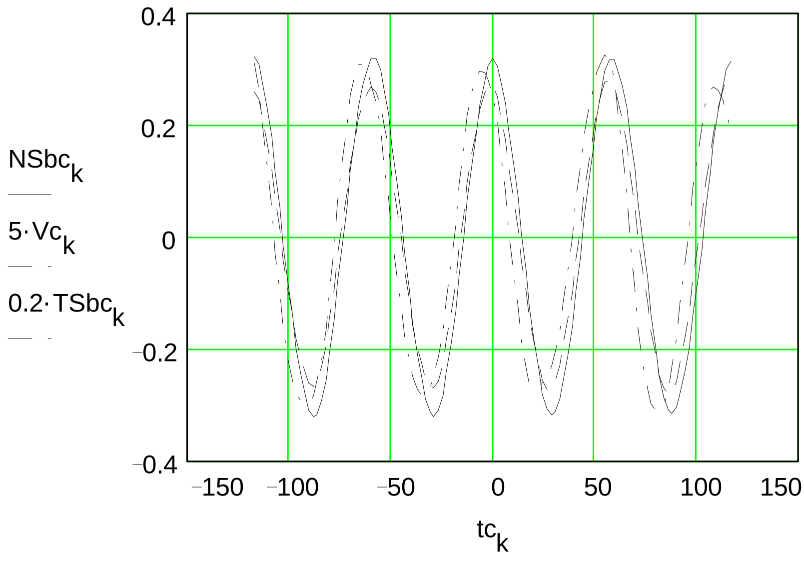

Fig. 4: Test 1330.199: Sample co-variance functions

Consequently in this case the transfer functions between the reference signal and the conditional signals reduce to single lines at the driving circular frequency. Their amplitudes are determined as the ratios of the amplitudes of the first harmonics of the co-variance functions in question and the auto-variance function of the reference rate of revolutions. Their phases are the phase differences for the first harmonics of the same functions.

Preliminary evaluations have shown that the transfer functions at higher order harmonics cannot be determined reliably even from transient manoeuvres. More detailed studies have shown that this fundamental problem cannot be solved even by advanced methods of spectral analysis e. g. based on auto-regressive models.

4.4 <u>Momentum Balance</u>

The momentum balance

$$M A + R(V) = (1 - t) T$$

includes the unknown mass M, i. e. the longitudinal inertia including the longitudinal added inertia, the unknown total effective resistance R under the prevailing conditions depending on the speed V as well as the unknown thrust deduction fraction t (!) and the measured thrust T.

In view of the small deviations from the service conditions under investigation the momentum balance may be linearized. For that purpose the decomposition of all quantities into their mean values and their oscillations around the mean values, e. g. the velocity

$$V = Vm + Vo$$

and the approximation

$$R(V) = Rm + Ro\ Vo$$

for the effective resistance are introduced. Subsequently the momentum balance can be decomposed into the real equation for the mean values

$$Rm = (1 - tm)\ Tm$$

and the equation for the oscillations, which can readily be transformed into the frequency domain, resulting in the complex equation relating the spectra of the oscillations:

$$(i\ o\ M + Ro)\ Vs = (1 - tm)\ Ts - Tm\ ts\ .$$

The parameters describe the actual conditions and are changing with the change of heading, i. e. with a change in waves and wind.

4.5 Identification

It is evident that the spectra to be used are the conditional spectra of the velocity and the thrust, which degenerate e. g. for the velocity to

$$Vs = Vt\ Nrs\ ,$$

Nrs denoting the spectrum of the reference rate of revolutions,which is no longer required for the identification, the complex equation reducing to

$$(i\ o\ M + Ro)\ Vt = (1 - tm)\ Tt - Tm\ tt\ .$$

Assuming the thrust deduction fraction to be constant, it can be seen that this equation together with the real equation for the mean values permits the identification of three of the unknown parameters M, Rm, Ro and tm provided the remaining one is given. A convenient algorithm for the solution of these equations is the iterative Levenberg-Marquardt method as implemented in MathCAD PLUS 5.0; User’s Guide (1994), pp. 499/501.

In the present case the mass could be considered as the appropriate quantity given and the results were very reasonable. But the mass can only be determined via the displacement and the density of the water at the pier, the consumption of fuel etc up to the manoeuvre plus the hydrodynamic inertia at the operational condition to be estimated. The whole procedure is not very reliable. So a simpler and more reliable method is in demand avoiding this estimation and to determine the relevant values at any time from measured values only and not indirectly from other data as usual.

As has been shown in the METEOR project this can be done by constructing two steady states from the data at hand, thus providing a fourth equation for the determination of all four parameters to be identified. But this alone does not solve the problem as long as the thrust deduction fraction is assumed to be constant.

A one parameter axiom or convention for the thrust deduction fraction is necessary in order to avoid the singularity of the problem arising from the assumption of a constant thrust deduction problem. Attempts to identify a more general thrust deduction 'law' are doomed to fail due the poor signal to noise ratio for the higher harmonics mentioned.

For displacement ships with fully submerged propellers a simple axiom relating the thrust deduction fraction and the hull advance ratio has been introduced and successfully used in many cases. In the present context of ventilated propellers with completely different characteristics the development has not yet reached this stage of maturity. Initial numerical experiments with the thrust deduction fraction depending inversely on the thrust deduction fraction or rather its root were not yet successful.

4.6 Scale effects

In order to determine the scale effects in question not only the whole set of data obtained on board the CORSAIR, but the corresponding model data will have to be carefully and systematically analysed. In the model situation the inertial force is replaced by the force directly measured at the towing balance.

Preliminary evaluations of a large number of tests full scale and model scale have shown that with a reduction of the advance ratio of the propellers the fully ventilated conditions may be changed to non-ventilated in a certain range, which may be pretty ill defined in a seaway, while in the circulating tunnel it was rather well defined and narrow.

5. CONCLUSIONS

The results show that the procedure described in principle provides a meaningful performance analysis, which cannot be otherwise achieved for full scale semisubmerged propellers. The evaluation of the corresponding model tests with a 1:8 scale model, which in the meantime have been performed in the large circulating tunnel of VWS, will provide the data for the determination of scale effects of SES.

6. ACKNOWLEDGEMENTS

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8. SYMBOLS

The few symbols used in the chapter on identification are explained were introduced. SI units are used consistently. So the ship speed in Figure 3 is in m/s. The only exceptions are mass, torque and the thrust, which are measured in t, kNm and kN, respectively.