# Analysis of asymmetrical shaft power increase during tight manoeuvres

**Michele Viviani[1], Carlo Podenzana Bonvino[1], Salvatore Mauro[2], Marco Cerruti[3], D.Guadalupi[4], A.Menna[4]**

[1] Department of Naval Architecture and Marine Engineering (DINAV), Genoa University, Genoa, Italy
[2] INSEAN, Rome, Italy
[3] Fincantieri C.N.I. Spa – Naval Vessel Business Unit - Genoa, Italy
[4] SPMM MARISTAT - Italian Navy – Rome, Italy

### ABSTRACT

In the present work the phenomenon of asymmetrical shaft power increase during tight maneuvers is investigated by means of the analysis of turning circle maneuvers at different speeds and rudder angles performed during sea trials for a series of twin screw naval ships; this analysis has allowed to underline a common trend for asymmetrical shaft power increase despite significant differences in ships considered; possible reasons for this shaft power increase have been examined, and data about an asymmetrical variation of wake fraction during maneuvers are reported, showing again a common trend but with larger scatter of data. In this view, a first investigation about the possibility of performing dedicated free running model tests and scaling their results to full scale, in order to improve prediction accuracy for a specific ship in preliminary design phases, has been carried out.

It is believed that, for unconventional propulsion plant arrangements, in which for instance two shaft axes are powered by the same prime mover via a unique reduction gear, automation plant will need to monitor carefully these effects, in order to avoid possible problems.

### Keywords

Hydrodynamics; Maneuvering; Propulsion; Sea trials; Model tests

### 1 INTRODUCTION

As it is well known, ships during maneuvers can experience large fluctuations of required shaft power from the propulsion plant. This is especially true in case of very tight maneuvers, like turning circle at, or in proximity to, maximum rudder angles, and can result in considerable increase of shaft power, or shaft torque if propeller revolutions are kept constant, up to and over 100% of steady values in a straight course recorded during the approach phase to the maneuver.

Despite the fact that this behavior is qualitatively well known, there is not a wide amount of quantitative data available in literature; however, these effects could be potentially dangerous, if not correctly predicted and cared for, for some particular kinds of propulsion plant, in which for instance two shaft axes are powered by the same prime mover via a unique reduction gear, like in some of the latest naval ships (see example in following Figure 1).

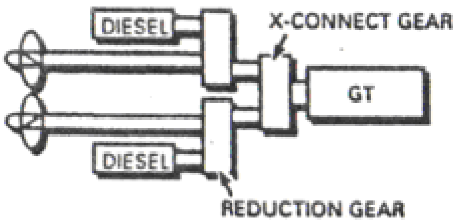


**Fig. 1: Propulsion layout with two shaftlines and common reduction gear**

In this case, the possibility of significant unbalances of forces on the reduction gear itself and of strongly different power increase for the shaft axes exists.

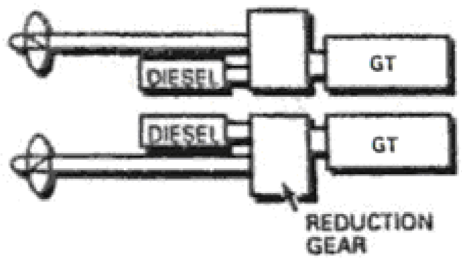


**Fig. 2:Typical propulsion layout with separated shaftlines**

In this work standard turning circle maneuvers at different speeds and rudder angles for a series of twin screw naval ships with two completely separated shaftlines and related prime movers (see example in previous Figure 2), have been analyzed, and a common trend for shaft power increase has been found.

Possible reasons for the shaft power increase have been investigated, apart from the obvious speed reduction during the maneuver; among them, oblique flow, asymmetrical wake fraction variation and tangential speed variation have been considered; all effects are likely to play a more or less significant role in the shaft power increase, but it is believed that, in view of the development of a simulator including ship maneuvering and automation plant, asymmetrical wake fraction variation is the most straightforward and easy to be evaluated from usual data recorded during sea trials; as a consequence, values of asymmetrical wake fraction variation for all ships analyzed are reported.

However, these data present a significant scatter, due to the fact that they “incorporate” also other effects whose entity varies from ship to ship, thus not allowing to use them directly for new ships in the preliminary design stages, unless they are very similar to those analyzed in the present study. In order to overcome this problem, a first investigation about the possibility of performing dedicated free running model tests and scaling their results to full scale has been carried out, comparing sea trials results for one of the ships considered to model tests results. It is believed that, once a procedure for scaling results with sufficient accuracy is obtained, free running model tests will represent the cheapest way to analyze the problem, if compared to CFD methods and complicated PMM campaigns with flow field evaluation.

## 2 SHIPS CHARACTERISTICS

In the following Table 1, main non-dimensional data of ships analyzed in the present work is presented, including block coefficient $C_B$, length to beam ratio L/B, beam to draft ratio B/T, rudder area percentage with respect to lateral area represented by LT; moreover, ranges of ship speed analyzed for all ships are reported, in terms of Froude number.

**Table 1: Main non-dimensional data of ships analyzed**

| | $C_B$ | L/B | B/T | $A_R$/LT | $F_R$ Range |
|---|---|---|---|---|---|
| Ship 1/1 | 0.64 | 6.61 | 2.92 | 2.1% | 0.08-0.28 |
| Ship 1/2 | 0.64 | 6.61 | 2.92 | 4.3% | 0.08-0.29 |
| Ship 2 | 0.48 | 5.29 | 3.21 | 1.9% | 0.11-0.27 |
| Ship 3 | 0.50 | 8.61 | 3.32 | 4.1% | 0.21-0.42 |
| Ship 4 | 0.48 | 6.91 | 3.46 | 3.4% | 0.22-0.44 |
| Ship 5 | 0.51 | 7.89 | 3.63 | 4.0% | 0.14-0.40 |

Dimensional data cannot be included in the present paper because of confidentiality reasons; nevertheless, it has to be underlined that very different ship types have been considered, ranging from rather slow Auxiliary ship and Replenishment and Logistic support ship to fast Frigates and Corvettes. Moreover, it has to be noted that in case of Ship 1 two different stern configurations on the same hull are analyzed, and namely Ship 1/1 with a single rudder configuration and Ship 1/2 with a twin rudder configuration.

All ships present a twin screw propulsion configuration, with completely separated propulsion plants, however prime movers are various, including Diesel Engines, Electrical Motors and Gas Turbines, or combinations of them; finally, both CPP and FPP configurations are present in the analysis.

## 3 SEA TRIAL DATA ANALYSIS

Data recorded during maneuvering sea trials for each ship included in Table 1 has been analyzed in detail; in particular, turning circle maneuvers (at different speeds and, when available, different rudder angles) have been considered; among all data available for each trial, the following have been considered in this initial analysis:

- Ship speed
- Propeller RPM
- Shaft Power (measured by means of torque-meter)

In all cases (except Ship 2) CPP are installed; unfortunately, effective pitch at different velocities during maneuvers was not recorded during sea trials, therefore some assumptions have had to be made for data analysis; it has been noted anyway that, except for highest speeds in which automation influence cannot be neglected, propeller pitch and RPM are kept constant (apart short transients) during the maneuver.

A total of 52 trials with different speeds and rudder angles for the 6 ships considered have been analyzed; in each test speed reduction and asymmetrical power increase are clearly visible; regarding power increase, in most cases a transient higher peak and a successive slightly lower stabilized value have been recorded after some oscillations, however in some trials power increases directly to the stabilized value without significant oscillations; as an example, in following figures 3-5 of data recorded for a turning circle maneuver are reported (Ship 2 - $F_R$ = 0.19 $\delta_R$ = 35° starboard).

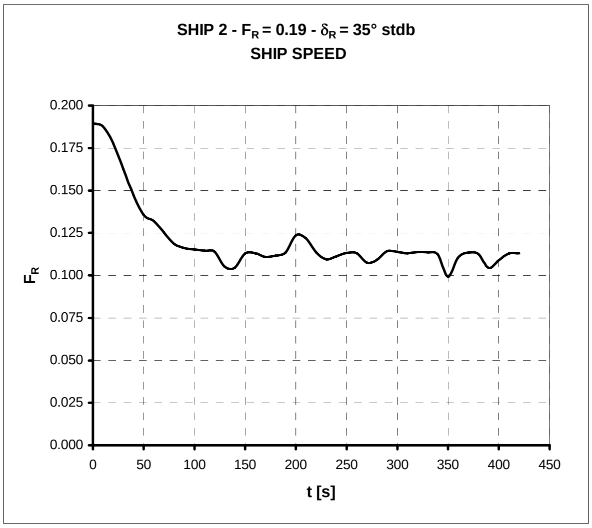


**Fig. 3: Typical ship speed time history**

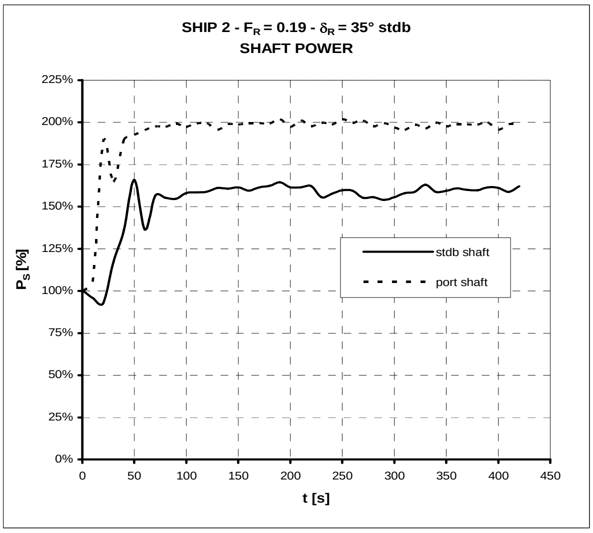


**Fig. 4: Typical propeller RPM time history**

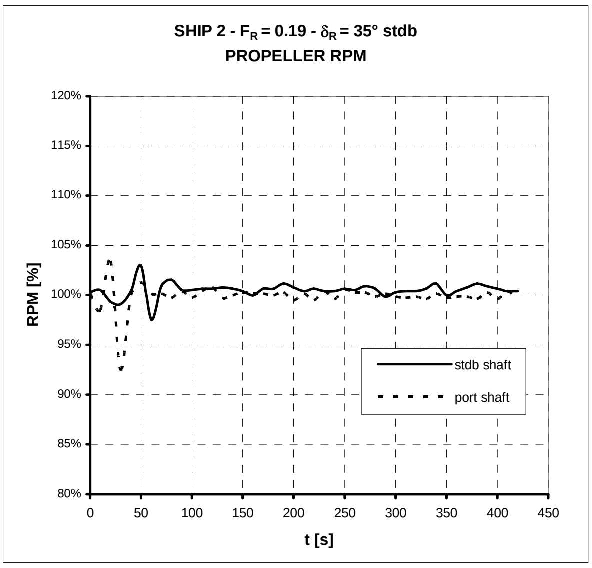


**Fig. 5: Typical shaft power time history**

As a preliminary analysis, power increase during maneuvers at different speeds and rudder angles with respect to power required for straight course in the approach phase have been evaluated, considering both peak and stabilized values; as an example, in following Figures 6-7 stabilized values for internal and external shaft for Ship 4 are reported in correspondence to various values of Froude Number analyzed; as it can be seen, in this case only maximum rudder angle (35°) was tested during sea trials.

It can be seen that, as expected, values are almost symmetrical for port and starboard maneuvers (considering unavoidable external disturbances during sea trials).

It is clear that external shaft power increase is higher (80-100%), than internal shaft power increase (45-55%); for what regards peak values (not reported here), in general they result about 10-15% higher than stabilized ones.

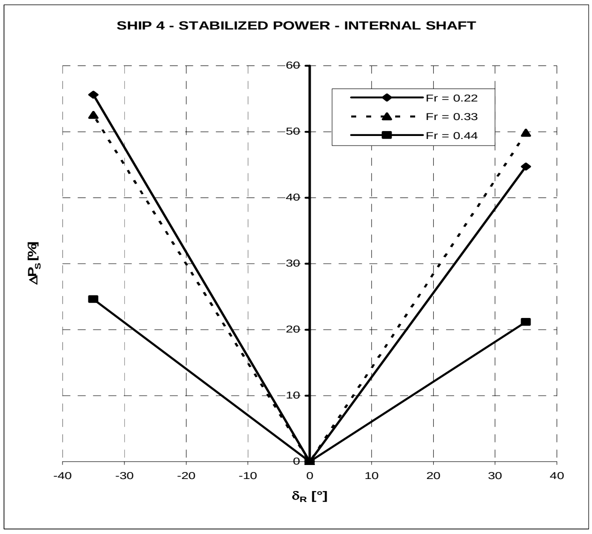


**Fig. 6: Ship 4 – Stabilized Power – Internal shaft**

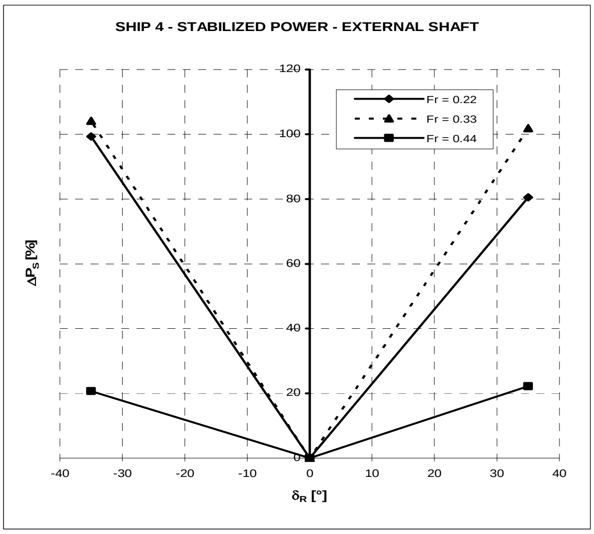


**Fig. 7: Ship 4 – Stabilized Power – External shaft**

It is also clear that, for the highest Froude number, automation plays a key role, limiting power increase for both internal and external shafts to about 20%, since at this speed propulsion plant is already utilized near to its full capabilities. In particular, for Ship 4 which is equipped with CPP, automation acts by means of pitch reduction, while in case of FPP (as for Ship 2), automation acts by means of RPM reduction; in all cases, anyway, qualitative behavior (i.e. reduced power increase) is similar.

Apart this evident influence of automation in correspondence to highest speed, there is not a specific trend related to Froude number, which appears not to be an important factor, while rudder angle (and corresponding speed reduction) has, as expected, a strong influence on power increase.

Finally, it has to be noted that, being RPM almost constant during all maneuvers, torque increase is equal to power increase reported in previous figures.

Despite ships analyzed have significant differences from many points of view as reported in previous paragraph, all of them present a common trend for what regards shaft power increase, which is similar to the one presented for Ship 4.

In order to present this general trend and provide data readily available during the initial design stages, stabilized power increases obtained for all ships are summarized in following Figures 8 and 9 for internal and external shafts respectively as a function of rudder angle; it has to be noted that, in order to obtain a better analysis, all tests in which automation appears to play an important role have been omitted. In both figures the mean line is drawn, together with two additional lines shifted up and down by 10%; as it can be seen, despite presenting a certain scatter, a clear tendency results in all cases.

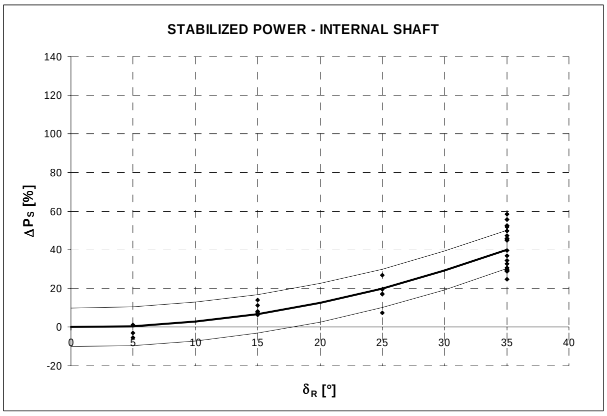


**Fig. 8: Stabilized power - Summary – Internal shaft**

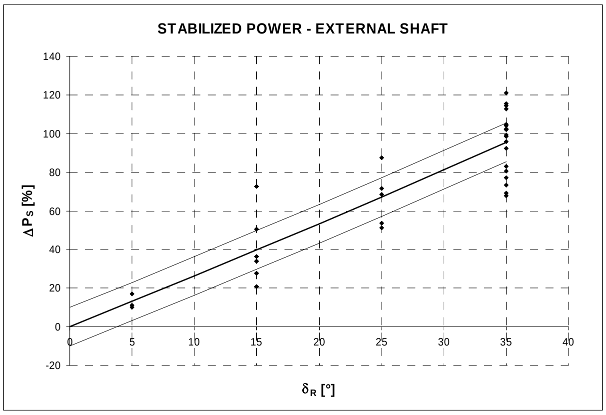


**Fig. 9: Stabilized power - Summary – External shaft**

Considering external shaft power increase, an almost linear increase with rudder angle results; in particular, stabilized power increase at maximum rudder angle, excluding the most disperse data, ranges from about 85% to about 105%, with a mean value of about 95%. Considering internal shaft, trend seems to be approximately quadratic with rudder angle, with stabilized power increases at maximum rudder angle ranging from 30% to 50%, having a mean value of about 40%. As already reported, peak power increases, when different from stabilized ones, result about 10-15% higher, both for external and internal shafts.

It has to be noted that unfortunately a significantly lower number of trials has been conducted in correspondence to the lower rudder angles, therefore quality of this analysis could be improved by adding other trials with similar ships focusing attention not only to maximum but also to intermediate rudder angles.

Nevertheless, it is believed that presented trends can be already useful in order to correctly consider this phenomenon which, as already mentioned, can be important in correspondence to particular propulsion system configurations, like the one reported in previous Figure 1, in which the two axes are strongly coupled by means of the reduction gear. Automation systems, therefore, cannot act as in the configuration with completely separated shafts considering only one propulsive line, but have to consider both of them. As an example, it is not sufficient in this case to consider only parameters of the prime mover (which as a mean can still be acceptable), but it is necessary to measure torque on both axes, since there can be strong discrepancies which are not visible in any other way.

Moreover, it has to be noted that in case of propulsion systems like the one reported in Figure 1, in which additionally FPP are adopted instead of CPP, this behavior could become even more critical since the only parameter adoptable for power reduction is shaft RPM.

Finally, possible effects on the reduction gear (in terms of stresses, deformations and vibrations) of the strong discrepancy between absorbed torque on the two shafts should be kept in mind.

## 4 POSSIBLE PHYSICAL EXPLANATION

In the following paragraphs, some possible explanations of the physical behavior analyzed are reported; in particular, two different approaches are presented:

- Consideration of global speed reduction during turning + asymmetrical variation of longitudinal speed
- Consideration of global speed reduction during turning + asymmetrical variation of tangential speed due to vortices generation

In both approaches, propeller working conditions during turning circle maneuver have been considered, in terms of new values of the propeller advance coefficient J (see Equation 1) or (which is equivalent) in terms of different angle of attack of each blade section.

$$J = V_a / ND \qquad (1)$$

where $V_a$ is the local propeller advance velocity, N are propeller revolutions and D is propeller diameter.

Variation of J is first of all due to ship speed reduction; as it is well known, advance velocity at propeller is linked to ship speed $V_S$ by means of the following equation:

$$V_a = (1-w)V_s \tag{2}$$

where w is the wake fraction; during turning circle, reduction of ship speed $V_S$, considering initially wake fraction as a constant, results in lower value of advance coefficient and consequently higher value of the typical thrust and torque coefficients $K_T$ and $K_Q$, defined as:

$$K_T = \frac{T}{\rho N^2 D^4} \qquad K_Q = \frac{Q_O}{\rho N^2 D^5} \qquad \text{(3.1 and 3.2)}$$

The effect of this variation is reported in following Figure 10 (point J1); starting from this first step, the two approaches mentioned previously are adopted as reported in following paragraphs, in order to reach final values of advance coefficient ($J_{ext}$ and $J_{int}$).

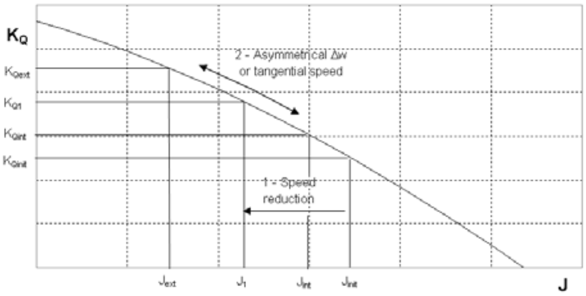


**Fig. 10: Asymmetrical variation of advance coefficient J**

### 4.1 Asymmetrical Variation of Longitudinal Speed

The present approach considers that asymmetrical power distribution is due to an asymmetrical variation of longitudinal speed, which is schematized by means of different variation of the wake fraction value for the two shafts; the logical scheme followed in this approach is somehow similar to a self-propulsion test, with some assumption needed in order to be able to utilize available data:

1. Evaluation of equivalent open water torque on internal and external shafts on the basis of recorded power and propeller revolutions, in accordance to (4)

$$Q_O = \frac{P\eta_r}{2\pi N} \tag{4}$$

where $\eta_R$ is the relative rotative efficiency, defined in (5) (adopting value from self-propulsion test)

$$\eta_r = \frac{Q_O}{Q} \tag{5}$$

2. Evaluation of correspondent torque coefficient $K_Q$ for both shafts on the basis of (3.2)
3. Evaluation of advance coefficient value needed in order to obtain $K_Q$, interpolating from propeller characteristic curves
4. Evaluation of correspondent advance velocity starting from (1)

$$V_a = JND \tag{6}$$

5. Finally, "effective value" of wake fraction can be computed starting from (2)

$$(1-w) = V_a / V_{s(evol)} \tag{7}$$

where $V_{S(evol)}$ is stabilized ship speed during turning circle maneuver

In most of cases (except Ship 1), a similar trend has been found on the basis of this analysis, i.e. flow on the internal shaft appears somehow to be accelerated (with a reduction of wake fraction value), while flow on the external shaft appears to be decelerated (with an increase of wake fraction value); in other words, power resulting uniquely from ship speed reduction effect is intermediate between internal and external shaft power recorded, then an opposite variation of advance speed is needed to obtain those values.

It has to be noted that, from a qualitative analysis of experimental results on DTMB model 5512 (DDG51) tested at PMM with 3D PIV, reported in (Longo et al. 2006), it can be seen that a flow acceleration at stern in correspondence to internal propeller location can effectively be experienced (confirming therefore present results), while a decelerating effect on the external shaft seems not to be recorded; it has to be considered, anyway, that this comparison can be only qualitative since results reported are referred to pure sway and pure yaw oscillating tests, which are significantly different from a stabilized turning circle and therefore can only provide a qualitative comparison.

In the following Table 2 values of wake fraction variation Δw, defined in (8) are reported in correspondence to maximum rudder angle and for different ranges of Froude Number (where *low* stands for a value lower than 0.15 and *high* for a value higher than 0.3).

$$\Delta w = w_{evol} - w \tag{8}$$

**Table 2: Values of wake fraction variation**

| | $F_r$ | $\Delta w_{int}$ | $\Delta w_{est}$ |
|---|---|---|---|
| **Ship 1/2** | Mean | -0.56 | -0.02 |
| **Ship 2** | Mean | -0.38 | 0.24 |
| | Low | -0.34 | 0.14 |
| **Ship 3** | Mean | -0.10 | 0.29 |
| **Ship 4** | High | -0.15 | 0.16 |
| **Ship 5** | Mean | -0.17 | 0.25 |

It can be seen that Ship 1 presents a significantly different behavior from the others, since in this case external shaft has a very low variation of wake fraction (which moreover presents a negative value instead of a positive one as for the other ships) while internal shaft has the largest variation. From this point of view, it is likely that influence of variation of tangential speed, as presented in following paragraph, is stronger than in other cases.

### 4.2 Asymmetrical Variation of Tangential Speed

In order to better analyze the different behavior of Ship 1/2, possible effect of tangential speed variation has been considered. This approach considers that, during turning circle maneuver in correspondence to certain hullforms, propeller can experience considerably varied flow with respect to a purely longitudinal one as in open water tests; in particular, in some cases, fully developed vortex could be present in correspondence to propeller location, as reported in following Figure 11, in which flow field measurements during static drift PMM tests of Series 60 hull are reported (Longo et al.2002). In particular, flow field reported is in correspondence to a longitudinal section at stern (aft perpendicular), and has been recorded during a static drift test with 10° drift angle with a Froude number of 0.316. As it can be seen, vortex shed from hull bottom is located in correspondence to a position which could be roughly the one of the internal shaft propeller during a turning circle maneuver.

As a result, propeller can be interested by an increase or reduction of relative tangential speed depending on its functioning, i.e. when propeller rotational direction is opposite or equal to vortex one respectively.

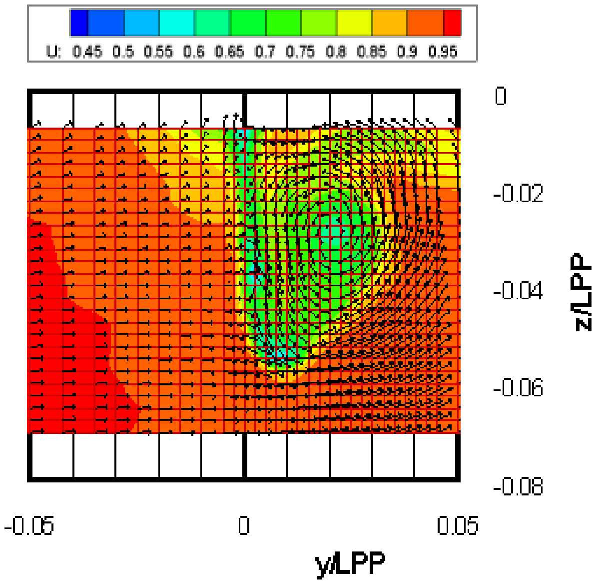


**Fig. 11: Flow field recorded during PMM trials for Series 60 ship in oblique flow (Longo et al. 2002)**

This tangential speed variation may further result in a correspondent higher or lower angle of attack on blade profiles and thus higher or lower absorbed torque and developed thrust.

It has to be noted that, in case of Ship 1/2, propellers rotation is inboard, therefore internal shaft would effectively experience a tangential flow reduction in case of vortex generation, which results in lower torque and, adopting $\Delta w$ approach presented in previous paragraph, in highly negative values (same reduction of angle of attack can be experienced with a higher $V_a$).

It has to be noted, moreover, that tangential vortex speed experienced during PMM trials reported in Longo and Stern (2002) is about 30% of longitudinal speed, thus confirming that its influence, at least in some cases, could be not negligible. In particular, Ship 1/2 presents a stern appendage configuration with a central skeg, which is substantially different from stern configuration of remaining ships; presence of this skeg could be a possible vortex source during turning circle, and this could result in the difference among $\Delta w$ results obtained in previous analysis, with wake fraction improperly including this tangential velocity effect.

### 4.3 Comparison of different approaches and possible future applications

Different approaches for physical explanation of the asymmetrical power increase have been presented in previous paragraphs 4.1 and 4.2. It has to be underlined that these two effects are not to be considered as alternative, since it is more likely that they are present contemporarily to some extent; adoption of only one of the two approaches implicitly includes the effect of the other. This results, as an example, in the different values of $\Delta w$ for different ships reported in previous Table 2, which include also possible variation of tangential speed, which has different values for different hullforms.

It has to be noted that, additionally, analysis of possible effect of oblique flow (both as longitudinal speed reduction and as variable tangential speed during propeller rotation) has been carried out, on the basis of Cassella (1971). Since however results from this analysis do not modify significantly what already reported (with slight changes of $\Delta w$ values reported in Table 2), a complete presentation is not included in present paper.

A complete insight of the problem could be obtained only by means of numerical simulations (probably still not completely feasible for such a complex phenomenon with ship manoeuvring with rudders and with propellers running) or by means of an extensive (and expensive) experimental campaign with the aim of analysing flow in correspondence to propeller location during manoeuvres.

Both these approaches would require a significant effort in terms of time and R&D, since they present problems which are still not completely overcome. Moreover, in order to have a clear understanding of the problem, analysis of different ships and hullforms should be carried out, thus further multiplying the effort needed.

From this point of view, it is believed that the values of wake fraction variations for different ships which have been computed, despite being affected by errors arising from experimental nature of data analysed (which were not recorded for the purpose of this analysis and are certainly affected by various disturbances) and by implicit inclusion of different effects (such as tangential speed), can be already readily applied to similar ships during design phases if required.

In particular, manoeuvring simulators can be modified in order to take into account also this phenomenon, and its effect on various components of propulsion system, if properly modelled, could be evaluated. This simulation approach can then be applied in order to analyse how different automation system strategies can influence and limit (if deemed necessary) any possible undesired effect.

Unfortunately, at the moment applicability of these Δw values seems to be limited only to ships similar to the ones considered, since they do not present a completely clear trend.

In case significantly different ships are considered, free running model tests appear to be probably the least expensive alternative to complicated numerical calculation or experimental campaigns with PMM; in this view, it has been considered necessary to analyse possible scale effects from model tests to sea trials, in order to limit prediction errors. As a consequence, a dedicated series of free running model tests has been performed by INSEAN at its facility at Lake Nemi on Ship model n°5, as reported in following Chapter 5.

## 5 FREE RUNNING MODEL TESTS ANALYSIS

Results of the dedicated free running model test campaign on Ship 5 (model scale 1:25) are summarized in the following Figures 12 and 13 for external and internal shaft respectively; in particular, values of the stabilized power are reported.

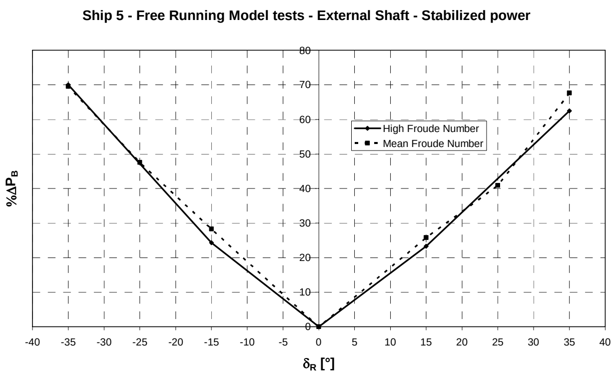


**Fig. 12: Ship 5 – Free running model tests – External Shaft**

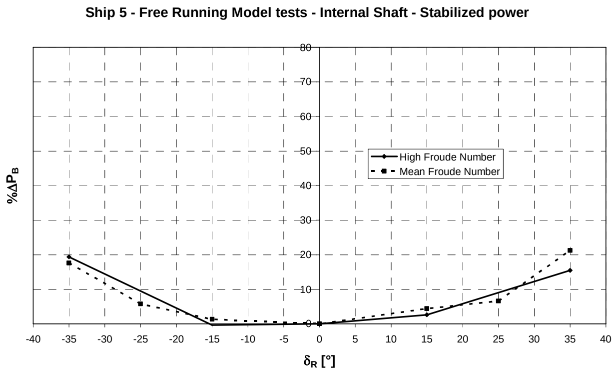


**Fig. 13: Ship 5 – Free running model tests – Internal Shaft**

As it can be seen, as expected external shaft present a significantly higher power increase also in this case, with values up to about 70% in correspondence to maximum rudder angle considered (35°), compared to the rather low increases experienced for the internal shaft (up to about 20% in correspondence to maximum rudder angle).

Moreover, it can be seen that very similar values are obtained for both speeds considered, and that no automation effect is present at higher Froude number, consistently with test conditions (constant RPM and fixed pitch propeller). It has to be noted that this information about highest ship speeds is useful for correct construction of simulators, and could not be obtained obviously from sea trials data analysis.

Data obtained during sea trials for the same ship are reported in the following figures 14 and 15 for external and internal shaft; it has to be noted that in this case mean values (port and starboard maneuver) are represented. It has also to be noted that, in order to be able to compare these results (in which propeller revolutions are reduced during maneuvers at high Fr) and model tests, $P/N^3$ variations (where N are propeller revolutions) are reported in figures instead of power variations.

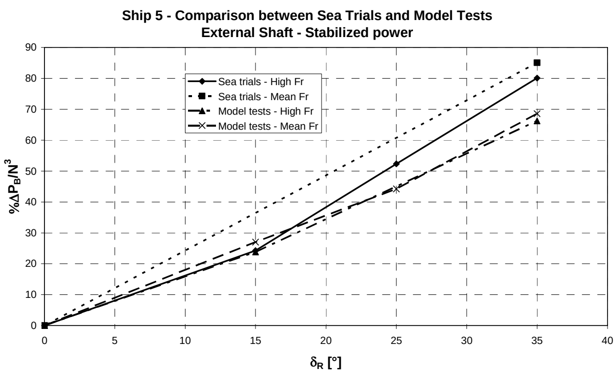


**Fig. 14: Ship 5 – Comparison between Sea Trials and Model Tests results – External Shaft**

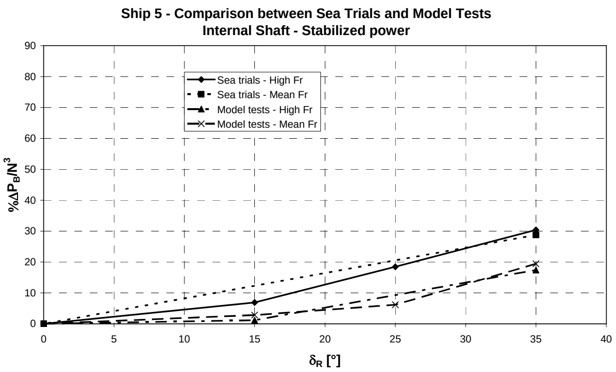


**Fig. 15: Ship 5 – Comparison between Sea Trials and Model Tests results – Internal Shaft**

From the analysis of Figures 14 and 15, it is clear that, as a general trend, free running model tests tend to underestimate power increases, with values lower of about 10-15% in correspondence to maximum rudder angle for both external and internal shafts. If lower rudder angles are considered, it can be seen that the same tendency appears for internal shaft, while for external shaft differences appear only for rudder angles higher than 20° (from this point of view, it has to be noted that data from sea trials at low Froude Number have been recorded only in correspondence to the maximum rudder angle, therefore the straight line resulting in the graph does not provide real data at low rudder angles).

It has to be noted that these results are only preliminary, and do not allow to draw a general conclusion, since a higher number of data would be needed to verify the tendencies and investigate possible physical reasons. Nevertheless, it is believed that this tendencies can be already applied in case simulations are needed in order to test different automation system strategies; it has to be noted moreover that, if asymmetrical wake fraction variation calculation is performed and the scale factor for torque increase is considered, mean values of -0.17 and 0.26 for internal and external shaft respectively are obtained, thus remarkably in line with data obtained from sea trials.

## 6 CONCLUSIONS

An analysis of a series of turning circle manoeuvres recorded during sea trials has been carried out for five different twin screw naval ships, with the aim of analysing phenomenon of asymmetrical shaft power increase.

As a result, a common trend for power increase has been recorded for all ships, despite their significant differences in type, size, speed and propulsion system configuration.

A first investigation of physical causes of the phenomenon has been carried out, considering asymmetrical variation of longitudinal speed and tangential speed, which are both likely to be present to different extents. Longitudinal speed approach (with asymmetrical wake fraction variation) is probably the most straightforward and the one which can be implemented in simulation software in the easiest way.

It is believed that, for unconventional propulsion plant arrangements which differ from the usual ones, automation plant will need to monitor carefully these effects, in order to avoid possible problems; in order to carefully analyze different automation strategies, ship maneuvering simulators could be modified in order to include the phenomenon analyzed, adopting data already present in this study (if similar ships are considered) or obtaining additional data from dedicated free running model tests if the ship analyzed is significantly different.

In order to investigate possible scale effects between model tests and full scale trials, an additional series of data from free running model tests for Ship 5 have been analysed, underlining that the asymmetrical power increases can be predicted with a reasonable accuracy, even if a possible underestimation appears; further tests would be needed in order to generalize the present results.

The next step of this analysis will be the modification of the maneuvering and propulsion plant simulation software already available at DINAV (see for example Altosole et al. 2003 and Benvenuto et al. 2001) in order to include these effects; it is believed that such a simulation software, which makes possible testing during design phases different automation strategies, will allow to reduce considerably risks connected to asymmetrical power increase and time needed for calibration of the automation plant itself during sea trials.

As an additional information, the maneuvering simulator will allow also to investigate possible influence of this asymmetrical power (and consequently propeller thrust) increase on usual ship maneuvering characteristics (such as advance, transfer, tactical diameter, overshoot angles), thus allowing to better calibrate mathematical models used in ship maneuvering.

## 7 ACKNOWLEDGEMENT

This work has been partially carried out as part of a Master Thesis by STV(GN) Laura Girotti and STV(GN) Giulio Dubbioso from the Italian Navy. The authors gratefully acknowledge contributions from Fincantieri C.N.I., Cetena, INSEAN and Italian Navy, which made available sea trials and model tests data for the present study. Special thanks to Mr. Luigi Grossi for his comments and suggestions during development of the present work.

## REFERENCES

Altosole, M., Figari, M., D'Arco, S., (2003), 'Design and Optimisation of Propulsion Systems by Dynamic Numerical Simulation'

Benvenuto, G., Brizzolara, S., Figari, M., 'Simulation Of The Propulsion System Behaviour During Ship Standard Manoeuvres', Proceedings PRADS 2001

Cassella, P., (1971a), 'Performance of a Screw Propeller in Non Axial Flow', Tecnica Italiana, (Maggio 1971), pp 151-161.

Cassella, P., (1971b), 'On the Propeller in Yaw: a Comparison between some Results obtained from the Equivalent Section theory and the Experimental Ones', Tecnica Italiana, (1971), pp 201-211.

Longo, J. & Stern, F., (2002), 'Effects of drift angle on model ship flow', Experiments in Fluids 32 (2002) 558-569

Longo, J., Yoon, H. S., Toda, Y. & Stern, F., (2006), 'Phase–Averaged 3D PIV/Wave Elevations and Force / Moment Measurements for Surface Combatant in PMM Maneuvers', Proceedings 26th Symposium on Naval Hydrodynamics, Rome