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Editors : Ömer Gören
Barbaros Okan
Şafak C. Karakaş

ITU Faculty of Naval Architecture and Ocean Engineering, İstanbul

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Hydrodynamic coefficients regressions analysis and application to twin screw vessels

M. VIVIANI
DINAV, University of Genova, ITALY
G. DUBBIOSO & M. SOAVE
Italian Navy
C. NOTARO
CETENA S.p.A., Genova, ITALY
R. DEPASCALE
Fincantieri C.N.I., Naval Vessesl Business Unit, Genova, ITALY

ABSTRACT: The problem of ship manoeuvrability has reached nowadays a significant consideration, both for merchant ships, with the adoption of IMO standards, and naval ships, with the production of various documents by NATO Specialist Teams. In literature many works regarding manoeuvrability of single screw slow/medium speed ships can be found, while a lack of information exists for what regards twin screw ships (cruise ships, RoRo ferries, megayachts, naval vessels), characterised by different form coefficients and more complex stern configuration due to appendages like skegs, shaft lines and brackets that can strongly affect manoeuvrability behaviour. In this hydrodynamic coefficients of a series of twin screw naval vessels have been evaluated considering different semi-empirical formulations proposed by various authors and standard manoeuvres (turning circle and zig-zag) have been simulated with the aid of a simulator tool. Discrepancies of predicted manoeuvres with respect to experimental full scale ones have been analysed considering parameters involving stern appendages and hull main dimensions in order to select most suitable regressions to study twin screw vessel manoeuvring performance in the earlier design stages. Moreover, linear hydrodynamic coefficients corrections related to stern appendages contribution have been developed on the basis of results of a system identification technique and of an analysis of a set of experimental data at PMM for a ship model equipped with different stern appendages configurations.

1 INTRODUCTION

The problem of ship manoeuvrability has increasingly grown in consideration during the last decades, both for merchant and naval ships; this resulted for merchant ships in the adoption by IMO of the RESOLUTION MSC137(76), which established minimum manoeuvrability standards to grant safety for all seagoing ships, and for naval ships in the work of NATO NG6 Specialist Team in Naval Ship Manoeuvrability (ST-NSM), which led to ANEP 70 with a set of preliminary criteria for NATO warships with the aim to grant a common manoeuvring capability to cope with specific mission requirements. As it is well-known, an estimation of ship manoeuvrability is strongly related to the accuracy in the determination of the hydrodynamic coefficients which specify the mathematical model of ship manoeuvrability used in the existing simulation tools. These coefficients are usually estimated, in a preliminary stage of design (in which in most cases it is not feasible to perform extensive experimental campaigns or time consuming RANS calculations), from regression formulae based on existing model-test data. During years various authors have proposed different regression formulae based on series of experimental data usually covering slow/medium speed single screw merchant ship characterised mainly by full shapes and high block coefficients. Consequently, when considering ships with geometrical and operational characteristics different from those considered by the regressions, manoeuvrability behaviour could not be predicted accurately, as e.g. in the case of twin screw naval vessels, characterized by higher operational speed and slender hull shapes with considerably less full stern shapes and longitudinal sections. Moreover, hull appendages for these ships are relatively larger than those for conventional single screw ships, including shaft lines with their brackets, rudders (in most cases twin configuration is adopted), skeg, affecting significantly ship manoeuvrability. Unfortunately, despite its importance, appendages influence is in some cases not properly evaluated if usual regression formulae are adopted, since "a mean appendage configuration" is implicitly included into them (regressions usually consider data from fully appended models); as a consequence, if the ship appendage configuration is different from the mean one, significant errors can be experienced. In order to overcome this problem a significant amount of model tests would be necessary if dedicated regressions had to be obtained and related costs would be considerable. In this work hydrodynamic coefficients of a series of 7 twin screw naval vessels with different hull forms and appendages configurations have been evaluated considering different semi-empirical formulations proposed in literature; macroscopic parameters of standard manoeuvres (turning circle and zig-zag) have been estimated with the aid of simulation tools and compared to the corresponding experimental ones obtained from full scale trials in order to find the most suitable regressions for applications to twin screw ships. Discrepancies obtained with each regression have been analysed as a function of appendages projected area and principal hull dimensions L, B, T (in particular the usual nondimensional coefficents based on them) and coefficient C_B in order to find possible trends that could deepen their relative importance and give more insight into differences between regressions. Moreover, because of the strong effect on manoeuvrability behaviour of twin screw vessels, particular attention has been devoted to understand stern appendages contribution to linear hydrodynamic coefficients and to obtain empirical corrections wich resulted by the application of two methods that will be described in the next sections, namely system identification by means of optimization technique (Viviani et al., 2003, 2007, 2009) and in analysis of captive model tests performed for a ship model with different stern appendages configurations to obtain semiempirical corrections.

2 REGRESSIONS ANALYSYS

2.1 *Ships analysed*

Ships investigated are a series of 7 twin screw ships with different principal dimensions, propulsion plant and mission requirements. In the following table, main nondimensional geometric characteristic of each ship comprising stern appendages characteristics in terms of projected area and Froude number correspondent to the manoeuvres analysed are listed:

Tab. 1 – Geometric Characthteristics of ship analysed

SHIP	CB	L/B	B/T	L/T	Fn	Alat/LT
1/1	0.62	6.61	2.92	19.28	0.209	0.048
1/2	0.62	6.61	2.92	19.28	0.209	0.098
3	0.47	6.91	3.46	23.88	0.33	0.159
4	0.49	8.61	3.32	28.55	0.282	0.139
5	0.59	5.76	3.9	22.45	0.302	0.205
6	0.55	7.4	3.88	28.67	0.179	0.167
7	0.5	7.89	3.63	28.63	0.248	0.147

Ship 1/1 and Ship 1/2 represent two different ships with the same hull but different stern appendages configurations, the former with a single central rudder and the latter with twin rudder plus a centerline skeg.

2.2 *Semi-empirical regressions considered*

In the following table 2 the various regressions analysed in the present work are listed. For the sake of brevity only the hull hydrodynamic coefficients considered by each regressions are reported, having omitted their formulations, which are reported in the references indicated in the last column.

Tab. 2 – Regression analysed in present work

regression	coefficients		ref.
	linear	non linear	
SSPA	Y_v Y_r N_v N_r Y_{uv} Y_{ur} N_{uv}	Y_{vv} Y_{vr} Y_{rr} + cross flow	(Bystrom,1988)
INOUE	Y_β Y_r N_β N_r	$Y_{\beta\beta}$ Y_{rr} $Y_{\beta r}$ N_{rr} $N_{\beta\beta r}$ $N_{rr\beta}$	(Inoue,1981)
Kijima '93	Y_β Yr N_β N_r	$Y_{\beta\beta}$ Y_{rr} $Y_{\beta\beta r}$ $Y_{rr\beta}$ N_{rr} $N_{\beta\beta r}$	(Kijima, 1993)
Kijima '03	Y_β Yr N_β N_r	$Y_{\beta\beta}$ Y_{rr} $Y_{\beta\beta r}$ $Y_{rr\beta}$ N_{rr} $N_{\beta\beta r}$	(Kijima, 2003)
Ankudinov	Y_v Y_r N_v N_r	Y_{vv} Y_{vr} Y_{rr} Y_{vrr} N_{vr} N_{rr}	(Ankudinov, 1993)
Clarke (1)	Y_v Y_r N_v N_r	Inoue	(Clarke, 1983)
Clarke (2)		SSPA	

Simulator based on each regression mathematical models have been developed in *Matlab-Simulink* language except for the first one, SIMSUP, based on SSPA regression and validated for various typology of single screw and twin screw ships (Puccio and Capurro, 1990, Capurro et al., 1994). It has to be noted that in the case of Clarke regression non linear hydrodynamic coefficients formulations are not included, and it was decided to adopt in one case Inoue's one on the basis of comparison of hydrodynamic forces and moments derived by PMM tests performed for Ship 1/1 and Ship 1/2 (Clarke 1); as an alternative cross flow drag formulations have been adopted (Clarke 2). In every case, following a modular type philosophy_ proper of modern manoeuvring simulators, a mathematical-model for predicting rudder forces and moments have been developed at DINAV by the authors on the basis of various models available in literature and validated by comparing rudder forces measured during PMM tests of Ship 1 model; principal features of rudder model are described briefly in the next sub-paragraph.

2.3 *Rudder forces and moments predictions*

Rudder forces and moments are very difficult to be evaluated because the flow field is very complex in the stern region of a ship in oblique motion and are also strongly affected by interference between rudder, hull and propeller. In the following points the main characteristics of the mathematical model of the rudder developed at DINAV are described, with the aim to give a basic overview about the principal hydrodynamic phenomena considered. Rudder forces are evaluated considering rudder open water characteristic properly modified by hydrodynamic interaction with propeller and hull as described in the following points:

- *Rudder type*: the model can evaluate forces and moments of different type of rudder, in particular spade and horn rudder (usually installed on high speed naval vessel and ferry); differences between rudder types/shapes are described in the model considering different lift coefficient (C_L) curves derived from experimental tests (Molland, 2006).
- *Flow at rudder :* the flow speed at the rudder position is calculated considering the vectorial sum of longitudinal speed and transversal speed originated by the coupling of sway and yaw motions. The longitudinal speed component is evaluated taking into account the longitudinal speed at rudder position due to the ship motions (ship longitudinal speed modified with the nominal wake fraction) and the propeller accelerated flow considering rudder position relative to propeller axis, slipstream diameter reduction and flow turbulence corrections. Effective longitudinal speed is calculated considering an average of the two axial velocities described considering rudder areas interested by the two axial flows, as reported in the next formula:

$$U_{ax\_rudder}{}^{2} = \frac{A_P}{A_R}\left[u_{propeller\_stream}\right]^2 + \frac{A_R - A_P}{A_R}\left[(1-w)u\right]^2 \qquad (1)$$

Where A_P and A_R are rudder area in the propeller slipstream and total rudder area respectively, u is advance speed and and $u_{propellerstream}$ is calculated with axial actuator disc theory with empirical corrections that describe flow turbulence (Bertram 2002); transversal speed is evaluated as function of sway and yaw velocities with the following expressions:

$$v_{trasv\_rudder} = v_{ship} + x_{rudder} r_{ship}$$

- *Effective flow angle:* Effective incident flow angle is calculated with the following relation:

$$\alpha_{effective} = \delta - \gamma \beta_{RE} \qquad (2)$$

β_{RE} is effective dridt angle, $\beta_{RE}=\gamma\beta_R$, β_R the drift angle at the rudder position:

$$\beta_R = \frac{(v_{ship} + x_{rudder} r_{ship})}{u_{ship}} \qquad (3)$$

and γ is the flow straightening coefficient that describes the disturbances due to the hull on the incoming flow to the rudder (in particular, the hull has a straightening effect on the flow), evaluated with statistical regression derived from experimental test; generally γ assumes a value between 0 and 1, and in present work it has been evaluated with the empirical formula presented by Kijima (1993). In the case of Ankudinov's mathematical model, two straightening coefficients have been considered for drift speed an rotational speed respectively (Ankudinov, 1993); in this case the effective drift angle at rudder position assumes the following expression:

$$\beta_{RE} = \frac{(\gamma_v v_{ship} + \gamma_r x_{rudder} r_{ship})}{u_{ship}} \qquad (4)$$

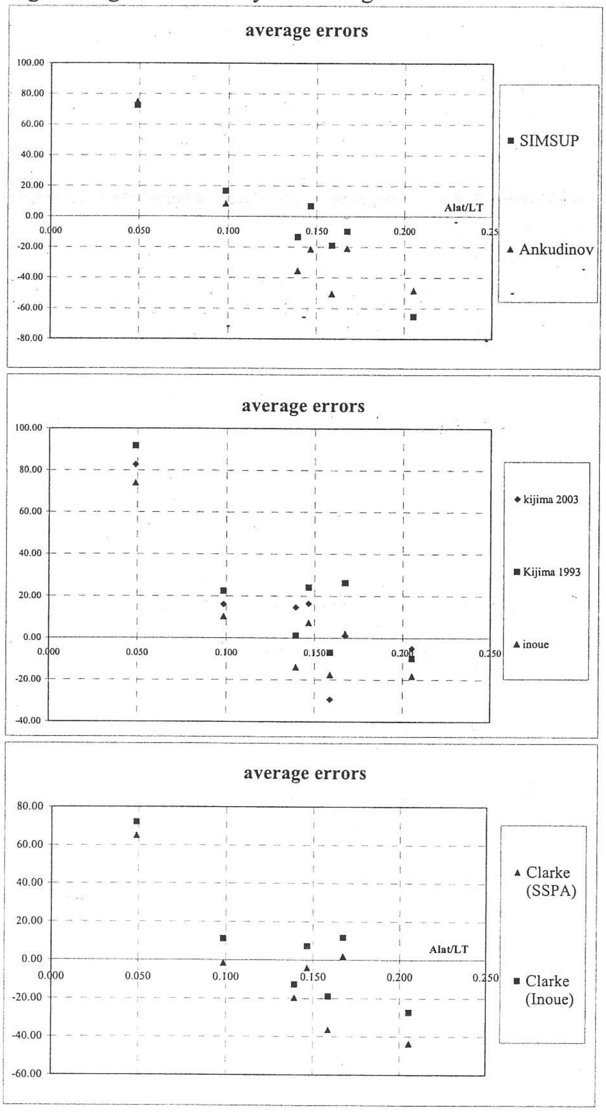
2.4 *Simulation results and comments*

Simulation of a series of turning circle and zig-zag manoeuvres with different rudder angles (for a total of 33 manoeuvres) have been performed for the 7 ships at speed reported in Tab.1 and discrepancies have been compared to full scale trial results (supplied by Cetena and Fincantieri) in terms of average errors for each type of manoeuvre. These errors have been plotted as function of appendages and hull geometric characteristics in order to gain a better insight into their influence on twin screw ship manoeuvrability behaviour. Among various parameters considered, as already anticipated appendages configuration has resulted the most important, whose influence tested regression methods are not able to fully capture. In the next figure 1 average errors as function of projected appendages area are plotted as an example considering separately the following groups for the sake of clarity:

- SIMSUP and Ankudinov;
- MMG2 (Inoue, Kijima'93, Kijima'03);
- Clarke with Inoue and SSPA non linear terms.

Average errors are evaluated considering mean value of errors on usual parameters of turning circle (advance, transfer, tactical diameter, final diameter, etc.) and zig-zag (overshoot angles and period) manoeuvre. Sign has been assumed positive when a more stable behaviour is obtained (larger turning circle or lower overshoot angles) and negative when a less stable behaviour is obtained.

Fig. 1. Regressions analysed average errors



As it can be seen from figures, Ship 1/1 manoeuvring characteristics (points on the left side with lowest values of A_{LAT}/LT) are predicted with considerably low accuracy (presenting errors higher than 70%) by all the regressions considered: this problem is probably caused by the relatively lower appendage area with respect to the other ships analysed, which probably differs from the "mean" one; on the other side all regressions predict Ship 4 (points on the right side with highest values of A_{LAT}/LT) as a more unstable ship, presenting again a rather high average error, for the same reason of Ship 1/1. For the remaining ships with intermediate appendages configurations, despite the relative lower discrepancies with respect to the extreme cases, regressions show a less_marked behaviour, with a certain scatter which is probably caused by more complex influence of hull geometry and hull-appendages interactions. However, SSPA and Ankudinov average errors present more regular monothonic trend, with less scatter, suggesting that appendages influence is the most important problem of these regressions, which on the contrary capture better other characteristics. Consequently these regressions have been further considered in order to develop an efficient and suitable method that may permit to correct hydrodynamic coefficients for a better evaluation of ship manoeuvring performances in the first design stages. In particular, in the following paragraphs two different methods will be described together with the relative results, which will be compared to original ones; in the first one, as reported in section 3, an identification technique based on optimization algorithms is applied to full scale manoeuvres of twin screw vessels considered in this study with the aim of obtaining directly the total hydrodynamic coefficients (comprehensive of bare hull and appendages contribution), while in the second one semiempirical formulations for evaluation of appendages hydrodynamic coefficients have been derived from PMM tests results of a ship with different stern appendages configurations in order to consider them in addition to bare hull derivatives.

3 SYSTEM IDENTIFICATION BY MEANS OF OPTIMIZATION TECHNIQUE

System identification by means of optimization technique is briefly described in present chapter; the reader is referred to (Viviani et al., 2003, 2007, 2009) for a more detailed and complete treatment about this topic. This procedure, developed by CETENA and Fincantieri together with Genoa University (Viviani et al., 2003), is the application of the program for numerical optimization FRONTIER (Spicer et al.,1998) developed by EnginSoft combined with the simulation program for surface ships SIMSUP (Cazzani et al.,2002)(Capurro et al.,1994) developed by CETENA. FRONTIER allows iteratively and automatically a series of calculations using different programs (in this case SIMSUP), in order to evaluate objective functions to be minimized or maximized by means of various optimizations algorithms (e.g Genetic Algorithms, Gradient search). Objective functions introduced for turning circle and zig-zag manoeuvres represent discrepancy between simulated and experimental manoeuvres in terms of usual macroscopic parameters; as an example below turning circle objective function is reported:

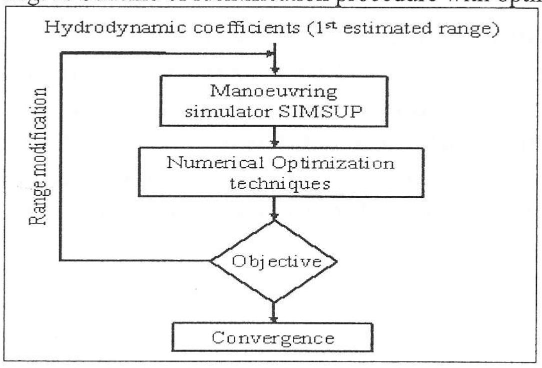
$$\left(\left|\frac{A-A_S}{A_S}\right|+\left|\frac{T-T_S}{T_S}\right|+\left|\frac{D_T-D_{TS}}{D_{TS}}\right|+\left|\frac{D_F-D_{FS}}{D_{FS}}\right|+\left|\frac{V_R-V_{RS}}{V_{RS}}\right|+\left|\frac{\nabla-V_S}{V_S}\right|+\left|\frac{T_{90}-T_{90S}}{T_{90S}}\right|+\left|\frac{(T_{180}-T_{90})-(T_{180S}-T_{90S})}{(T_{180S}-T_{90S})}\right|\right)/8 \qquad (5)$$

where A=Advance, T=Transfer, D_T=Tactical Diameter, D_F=Steady Turning Diameter, V_R=Stabilized yaw rate velocity, V_S=Stabilized absolute speed, T_{90}=Time corresponding to 90° heading variation, T_{180}=Time corresponding to 180° heading variation.

The identification procedure, schematized in the next fig. 2, has been applied systematically to the series of twin screw vessels considered in this study and is structured in general as follows:

- Starting from an initial range of variation for the investigated coefficients a large number of combinations of hydrodynamic coefficients is generated randomly by the program and corresponding simulations are performed;
- The best 20 (about) solutions of this first calculation are assumed as input population for a second optimization made with a Multi Objective Genetic Algorithm (MOGA); the range of variation of the coefficients given in input is varied considering values corresponding to the best solutions identified by the previous step of calculation.

Fig. 2. Scheme of identification procedure with optimization



The procedure is repeated iteratively with a sequence of MOGA reducing the range of investigation step by step until convergence is reached.

The results obtained with optimization procedure have been analysed, trying to relate coefficient values (or coefficients variations) to parameters of the ships considered. In particular, parameters selected for this analysis were related to hull main dimensions (L/B, L/T, B/T, C_B) and to appendages parameters (longitudinal profile characteristics, i.e. area and longitudinal centre, of hull plus appendages and of appendages alone). In the latter case promising correlation has been found between non-dimensional values of appendages surfaces and hydrodynamic coefficients variations with respect to their original values. As an example, trends for N_r and Y_v are plotted in the next figures:

Fig. 3. $Yv_{\%}$-appendages area correlation

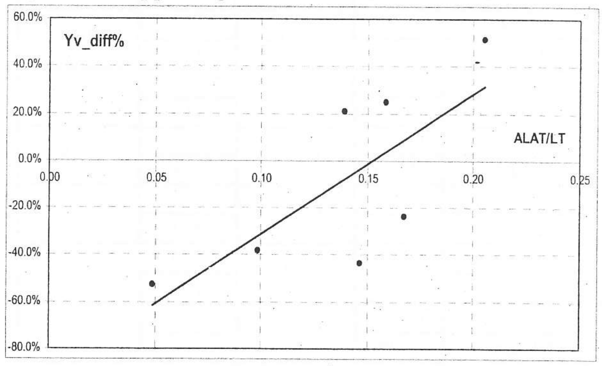
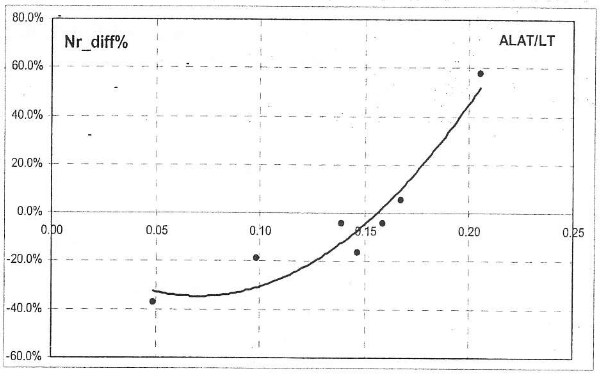


Fig. 4. $Nr_{\%}$-appendages area correlation



It has to be underlined that the two moment coefficients Nv and Nr show a higher correlation with appendages, while data are more sparse in the case of lateral force coefficients Yv and Yr; possible reason for this are cancellation effects which affect more significantly their convergence in the optimization process. Once the high importance of appendages configuration has been found, a series of possible parameters including them has been analysed in order to search for the best correlations with coefficients variations; as a result, they have been linked to different parameters, as follows.

$$\begin{aligned}
\Delta Yv &= f\left(A_{app}/LT, L/T\right)\\
\Delta Yr &= f(A_{app}/LT, X_{app}/L, L/T)\\
\Delta Nv &= f(A_{app}/LT, C_B, B/T)\\
\Delta Nr &= f(A_{app}/LT, X_{app}/L, L/T)
\end{aligned} \qquad (6)$$

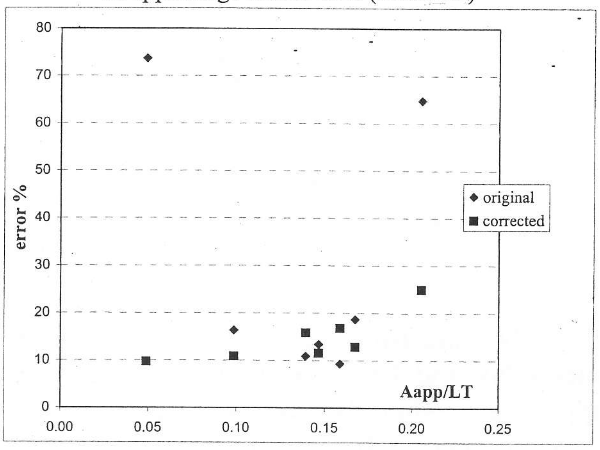
As a validation of the expression adopted, simulation of turning circle and zig-zag manoeuvres have been performed for all the ships selected in this study applying directly appendage correction to SIMSUP hydrodynamic coefficients. Errors resulting from simulations with original and corrected

SIMSUP coefficients are reported in following table 3 and figure 5, where not satisfactory consideration of appendages with SIMSUP original regressions is clear. In this case, error reported has an absolute value without considering positive or negative valuefor more or less stable behaviour.

Tab. 3 – Results with appendages corrections (SIMSUP)

SHIP	MANOEUVER	ORIGINAL		CORRECTED	
		ERROR	AV. ERROR	ERROR	AV. ERROR
1/1	TURNING	85.21%	77.84%	11.3	9.7
	ZIG-ZAG	70.47%		8.1	
1/2	TURNING	14.48%	14.40%	8.4	10.9
	ZIG-ZAG	14.32%		13.3	
3	TURNING	12.23%	26.85%	10.3	16.8
	ZIG-ZAG	41.48%		23.3	
4	TURNING	13.22%	14.17%	14.9	15.9
	ZIG-ZAG	15.12%		16.8	
5	TURNING	63.35%	67.30%	27.7	25
	ZIG-ZAG	71.24%		22.3	
6	TURNING	7.79%	20.21%	12.2	11.6
	ZIG-ZAG	32.63%		10.9	
7	TURNING	16.69%	19.94%	12.9	12.9
	ZIG-ZAG	23.18%		12.8	
TOT ERROR%		34.4%		14.7	

Fig. 5. Average errors before and after corrections as a function of appendage lateral area (SIMSUP)



4 ANALYSYS OF EXPERIMENTAL CAPTIVE MODEL TEST

The second approach consists of some semi-empirical correction imparted to hydrodynamic coefficients calculated with regression formulae; in particular this procedure recalls the original one proposed in Jacobs (1966), in which complete hull hydrodynamic derivatives were calculated as a linear superposition of a bare hull and appendages terms evaluated theoretically by low aspect ratio wing theory. Various authors (e.g. Burcher 1972, Eda and Crane 1988, Clarke et al. 1982) have further investigated these complex phenomena and it was remarked that appendages contribution to manoeuvring performance of a ship is strongly related to interactions effects with the hull; the hull disturbs the flow reducing hydrodynamic angle of incidence of appendages incoming flow and consequently the force developed is lower when compared to an open water (undisturbed) flow. This effect is considered by means of a "flow straightening factor" γ (simular to the one introduced in rudder treatment) that corrects the theoretical value of appendage derivatives and its value is about 0.3 as reported in (Clarke, 1982) or evaluated by the following expression reported in (Ankudinov 1993) in the case of rudders:

$$\gamma = \frac{1}{1-C_B} \qquad (7)$$

In the following a procedure adopted at DINAV in order to analyse captive model tests results performed at PMM on Ship 1 equipped with more than ten different stern appendages configurations is described; in particular the principal aim of this analysis has been to find empirical corrections to Jacobs theoretical formulas and to relate them to appendages geometrical characteristics in order to better evaluate their contribution to bare hull derivatives. It has to be pointed out, in fact, that appended hull hydrodynamic coefficients calculated adding appendages effects evaluated by means of Jacobs theoretical formulae and hull contribution give rise to an over-prediction of ship dynamic stability with resulting poor steering ability due to the lack of consideration of flow straightening effect. The procedure adopted is briefly summarized in the following points:

- ship configurations which differentiate each other for only one appendage (for example ship without skeg and with skeg, all other appendages remaining the same) are considered, and differences in hydrodynamic coefficients are evaluated;
- linear hydrodynamic coefficients of the additional appendage are evaluated by means of theoretical formulas including the unknown flow straightening factor γ which has to be determined case by case; for example appendage linear hydrodynamic lateral force is calculated with the following expression:

$$Y'v_{app} = -\gamma_s \mid A'_{app}\left(\frac{\partial C_L}{\partial \beta}\right)_{app} \mid \qquad (8)$$

- coefficients of the additional appendage are summed to those of the ship without it; sway and yaw lever is calculated as the ratio of moment and lateral force coefficients as below:

$$lv = \frac{Nv_{hull\_\exp} + Nv_{app}}{Yv_{hull\_\exp} + Yv_{app}} \qquad (9)$$

- comparing this value with the experimental one relative to the same appendage configuration, the unknown flow straightening coefficient γ can be evaluated

- analogous of procedure is followed for the evaluation flow straightening coefficient for yaw motion.
- finally, sway and yaw flow straightening coefficients have been averaged for the sake of simplicity, in order to have a unique value

Average flow straightening coefficients have been collected for each type of appendage and their values have been analysed in terms of appendages geometric characteristics, longitudinal position relative to amidship (adopted as the origin of the reference system) and lateral position. A promising correlation has been found relative to appendage aspect ratio parameter only. However it should be emphatized that appendages lateral position is a fundamental parameter to be considered because it could describe possible hull mask effect when combined with other local stern geometric characteristics; the simple functional relation with only aspect ratio is due to the low number of points considered which prevents to analyse properly the effect of lateral position.

Hydrodynamic coefficients evaluated with Ankudinov regressions have then been corrected taking into account appendages effects evaluating their hydrodynamic coefficients by means of theoretical expressions corrected with the evaluated flow straightening coefficient γ. The following procedure is adopted:

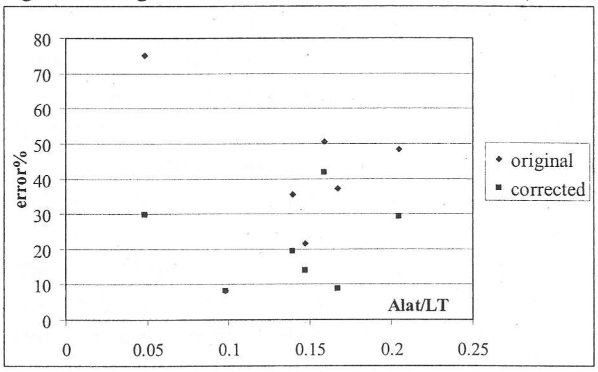
- the ship with the lower average error is selected as reference ship; from figure 1 it is deduced that ship 1/2 presents the lowest error.
- for this ship all appendages hydrodynamic coefficents are evaluated and then subtracted to regression hydrodynamic coefficients in order to obtain bare hull hydrodynamic coefficients.
- ratio of bare hull and appended hull hydrodynamic coefficients is evaluated for the linear derivatives, and it is assumed that it remains constant for all ships; as a consequence, this ratio is applied to original hydrodynamic coefficients for all the remaining 6 ship considered in this study in order to evaluate their bare hull hydrodynamic coefficients.
- for each ship appendages hydrodynamic coefficients are calculated and summed to bare hull derivatives, obtaining corrected hydrodynamic coefficients.

As a validation of the method adopted, simulation of turning circle and zig-zag manoeuvres have been performed for all the ships selected in this study correcting hydrodynamic coefficients as described above. Simulation errors resulting from simulations with original and corrected Ankudinov coefficients are reported in following table 4 and figure 6, showing a remarkable improvement of original results, which however is less evident with respect to SIMSUP corrections by means of optimization technique.

Tab. 4 – Results with appendages corrections (Ankudinov)

SHIP	MANOEUVER	ORIGINAL		CORRECTED	
		ERROR	AV. ERROR	ERROR	AV. ERROR
1/1	TURNING	91.14	75.03	28.80	29.81
	ZIG-ZAG	58.92		30.82	
1/2	TURNING	5.71	8.29	5.71	8.29
	ZIG-ZAG	10.87		10.87	
3	TURNING	29.86	50.50	25.55	41.72
	ZIG-ZAG	71.14		57.90	
4	TURNING	39.51	35.54	25.85	19.34
	ZIG-ZAG	31.58		12.83	
5	TURNING	37.44	48.32	29.13	29.29
	ZIG-ZAG	59.19		29.46	
6	TURNING	35.08	37.15	0.88	8.85
	ZIG-ZAG	39.22		16.82	
7	TURNING	27.09	21.43	13.80	13.79
	ZIG-ZAG	15.77		13.78	
TOT ERROR%		39.5		21.6	

Fig. 6. Average errors before and after corrections (Ankudinov)



5 CONCLUSIONS

In this study several regressions for the calculation of hydrodynamic coefficients describing the forces acting on a manoeuvring ship have been implemented in a mathematical model with the aim to verify their applicability to study manoeuvrability performances of a series of seven twin screw naval vessels in the early design stages. Discrepancies among simulated and full scale trials results have demonstrated that original regressions do not capture with sufficient accuracy stern appendages influence of this type of ships mainly due to the fact that they are based on an average stern appendage configuration which can be different to the one effectively adopted. This phenomenon is very difficult to understand because appendage inflow is strongly related to its position and to stern hull geometry; however disregarding this aspect when studying twin screw vessels manoeuvrability performances at the first design stages could lead to inaccurate predictions. In order to overcome this problem, two different methods have been proposed and applied by the authors to correct linear hydrodynamic coefficients evaluated with regression formulae in terms of appendages geometric characteristics, namely system identification by means of optimization technique and semi-empirical corrections. Both procedures are successful in reducing considerably the average errors in particular of those ships whose initial error was very large due to inaccurate consideration of appendages effect; in other cases, namely those with mean values of appendage projected area, more pronounced scatter suggests that further corrections should take into account other parameters relative to hull geometric characteristics, in particular in proximity of appendages location.

Results of this study are already promising, however it is believed that further efforts have to be directed towards a better understanding of the complex phenomenon of the influence of appendages effects on twin screw ship manoeuvrability, in order to include them in relatively simple, but helpful in the preliminary design stages, simulation tools.

Considering relative merits of the two procedures, the first one seems to give the best results because some non linear effects are implicitly considered in the optimization procedure, since the resulting linear coefficients include also corrections for the higher order effects which are kept constant during the identification process (Viviani et al. 2009). Corrections determined with the second one are suitable for ship stern shapes similar to the one investigated experimentally, thus producing errors when applied to different configurations; moreover, in this case corrections include linear terms only.

In general, it has to be pointed out that the application of both procedures is limited only to ships rather close to those investigated in the study, because hull geometries influence strongly the flow in the stern region (this problem is probably more important for the second method). Moreover, the number of data analysed (7 ships) is still too low and needs further validations. In order to improve corrections obtained and extend their validity, the first procedure should be extended to different series of similar ships for which experimental data of sea trials are available; for what regards the second procedure, a large number of expensive experimental captive model tests with different stern appendages configurations would be needed. From this point of view, therefore, the first procedure seems to be more applicable, due to its relatively low cost in case a significant number of experimental data is available, as in the case of Shipyards or Research centres.

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