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Contents

Improving the Propulsive Efficiency of Full Form Ships

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SYNOPSIS

Shipowners have for several years now been offered the choice of a wide range of propulsion appendages, each of which is claimed by its designer to save fuel or increase ship speed for no increase in consumption. In the absence of a truly unbiased assessment of the relative merits of these appendages, Shell International Marine decided, at the end of 1985, to conduct its own study. At the beginning of 1986 therefore, a hydrodynamicist from MARIN was seconded for this purpose. The study included a review of all available literature, interviews with designers, questionnaires and theoretical studies, resulting in a series of review reports and, ultimately, software which can identify the appendage(s) most likely to benefit any individual ship. This paper outlines some of the findings and describes the facilities available in the software.

INTRODUCTION

Shipowners have for several years been offered the choice of a wide range of propulsion appendages, each of which is claimed by its designer to save fuel or increase ship speed for no increase in consumption. Until now there has been no independent method of evaluating these claims and assessing their relative commercial benefits. It has long been recognised that an appendage which gives the best returns on one ship may not do so on another, but the specific parameters of hull and propeller which affect this have never been completely identified.

Shell International Marine (SIM) therefore perceived a need to establish, primarily for ships under its direct control, a systematic method for the ranking of propulsion appendages for each individual ship. It was recognised that for some devices detailed design calculations and possibly model tests would be necessary before a final prediction of performance and cost could be made.

However, the objective was to identify those appendages worthy of further detailed study, not to produce guaranteed performance figures. For this reason a combination of theoretical and empirical techniques was used. The specific appendages studied were:

- Vane wheel
- Wake improvement duct
- Reaction fin
- Rudder bulb/fin
- Guide fins
- Asymmetric stern
- Integrated duct/propeller
- Added thrust fins

and the particular questions to which answers were sought for each appendage were:

What are the hydrodynamic principles by which it operates?

How can performance improvements be calculated?

Is there any sensitivity to laden or ballast conditions?

What are the costs for design, manufacture, royalty (if any), tank testing, delivery and fitting?

Could the performance improvement be increased by changing the propeller?

Are there any constraints on who manufactures it?

How long does it take to design and manufacture?

What guarantees are given on design, materials and workmanship?

What assistance is given with fitting to the ship?

What testing procedure (if any) is advised for verification of the performance prediction?

What full-scale experience is available and what agreement is there between prediction and trial?

Is it patented?

Michael Osborne was awarded a BSc (Hons) degree in Naval Architecture by the University of Newcastle upon Tyne. In 1966 he joined Cammell Laird & Co. Ltd as a Design Draughtsman in the Ship Design Office before moving to Lloyd's Register of Shipping in 1968. During his time with LRS he progressed from Trainee Surveyor in the London Office to Ship Surveyor in Newcastle upon Tyne and Szczecin, Poland, ending up in the Advisory and Projects Section. Mr Osborne then moved to Hedley, Fraser & Co. as a Naval Architect and was involved in a wide range of consultancy activities, before joining R & H Hall Ltd as Naval Architect responsible for the supervision of the design and construction of a fleet of coasters. In 1980 he joined Shell International Marine as Naval Architect, working on a variety of new construction projects before becoming Chief Naval Architect responsible for the Naval Architecture Department in 1985. This position involves input to the complete building cycle from conceptual design to sea trials and the provision of technical advice on operational problems from performance optimisation to structural maintenance.

FINDINGS OF THE STUDY

A brief summary of the findings of the study is given below for each appendage.

Vane wheel

The vane wheel is a freely rotating propeller mounted on the end of the propeller hub. Its diameter is typically 1.2 times that of the propeller. The pitch of the part of the blades within the propeller slipstream is designed to rotate the wheel, whereas the pitch of the outer part of the blades is designed to produce forward thrust.

The most critical parameter in determining the effectiveness of the vane wheel is the propeller thrust coefficient, C_T, where

$$C_T = \frac{T}{\frac{1}{2}\rho V^2 \left(1 - W_t\right)^2 \pi \frac{D^2}{4}}$$

and T is the propeller thrust, ρ is the specific gravity of water, V is the ship speed, W_t is the wake fraction, and D is the propeller diameter. In general, the higher the thrust coefficient, the greater the potential for the savings to be achieved by adding a vane wheel.

Two approaches may be considered for making engineering approximations of the possible savings from the vane wheel.

Reference (1) provides the curves reproduced in Fig. 1. These are envelope curves of optimum efficiency for propeller alone and propeller + vane wheel combination. C_T is plotted against λ , where $\lambda = J/\pi$, $J = V_a/nD$, n is the rate of revolution, and $V_a = V(1 - W_t)$.

The optimum open water efficiency of the propeller alone is found by entering the diagram with λ and C_T for the propeller. The values are then recalculated to account for the larger diameter of the vane wheel and the open water efficiency of a propeller + vane wheel combination is estimated. However, the expected gain is not simply the gain in open water efficiency. The curves in Fig. 1 assume that an optimum propeller + vane wheel combination is applied, which may imply a different propeller to that used in the first part of the calculation. There is also a reduction in hull efficiency because of the increased diameter of the vane wheel. In addition, this estimate ignores the rotational energy which is recovered by the rudder.

To overcome some of these problems, the second approach, used in the SIM computer program, examines the individual components of propeller efficiency:

$$\eta_o = \eta_{Ax}\eta_{Rot}\eta_V$$

where η_o is the propeller open water efficiency, $1 - \eta_{Ax}$ is the axial loss, $1 - \eta_{Rot}$ is the rotating loss, and $1 - \eta_V$ is the viscous (frictional) loss. η_{Ax} and η_{Rot} are calculated from propeller theory, while η_o can be found from design charts. η_V is then calculated from $\eta_V = \eta_o/\eta_{Ax}\eta_{Rot}$

A similar process is then used to determine η_{Ax}, η_{Rot} and η_V for the propeller + vane wheel combination. Finally, changes to hull efficiency are estimated and the effect of the rudder on recovery of rotational losses is also included, giving a revised propulsive efficiency for the propeller and vane wheel.

Estimates made by this method have been found to agree sufficiently closely with predictions made by the designers to justify its use as a first approximation.

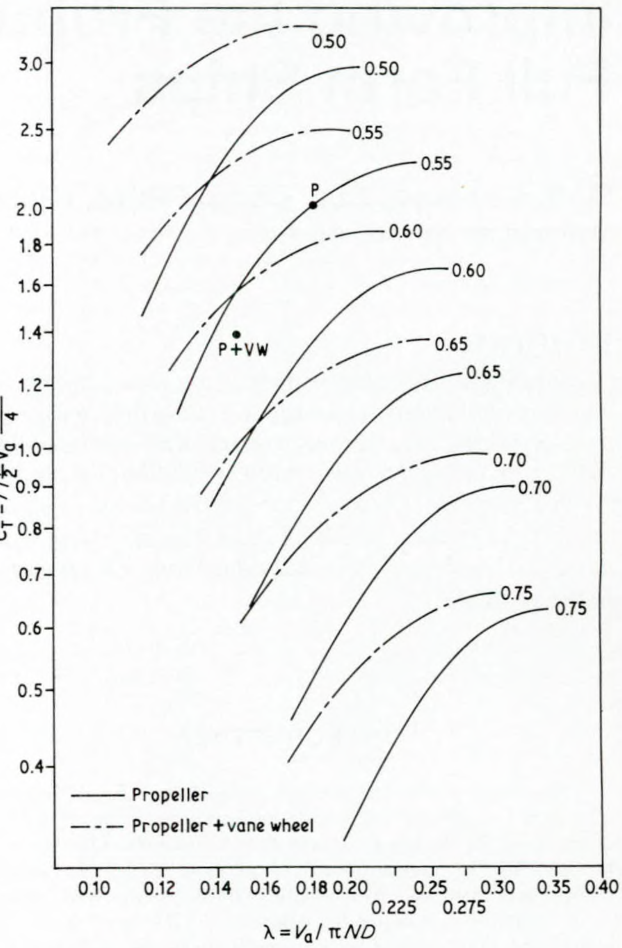

FIG. 1: Optimum efficiency curves for propeller and vane wheel

Table I: Combination of appendages

	VW	WID	RF	RB/F	GF	ID/P	ATF
Vane wheel (VW)	—	P	H	H	A	A	H
Wake improvement duct (WID)	P	—	X	P	P	X	P
Reaction fin (RF)	H	X	—	H	X	X	H
Rudder bulb/fin (RB/F)	H	P	H	—	P	A	X
Guide fins (GF)	A	P	X	P	—	X	P
Integrated duct/propeller (ID/P)	A	X	X	A	X	—	A
Added thrust fins (ATF)	H	P	H	X	P	A	—

A = savings additive, P = savings partially additive, H = hydrodynamically incompatible, X = physically incompatible

Wake improvement duct

The duct designed by Professor Schneekluth accelerates the flow into the top half of the propeller disc and decelerates it slightly into the lower half, achieving a more homogeneous wake. Propeller open water efficiency is thus improved, but additional savings are probably produced by forward thrust on the duct and by reduction of separation.

Hulls which would benefit most from a wake improvement duct are therefore those which suffer a greater than normal vertical asymmetry of wake and those which indicate a potential for separated flow at the aft end. Full form ships usually fall into both these categories. The extent of fuel saving achieved depends on:

1. Waterline angles at the aft end.
2. Shape of waterlines.
3. Angle of flow forward of the propeller.

More details are given in Ref. (2), which quotes a saving of 8% being achieved on average. This is generally confirmed by performance figures from ships operated by Shell Group companies. However, because ducts are fitted during a drydocking, and the hull and propeller are cleaned at the same time, it is difficult to be precise about how much improvement can be attributed to the duct alone.

Since the duct is usually designed for flow angles at loaded, even keel draughts, its effectiveness at ballast draughts with heavy trim angles may be reduced. Full-scale experience with the Schneekluth duct has shown it to be effective in reducing vibration levels as well as bunker consumption.

Reaction fin

The reaction fin consists of a set of fixed vanes mounted forward of the propeller and radiating from the tailshaft housing. They are supported at or near their tips by a ring structure. Their effect is to cause a pre-rotation of the flow into the propeller and a reduction of the rotation losses. In addition there is a small thrust from the fins and ring.

Results published in Ref. (3) by Mitsubishi Heavy Industries suggest that a greater saving can be made on a ship with a U-shaped aft body than on a ship with a V-shaped aft body.

As a first approximation it can be assumed that the reaction fin recovers all the rotational losses, calculated as described in the section on the vane wheel. However, some of these rotation losses are, without the reaction fin, recovered by the rudder. Estimates made by the SIM computer program allow for this.

Rudder bulb/fin

The purpose of the rudder bulb is to reduce the drag behind the propeller hub, and the fins recover some of the rotational losses of the propeller. These are two separate effects which are hydrodynamically independent and therefore additive.

Ships which benefit most are those with large ratios of hub diameter/propeller diameter, such as apply in the case of controllable-pitch propellers, and those with large propeller rotational losses (high C_T value).

The drag caused by the eddies behind the propeller hub can be estimated from information given in Ref. (4) by Hoerner. The reduction in rotational losses is calculated in a way similar to that used for the reaction fin described above. Finally, the additional frictional drag of the bulb and fins is deducted from the saving predicted.

Added thrust fins

The use of fins aft of the propeller, mounted on the rudder or horn, was first suggested by Wagner many years ago. The concept has recently been developed by I. H. I. In principle the fins operate at a small angle of attack to the propeller slipstream and thus generate forward thrust. If rotational losses were eliminated entirely, propeller efficiency would increase by about 5-10%, depending on the propeller design. However, a large part of these losses is recovered by the rudder, which acts as a fin in this respect. According to Ref. (5), about half the remaining rotational losses are recovered by an additional pair of fins.

The thrust generated by the fins is additional to the reduction of rotational energy loss. The total saving therefore could be in the region of 1.5-5% of the DHP.

Guide fins

It has been found that ships which are characterized by a strong vertical component to the flow forward of the propeller benefit from fitting vanes on the sternframe to straighten the flow into a more horizontal direction. Three effects contribute to this improvement:

1. The propeller efficiency is improved by the better inflow.
2. Reduction in hull resistance due to suppression of downward flow.
3. Thrust on fins.

A design method, based on flow pattern observation, has been developed by Dr Grothues-Spork of the Berlin model basin. Ship characteristics which are relevant to the amount of saving achieved, in the region of 2-4%, are:

- Beam/draught ratio.
- Shape of frames over after 15% of hull.
- Strength of bilge vortex.
- Vertical component of flow forward of the propeller.

Integrated duct/propeller

The concept of a duct placed immediately forward of the propeller has been developed by Mitsui Engineering and Shipbuilding and by Hitachi Zosen. The motivation was a desire to eliminate the erosion frequently observed when a duct was placed around the propeller.

Three factors combine to reduce the propulsive power requirements:

1. Homogenization of the wake, resulting in higher propeller efficiency.
2. Reduction of hull resistance.
3. Forward thrust generated by the duct.

Ships with unhomogeneous wakes would therefore benefit from the fitting of a duct. In addition to a performance improvement of 1-2% due to the increased propeller efficiency, there would probably be a reduction in vibration levels. The reduction in hull resistance is due to the reduction in separation and vorticity which the duct induces. Full form ships are likely to suffer from both unhomogeneous wakes and flow separation, making them the highest potential gainers from application of a duct.

Duct thrust is related more to propeller loading than to hull form and is thus less dependent on ship type.

The percentage saving in propulsive power can be estimated from a knowledge of the frame shape at the aft end and the power coefficient, B_p, of the propeller:

$$B_p = \frac{N P_D^{0.5}}{V_a^{2.5}}$$

where N is the propeller speed in rev/min, P_D is the delivered horse power, and V_a is the propeller velocity of advance.

The most comprehensively reported full-scale measurements are those made on *ESSO COPENHAGEN* and published in Ref. (6). These showed that the savings vary over the speed range, but weather corrections may have influenced this conclusion. More confidence can be placed in the conclusion, drawn from both model tests and full-scale trials, that a greater saving is made at ballast draughts than at laden draughts. The *ESSO COPENHAGEN* trials showed savings to vary from 4 to 10% depending on speed and draught.

Combination of appendages

Cynics frequently remark that if all the available appendages were fitted, a ship would actually generate power. Some of them, however, are obviously physically incompatible, ie they cannot both be fitted in the same place on the ship. An obvious example of this is the reaction fin and integrated duct propeller. Others, on the other hand, may be hydrodynamically incompatible, such as the added thrust fins and vane wheel, both of which extract rotational energy from the slipstream.

Some combinations are partially complementary. The Schneekluth duct and the vane wheel could, for example, be fitted on the same ship, but since the effect of the duct is to unload the propeller slightly (reduce the thrust coefficient), the savings from the vane wheel would be reduced.

Other combinations may be totally additive in their savings. An integrated duct and vane wheel, for example, could prove such a combination. Table I is an attempt to indicate which combinations would be feasible.

THE SIM APPENDAGE EVALUATION PROGRAM

A flowchart of the program is given in Fig. 2. The first step is to establish the design condition for the propeller by estimating the hull resistance and propulsion factors using the method of Holtrop and Mennen from Refs (7) and (8). Since it is important to have a reasonably accurate assessment of the wake fraction, this is checked by reference to a propeller design chart. If one is not available, the program will generate one using the Wageningen B series polynomials from Ref. (9). An example of the diagram is given in Fig. 3. The original wake fraction computed from Ref. (8) was 0.42, giving $\sqrt{B_p1} = 1.3$ and $\delta = 276$. Since the P/D of the propeller is 0.636, the points do not coincide. Increasing the wake fraction by trial and error eventually determines the point at which the values are coincident: $\sqrt{B_p1} = 1.6$ and $\delta = 326$. The wake fraction necessary to achieve this is 0.46.

Having established the wake fraction at the design point, the various propeller coefficients are calculated (η_o, η_V, η_{Rot}, η_{Ax}, C_T etc.). The main appendage menu is then displayed and the user can make calculations for savings and costs for any number of the devices. The final step is the calculation of yield, net present value (NPV) and payback for each of the appendages required.

Example

An example of the application of the SIM program is given in the Appendix. The ship chosen is a typical tanker of about 80 000 dwt. The savings and application costs for each appendage are calculated using the techniques outlined previously.

In the results presented the wake improvement duct appears to be the best option, but if NPV were to be calculated over a period longer than the 5 years used, the vane wheel or integrated duct/propeller would eventually give higher returns. Decisions on which, if any, device is to be applied must therefore be based on such factors as the remaining life of the ship, expected changes in fuel price and operational profile.

RELEVANCE TO FULL FORM SHIPS

The study was not constrained in any way to satisfy the requirements of only full form ships and the resulting techniques are applicable to a wide range of ship types.

In identifying those appendages which are likely to be of benefit to full form ships it must be remembered that the propellers of tankers and bulk carriers are usually lightly loaded, that is they have a relatively low C_T value. This has been reinforced by the recent trend to large diameter, low rotational speed propellers. Rotational losses are therefore relatively low, and so those devices which work on the principle of recovering rotational losses are likely to give lower improvements on full form ships.

This is not to say that they are never economic on full form ships, and there may well be a case for installing a slightly less efficient highly loaded propeller combined with a vane wheel, for example. The savings from such a combination could still give an attractive payback time.

CONCLUSIONS

A system has been developed, using theoretical and empirical techniques, to identify the parameters which affect the savings achieved by a comprehensive range of hull appendages. This can be used to rank those appendages in order of economic merit for any hull/propeller combination, enabling further studies to be concentrated on those appearing near the top of the list.

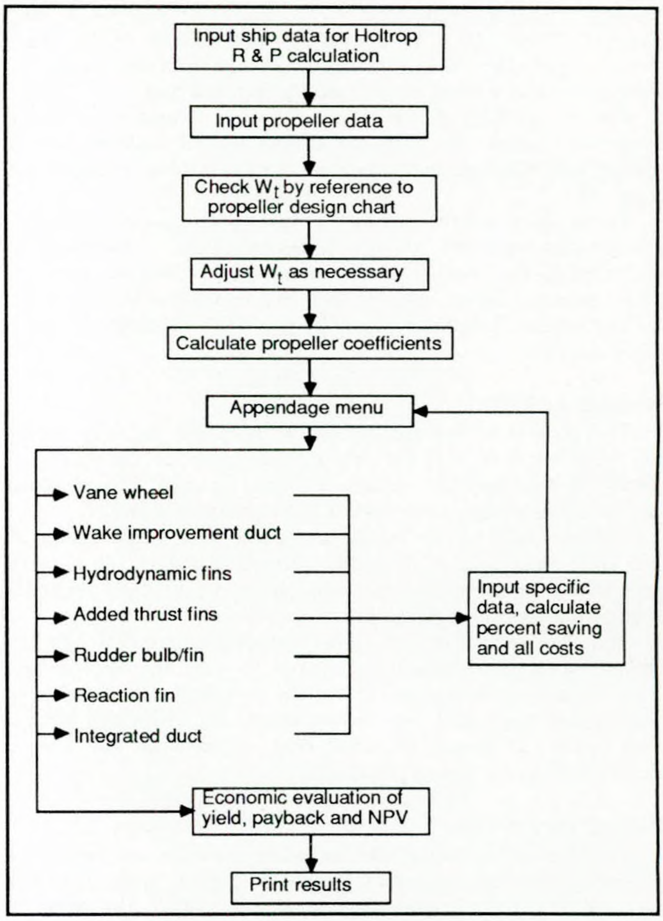

FIG. 2: SIM appendage evaluation program

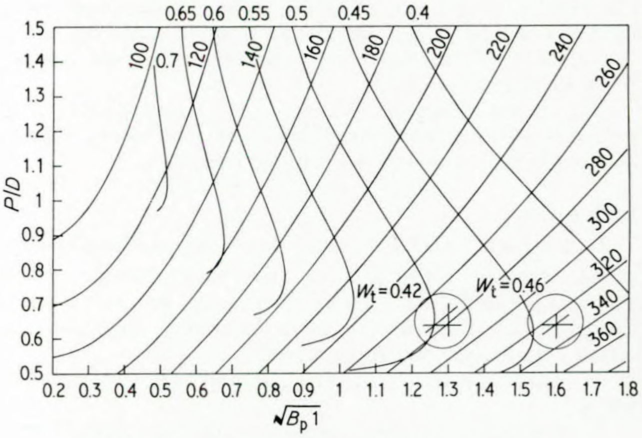

FIG. 3: Diagram used to obtain wake fraction

REFERENCES

1. O. Grim and K. Meyne, 'Propeller und Leitrad'. Kontakt Stadium, Institute fur Schiffbau derUniversitat Hamburg (March 1984).
2. H. Schneekluth, 'Wake equalising duct, state of development'. 6th Lips Propeller Symposium (1986).
3. K. Takekuma, 'Evaluation of various types of nozzle propellers and reaction fin as the device for improvement of propulsive performance of high block coefficient ships'. Shipboard Energy Conservation Symposium, SNAME, New York (1980).
4. S.F. Hoerner, *Fluid Dynamic Drag* (Published by the author, 1965).
5. S. Ishida and Y Shiroze, 'Study of recovery of rotational energy in propeller slipstream'. *I.H.I Engineering Review*, Vol. 16, No. 13.
6. H. Narita et al., 'Deveolpment and full-scale experiments of a naval integrated duct propeller'. *Trans SNAME*, Vol. 89 (1981).
7. J. Holtrop and G. Mennen, 'An approximate power prediction method'. *International Shipbuilding Progress*, Vol. 29 (July 1982).
8. J. Holtrop, 'A statistical re-analysis of resistance and propulsion data'. *International Shipbuilding Progress*, Vol. 34 (November 1984).
9. M. W. C. Oosterveld and P. van Oossanen, 'Further computer-analysed data of the Wageningen B-screw series'. *International Shipbuilding Progress*, Vol. 22 (July 1975).

APPENDIX

Example of the use of the SIM Appendage Evaluation Program

Ship particulars

Lbp	233.00 m
Beam	39.35 m
Draught	12.19 m
Speed	14.75 knots
Shp	14 280.0 hp
Propeller speed	122.0 rev/min
C_B	0.808
C_M	0.995
C_P	0.812
C_{WL}	0.908

Propeller particulars

Diameter	6.48 m
Pitch ratio	0.636
E.A.R.	0.55
No. of blades	4
Hub diameter	0.98 m

Estimated characteristics

Thrust deduction	0.209
Wake fraction	0.42 to 0.46
$\sqrt{B_p}$	1.30 to 1.60
δ	276.0 to 326.0
η_o	0.439
η_H	1.464
C_T	3.931
η_{Ax}	0.621
η_V	0.742
η_{Rot}	0.954

Assumptions used for economic evaluation

Annual bunker consumption	12 000 tonnes
Bunker cost	$100/tonne
Discount rate	8%
Fuel Inflation rate	5%

Results of economic evaluation

	Saving (%)	NPV over 5 years ($)	Payback (years)	Yield (%)
Vane wheel	9.0	246 871	2.4	74.2
Wake improvement duct	6.3	304 471	0.7	>100
Guide fins	3.0	121 748	1.9	>100
Added thrust fins	1.6	-106 817	12.8	-24.7
Rudder bulb/fin	1.5	26 000	4.0	21.3
Reaction fin	3.7	-146 554	9.3	-16.2
Integrated duct/propeller	10.5	78 893	4.4	15.7

It must be emphasized that these results apply only to the particular ship and propeller combination described above. For other combinations different appendages could well be more beneficial.