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Experimental Studies to Modify the Velocity in the Wake of Ships' Hulls

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SUMMARY Two ships are considered. The first, a 13000 tonne roll-on roll-off cargo ship suffered from severe stern vibration caused by the propeller operating in a strongly non-uniform velocity field. The second, a 33000 tonne bulk carrier, had reduced manoeuvrability after a propeller tunnel was fitted to the stern. The results of wind tunnel tests on models showed that vortex generators could be used to make the flow in the wake more uniform, and increase the velocity of the flow near the rudder. Based on these tests, vortex generators were fitted to each ship to cure the stern vibration and steering problems.

NOTATION

C_Y = $Y/(0.5\rho U^2 S)$ = side force coefficient
R = Radius of propeller
r = Radius from centre of propeller shaft
S = Surface area of model
U = Freestream velocity
u = Axial velocity component of the flow
Y = Side force - positive to port
α = Angle of incidence of rudder measured from the centreline of the model
θ = Angular position in the propeller plane. Origin at top dead centre
ρ = Density of fluid

1 INTRODUCTION

To reduce voyage times, improve cargo handling, and keep construction costs to a minimum, there has been a trend in ship design towards higher speeds, fuller aft lines, and single controllable pitch propellers. But these trends have made it difficult to design the stern of the hull to provide a sufficiently uniform flow of water into the propeller and near the rudder to prevent excessive stern vibration, propeller cavitation, noise, and steering problems.

A strong, circumferentially non-uniform, velocity distribution of the flow into the propeller will cause cyclic changes in flow incidence to each blade, causing it to cavitate intermittently and propagate a strong pressure pulse through the water to the hull. This introduces vibration at the propeller blade frequency in addition to normal cyclic variations in thrust and torque. By ensuring that the velocity distribution of the flow into the propeller is sufficiently uniform excessive hydrodynamically-induced stern vibration can be avoided. In addition, since the rudder usually operates in the area of smallest velocity in the wake steering problems can also be avoided by increasing the velocity in this region.

Although consideration is usually given to providing a suitable velocity distribution in the wake during the initial design, its significance in contributing to stern vibration and propeller cavitation has only recently been realized. Consequently, ships have been built which inadvertently suffer from one or more of these problems. It then becomes necessary to modify the ship in the simplest way possible, so that it can perform adequately at its design conditions. The modification usually consists of some form of flow deflector (Vossnack and Voogd, 1973) which increases the velocity in the wake enough to either reduce the propeller-induced vibration to a satisfactory level or improves the flow near the rudder so that its sideforce at incidence is increased. These deflectors mostly involve a power penalty which is accepted provided it is not too large.

Two cases are considered in this paper; the first involves excessive propeller induced stern vibration of a 13000 tonne roll-on roll-off cargo ship, and the second concerns poor manoeuvrability of a 33000 tonne bulk carrier.

2 PROPELLER INDUCED STERN VIBRATION

During acceptance trials, it was found that a recently built roll-on roll-off cargo ship suffered from excessive stern vibration. The ship is 132 m long, and it has a full load displacement of 13000 tonne, with a 21.6 m beam and a 7.3 m draught. It has a 4.9 m diameter, four blade, controllable pitch propeller. To ensure the safety of the ship and provide a reasonable degree of habitability, it was restricted to operate at 16 knot instead of its design speed of 18 knot.

2.1 Cause of Stern Vibration

Tests on the ship indicated that the vibration occurred mainly at the propeller blade frequency, and that it increased in amplitude with power. From this, and other information available from existing model tests, it was concluded that the vibration was caused by the propeller operating in a strong circumferentially non-uniform velocity field, possibly with a significant amount of cavitation.

2.2 Method of Reducing Stern Vibration

The most obvious remedy for the stern vibration is to improve the velocity distribution in the propeller plane. Modification to the stern lines is unacceptable because of the cost involved. Conventional methods, such as fitting a propeller tunnel or stern fins (Vossnack and Voogd, 1973; Huse, 1974) had been tried previously, but they had not been successful with this hull.

In parallel with other studies to find a solution to the problem, tests on a model were carried out in the 2.7 m x 2.1 m low speed wind tunnel at the

Aeronautical Research Laboratories. This investigation was aimed at re-energizing the boundary layer to improve the velocity in the wake, using aerodynamic techniques. The case appeared to be appropriate for the use of vortex generators which are inexpensive, efficient, and simple to make and fit. They operate by re-directing high velocity fluid from outer regions of the boundary layer, along a helical path, to mix with retarded fluid near the body surface. The model tests were therefore aimed at developing a set of vortex generators which could be attached to the stern to create a sufficiently uniform velocity distribution of the flow into the propeller while, at the same time, having a minimum power penalty.

2.3 Wind Tunnel Tests and Equipment

The tests in the wind tunnel were made with a 1/48 scale 'mirror image' model of the below-waterline portion of the hull in both full load and ballast conditions. For this particular investigation, viscous effects are dominant, and eliminating wave action by using a reflex model is not significant. The Reynolds number was kept as high as possible and the tests were mostly made at a value of 1.2×10^7. Neither the propeller nor the rudder were fitted to the model.

Tests were made for systematic variations in generator number, position, aspect ratio, angle of attack, and height. Thin vane-type vortex generators with a triangular planform were used because of their known efficiency under the conditions likely to be experienced at the stern of a ship. Each generator was fitted normal to the surface of the hull and located so that it did not protrude beyond the maximum draught and beam. The effectiveness of the generators was mainly judged from surface flow visualization over the stern, velocity surveys in the plane of the propeller, and resistance tests.

2.4 Results of Model Experiments

The vortex generators which gave the 'best' results are shown fitted to the model in figure 1. A total of four vortex generators were used; the two aft generators having a height of 12.7 mm and a length of 45.7 mm, and the two forward generators a height of 15.9 mm and a length of 57.2 mm. Using the criteria of Huse (1974), and Johnsson and Sontvedt (1972), it was estimated that the velocity distribution produced by these generators would reduce the stern vibration to a satisfactory level, with an acceptable power penalty.

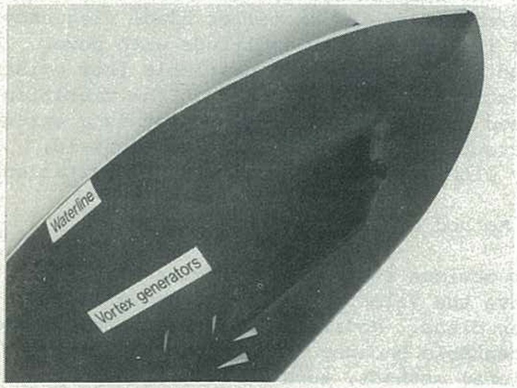

Figure 1 Vortex generators on the cargo ship model

2.4.1 Surface flow pattern

The surface flow pattern over the stern of the model in the full load condition without vortex generators is shown in figure 2. The dark area just forward of the propeller arch shows the region of very low velocity possibly with some separation.

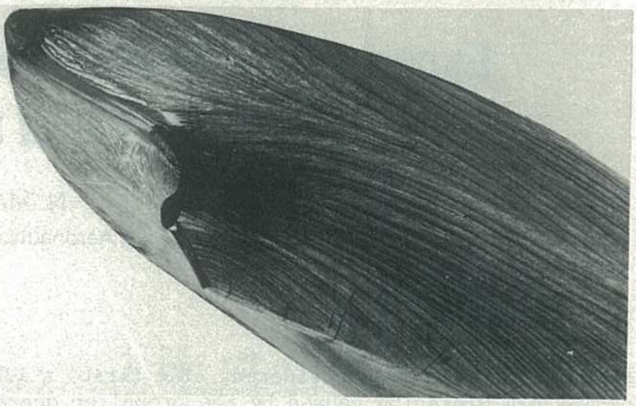
Figure 2 Surface flow pattern on the bare hull

The pattern with the vortex generators attached to the stern is shown in figure 3. The dark lines aft of the vortex generators indicate the path of the high energy vortices which have eliminated the low velocity region forward of the propeller arch.

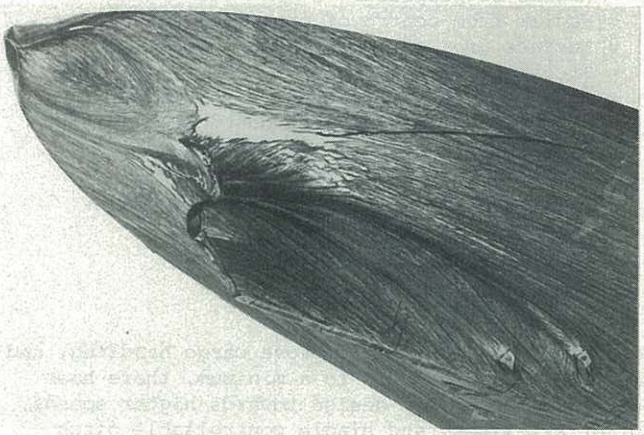
Figure 3 Flow pattern with vortex generators

2.4.2 Axial velocity distributions

The axial velocity distributions of the flow in the plane of the propeller for the bare hull and with the vortex generators attached are shown in figures 4 and 5 respectively, for the model in the full load condition. Results are shown over one side of the propeller disc from the top, $\theta=0^o$, to $\theta=120^o$, the velocities being constant from 120^o to 180^o. Similar results were obtained on the opposite side of the disc.

The large variation in axial velocity that the propeller was originally required to cope with as it rotated, is shown in figure 4. At the top of the propeller, the velocity is less than 15% of the freestream velocity, but after a quarter of a turn, it is almost equal to the freestream velocity. The substantial increase in axial velocity obtained with the generators, especially near the top of the propeller where the axial velocity is now approximately 55% of the freestream velocity, is shown in figure 5. Similar improvements in velocity were obtained in the ballast condition.

2.5 Application of Model Results to the Ship

Scale effects produced by testing the model at a Reynolds number of 1.2×10^7 instead of 1.1×10^9

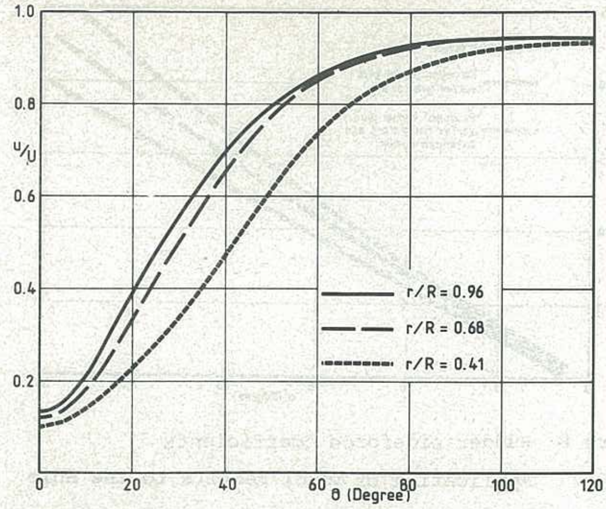

Figure 4 Axial velocity distribution of the flow in the propeller plane of the bare hull

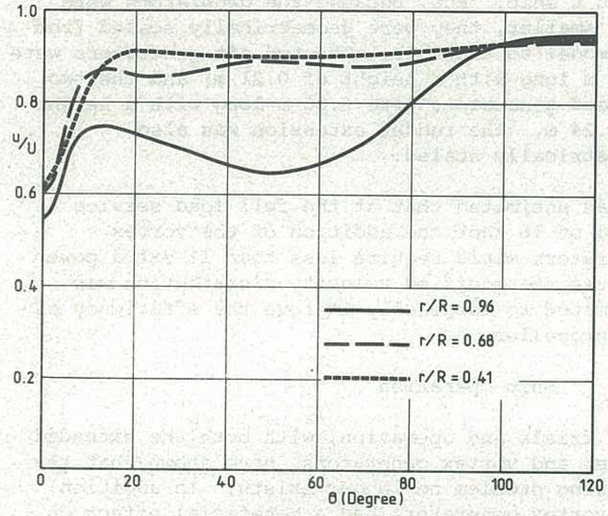

Figure 5 Axial velocity distribution of the flow in the propeller plane with vortex generators

corresponding to the ship, will cause differences in the relative boundary layer thickness, velocity distribution, and flow directions between the 'smooth' model and actual ship. In this case, the boundary layer on the ship is only approximately 40% of the thickness obtained by geometric scaling from the model. Simple geometrical scaling of the generators will result in oversize units being fitted. However, structural roughness and fouling increase the thickness of the boundary layer on the ship and offset scale effects by a considerable amount. Furthermore, the effects of wave action at the stern, propeller suction, and asymmetrical flow caused by ship motions (such as rolling) in a seaway must also be considered in the extrapolation. After taking all of these factors into account, it was concluded that the size of the generators on the ship should be 83% of their geometrically scaled size. The two aft generators have a height of 0.51 m and a length of 1.83 m, and the two forward generators a height of 0.63 m and a length of 2.29 m. It was estimated that at the service speed of 18 knot the vortex generators would incur a power penalty of approximately 15% for the fully loaded ship, and 12% in ballast.

2.6 Ship Trials

As no other proposal had given comparable improvements in the velocity distribution to the propeller and since no more time was available to refine the design of the generators because the ship was being drydocked, the vortex generators in figure 1 were scaled and fitted to the ship. Sea trials in full load and ballast conditions were successful as the stern vibration, which had been severe above 16 knot, was reduced significantly, and the ship could be operated at its design speed of 18 knot.

3 MANOEUVRING

Cavitation, stern vibration and noise problems had occurred during trials of a recently built 33000 t single-screw bulk carrier. The ship has a service speed of 16 knot, is 173 m long, and has a 25 m beam and 9.8 m draught when fully laden. The problems were again attributed to the propeller working in an uneven velocity distribution. But, in this case, the ship had been fitted with a propeller tunnel which had successfully eliminated the cavitation and vibration problems. After the propeller tunnel had been fitted, difficulty was experienced in manoeuvring, especially when the ship was fully loaded and operating in shallow water or at low speeds.

The Laboratories investigated the problem with the aim of using vortex generators to increase the velocity of the flow near the rudder, so that the steering characteristics could be improved without major structural modifications. But, because the propeller tunnel cured the vibration and cavitation, and because it is a costly structure, a solution was required which enabled its retention.

3.1 Experiments

A similar model testing procedure was adopted to the previous case except that the model was fitted with a rudder and tested in simulated deep sea and shallow water. Model yaw and rudder sideforce tests were made in addition to the wake velocity, surface flow visualization, and resistance tests.

3.2 Experimental Results

Tests showed that the reduced manoeuvrability of the ship was due to an increase in directional stability caused by fitting the propeller tunnel. Although the tunnel increased the velocity of the flow near the centre of the rudder it also shielded the upper portion, and the small resultant increase in effectiveness was insufficient to overcome the increased directional stability.

3.2.1 Effect of vortex generators

Tests were made for systematic changes in the design parameters of the vortex generators. While the axial velocity of the flow through both the upper and lower sections of the propeller disc was usually increased, a greater increase was produced at the sides of the disc, and the overall effect was to make the velocity distribution less uniform. This is not satisfactory as the risk of stern vibration was increased. Subsequent tests were aimed at increasing the flow through only the lower section of the propeller disc, and the most suitable set of vortex generators developed is shown in figure 6. In this case, the vortex generators were relatively small, and the two aft generators had a height of 3.56 mm and a length of 12.7 mm and the two forward generators a height of 4.06 mm and a length of 14.5 mm. The choice between the different vortex generator systems was based on a compromise between the uniformity of the velocity distribution of the flow to the propeller, the increase in sideforce produced by the rudder, and the resistance penalty.

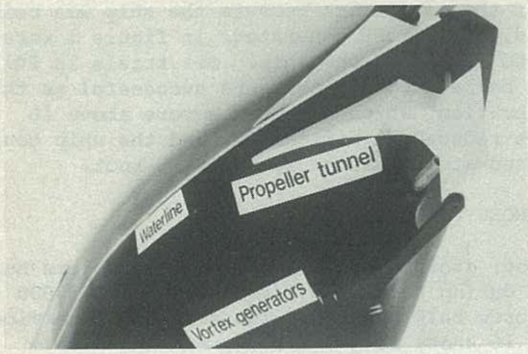

Figure 6 Vortex generators on the bulk carrier

Examples of the axial velocity distributions obtained in the propeller plane for the case with a 3.7 m underkeel clearance are shown in figure 7. Results are shown for the bare hull, and with the vortex generators fitted. The improvement in flow velocity over the lower part of the propeller disc, produced by the vortex generators, is represented in each case by vertical lines. Similar improvements in velocity were produced at the rudder.

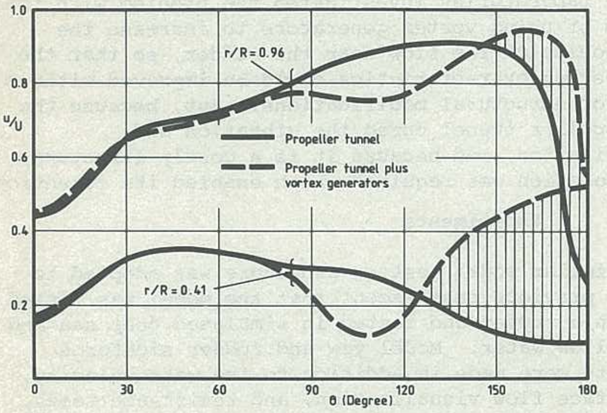

Figure 7 Axial velocity distribution of the flow in the propeller plane of the bulk carrier model

The side force produced by the rudder at incidence for the bare hull and the hull with generators is shown in figure 8, again for an underkeel clearance of 3.7 m. At an angle of incidence of 20°, the generators produced a 16% increase in side force. With the clearance reduced to 0.9 m a 17% increase was obtained. An increase of this magnitude was estimated to be just sufficient to restore the ship to its original manoeuvring capability.

3.2.2 Larger rudder

A larger rudder had been considered at the start of the investigation, but was not pursued at that stage because the permissible extension was small, and it was estimated that the increase in sideforce would not be sufficient. But, since the sideforce produced with vortex generators alone allowed no margin for safety, it was decided to extend the rudder also. This took the form of a plate equivalent to 0.30 m full scale, or 8% of the chord, added to the trailing edge. A larger extension was precluded by limited power of the existing steering gear.

The side force coefficients with both the extended rudder and vortex generators are shown in figure 8. At a rudder angle of 20° the side force compared with the original hull was increased by 27% with a 3.7 m clearance, and 25% with a 0.9 m clearance. It was estimated that this would provide the ship with the required manoeuvring capability.

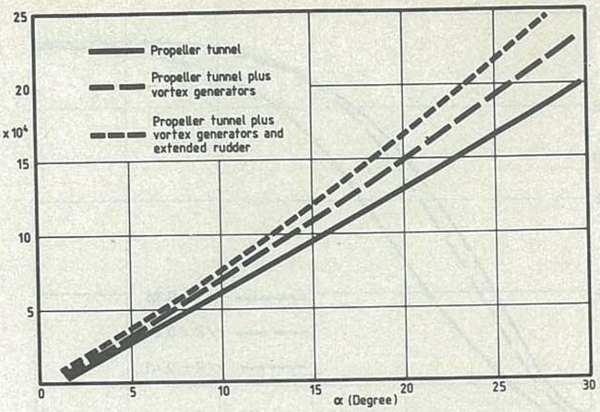

Figure 8 Rudder sideforce coefficients

3.3 Application of Model Results to the Ship

The vortex generators were scaled to the ship using a similar approach to that used previously for the 13000 t ship. But, because the generators were much smaller, they were geometrically scaled from the model to the ship. The two aft generators were 0.76 m long with a height of 0.21 m; and the two forward generators were 0.86 m long with a height of 0.24 m. The rudder extension was also geometrically scaled.

It was estimated that at the full load service speed of 16 knot the addition of the vortex generators would require less than 1% extra power because the modified velocity distribution was estimated to marginally improve the efficiency of the propeller.

3.4 Ship Operation

Ship trials and operation, with both the extended rudder and vortex generators, have shown that the steering problem no longer exists. In addition, the vortex generators had a beneficial effect on the efficiency of the propeller and the service speed was increased by approximately a quarter of a knot.

4 CONCLUDING REMARKS

The two examples discussed indicate how wind tunnels and associated aerodynamic techniques can be useful for investigating hydrodynamic problems. In particular, they show how vortex generators can be used on ships' hulls to modify the velocity distribution of the flow in the wake to improve stern vibration and steering characteristics. Often, these problems do not become evident until after a ship has been built and trials carried out, and the use of vortex generators as a cure at that stage may be advantageous compared with the more conventional methods of modifying a ship's wake.

5 REFERENCES

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