THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
One World Trade Center, Suite 1369, New York, N.Y. 10048
Paper to be presented at the Ship Vibration Symposium
Arlington, Va., October 16-17, 1978

Some Hydrodynamic Considerations of Propeller-Induced Ship Vibrations

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ABSTRACT

Present-day ships still suffer from vibrations. A survey of some hydrodynamic aspects associated with propeller induced vibrations is given.

A very important parameter is the increasing propeller load, which causes the structure of the effective wake field to differ essentially from the nominal wake field. This is strongly related with the increased interaction between hull and propeller.

The non-homogeneity of the wake field induces hydrodynamic excitations via the running propeller. These excitations on the hull structure and on the propeller shaft, generate noise and vibration problems. Vibrations on board ships are therefore often effectivily reduced by affecting these excitations. This can be done fruitfully by changing the wake field. For existing ships, efficient devices to realize this are based on the effect of the propeller on the flow ahead, which effect increases with propeller load. Such devices are, for example, partial stern tunnels and fins. No negative effects of such devices on the propulsive performance need occur.

Due to the dominant role of the effective wake field, which still cannot be measured accurately, theoretical investigations, using the nominal wake field as input, are therefore susceptible to inaccuracies.

INTRODUCTION

Ship vibration is a combined hydrodynamical/mechanical problem. Therefore, in the design of new ships, particularly those with higher propulsive powers in comparison with previous ships, the combined problem has to be studied. The hydrodynamical part forms a very complex, multi-component, multi-related problem. The main parameters are those describing the hull lines (especially those of the afterbody) and the propeller. At the required ship speed, the propeller must absorb a certain power at a given rate of revolutions. This determines the propeller load, which - in turn - changes the flow along the hull (the characteristics of which are determined by the hull lines) in the vicinity of the propeller to form what is termed the effective wake field. The non- homogeneity of the structure of this wake field causes the blade loading to fluctuate with time, which causes a corresponding change in the cavitation pattern. The final result of this multi-component, multi-related problem is that the unsteady loading and cavitation cause a fluctuating pressure field on the hull and the propeller, which excite the hull girder and the shafting.

In the mechanical problem, the main parameters are those describing the stiffness distribution (the construction), the mass distribution (the loading condition) and the excitation forces. These three parameters are virtually independent; only the excitation is related to the developed power, which relation is a very complex one as explained above. Although the mechanical problem is still a very difficult and a tedious one to deal with, the hydrodynamical problem is a considerably less perceptible task. For example, small changes in the hull geometry will hardly affect the hull response, but can affect considerably the excitation forces and, in proportion, the vibration level. Only in cases of completely new ship designs a detailed analysis of the overall dynamic response characteristics is required. For small variations in the overall ship structure, mechanical analyses may be restricted to local structures.

Based on the experience of many model tests, supplementary calculations and full-scale information, the various parameters mentioned above, are dealt with in this paper and attention is focussed on the strong interrelation of all these parameters. Figure 1 shows a block diagram of this interrelation.

HYDRODYNAMIC EXCITATION

General Considerations

The hydrodynamic excitation, as

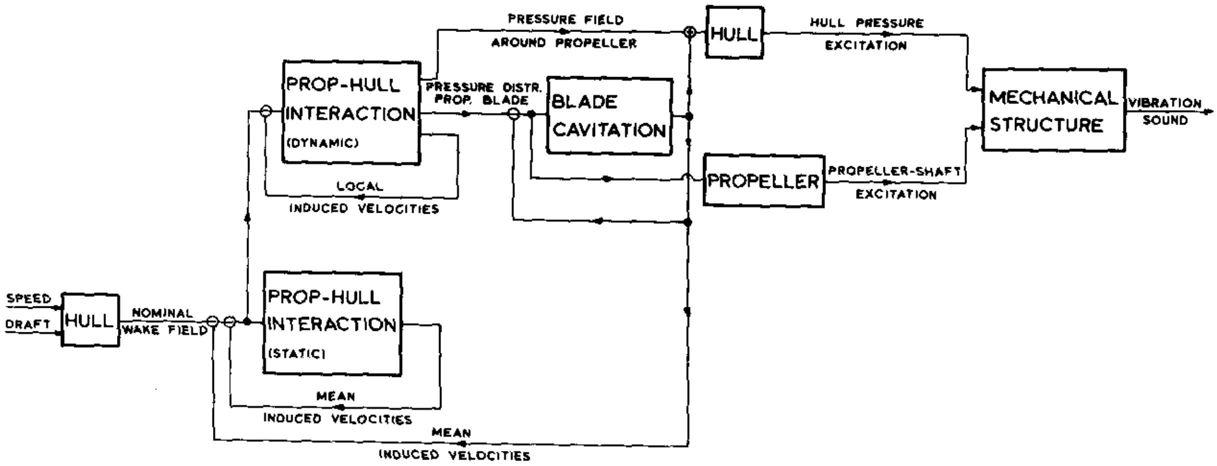


Fig. 1. Block diagram showing the interrelationship between the parameters affecting propeller-generated vibrations and sound on board of ships

generated by the running propeller, consists of two virtually independent systems:

- hull pressure forces and moments,
- propeller shaft forces and moments.

In the generation of hull pressure forces and moments, the hydrodynamical phenomena on the propeller blades close to the hull are directly responsible, whereas in the generation of propeller shaft forces and moments the phenomena over the entire propeller disc are important. For the hull pressure excitations mainly the lower harmonics of the wake field are important, whereas for the propeller shaft excitations only some of the higher components are important. For this reason one can state that both excitation systems are almost independent of each other and that their mutual relation will differ from one ship to another.

Many experts have stated that in the generation of ship vibrations very often the propeller shaft excitations are responsible, sometimes accompanied by resonances in the shafting. This was probably the case many years ago. It is contrary, however, to recent NSMB experience. In recent years, nearly all excessive vibration problems were solved by reducing the hull pressure fluctuations, i.e. by reducing the hull pressure forces and moments.

The attention in this paper is, therefore, mainly focussed on the physics of the hull pressure excitation, also because of the fact that propeller shaft excitation already has been dealt with in detail /1,2,3/.

An Overall Description of the Hull Pressure Forces

The fluctuating load on the propeller is associated with a fluctuating pressure field on the blades, which generates pressure fluctuations over the hull surface in the neighbourhood of the propeller. This pressure field is influenced considerably by the occurrence of cavitation on the blades /4,5,6/. The occurring fluctuating propeller load and the pressure field are directly related to the effective wake field. The dominant components of the hull pressure fluctuations consist of the lower harmonics of blade rate frequency.

The cavitation behaviour of the blades is often rather abrupt. Cavity growth is often explosive and cavity decline is implosive. Because of this aspect, high pressure fluctuations are induced, generally at high frequencies. In this way, and because of the blade number, the higher blade-rate harmonics of the hull pressure excitations are reinforced.

It should be noted that this explosive (implosive) behaviour strongly depends on the variations in the blade loading and thus on the variations in the wake field. Smoothing the irregularities in the wake field will suppress this explosive (implosive) behaviour, thereby obtaining a large reduction in the hull pressure fluctuations, so that the vibrational level on board the ship is reduced. It is especially because of the attenuation in the explosive character of the cavities that a striking reduction in the vibration level is obtained.

EFFECT OF PARTIAL STERN TUNNELS

120.000 m^3 LNG Carriers

Over the last 5 years model tests have been performed at the NSMB for a number of 120.000 m^3 LNG carriers to determine the propeller-induced hull pressure excitations. Due to the dominant role of cavitation, these tests were performed in the cavitation tunnel or the depressurized towing tank. These 120.000 m^3 LNG carriers, are all about 260 m long and are propelled by a single propeller with an average diameter of 7.6 m, absorbing about 40.000 SHP at an RPM around 105. With a mean value for the L/B ratio of 6.4 and for the B/T ratio of 3.8 the average loaded displacement is 95.000 tons. An average speed of 20 knots is attained. Figure 2 shows the partial body plans of these ships. The various types of afterbodies are clearly indicated. For general information, Table I gives the cavitation number and the wake inequality parameter, as defined in reference /13/, together with the K_T and K_Q values.

Table I also gives the amplitudes of the vertical pressure force fluctuations with respect to the mean thrust, as well as the thrust fluctuations with respect to the mean thrust. It can be seen that the amplitudes of the fluctuating vertical force are higher than the thrust fluctuations, but still in the lower range of values quoted by DnV /7/; viz.: 5 - 20% of mean thrust.

From full-scale measurements, information has been obtained about the vibration levels for some of these ships. These were found to be low.

On considering Table I, it can be seen that the application of partial stern tunnels leads to a significant reduction in the pressure fluctuations. This is due to the fact that the wake field becomes more homogeneous. In the cases considered, the suppression of the dynamic behaviour of the cavitation has been found to be so effective that the corresponding decrease of the pressure fluctuations is larger than the increase of the pressure fluctuations due to the reduced propeller-tip clearance.

As an example, Figure 3 shows the effect of the stern tunnel of the nominal wake field of container ship B (see Figure 4). The wake pattern has become more homogeneous and a reduction in the dynamical behaviour of the cavitation resulted. As will be illustrated later, such an improvement of the nominal wake field has been found to be rather an exception than a rule.

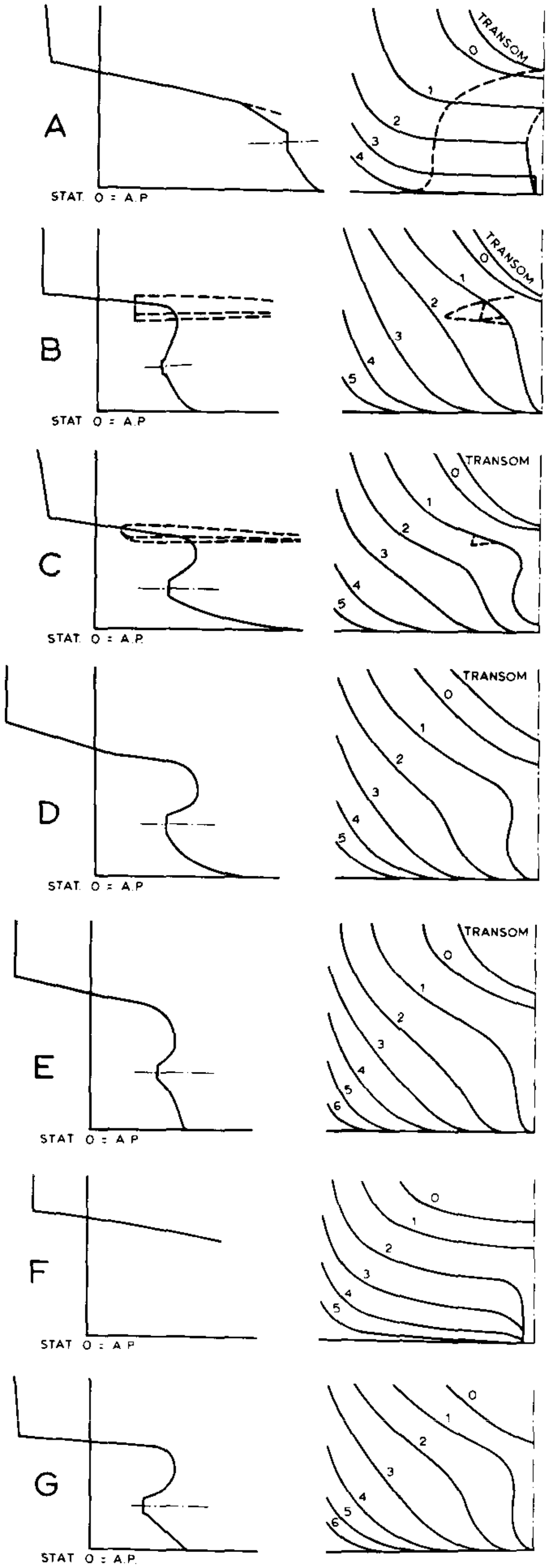


Fig. 2. Partial body plans of various 120.000 m^3 LNG carriers

Table I. Particulars of 120.000 m^3 LNG carriers

Ship identification Fig. 2	thrust coefficient K_T $(= \frac{T}{\rho n^2 D^4})$	torque coefficient K_Q $(= \frac{Q}{\rho n^2 D^5})$	cavitation number at tip σ_N $(= \frac{P_o - P_v + \rho g h}{\frac{1}{2}\rho n^2 D^2})$	wake inequality parameter at tip $(\frac{w_{max} - w_{min}}{1-\bar{w}})$	thrust fluctuation in % of mean thrust	torque fluctuation in % of mean torque	amplitude of 1st, 2nd and 3rd harmonic of vertical hull force in % of mean thrust before application of partial stern tunnel	amp 2nd mon hul mea app par tun
A	0.19/0.22	0.026/0.033	1.34/1.26	0.37	1.5/1.3	1.2/1.3	4.2/5.1 3.0/2.7 0.3/0.2	
B	0.21	0.030	1.27	0.86	-	-	3.6 0.9 0.2	
C	0.19	0.027	1.33	0.58	-	-	6.3 6.8 3.1	
D	0.22	0.029	1.28	0.49	2.7	1.5	4.3 6.2 1.9	
E	0.22	0.029	1.36	0.92	4.1	2.5	9.6 4.8 1.4	
F	0.19	0.033	1.46	0.32	0.7	0.5	1.0 0.05 0.05	
G	0.23	0.032	1.16	0.69	3.1	2.0	6.5 7.6 3.4	

Nomenclature:

T = propeller thrust
Q = propeller torque
ρ = density of water
n = rate of rotation of propeller
D = propeller diameter
P_o = atmospheric pressure
P_v = vapour pressure
g = acceleration due to gravity
h = distance in meter of propeller shaft below water surface
w = local value of Taylor wake fraction
$\bar{w}$ = circumferential mean wake at tip radius

Second Generation Container Ships

Many of the second generation container ships suffer from vibrations. For some of these ships, model tests were performed to solve the occurring problems. Generally, the cause was considered to be the propeller design, but often the poor wake field turned out to be the main cause.

In Figure 4 the afterbody lines are indicated. The length between perpendiculars is about 200 m, the L/B ratio is around 7.0 and the B/T ratio about 3.3. The single propeller, with an average diameter of 6.7 m, absorbs about 30.000 SHP at 110 RPM and realizes a speed of 22 knots. See for further information Table II. The exception is ship B, which is somewhat smaller.

Nearly all of these ships have now been provided with a stern tunnel as shown in Figure 4. For some ships a different propeller design was also investigated, but only in case D a new propeller design resulted in a strong reduction of the excitation forces. In this case the original propeller displayed rather extended and thick sheet cavitation. Adopting skew, and a different pitch, camber and thickness distribution the indicated results followed. However, this was found to be rather an exception. Generally, a further optimization of the propeller resulted in marginal improvements.

It is interesting to see that the applied partial stern tunnels particularly affect the higher harmonics of the hull pressure excitations (see Table II). This is confirmed by full-scale measurements which generally show a decrease of the 2nd harmonics of the vibrations on board the ship and an accompanying reduction in noise.

Other Ships

In Figure 5, the body plan of a Great Lakes carrier is shown /8/. During model tests in the cavitation tunnel, a propeller-hull-vortex (PHV) cavity was observed as shown in Figure 6. The instantaneous pressure at one of the pressure pick-ups is indicated by the vertical position of the needle at the left hand side of each picture at the same moment the photograph was taken. More information about this investigation can be found in reference /8/. In this case the PHV cavitation was suppressed by means of small vertical fins, mounted on the afterbody over the propeller plane, parallel to the water motion. This, however, did not influence the hull pressure forces. Only after the application of a partial tunnel the hull pressure forces were signidicantly reduced. This was confirmed on the full scale.

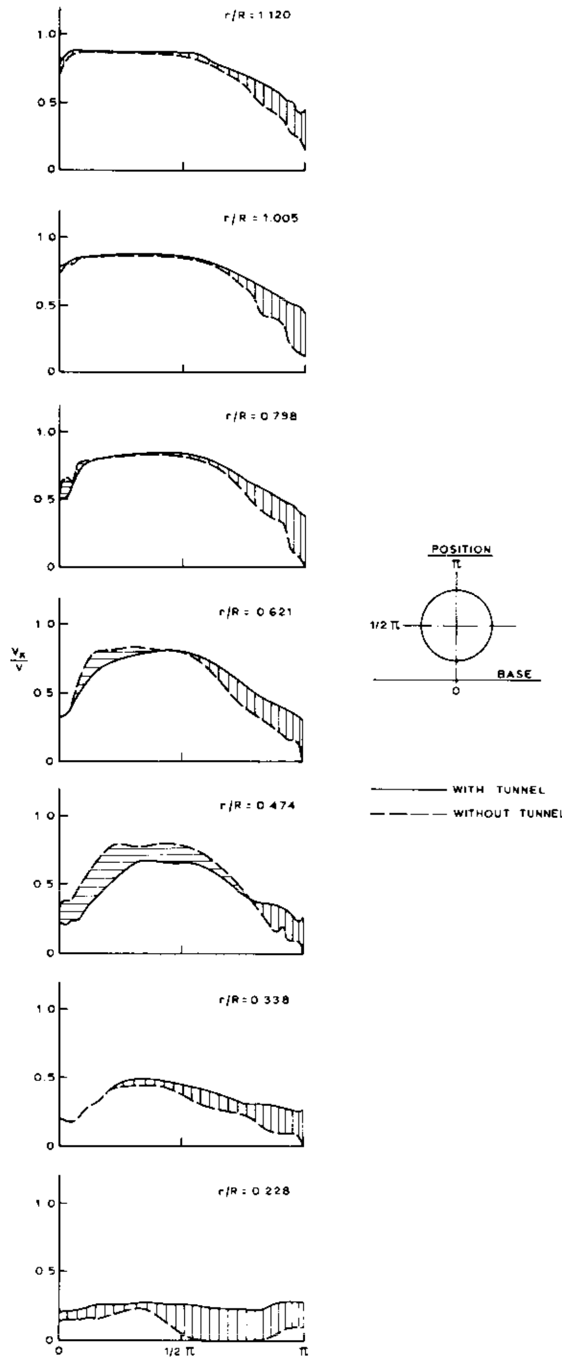


Fig. 3. Effect of partial stern tunnel on gradient in nominal wake field at top position (axial wake velocity only) for containership B of Figure 4 /12/.

Table II. Particulars of second generation containerships.

Ship identification Fig. 4	thrust coefficient K_T $(= \frac{T}{\rho n^2 D^4})$	torque coefficient K_Q $(= \frac{Q}{\rho n^2 D^5})$	cavitation number at tip σ_N $(= \frac{P_o - P_v + \rho g h}{\frac{1}{2}\rho n^2 D^2})$	wake inequality parameter at tip $(\frac{w_{max} - w_{min}}{1-\bar{w}})$	amplitude of 1st, 2nd and 3rd harmonic of vertical hull force in % of mean thrust		full-scale vibration level before application of partial stern tunnel	full-scale vibration level after application of partial stern tunnel
					before application of partial tunnel	after application of partial tunnel		
A	0.23	0.042	1.38	0.76	6.8/4.2 2.0/2.0 *) 1.9/0.5	-	unacceptable	acceptable
B	0.16	0.024	1.01	0.38	-	-	unacceptable	improved
C	0.22	0.034	1.39	0.59	12.6 12.4 7.7	15.3 4.0 0.9	unacceptable	acceptable
D	0.20/0.21	0.033/0.039	1.55/1.40	-	32.7/12.1 13.6/14.6 *) 5.4/ 5.7	-	unacceptable	?
E	0.21	0.038	1.43	-	28.0 6.9 4.4	41.9 3.4 1.4	unacceptable	?

*) different propellers

Nomenclature:

T = propeller thrust
Q = propeller torque
ρ = density of water
n = rate of rotation of propeller
D = propeller diameter
P_o = atmospheric pressure
P_v = vapour pressure
g = acceleration due to gravity
h = distance in meter of propeller tip below water surface
w = local value of Taylor wake fraction
$\bar{w}$ = circumferential mean wake at tip radius.

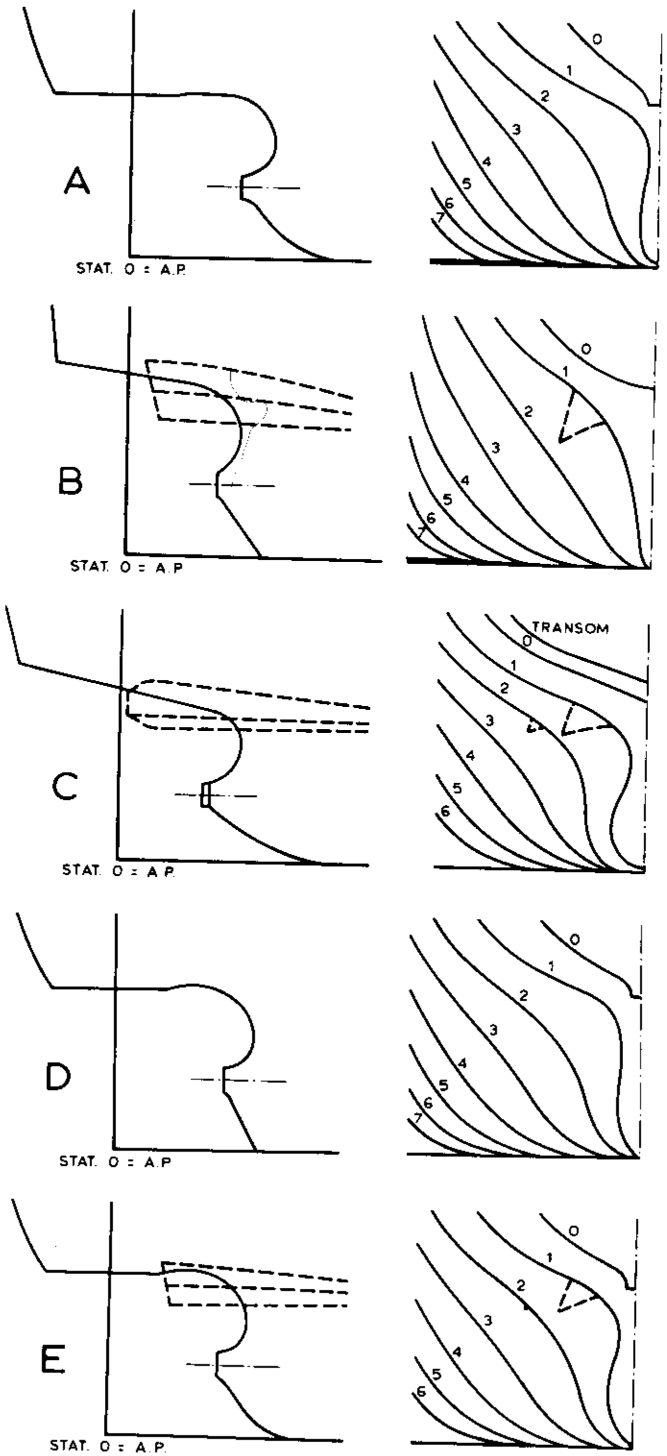
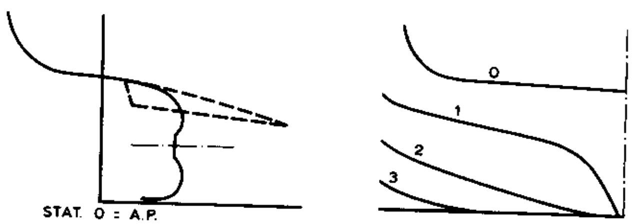


Fig. 4. Partial body plans of various
second generation contain

The general experinece is that PHV cavitation itself does not lead to high pressure fluctuations on the hull, but that it is caused by the same source as for the pressure fluctuations, namely the cavitation on the blades. Because of interaction, the PHV cavitation can probably reinforce the cavitation on the propeller blades. Its direct influence on the hull pressure fluctuations will be very local, namely where it touches the hull.

In Figure 7, a part of the body plan of a dredger is given, for which the effect of the stern tunnel on the nominal wake field is shown in Figure 8. Due to the high block coefficient of the vessel, the flow on the afterbody in front of the propeller separates, resulting in the formation of a very non-uniform wake. The tunnel strongly suppressed the occurrence of flow separation. The result was a reduction in the vibration level on the bridge deck of about 80 percent. The major vibrations were of blade frequency; the amplitudes of the higher harmonics were small.

In Figure 9 the partial stern tunnel as realized for the above dredger is shown. For the dredger and container ship B, flow separation occurred on the hull in front of the propeller as already discussed. In general, the suction of the propeller will suppress such flow separation. The application of a partial stern tunnel often already leads to an improvement in the nominal wake field as illustrated by Figures 3 and 8. The case of the Great Lakes carrier, however, is typical of a class of ships in which flow separation does not occur on the hull in front of the propeller, but on the hull above the propeller. It is not suppressed by propeller suction but, in contrary, caused by propeller suction. In these cases, the application of a partial stern tunnel does not lead to an improvement of the nominal wake field but only of the, so-called, effective wake field.



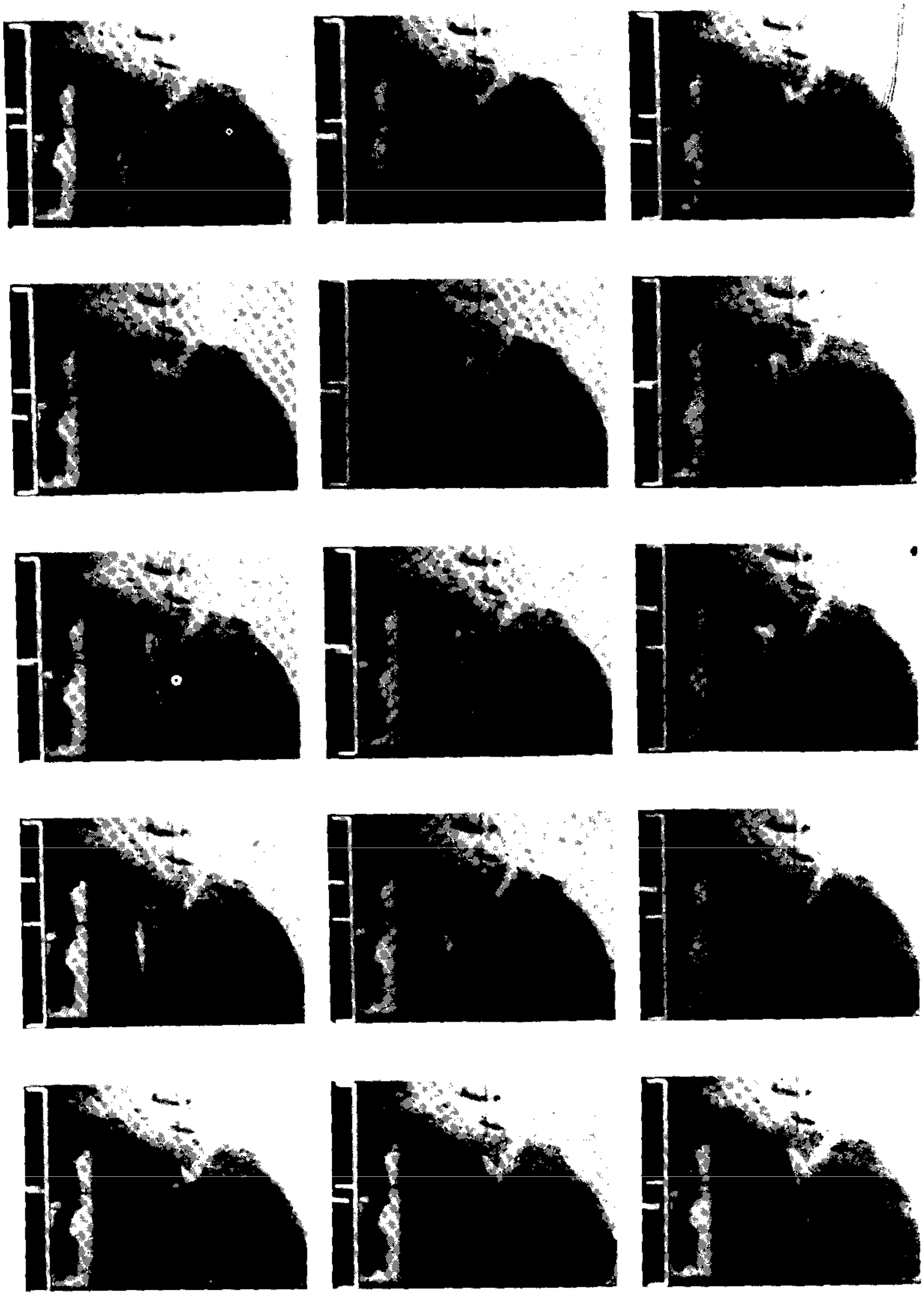


Fig. 6. Simultaneous visualization of pressure signals and cavitation phenomena on model of a Great Lakes carrier /8/.

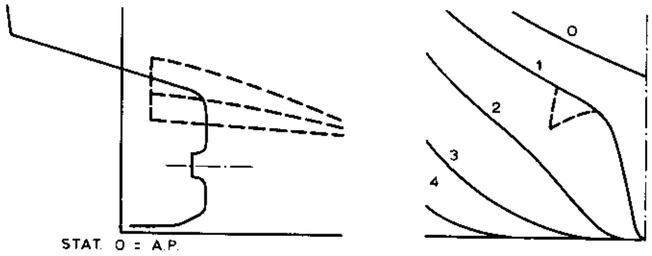


Fig. 7. Partial body plan of a dredger /12/.

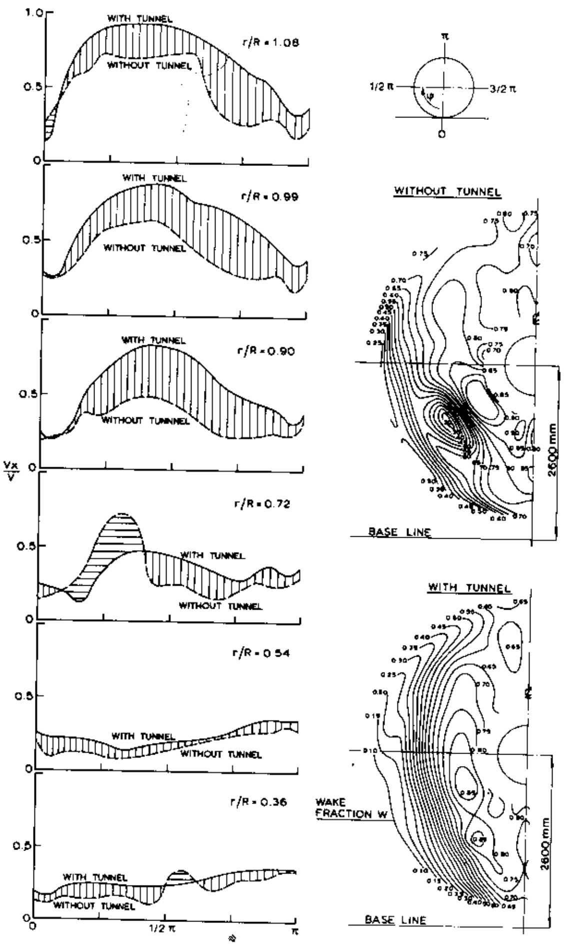
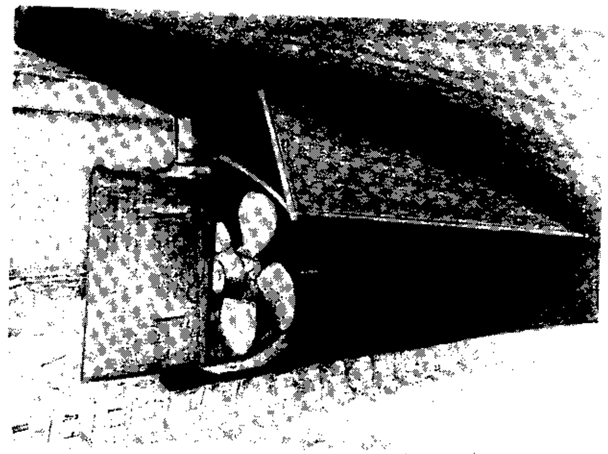


Fig. 8. Effect of partial stern tunnel on homogeneity of the nominal wake field (axial wake velocity only) of the dredger of Figure 7 /12/.



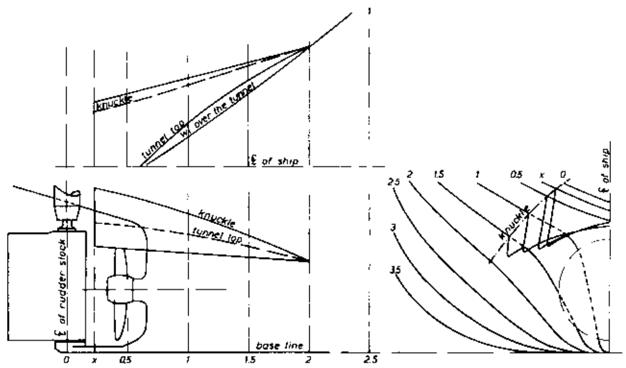


Fig. 9. Tunnel construction adopted to improve wake field of a dredger to reduce hull vibrations /12/.

THE EFFECTIVE WAKE FIELD

Diffuser Tests

By means of a diffuser /19/, as shown in Figure 10, mounted behind a ship model in such a way that its orifice coincides with the propeller plane (see Figure 11), the flow-sucking action of the propeller on the wake field is simulated. With a 5-hole Pitot tube, mounted in the orifice, the wake field can be measured. Accounting for the diffuser-induced velocities on the flow, an impression is obtained of the structural change of the nominal wake field, because of the flow-sucking effect of the propeller. The thus obtained wake field is termed the effective wake field. By varying the length of the diffuser at a constant diffuser angle, a variation of the simulated propeller loading is obtained. In this way an impression of the propeller loading on the wake is derived /9/.

In Figures 12 and 13 the result is shown for the axial and transverse velocity distributions respectively. The measurements were performed on a 12 m model of a tanker with a bulbous stern.

Most pronounced in this case are the following features of the propeller-hull interaction with increasing propeller loading as quoted from /9/:

- the bilge vortex shifts radially towards the propeller axis and downwards;
- the strength of the bilge vortex increases;
- the wake peak associated with the center of the bilge vortex is reduced;
- the wake fraction decreases.

To demonstrate that the effective wake field is more determinative for propeller-induced phenomena, the effect on the fluctuating hydrodynamic propeller shaft excitations is considered in Figure 14. The calculation of these excitations was carried out by means of a computer program based on unsteady lifting surface theory. The results are compared with results of model tests. On using the effective wake field instead of the nominal wake field as input for the calculations, an improvement in the correlation is evident, although some discrepancies still remain /9/.

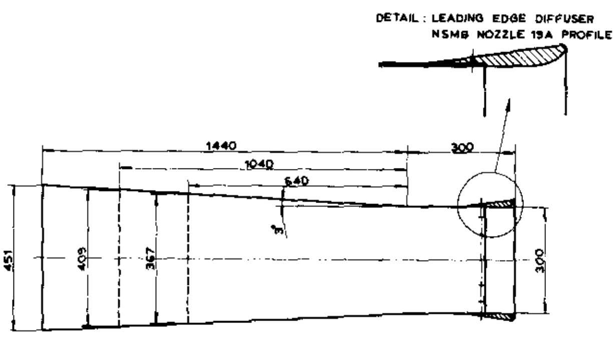


Fig. 10. Geometry of diffusers used to simulate flow-sucking action of propeller /9/.

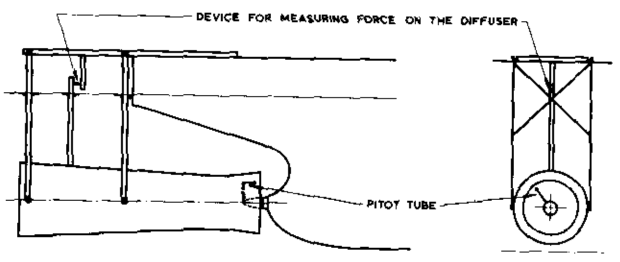


Fig. 11. Test set-up adopted to measure simulated effective wake field /9/.

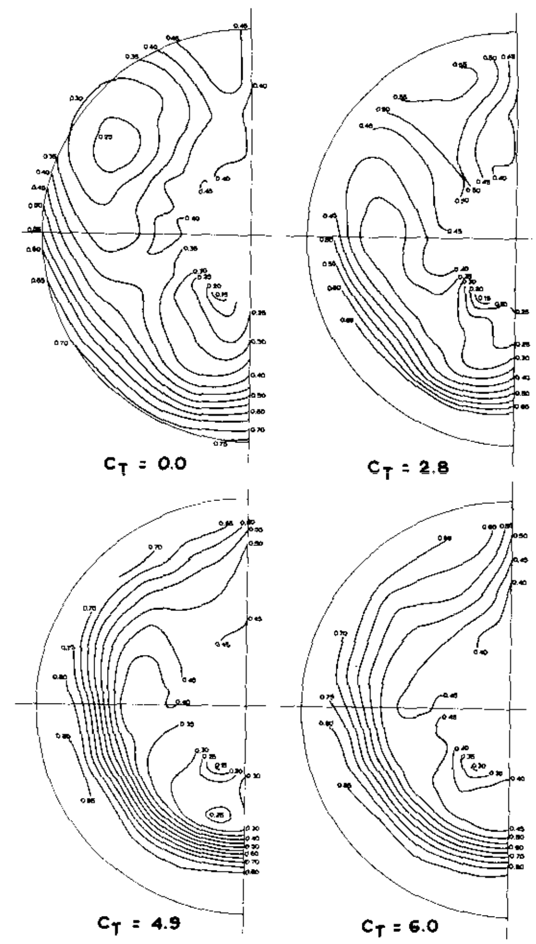


Fig. 12. Axial velocity distributions of nominal (C_T = 0.0) and simulated effective wake fields (C_T = 2.8, 4.9 and 6.0) /9/.

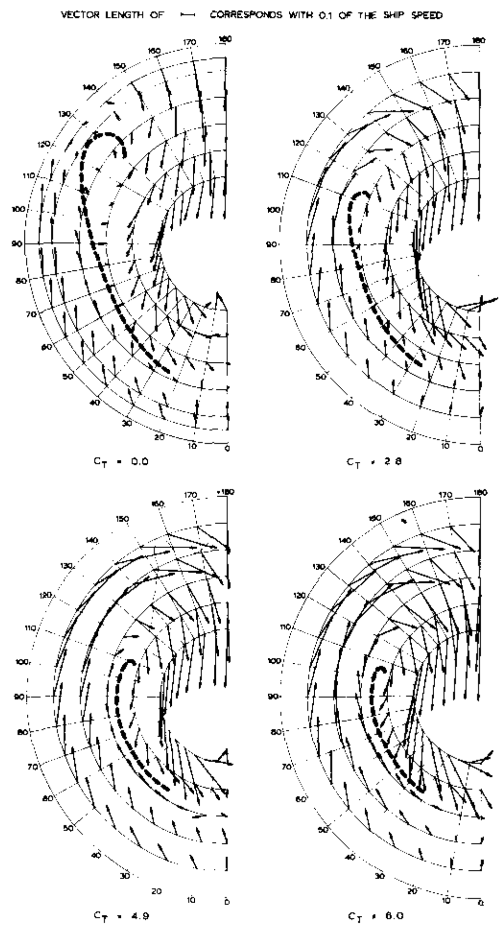


Fig. 13. Transverse velocity components in nominal (C_T = 0.0) and simulated effective wake fields (C_T = 2.8, 4.9 and 6.0) /9/.

Effect of Partial Stern Tunnel on Effective Wake Field

Using the model of the Great Lakes carrier /8/, an attempt was made to investigate the effect of the partial stern tunnel on the effective wake field. Measurements were made with Prandtl tubes in front of the operating propeller. In these tests the propeller was moved aft to make space for the Prandtl tubes. The measurements were performed in the original propeller plane. In Figure 15 the adopted test set-up is shown.

Figure 16 shows the thus derived effective wake in comparison with the nominal pattern. As could be expected the influence of the stern tunnel increases in the regions closer to the tunnel.

An example of the fact that the stern tunnel has an important effect on the effective wake field is obtained from propulsion tests. These often show that a higher propulsive efficiency is obtained after the application of a tunnel.

As shown by Figure 16, the flow velocity in the upper part of the propeller disc increases after application of a stern tunnel. This results in a slight increase in the mean flow velocity over the propeller disc, causing the open water efficiency of the propeller to become higher. General experience indicates that this occurs without adversaly effecting the so-called hull and relative rotative efficiencies. For the Great Lakes carrier a reduction in the absorbed power of 2% was obtained over the entire speed range /8/.

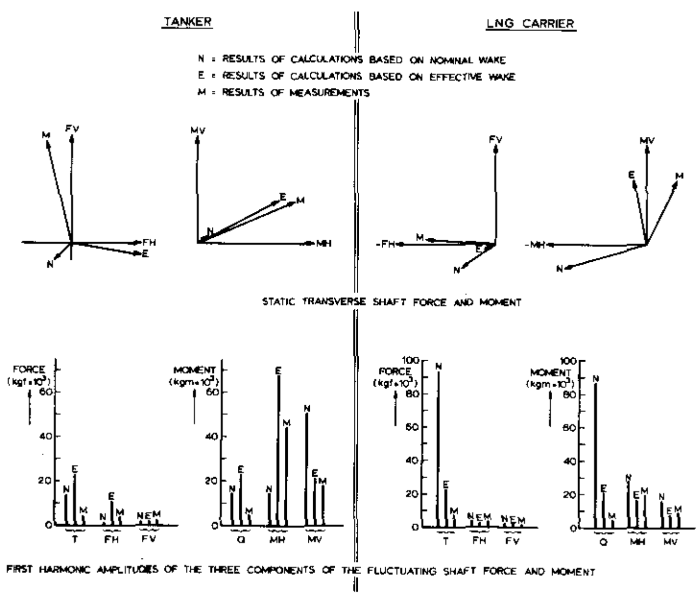


Fig. 14. Comparison of calculated and measured components of the shaft forces and moments /9/.

Actually, this improvement in propulsive efficiency is used to determine preliminarily whether or not a particular stern tunnel design may be expected to act satisfactorily in reducing the hull pressure excitations. Usually, a self-propulsion test is carried out with a ship model fitted with and without the partial tunnel to investigate if an improvement in the performance occurs.

Another way to study the effect of a partial stern tunnel is to visualize the water flow in front and above the propeller by means of tufts /8/. In Figure 17 the body plan of a bulk carrier is shown for which such tests were performed. The results are shown in Figures 18 and 19. In the first Figure the flow around the aft part of the ship is shown, with and without operating propeller. The large increase in flow separation induced by the propeller is evident. In Figure 19 results are given of the tests with the model provided with a partial stern tunnel. Without operating propeller some separation is still present. However, when the propeller operates, separation can no longer be detected.

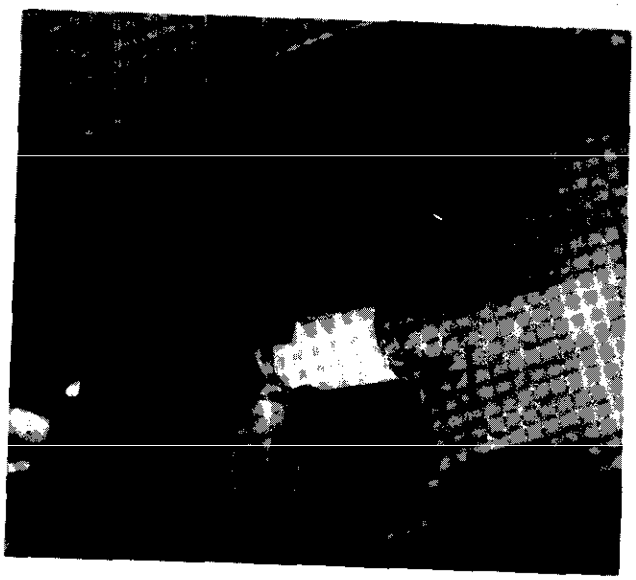


Fig. 15. Prandtl Pitot tubes in front of propeller, mounted on model of Great Lakes carrier /8/.

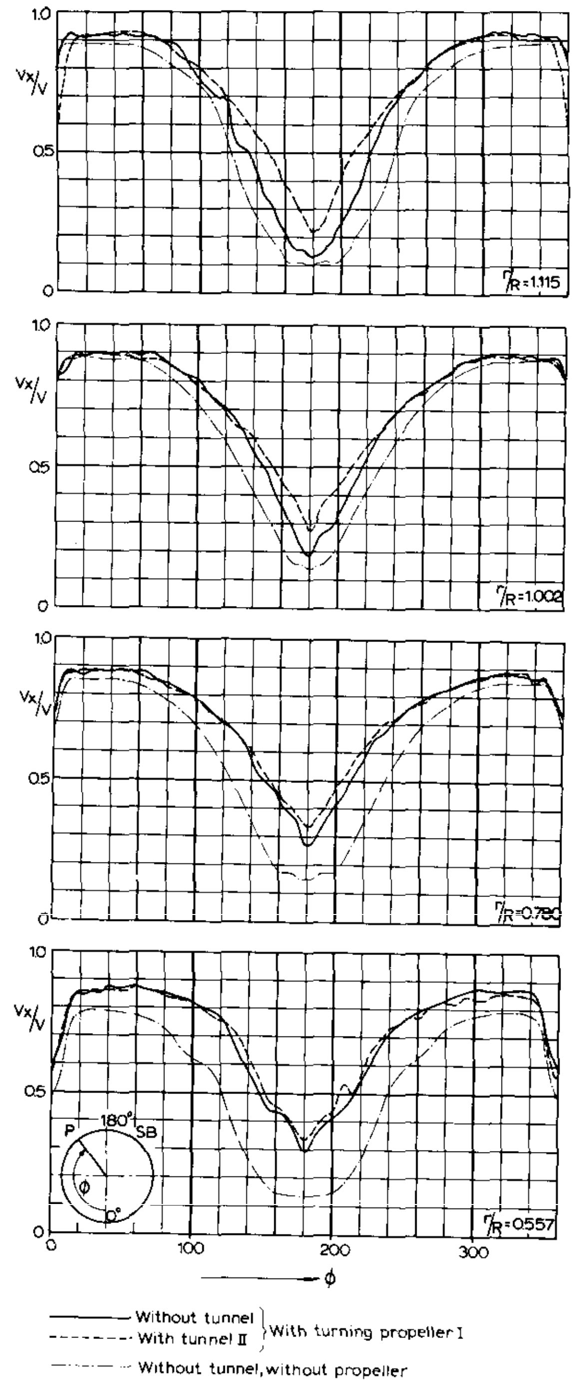


Fig. 16. Circumferential distribution of axial velocity components behind model of Great Lakes carrier /8/.

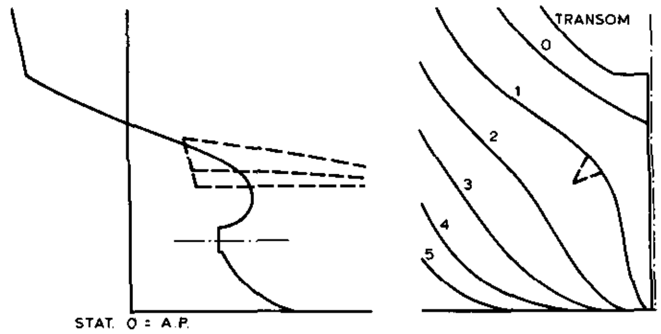


Fig. 17. Partial body plan of a 80,000 DTW bulk carrier.

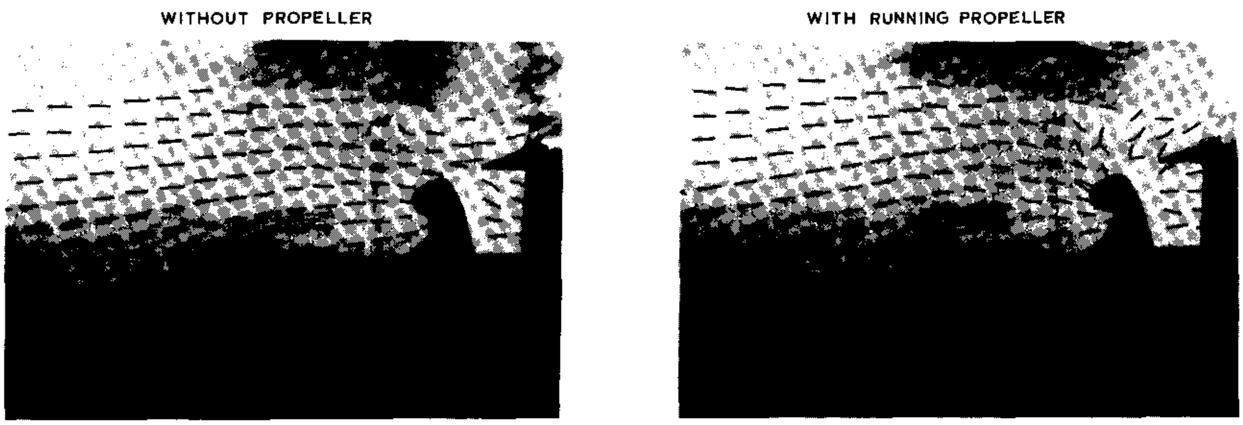


Fig. 18. Results of flow visualization tests on model of 80,000 DWT bulk carrier with and without running propeller (original hull form) - for reasons of clarity, the tuft positions have been retouched.

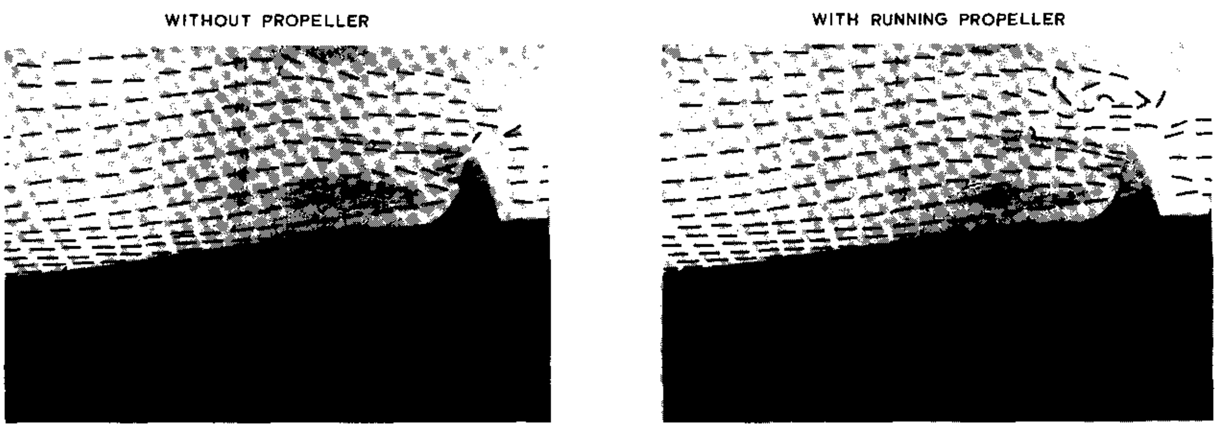


Fig. 19. Results of flow visualization tests on model of 80,000 DWT bulk carrier with and without running propeller (with partial stern tunnel) - for reasons of clarity, the tuft positions have been retouched.

STRUCTURAL RESPONSE

Hull Girder

In Figure 20, the structural response of the aft part of a ship to an exciter mounted in the afterbody is shown and compared with the results of calculations in which no account of damping has been made. It can be seen that in the lower frequency range the hull girder behaves virtually undamped. In the higher frequency range, however, (especially in the neighbourhood of the blade rate frequency at service speed), the response curve is almost flat.

Although this nature of the response curve is somewhat exaggerated by using a logarithmic presentation, it is clear that in the frequency range of the more complex vibration modes, the structure is no longer subject to strong magnifications due to resonance phenomena. This is related to the density deformation /10/ or the high stress concentrations that occur /11/. Therefore, in general it can be said that in the neighbourhood of the blade frequency at service speed, the hull girder response is to a high degree independent of the frequency /12/.

Local Structures

For local structures such as panels, deck-houses and shafting systems, of which the fundamental resonance is in the neighbourhood of the blade rate frequency at service speed, the effect of structural damping is very small. This is because of the simple vibration pattern, in contrast to that of the hull girder. It follows therefore, that local structures have to be designed such that resonance will not occur.

Propeller-generated unsteady forces and moments can result in high bearing reactions, due to resonance of the shafting, which excite the ship. These bearing reactions can become of the same order as the hull pressure forces and therefore, because of resonance in the shafting, these unsteady forces and moments in the propeller shaft have also to be considered very carefully and resonance of the shafting has to be avoided.

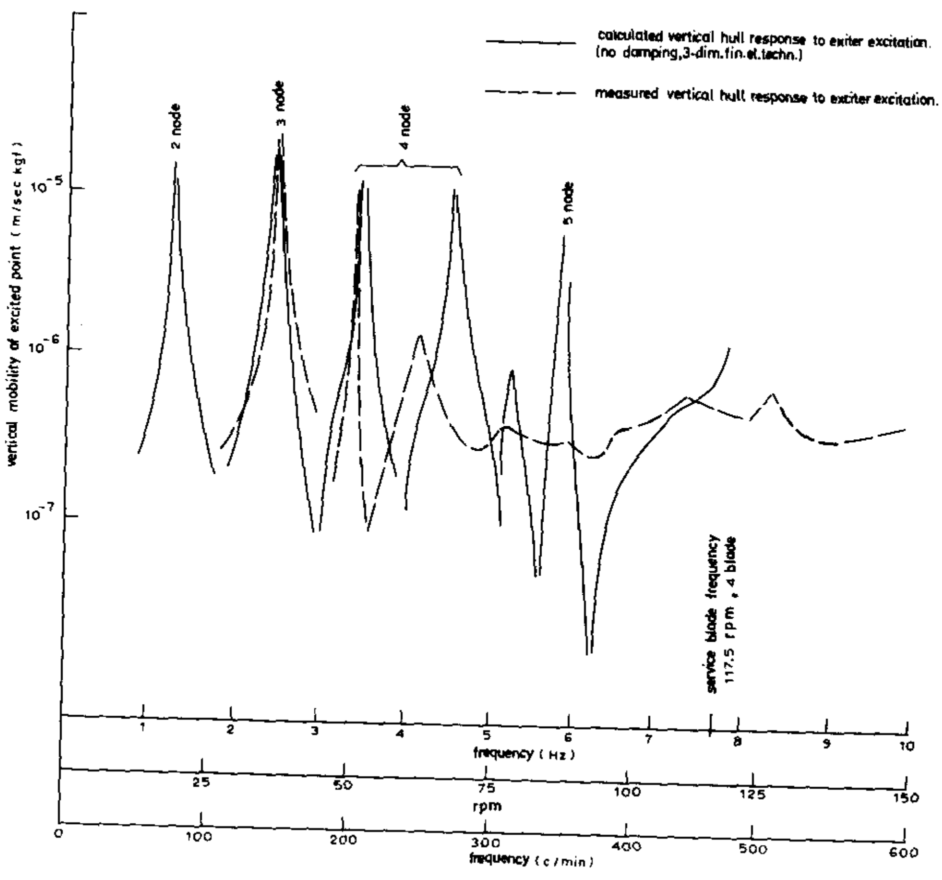


Fig. 20. Vertical hull response to vertical hull excitation /12/.

CONCLUDING REMARKS

In the design of present-day ships considerable effort is required to obtain vibration and noise levels below the prescribed limits. These limits are, furthermore, constantly being reviewed, thus becoming more difficult to satisfy. The ships themselves have high shaft powers and their construction becomes more sensative to dynamic excitation.

A specific example is the current trend in the design of Ro-Ro ships, which have the additional drawback of a flat hull form above the propeller in connection with the desire to obtain a wide deck access. Together with the fact that these ships usually have a restricted draft and therefore relatively small propellers, which are often controllable pitch propellers for manoeuvring purposes, an unfavourable combination of important characteristics, opposing the realization of acceptable excitation and vibration levels, is formed.

Acceptable excitation and vibration levels should be persued in the design stage. To this end the flow around the aft body, in combination with the running propeller, should be optimized with respect to propeller-induced excitations. This can be achieved by carrying out flow-visualization and self-propulsion tests. Once an optimum afterbody design has been achieved, the propeller design has to be optimized with respect to cavitation and associated hydrodynamic excitation.

This problem can, at this time, only be adequately dealt with by means of model tests. Analytical procedures for the calculation of cavitation on propellers and associated phenomena require the effective wake field as input. Standard measuring procedures to determine this flow field are not yet available, however. It follows that for the time being theoretical studies at best serve as a qualitative approach of this problem.

To determine whether or not the obtained excitation levels will lead to an acceptable vibration level, a comparison with similar, existing ships has to be carried out or a response calculation has to be performed.

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