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AN INVESTIGATION OF A FLOW-EXCITED VIBRATION OF THE USS FORREST SHERMAN (DD 931)

by

M.S. Macovsky, R.J. Duerr, and D.A. Jewell

HYDROMECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

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Report 1188

SUMMARY

PROBLEM

The problem was to investigate the possibility that flow conditions caused an athwartship hull vibration of the USS FORREST SHERMAN (DD 931).

FINDINGS

The occurrence of rudder cavitation due to high speed and large effective angles of attack of the rudders has been reasonably well substantiated. It is possible that the periodic alteration of lift due to cavitation was sufficiently large to excite the natural vibration of the combined rudder-hull system. Realignment of the rudders with the flow would retard cavitation. Realignment of the rudders did diminish the vibration. It is also possible that the vibration is a flutter phenomenon.

RECOMMENDATIONS

The presence of cavitation should be visually ascertained by shipboard observation, and correlated with the occurrence of vibration. Studies of the periodicity and magnitude of variation of the effects of cavitation on control appendages should be undertaken to determine the mechanism of the excitation.

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ABSTRACT

The source of a 4-cps hull vibration of the USS FORREST SHERMAN (DD 931) was found to be at the rudders. Full-scale tests showed that ventilation was not the cause of the vibration. Calculations and model tests have shown that the effective fluid velocities and rudder angles promote cavitation. Evidence of paint removal from the rudders indicates that cavitation occurred. Experimental evidence by others indicates that cavitation could excite the vibration.

INTRODUCTION

During initial operation of the USS FORREST SHERMAN (DD 931) unacceptably high athwartship hull vibrations were observed at shaft speeds greater than 270 rpm (29 knots). The vibration frequency remained constant at approximately 4 cps for all shaft speeds. Investigation of the source of this vibration was first undertaken by the Boston Naval Shipyard. Later, at the request of the Bureau of Ships,[1] the David Taylor Model Basin conducted investigations to assist in identifying both the source of vibration and the mechanism of its excitation. This report is concerned mainly with identifying possible sources.

By means of the tests conducted by Boston Naval Shipyard personnel, the vibration was traced to the rudders, particularly the rudder angle. For example, during one of the tests in which dynamic strains of the rudder stocks were being measured[2] it was observed that "the 4 CPS strain disappeared on the port rudder stock in a left rudder turn and remained on the starboard rudder stock. When a right turn was made, the converse condition existed. . . ." The fact that the twin rudders on this vessel were installed at an angle of 3 degrees with respect to the ship's centerline (trailing edge directed toward the centerline) attracted further attention to the rudders. This type of installation was justified by a model test[3] which predicted minimal shaft horsepower for the prototype with this rudder configuration. Model test studies conducted at the Model Basin and full-scale studies on the DD 931 have verified the above hypothesis concerning the source of vibration. For example, by aligning the rudder chords parallel to the ship's centerline, the vibration was eliminated—or essentially postponed to a speed range beyond the maximum speed for this class of vessels.

Mr. N.L. Ficken performed the wake survey to determine the effective velocity field at the rudders.

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[1] References are listed on page 15.

MODEL BASIN WORK

This report summarizes the Model Basin's investigation of this problem through June 1956. The studies which have been conducted are:

1. A flow study of a self-propelled model of the DD 931 hull
2. Full-scale tests
    a. Rudder ventilation
    b. Toe-angle effects
3. Wake survey
4. Cavitation studies
    a. Calculation of cavitation speeds.
    b. Model tests
    c. Full-scale paint removal pattern
5. Flutter

The pertinent results of other investigations have been included to indicate the possible mechanism of excitation of the vibration.

1. FLOW STUDY OF SELF-PROPELLED MODEL

Flow unsteadiness associated with separation at the bow of the vessel was considered to be a possible source of the vibration. Past experience with similar hull forms indicates that separation at the bow was not likely. However, to investigate such a possibility and further to detect some area of possible flow disturbance which might excite vibration, a powered model of DD 931 hull was installed in the TMB circulating-water channel for flow visualization studies. Ink was injected into the flow at various stations along the hull, for qualitative evaluation of the flow. These model tests firmly repudiated the existence of unsteady flow at the bow. The only area of suspicion detected by these surveys was at the rudders. At the higher speed range, serious rudder ventilation occurred for all rudder angles. The fact that the tops of the rudders at the trailing edges are close to the transom (about 2 in. full scale) made it appear possible for a ventilation path to be established at the critical vibration speeds. Unsteady lift caused by ventilation on the prototype rudders was considered as a possible explanation of the source of excitation.

2. FULL-SCALE TESTS

a. Rudder Ventilation

As a result of the flow visualization studies, the existence of ventilation in the critical speed range of the FORREST SHERMAN was investigated. The procedure employed for this

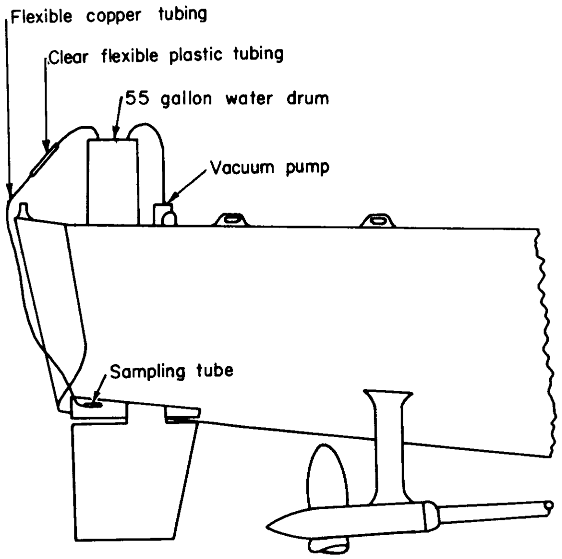

Figure 1 – Sampling Tube Installation

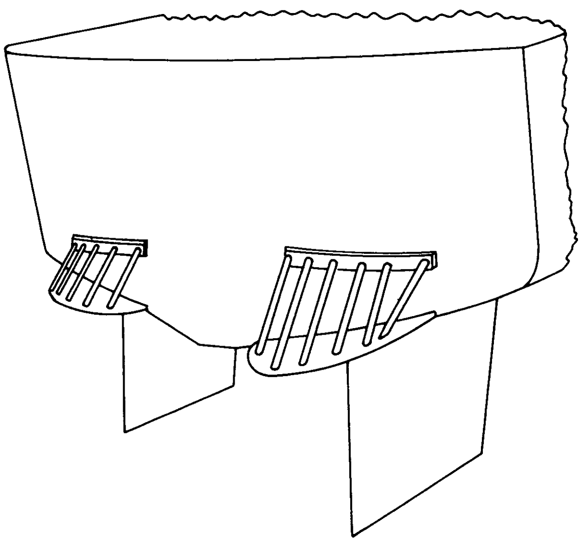

Figure 2 – Transom Plate Installation

purpose consisted of sampling the flow at four points near the top of the rudders, in regions which were expected to be ventilated. Sampling tubes were attached to the hull, as indicated in Figure 1. Flow samples were sucked through these tubes and examined for evidence of air-water mixtures in a transparent section. A suction pump was included in the system to overcome the static head to the ship's fantail, where the observations were made. No indication of ventilation was observed by this technique.

Semicircular (3-foot radius) plates had been previously prepared for horizontal installation at the transom, to retard ventilation. The plates were installed and tested for further confirmation. This installation is shown in Figure 2. The plates did not influence the vibration. It was concluded that ventilation was neither present nor related to the vibration problem.

b. Toe-Angle Effects

Concurrent with the ventilation tests, a study of the effect of rudder orientation was made. Rudder-angle sensitivity had been detected during ship turns, as described in the Introduction. In order to study rudder-angle effects, adjustable tiller links were installed between the tiller arm and ram crosshead. The results of these tests are reported in detail in Reference 2. It was observed that the vibration amplitude was dependent on the rudder toe angle.* Figure 3, reproduced from the Boston report,[2] shows that the athwartship vibration was essentially eliminated by setting the rudders parallel to the ship's centerline, and was somewhat better when oriented with some toe-out.

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*Toe angle refers to the trailing edge of the rudder. Toe-in, therefore, designates trailing edge pointing inboard and vice versa.

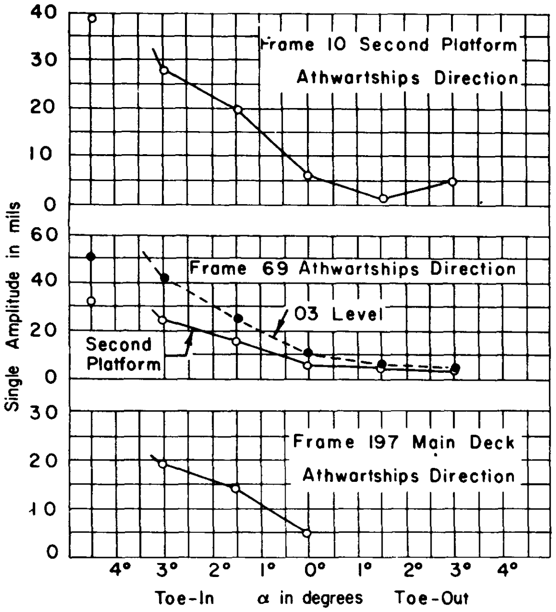


Figure 3 – 4-CPS Vibration Amplitude versus Rudder Toe Angle

All measurements are at 300 rpm (32 knots) except 4½ degrees toe-in, which is at 285 rpm (30.5 knots).

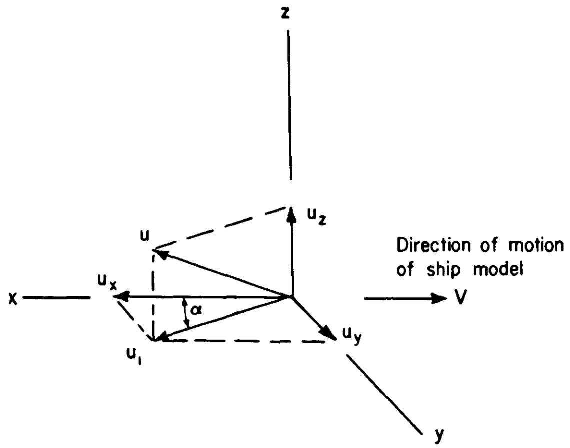


Figure 4 – Velocity Components and Directional Angle

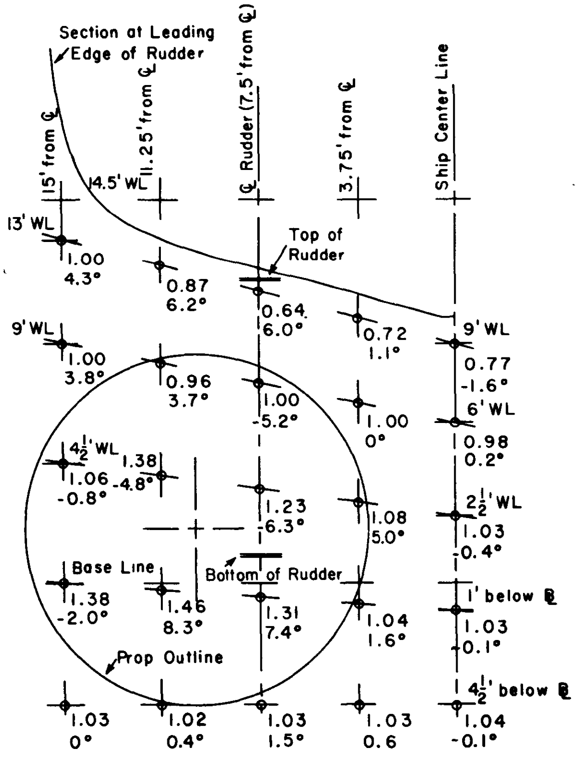


Figure 5 – Velocity Field at Rudder Leading Edge

At each location, the upper figure is the value of u_x/V and the lower figure is the value of α.

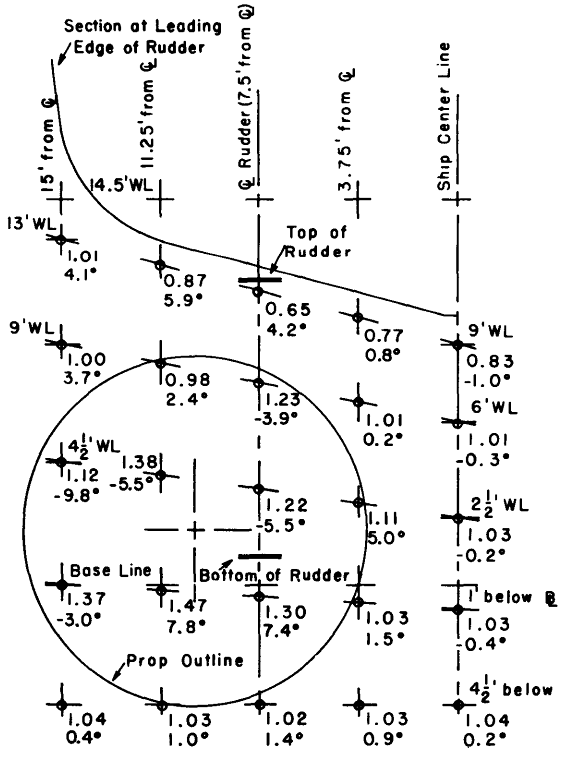


Figure 6 – Velocity Field at Rudder Stock

At each location, the upper figure is the value of u_x/V and the lower figure is the value of α.

Obviously, the athwartship vibration was flow-excited, and the mechanism produced an athwartship driving force. The mechanism can consist of any unsteady flow phenomenon which affects the lift characteristics of the rudders. A study of the flow field at the rudders was required, to aid in identifying the mechanism.

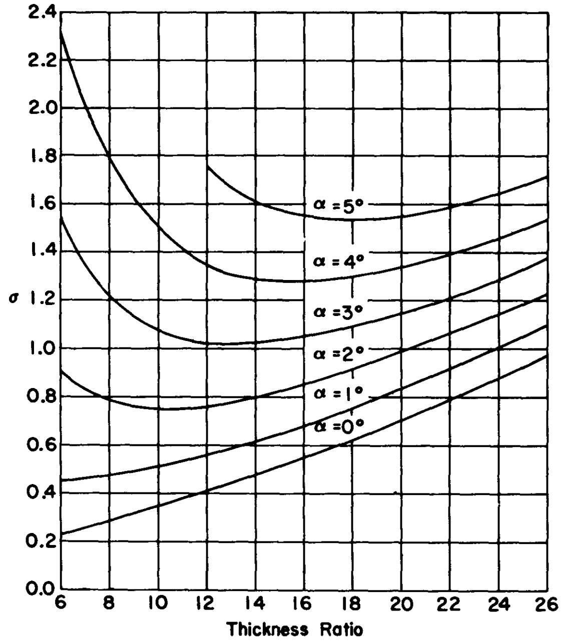


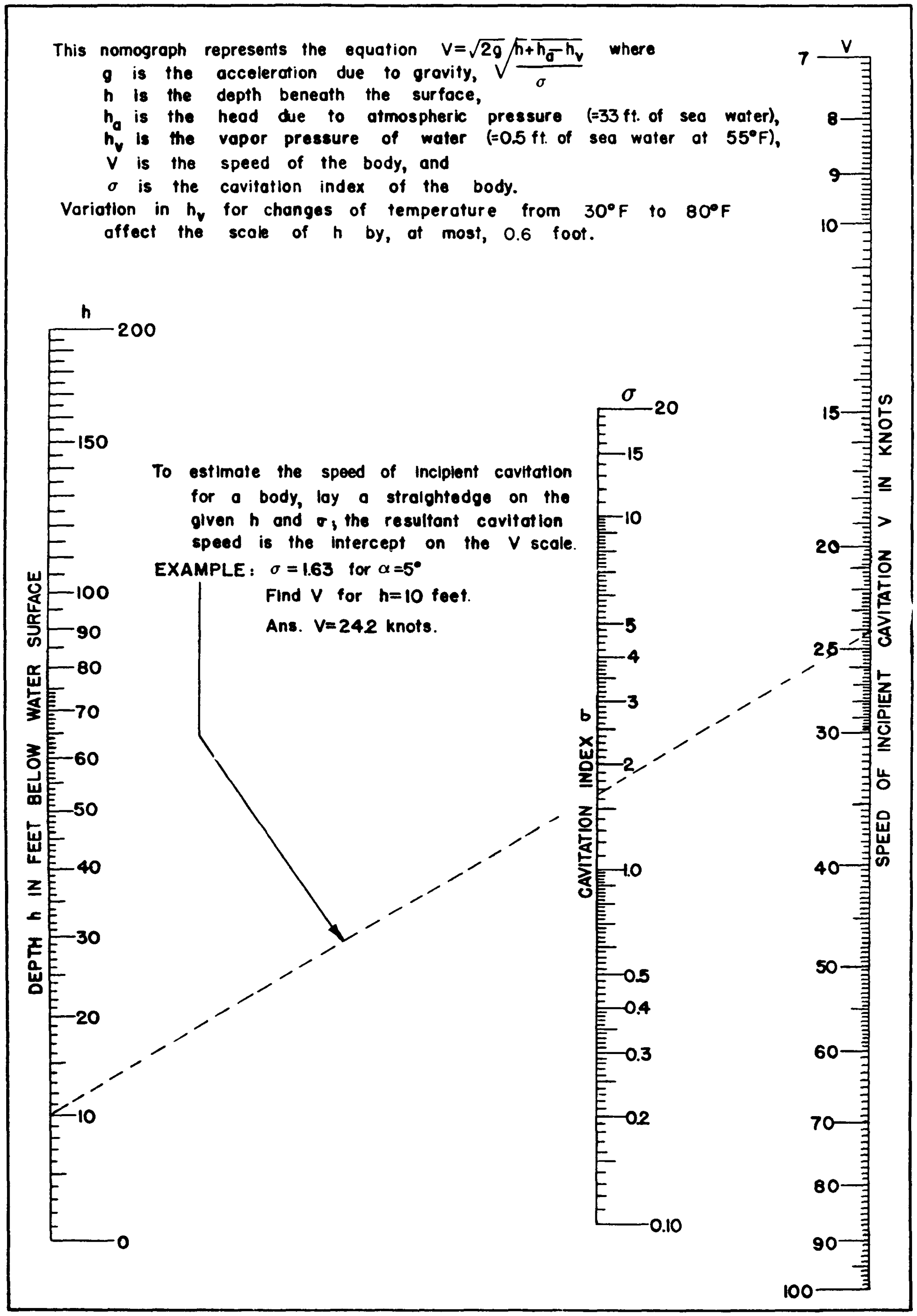
Figure 7 – Cavitation Index versus Thickness Ratio

3. WAKE SURVEY

A wake survey was conducted behind a powered model of the DD 931 class hull, to determine the effective velocity field at the rudders. The velocity components and directional angle are shown in Figure 4. The x-axis is taken in the direction opposite to the model velocity V, the y-axis athwartship (inboard), and the z-axis upward. The flow velocity u has the rectangular components u_x, u_y, and u_z. α is the angle between the x-axis and u_1, where $u_1^2 = u_x^2 + u_y^2$ (α is positive when u_y is positive). Values of the speed ratio u_x/V and α are shown in Figures 5 and 6. Since cos α is nearly one, u_x is approximately equal to u_1. Figure 5 shows the flow field at the leading edge of the port rudder, and Figure 6 shows the flow field at the port rudder stock. It appears that, with the model rudders toed-in 3 degrees, an effective angle of attack of about 7 degrees would exist over most of the rudder. The low pressure face would be outboard. The local flow velocity at the rudders is as much as 25 percent greater than the model speed (7 knots). Although these data might not be truly representative of the full-scale conditions at all speeds, they demonstrate that (1) the flow velocity at the rudder can considerably exceed the ship's velocity, and (2) the direction of flow at the rudders is not parallel to the ship's centerline, and the effective angle of attack varies appreciably over the entire rudder. Since the model test was conducted with Froude scaling, the test data approximate full-scale conditions. However, full-scale local boundary-layer and separation effects were not exactly duplicated by the test conditions.

4. CAVITATION STUDIES

The possibility of full-scale cavitation was investigated by theoretical calculations, by model rudder tests in a water tunnel, and by inspection of the DD 931 rudders.



This nomograph represents the equation $V=\sqrt{2g}\sqrt{\frac{h+h_a-h_v}{\sigma}}$ where

g is the acceleration due to gravity,

h is the depth beneath the surface,

h_a is the head due to atmospheric pressure (=33 ft. of sea water),

h_v is the vapor pressure of water (=0.5 ft. of sea water at 55°F),

V is the speed of the body, and

σ is the cavitation index of the body.

Variation in h_v for changes of temperature from 30°F to 80°F affect the scale of h by, at most, 0.6 foot.

To estimate the speed of incipient cavitation for a body, lay a straightedge on the given h and σ; the resultant cavitation speed is the intercept on the V scale.

EXAMPLE: $\sigma = 1.63$ for $\alpha = 5°$

Find V for h=10 feet.

Ans. V=24.2 knots.

Figure 8 – Cavitation Nomograph

a. Calculation of Cavitation Speeds

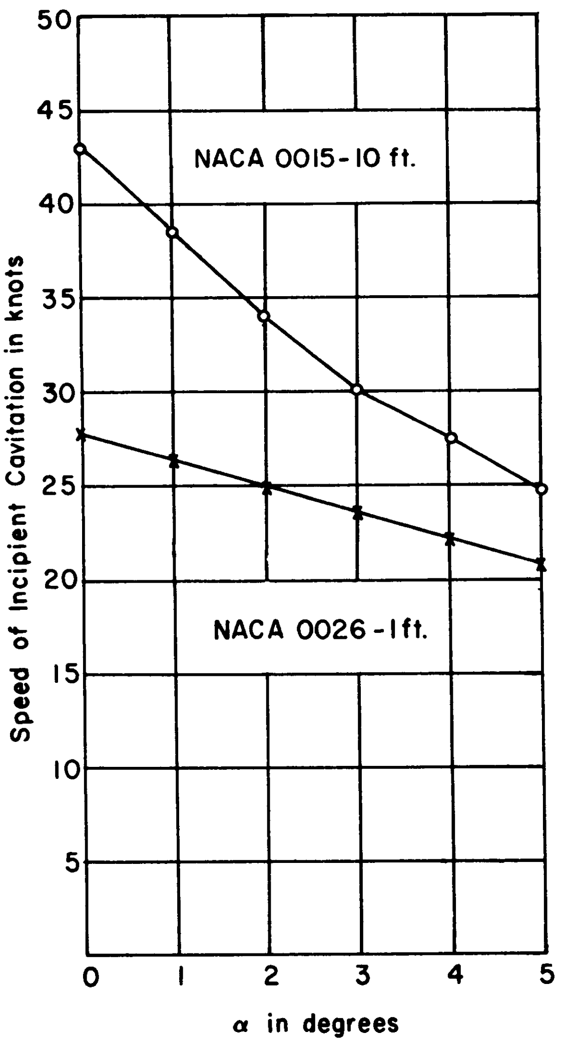


Figure 9 – Speed of Incipient Cavitation versus Attack Angle

The rudder is a tapered strut based on the NACA 00XX symmetrical series, varying from a 0027 section at the top to a 0012 section at the bottom. In order to estimate the speed of incipient cavitation, the cavitation indices (σ) were computed for the various sections by assuming two-dimensional struts of infinite aspect ratio. The computational results are shown in Figure 7 for attack angles from zero to 5 degrees. A TMB cavitation nomograph to facilitate deviation of the cavitation speeds is shown as Figure 8. For example, at the top of the rudder at zero degree attack angle, $\sigma = 0.97$ from Figure 7. If the effective depth of water at the top of the rudder is assumed to be 2 feet for the speed range in excess of 25 knots, the predicted cavitation speed is found to be 28.4 knots, by use of the nomograph. Since the actual rudders are of low-aspect ratio, and the flow over them is three-dimensional because of their taper, the computed values of σ and the incipient cavitation speeds are too high. As a guide to design, the two-dimensional computations indicate the importance of the thickness ratio as a cavitation parameter. The speed of incipient cavitation as a function of attack angle was determined by use of the calculated cavitation indices and the cavitation nomograph for the top and bottom of the rudder. The resultant relationships are shown in Figure 9.

b. Model Tests

Cavitation tests on a model of the DD 931 type rudder including the fixed stock fairing were conducted in the TMB 24-inch variable-pressure water tunnel. Figures 10-14 show the cavitation patterns for various rudder angles. In each instance it can be seen that the stock and its fairing cavitated before any other part of the rudder system. Figure 10 shows that cavitation at zero attack angle occurred first at a point where the section profile was

(Text continued on page 10.)

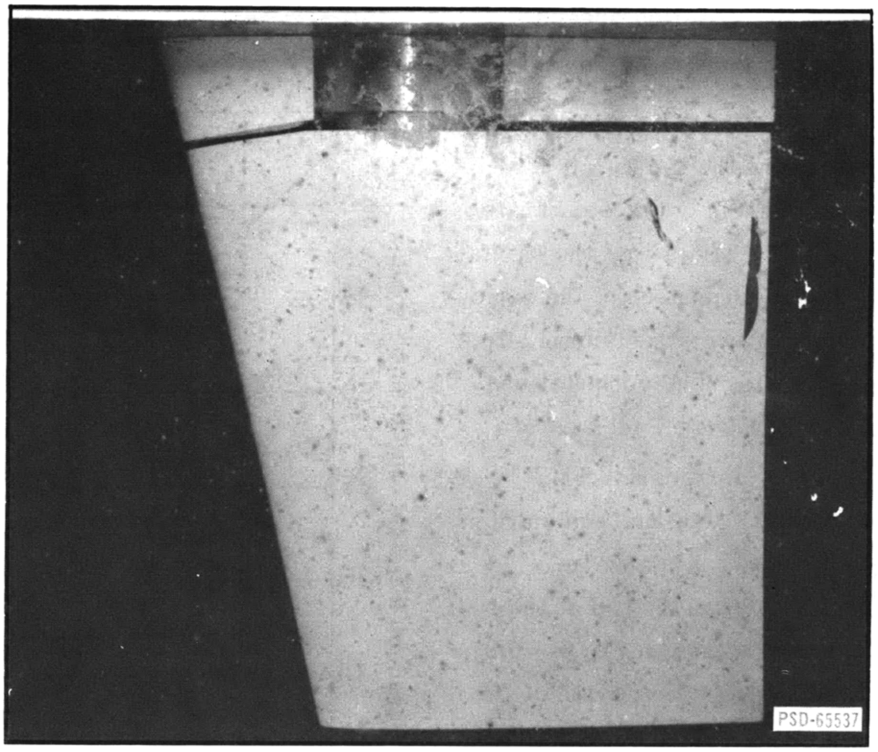


Figure 10 – Cavitation on Model Rudders at 0 Degree, 34 Knots

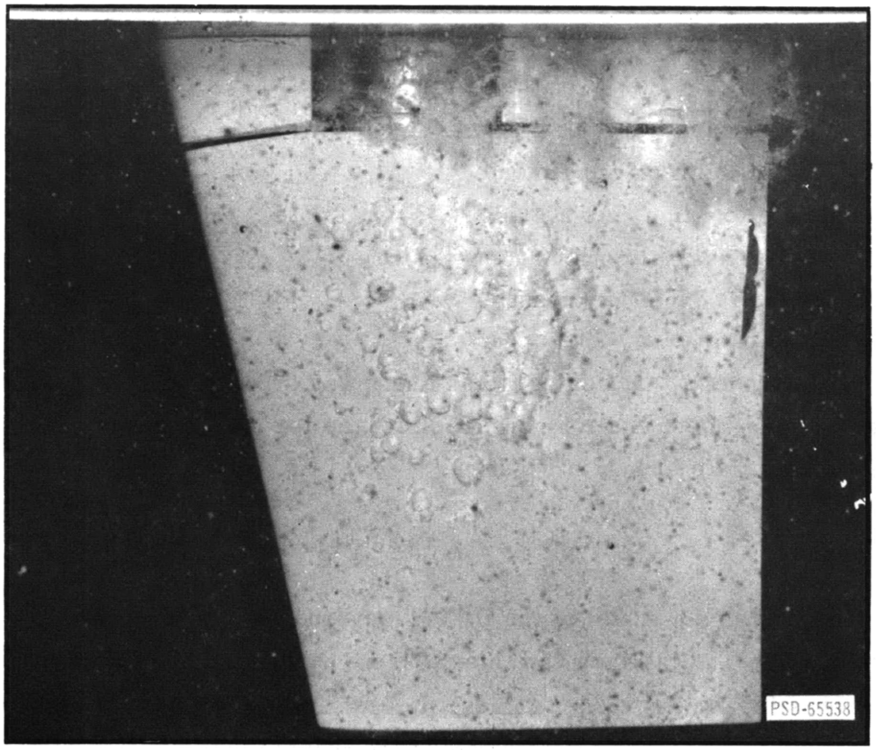


Figure 11 – Cavitation on Model Rudders at 0 Degree, 40 Knots

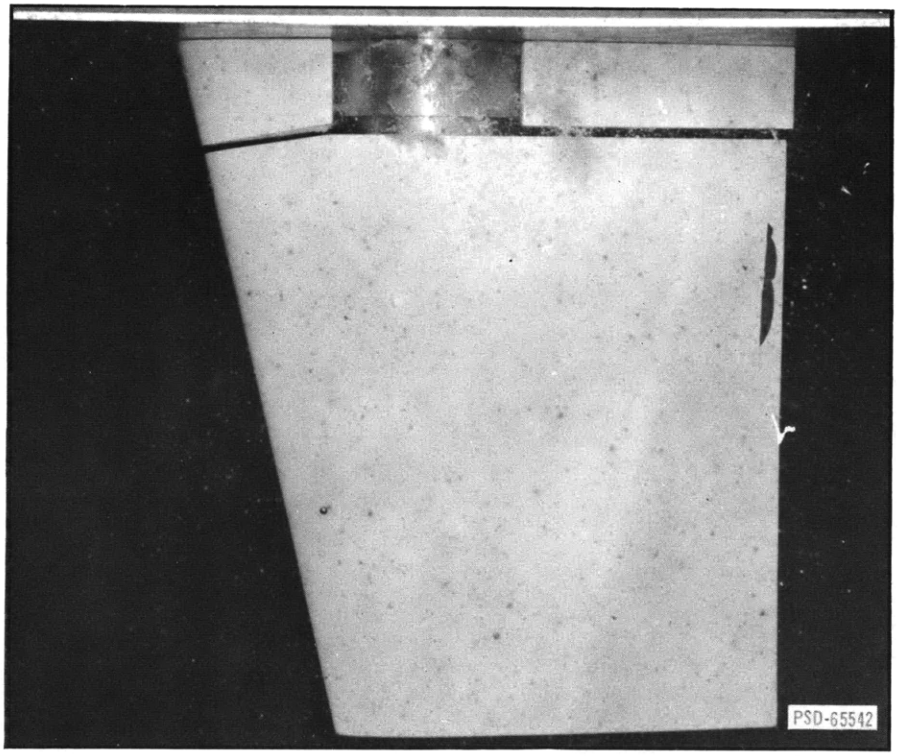


Figure 12 – Cavitation on Model Rudders at 3 Degrees, 31 Knots

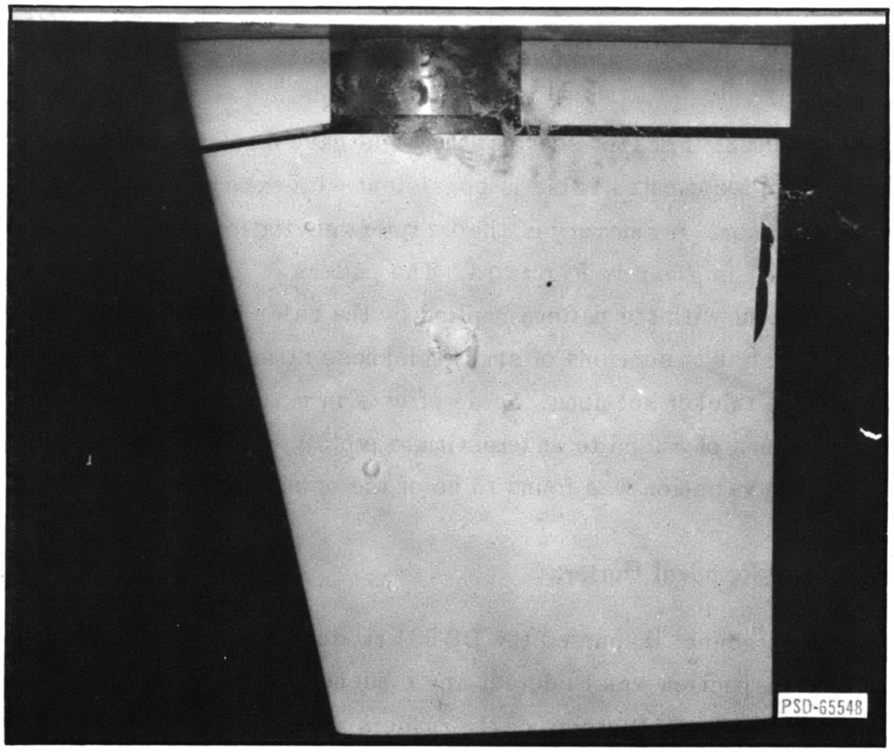


Figure 13 – Cavitation on Model Rudders at 6 Degrees, 28 Knots

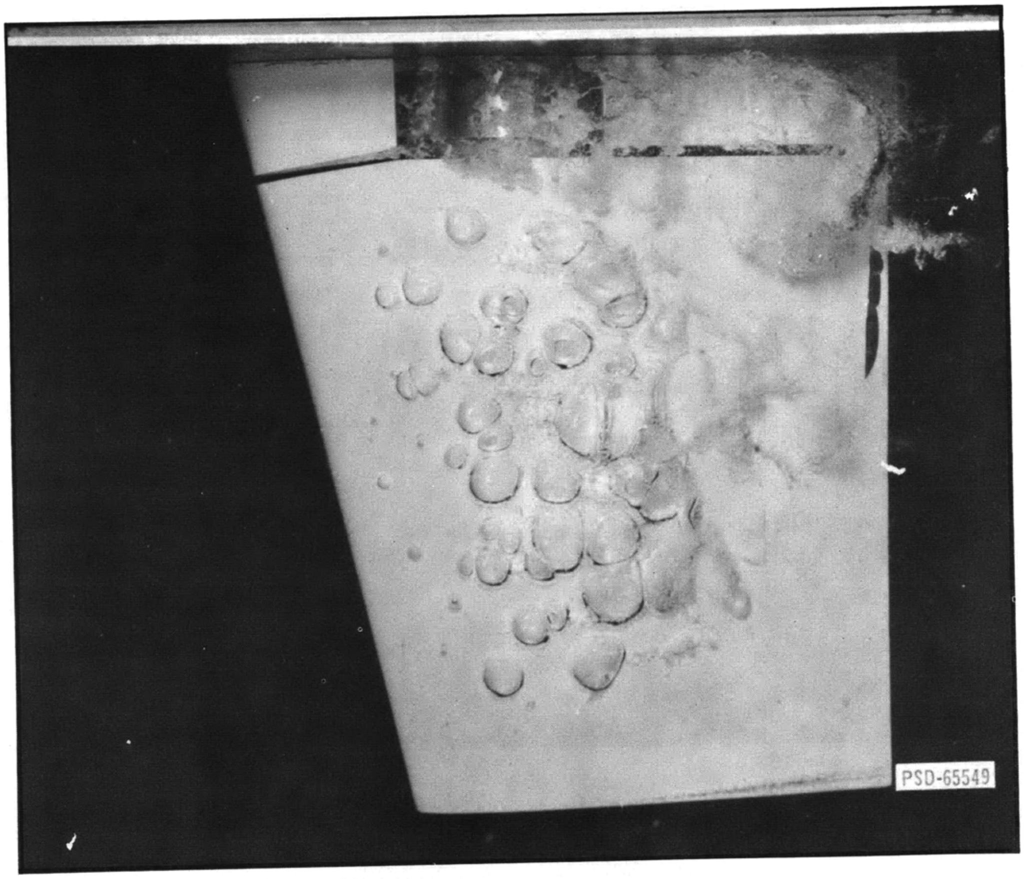


Figure 14 – Cavitation on Model Rudders at 6 Degrees, 35 Knots

approximately NACA 0023. For that section, the tests gave $\sigma = 0.67$, whereas the computed value is 0.84. This high computed value is consistent with expectations, due to the two-dimensional approximation. A summary of the incipient cavitation indices for the model rudder at various attack angles is given in Figure 15. The pattern of cavitation observed during the model tests is consistent with the pattern implied by the calculated curves. Both families of curves demonstrate that strut sections of small thickness ratio are more angle-sensitive to cavitation than are the thicker sections. Scale effects in model cavitation testing have been observed.[4] Model values of σ tend to underestimate prototype conditions. In comparable sonar dome experiments[5] the variation was found to be of the order of 15 percent.

c. Full-Scale Paint-Removal Pattern

Model Basin personnel inspected the DD 931 rudders while the ship was in drydock. The purpose of this inspection was to detect any evidence of cavitation such as erosion or pitting of the painted surface. Pictures of the rudders are shown as Figures 16-18. Fortunately, the DD 931 was a relatively new vessel so that the paint-removal pattern could be reasonably well evaluated. With the rudder trailing edges toed-in, the effective angle of attack resulted in reduced pressure on the outboard faces, which could produce cavitation on normal straight courses at high speeds. Such normal operation could explain the almost complete paint removal from the outboard faces of both rudders. It would also account for the sharp demarcation of a flow stagnation zone at the leading edge, as shown in Figure 17. The inboard faces have also been partially bared and their paint-removal patterns are the pattern of cavitation distribution. During turns at large rudder angles it is likely that cavitation will occur on the inner face and, with it, paint removal. At high attack angles, shedding of cavitating tip vortices should be expected to occur at the bottom of the rudder. The strength of these vortices is greater for a sharply truncated edge of the DD 931 rudder type than for a similar rudder having a rounded bottom. Such vortices are evidenced by the photograph of the model in Figure 14. The paint-removal pattern of both inboard faces of the DD 931 rudders is evidence of the probable existence of these cavitating tip vortices. As a matter of observation, the entire cavitation pattern on the model (Figure 14) resembles the paint removal pattern of the inboard face of the DD 931 starboard rudder.

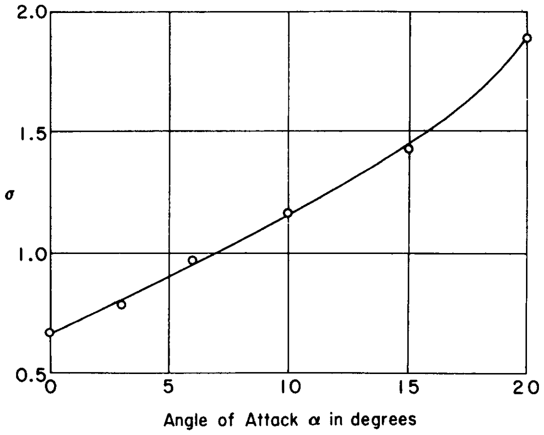


Figure 15 – Cavitation Index versus Attack Angle for Model Rudder

Throughout this discussion, it has been tacitly assumed that paint is removed by cavitation. It is quite possible that paint removal could also occur because of reduced pressures, which could tend to lift the paint from the surface. During the cavitation process, reduced pressures are augmented by the definitely deteriorating effects of collapsing cavitation bubbles.

5. FLUTTER

It is possible that conditions necessary for flutter of the rudder were closely approached because of coupling of the natural vibrations of the hull and rudder systems. If those conditions were indeed approached, the large-scale vibration could be a warning of impending flutter. A theoretical investigation of the conditions required for flutter excitation has been made recently at the Model Basin. An experimental program is being undertaken to explore the validity of the analysis and its application to this vibration problem. The manner in which the mechanical system, consisting of the hull, the rudder, and connecting linkage, is involved in the vibration is the subject of those studies.

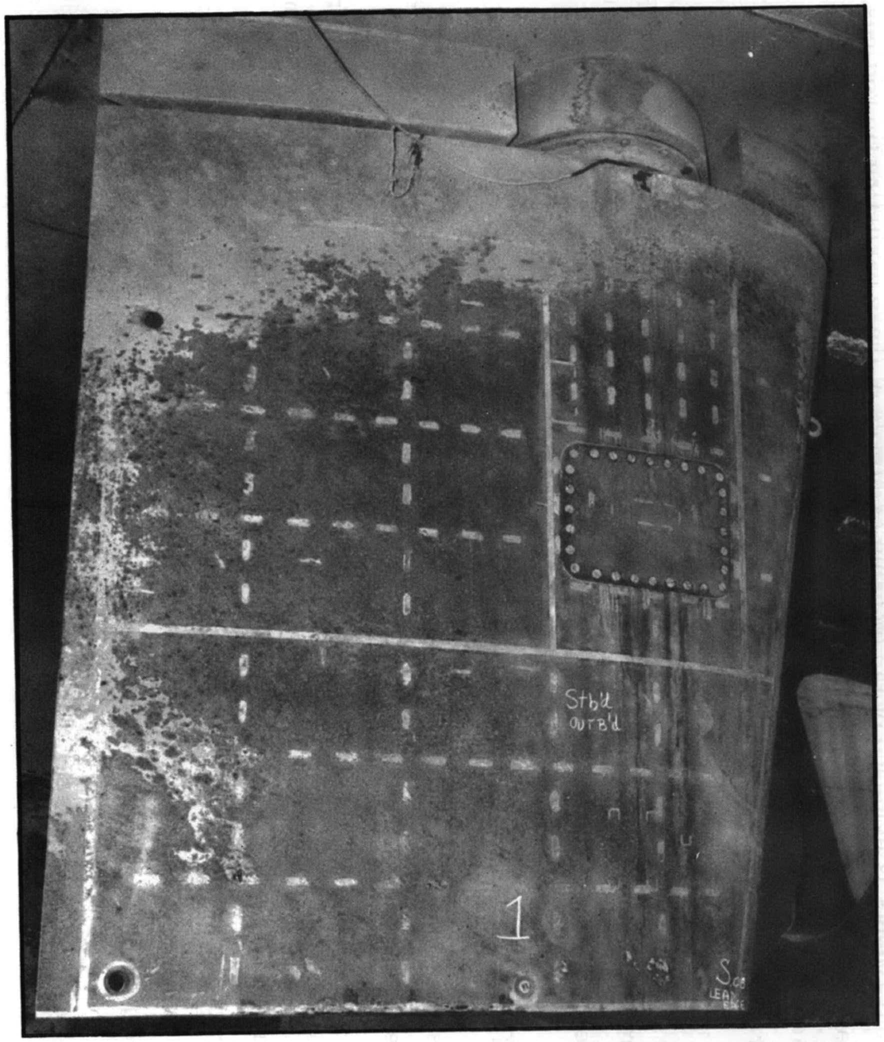


Figure 16 – Outboard Side of Starboard Rudder

Figure 17 – Leading Edge of Starboard Rudder

Figure 18 – Inboard Side of Starboard Rudder

DISCUSSION

In a recent report, Kermeen[6] indicates the mechanism by which cavitation could excite vibrations. He observed:

> "When the cavitation area is on the order of one-half to one chord in length, severe buffeting forces may be encountered particularly at higher attack angles. The buffeting is caused by violent fluctuations in the cavitation which may cause the hydrofoil to change from nearly fully wetted to full cavity flow very rapidly. . . . Buffeting may occur at all attack angles, but its severity increases with attack angle. When the cavitation number is reduced so that the cavity closes downstream of the hydrofoil, the buffeting ceases and the forces are steady. . . ."

This observation indicates that large-scale changes in the lift and moment can occur. Kermeen's report contains photographs of fluctuating cavities which cause buffeting of a hydrofoil at an angle of attack of 12 degrees. The corresponding cavitation indices were between $\sigma = 0.833$ and $\sigma = 1.780$. Cavitation indices of that order occurred on the model rudder at angles of attack above 4 degrees, as shown in Figure 15. Therefore, it is quite likely that such fluctuating cavitation was produced on the ship rudders at the speeds and rudder angles at which the vibration occurred.

The forces on the hull caused by fluctuating cavitation on the rudders do not necessarily cancel because of symmetry about the ship's vertical centerplane. There is no evidence to support the belief that the cavities on the rudders will repeatedly collapse at the same instant. Examination of records of simultaneous torsional strains in the rudder stocks shows that the phase relation between the exciting forces on the rudders will not tend to cause cancelation. Figure 7 of Reference 2 shows simultaneous torsional strains obtained while changing rudder angle; however, the pattern of amplitudes and phases obtained in this case is similar to that obtained for the rudders held at fixed angles.

CONCLUSIONS

It has been determined that the source of vibration is located at the rudders. Rudder ventilation is not the cause. The presence of cavitation has been verified as well as is possible without actual visual observation. Assuming an effective attack angle of 3 degrees and a water depth of 2 feet near the top of a rudder, the predicted cavitation speed is 31 knots. Although this is somewhat higher than the observed critical vibration speed, there are a number of factors present in the prototype which could cause cavitation at ship speed less than 31 knots. These factors are:

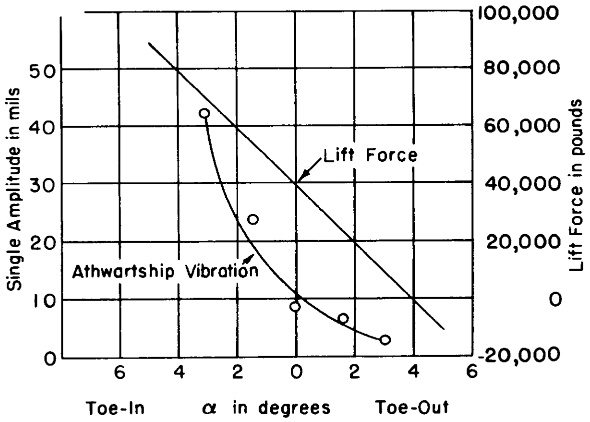
1. The effective flow angle at the rudder is not the same as the preset toe angle. A preset toe-in angle serves to increase the effective angle of attack. However, the flow angle is not a well defined constant quantity, since it is a function of propeller rpm.

2. The effective velocity at the rudder can be greater than the forward velocity of the ship. Although the upper portion of the rudder is influenced by the reduced velocity in the ship's boundary layer, the lower portion would be subjected to increased velocities arising from the propeller slip stream.

If one accepts a toe-out angle of 4 degrees as the effective zero angle for the rudder, based on Figures 5 and 6, then two important conclusions can be drawn from Figure 19 (reproduced from Figure 16 of Reference 2):

1. At 4 degrees toe-out the lift force is zero, and for small effective attack angles near this setting, rudder cavitation would not be expected in the (normal) operating speed range. This is consistent with the vibration amplitude curve also shown in Figure 19. The preset toe-in angle of 3 degrees represented an effective attack angle of 7 degrees, which constitutes a serious cavitation problem. The model cavitation index at 7 degrees is $\sigma = 1.0$. For a depth of 3 feet, cavitation at a local velocity of 28 knots would be expected. It has been shown that a local velocity of 28 knots at the rudder could occur at a ship speed of 22 knots. Hence, cavitation could start at this speed, and at a ship speed of 28 knots could be sufficiently serious to cause buffeting.

Figure 19 – Vibration Amplitude and Lift Force versus Rudder Toe Angle at Maximum Ship Speed



2. From the plotted lift curve, it is obvious that the lift developed on one rudder is quite large, being of the order of 70,000 lb. Periodic change of the lift due to cavitation fluctuations could provide the athwartship driving forces necessary to cause the vibration.

RECOMMENDATIONS

The onset of cavitation on the ship's rudders should be observed and correlated with recorded vibrations. Also studies of the periodicity and magnitude of variation of the effects of cavitation on control appendages should be undertaken.

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