Marine Systems Supplement

An Experimental Investigation of Flutter of a Fully Submerged Subcavitating Hydrofoil

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This paper presents the results of an investigation of the flutter characteristics of a fully submerged subcavitating hydrofoil. The foil suffered a catastrophic flutter failure at a speed of approximately 48 knots. Comparisons are made with various prediction methods, neither the two-dimensional nor the three-dimensional theoretical calculations yielding results of the correct order of magnitude. Calculations employing measured three-dimensional oscillatory coefficients gave a highly conservative prediction for flutter speed.

Introduction

The possible occurrence of classical bending-torsion flutter of a fully submerged subcavitating hydrofoil has been questioned repeatedly over the past several years. In the absence of definitive and authoritative evidence of such a flutter occurrence or related experimental data, opinions have ranged from the impossibility of flutter to speculation as to the inapplicability of conventional aerodynamic flutter theory.[1] As part of a fundamental experimental investigation into these questions, the authors have conducted a series of tests with special hydrofoil models capable of providing directly the three-dimensional coefficients of oscillatory lift and moment caused by cantilever wing bending and torsion in water. These data cover a range of low values of reduced velocity and have been presented in detail elsewhere.[2,3] A bending-torsion flutter model also was constructed and tested as part of this research program, and it is the presentation of data regarding this flutter model to which the present paper is directed.

Experimental Program

Description of Flutter Model

The hydrofoil flutter model (Fig. 1) deliberately was designed to be flutter prone in order to provide a definite experimental point for correlation with various analytical predictions. A mass ratio ($\mu = m/\pi\rho b^2$) of unity was selected arbitrarily for the model as being small enough to demonstrate behavior in the range of interest to hydrofoil applications, but large enough to insure that flutter would occur. This mass ratio is also about as large a value as can be achieved practically with a 12%-thick foil section of solid lead. A NACA 16-012 airfoil section was chosen in order to have the center of gravity near midchord. The elastic axis was located well ahead of the center of gravity, and the bending and torsional stiffnesses were held low in order to obtain a low flutter speed. Further, in order to simplify and enhance the accuracy of the analytical procedures, the model parameters were made uniform spanwise, and the spar, being the only continuous spanwise member, provided a well-defined elastic axis.

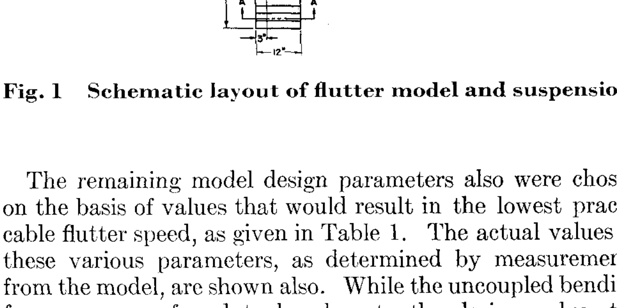

Fig. 1 Schematic layout of flutter model and suspension.

The remaining model design parameters also were chosen on the basis of values that would result in the lowest practicable flutter speed, as given in Table 1. The actual values of these various parameters, as determined by measurements from the model, are shown also. While the uncoupled bending frequency was found to be close to the design value, the torsional frequency was approximately twice as large as the design value, primarily as the result of failing to account properly for the stiffening effects of the spar attachments.

The model was composed of isolated spanwise strips connected by a single H-beam spar. The spar was machined from 4340 steel and was designed to have a high chordwise bending stiffness as compared with the lateral bending and torsional stiffness. The foil contour was formed by cast lead sections with imbedded steel webs to provide additional rigidity. The webs were first welded into steel blocks, which then were allowed to project from the lead castings to provide for mount-

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ing to the spar caps. A typical section is shown in Fig. 2. Each lead section was approximately 1.90 in. wide, separated from the adjacent section by a gap of approximately 0.10 in. and sealed with Silastic RTV 731 approximately 0.10 in. thick. The foil contour was filled out over the spar caps with a lead-filled plastic poured in place and trimmed to contour. This material was of such composition that it would hold its shape, but without contributing significantly to the spar stiffness. A stainless-steel plate was employed to close the tip of the model.

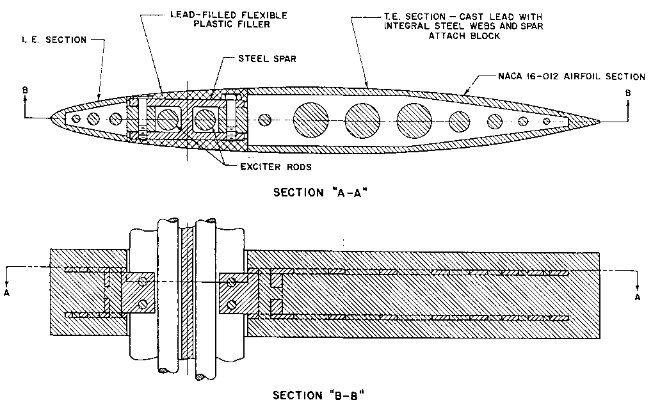

Fig. 2 Details of flutter model construction.

Model Suspension and Excitation System

The spar extended past the model root, and fittings were attached for mating with the same support fairing used for the load-measuring models employed earlier.[3] The root end therefore was held rigidly so that the model was cantilevered vertically from the towing carriage (Fig. 1).

An internal system for dynamic excitation of the model was desired in order that no disturbance to the fluid flow would result. This system consisted simply of two $\frac{7}{16}$-in. diam rods passing through the spar on each side of the web (Fig. 2) and anchored to the model tip, but free floating along the rest of the span and extending through the model root and up to the upper side of the carriage frame. Crank arms connected with links were attached to the upper ends of the rods, and a cable attached to the end of these cranks extended to the sides of the towing carriage. When the cable suddenly was pulled, the torque applied to the rods twisted the model tip slightly. The rods were designed also to serve as components of a brake system to prevent structural damage to the model should a violent mode of flutter be encountered. For this purpose, the cranks at the top ends of the rods could be clamped between two manually operated levers to increase the over-all torsional stiffness of the model.‡

Fig. 3 Flutter model following catastrophic failure at 48.1 knots.

‡ Because the torsional stiffness of the model was actually much higher than originally anticipated, the added stiffness provided by the clamped rods was not significant, and thus the braking system was rendered ineffective.

Instrumentation and Test Procedures

Instrumentation consisted of two strain-gage bridges on the spar root, one being sensitive to spar bending and one to spar torsion. Signals from these bridges were recorded on an oscillograph, and additionally, the torsion signal also was displayed on an oscilloscope. A high-speed motion picture camera was stationed at a single point along the length of the towing basin. All of the tests were conducted on the high-speed carriage at the David Taylor Model Basin.

The towing carriage speed was varied in increments of approximately 5 knots, from an initial speed of 10 knots. As soon as a given speed was established, the recording oscillograph was started and the exciting cable pulled, so that logarithmic decrements of the signal decay from the two strain-gage bridges were thereby recorded. The decay of the torsion signal was simultaneously observed on the oscilloscope (Polaroid photo) and the logarithmic decrement obtained immediately. Thus, it was possible to maintain a continuing surveillance of the system damping as carriage speed increased. Some of the records taken at the higher carriage speeds were repeated.

Catastrophic Failure

At a carriage speed of approximately 45 knots, the measured logarithmic decrement showed a significant decrease in damping, and therefore the next speed increment was selected to be only $2\frac{1}{2}$ knots. However, the actual carriage speed was 48.1 knots, resulting in a strong flutter condition growing from the initial disturbance applied to the model and leading to catastrophic failure of the model within a few seconds. Structural failure occurred at the spar root, as shown in Fig. 3. The model then slid off the exciter rods (which were bent to an angle of about 90°), rose completely out of the water, and impaled itself in the rear wall ($\frac{1}{8}$ in. aluminum sheet) of the test bay of the carriage (Fig. 4).

The flutter frequency was approximately 17.5 cps, resulting in a value of reduced velocity at flutter of $(V/b\omega)_F = 1.48$. By a rather fortuitous circumstance, the oscillatory motion of the foil had just attained rather large amplitudes as it passed the point at which the motion picture camera was stationed, so that a short film record was obtained. The film shows some cavitation arising from these large-amplitude motions just prior to the structural failure.

Table 1 Flutter model design parameters

Model design parameters	Design value	Actual value
Aspect ratio, Æ	5.00	5.00
Semichord, b	0.50 ft	0.50
Mass ratio, μ	1.00	0.99
Elastic axis location, a	−0.50	−0.50
Center-of-gravity location, x_α	0.50	0.524
Radius of gyration, $r_\alpha{}^2$	0.50	0.512
Bending stiffness, EI	3.08×10^6 lb-in.^{2}	3.40×10^6 lb-in.^{2}
Torsional stiffness, GJ	0.311×10^6 lb-in.^{2}	0.973×10^6 lb-in.^{2}
Frequency ratio, ω_h/ω_α	1.00	0.490
Torsion frequency, ω_α	10.0 cps^a	20.5 cps^a
Total weight	...	121.2 lb

^{a} Uncoupled natural frequencies in air.

Analysis

Three flutter analyses have been performed in order to compare various prediction methods with the measured flutter speed of this model. All of the various analyses are based on a ten-station, strip-theory, Rayleigh-type calculation[4] and differ from each other only in the values employed for the oscillatory lift and moment coefficients.

One analysis was made employing conventional two-dimensional theoretical coefficients,[4] and one was made employing modified three-dimensional theoretical coefficients;[5] the third analysis employed the measured three-dimensional coefficients.[3] The measured three-dimensional coefficients were originally obtained in terms of moment about the 31% chord position. The more conventional quarter-chord coefficients are then obtained from the relations

$$L_h = L_{hh} \qquad L_\alpha = L_{h\alpha}$$

$$M_h = M_{\alpha h} + m_b/bL_{hh} \qquad M_{\alpha\alpha} = M_{\alpha\alpha} + m_t/b_{hh}$$

where $m_b/b = 0.1131$ for the bending model, and $m_t/b = 0.1108$ for the torsion model. The elastic axis was located at the quarter-chord position in both models.

The results of the various flutter analyses, together with the relevant experimental data§ discussed earlier in this paper, are presented in Fig. 5 in terms of the exponential decay factor δ vs speed V. Points at which these curves intercept the speed axis are defined as critical flutter speeds.

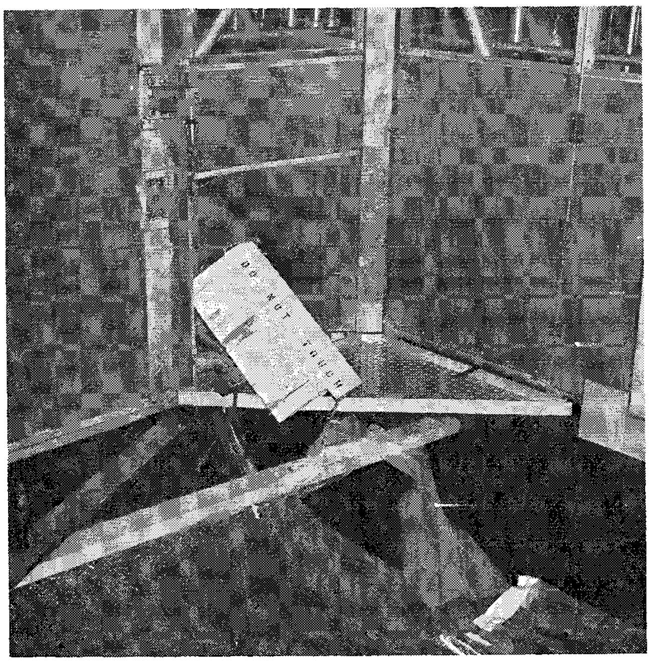

Fig. 4 Flutter model impaled in towing carriage wall following catastrophic failure.

Another comparison between the various analyses and the experimental data is shown in Fig. 6 in terms of the coupled torsional frequency vs speed. The calculated values employing theoretical three-dimensional coefficients appear to give a trend most closely approximating that of the experimental data.

Discussion

The results given in Fig. 5 are striking in their differences. The two-dimensional theory predicts no critical speed at all, whereas the three-dimensional theory leads to a critical speed that is unconservative by more than 100%. The calculation employing measured three-dimensional coefficients, on the other hand, predicts a flutter speed that is conservative by a substantial amount. Obviously, none of these can be considered a satisfactory prediction of critical flutter speed.

Based on previous aeronautical experience with similar techniques,[6] it would normally be expected that the calcula-

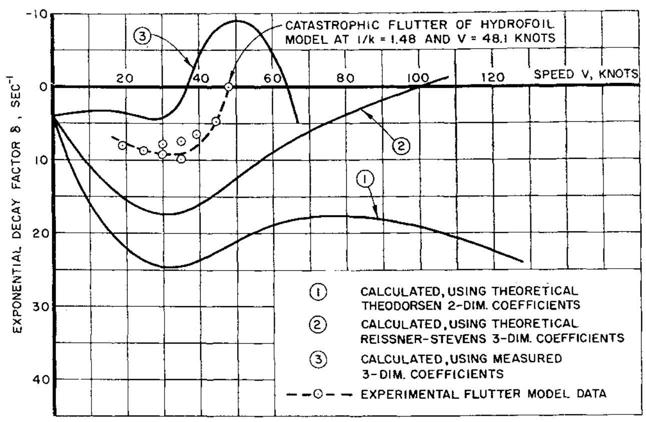

Fig. 5 Flutter model exponential decay factor vs speed.

tion of flutter speed employing measured three-dimensional coefficients would yield a value in very close agreement with the measured flutter speed. As was pointed out in Ref. 3, however, the measured coefficients employed here are known to be somewhat low in magnitude, particularly the moments, because of attenuation of response of the measuring system to loads aft of midchord, with an unknown effect on phase angles. This, coupled with some uncertainties in data reduction because of impure modes and high noise levels, lends some doubt as to the ability to predict accurate flutter speeds with these measured coefficients.

Another factor that may warrant consideration resides in the observation of some partial cavitation occurring on the model during the large-amplitude oscillations just preceding structural failure. There is, however, no evidence that this cavitation occurred before large amplitudes were built up.

Perhaps one more observation may be pertinent to this discussion. During the course of these calculations, some small changes in the numerical values of the various coefficients were made with very large effects on the value of the

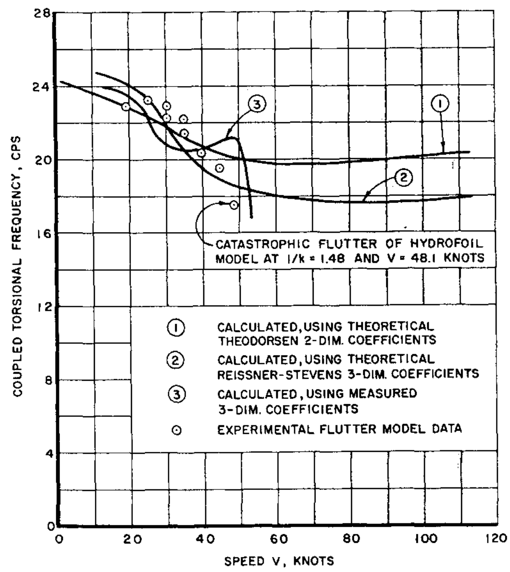

Fig. 6 Coupled torsional frequency vs speed.

§ The multiple experimental points at certain values of speed show the scatter of values of logarithmic decrement obtained for different test runs at that speed.

critical flutter speed.¶ At least, one should conclude that, for the model parameters involved here, the critical flutter speed is extremely sensitive to the values of the oscillatory coefficients.

The results of analytical predictions of flutter speeds of fully submerged subcavitating hydrofoils should be viewed with skepticism, and substantiating evidence from model tests should be obtained whenever possible.

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¶ These studies, aimed at developing a semiempirical flutter prediction technique more generally valid than the conventional calculations reported here, are continuing.