Engineering Notes

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Dynamic Hinge Moment of a Low Aspect Ratio Control Surface

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Introduction

UNDERWATER vehicles are almost always guided by small, low aspect ratio control surfaces located near the stern. During a given set of maneuvers, these control surfaces are subject to unsteady hinge moments. In order to evaluate the capabilities of the hydraulic systems used to actuate the control surfaces, it is necessary to know the dynamic hinge moment of the control surface. During a given maneuver, the control surface deflection $\beta(t)$ as a function of time is known and, in most instances, its complex Fourier transform can be computed, i.e.,

$$G(i\omega) = (2\pi)^{-1}\int_{-\infty}^{\infty}\beta(t)e^{-i\omega t}dt \qquad (1)$$

The dynamic hinge moment, $M(t)$ can then be obtained through another Fourier integral involving the complex admittance of the system. Mathematically, we write

$$M(t) = \int_{-\infty}^{\infty}T(i\omega)G(i\omega)e^{i\omega t}d\omega \qquad (2)$$

where $T(i\omega)$ is the complex mechanical admittance of the control surface. It is a measure of the amount of energy the system admits to pass through itself or to be generated in response to a given amplitude of sinusoidal input. Jones[1] has developed computer programs to evaluate the Fourier integrals of Eqs. (1) and (2).

The complex admittance is a function of the particular control surface geometry and must be either measured experimentally or predicted. Smilg and Wasserman[2] have used two-dimensional flutter theory based on Theodorsen's theory to develop methods of predicting the harmonic response of three-dimensional wings with flaps. This theory has been used to predict the complex admittance function of a low aspect ratio hydrodynamic flapped control surface. The results are compared to an admittance function measured experimentally in the 48-in. water tunnel of the Applied Research Lab., The Pennsylvania State University. The results compare favorably, which suggests that the relatively simple-to-apply theory and tables of Smilg and Wasserman (these tables are also found in Scanlan and Rosenbaum[3]) may be used with a fair degree of accuracy to predict the dynamic hinge moments of low aspect ratio control surfaces.

Analysis

The theory used to predict the complex admittance of a low aspect ratio control surface is based on the analysis and tables of Smilg and Wasserman. The tables include various hydrodynamic coefficients (lift, drag, pitching moment, hinge moment, etc.) as functions of a reduced frequency $k_o = \omega b_o/U$, where U is the free-stream flow velocity, b_o is the root semi-chord of the wing and ω is the circular frequency of oscillation of the surface. The actual geometry of a general control surface and flap can be approximated by a series of two-dimensional rectangular strips whereby, using the tables of Refs. 2 or 3, the hinge moment and phase of each strip can be evaluated as a function of frequency. The total hinge moment will then be the complex superposition of all the strips.

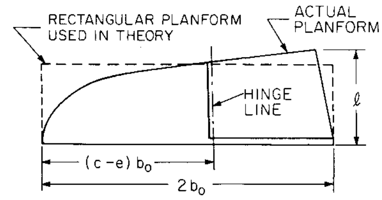

Fig. 1 Sketch of the low aspect ratio flapped control surface.

In the case of a low aspect ratio configuration, it is assumed that the control surface can be replaced by a single rectangular strip whose span and chord correspond to those of the actual configuration, e.g., Fig. 1. The hydrodynamic hinge moment per unit span is then given by

$$M_\beta(i\omega) = \pi\rho b_0{}^4\omega^2\beta_{max}[T_\beta - P_\beta(c-e)] \qquad (3)$$

where β_{max} is the peak amplitude of the deflection in radians, ρ is the fluid mass density, T_β is the frequency-dependent hinge moment coefficient of the flap, P_β is the frequency-dependent lift coefficient of the flap, and $(c - e)b_o$ is the distance between the hinge line and leading edge of the flap. The complex coefficients T_β and P_β are tabulated in Smilg and Wasserman. The admittance function can be written from Eq. (3) in nondimensional form:

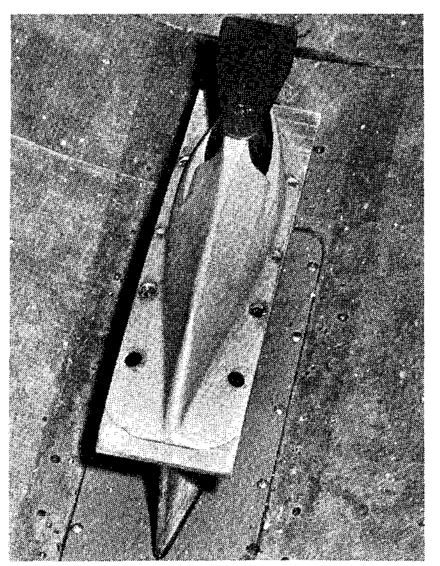

Fig. 2 Photograph of the control surface in the test section of the 48-inch water tunnel.

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Index categories: Marine Hydrodynamics, Vessel and Control Surface; Marine Vessel Trajectories, Stability, and Control.

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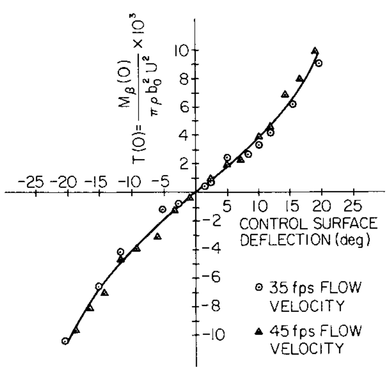

Fig. 3 Steady-state hinge moment coefficient of the control surface per unit span.

$$T(i\omega) = M_\beta(i\omega)/\pi\rho b_0^2 U^2 \beta_{\max} = k_0^2[T_\beta - P_\beta(c - e)] \quad (4)$$

which has the form of a frequency-dependent hinge moment coefficient. As the frequency approaches zero, we would expect $T(i\omega)$ to approach the steady-state hinge moment coefficient for the deflection $\beta_{\max}$.

Experiment

A hydrodynamic model of the low aspect ratio control surface sketched in Fig. 1 was installed in a 48-inch water tunnel[4] as shown in Fig. 2. The aspect ratio ℓ^2/S, where ℓ is the span and S is the surface area, of this particular control surface is 0.6. The hinge shaft was instrumented with strain gages in such a way that the output voltage was proportional to torque. The flap could be deflected either to a fixed position or harmonically by a specially designed hydraulic system. In measuring the admittance of the system, excitation frequencies fell in the range of 0.5 to 50 Hz. The deflection of the flap was monitored by the output voltage of a feedback potentiometer located in the control surface. The deflection and hinge moment were recorded simultaneously on a pen brush recorder from which modulus and phase could be read.

The steady-state and dynamic hinge moments were measured with the tunnel operating at either 35 or 45 ft/sec flow velocity and 20 psi pressure. The pressure was adjusted at a high value so that the control surface would not cavitate.

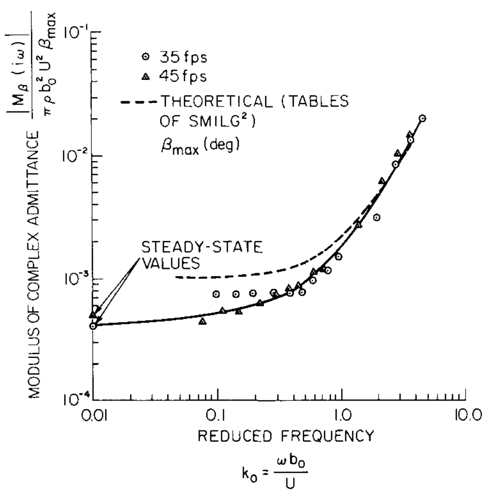

Fig. 4 Modulus of the complex frequency dependent hinge moment coefficient.

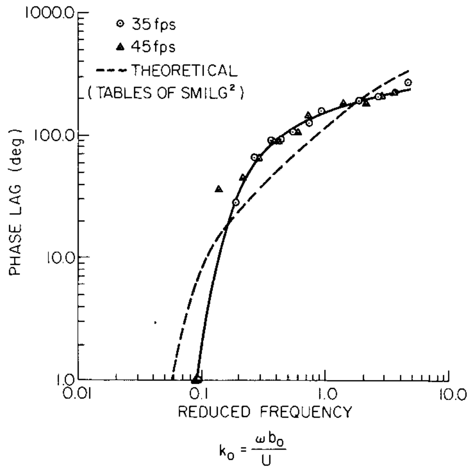

Fig. 5 Phase lag between the hinge moment and flap deflection.

The steady-state hinge moment coefficient as a function of flap deflection measured in the water tunnel is shown in Fig. 3. This coefficient is normalized as Eq. (4) without the deflection angle $\beta_{\max}$, meaning it is a hinge moment coefficient per unit span for a given value of β.

The dynamic data were reduced from the pen brush recordings for harmonic excitation of the flap. The modulus of the complex admittance is shown in Fig. 4 where the flap deflection is in degrees. The measured values are compared to a prediction made by assuming a rectangular planform of the control surface and utilization of the tables presented in Smilg and Wasserman. The agreement is good at the higher values of reduced frequency. The discrepancy at the lower values is due to the rectangular planform assumption where one would expect the geometry to become more important as the frequency approaches zero. The phase lag between the hinge moment and deflection is shown in Fig. 5. The phase approaches 180° at high frequencies and zero at very low values.

From the comparison of analysis to experiment, we may conclude that a rectangular planform approximation to a low aspect ratio hydrodynamic flapped control surface provides an efficient means of computing the dynamic hinge moment through use of the tables of coefficients developed in Ref. 2.

References

[1]Jones, K. L., "Implementation of the Fast Fourier Transform Algorithm on a Small Digital Computer," M. S. Thesis in Computer Science, The Pennsylvania State University, University Park, Pa., Sept. 1969.

[2]Smilg, B. and Wasserman, L. S., "Application of Three-Dimensional Flutter Theory to Aircraft Structures," Air Force Technical Rept. 4798, 1942.

[3]Scanlan, R. H. and Rosenbaum, R., *An Introduction to the Study of Aircraft Vibration and Flutter*, MacMillan, New York, 1951.

[4]"The Garfield Thomas Water Tunnel," Serial No. NOrd 16597-56, Sept. 1959, The Pennsylvania State University, College of Engineering and Architecture, University Park, Pa.