The optical correlator would be a useful research tool in such studies.

The development work described here is still in the early stages. The eventual goal is to develop a compact simple sonar signal processing component that will be universal enough to find wide applications in marine systems of the future.

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Dynamic Testing of the 80-Knot Hydrofoil Craft FRESH-1

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The FRESH-1 is a hydrofoil test craft designed to do high-speed hydrofoil research. It is thoroughly instrumented to sense and record craft motions, crew responses, engine performance, and foil force characteristics. Prior to a flight test, test maneuvers are performed on a six-degree-of-freedom analog computer simulation of FRESH-1. This allows the test time to be planned efficiently and provides predictions of the craft response for each test. All test data are recorded on an onboard magnetic tape recorder. In addition, certain critical channels of information are telemetered to a ground station where this data is displayed in the form of oscillographs and *X-Y* plots that can be interpreted readily by engineering specialists. A real time data reduction system allows the lift characteristics of a test foil to be presented instantaneously, as data describing the foil characteristics are obtained from testing. This system allows plots such as foil lift coefficient vs angle of attack at constant speed, foil depth, and flap angle to be displayed. Three methods of measuring the dynamic performance of hydrofoil craft have been evaluated in tests on FRESH-1: step response, frequency response by sinusoidal excitation, and frequency response by statistical correlation techniques. A comparison of the results of these methods is discussed.

Introduction

THE FRESH-1 is a hydrofoil research craft designed and built by The Boeing Company for the U. S. Navy Bureau of Ships under Contract NObs-4472. It provides a high-speed test facility for large-scale hydrofoil systems. The FRESH-1 not only measures foil hydrodynamic data, but also provides basic design information concerning the control system and operating procedures required by the test foils. An important part of the FRESH-1 test facility is an analog computer simulation of the craft, the test foils, and the control system. The simulation provides a means of predicting test craft responses and analyzing craft behavior. The purpose of this paper is to describe the FRESH-1 facility and its application to hydrofoil research and design.

Test Facilities

Craft

The FRESH-1 craft is shown in Fig. 1 during test operations on Puget Sound. The foils and struts are attached to lateral beams between the twin hulls. These beams may be positioned at several different longitudinal attachment points providing a great deal of freedom in the choice of the foil locations. Figure 1 shows the foils arranged in a conventional configuration with two foils forward and one aft. The FRESH-1 also has been operated in a "canard" configuration with one foil forward and two foils aft. Since the craft is powered by a turbofan jet, the propulsion system does not disturb the water flow around the test foils. Electrical and hydraulic power are furnished by a turbine-driven auxiliary power unit and by the main engine, respectively. Auxiliary power systems have been designed with sufficient capacity to accommodate a wide range of future hydrofoil systems. The onboard FRESH-1 data system records 84 continuous channels of information as well as 20 samples/sec of 82 other channels and 1 sample/sec of 176 pressure channels. With this large data recording capacity, a very complete record of the performance of all craft systems is maintained during all test operations. Foil performance is measured by a force balance located between the strut and the lateral beams providing a measure of the foil-strut assembly's lift, drag, and side forces. Pressure measurements also are made at critical points on the foil and strut. For a more complete description of the FRESH-1 craft, see Refs. 1–3.

Mobile Ground Station

The FRESH-1 has a crew of three and can carry one additional observer-passenger. A telemetry link between FRESH-1 and a mobile ground station allows test data to be

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monitored by engineering personnel during actual tests. Fourteen channels of telemetry data are available for this purpose. This information is presented in the form of oscillograph records and *X-Y* plots, which are used primarily to display foil lift characteristics. Since the foil lift is a function of speed, angle of attack, flap angle, and foil depth, it is necessary to do some data reduction in order to present such a function of four variables as a simple two-dimensional plot. This data reduction consists of assuring that three of the independent variables have constant, preassigned values, whereas the dependent variable is plotted vs the fourth independent variable. For example, plots of foil lift vs flap position may be obtained while speed, angle of attack, and foil depth are held constant. A Boeing-designed data reduction device monitors the test data and plots data only when the three independent variables are at their preassigned values. A system of indicator lights on the device allows an operator to recognize quickly an off-data condition and advise the FRESH-1 pilot by radio of the correction required to return the craft to the test condition. The use of several *X-Y* plotters, each recording data for particular preset independent variable values, permits the efficient gathering of data with minimum effort on the part of the crew.

Computer Simulation

A six-degree-of-freedom analog simulation of FRESH-1 has been used throughout the craft development and test program. This simulation contains a separate nonlinear representation of each foil and strut, pertinent control system nonlinearities, and sinusoidal wave generation features that allow the response of the hydrofoil system in a sinusoidal seastate to be studied. A complete simulation of the automatic control system hardware, sensor dynamics, and servo actuation is included. The simulation will operate in either real-time or in $\frac{1}{10}$real-time and in either a continuous or a repetitive mode. Both the $\frac{1}{10}$ real-time and the repetitive modes of operation are extremely useful in reducing the amount of computer time required to study a given situation.

Test Operations

Probing New Foilborne Conditions

Prior to operating the FRESH-1 at a new foilborne condition, the simulation is first operated at and around this new condition to determine if any potentially dangerous situations can be foreseen. Predictions of steady-state flap deflections, pitch angles, and foil depth errors are made by slowly scanning the simulated craft over the new foilborne condition. The computer output in these cases may be in the form of plotted functions, such as static flap deflections vs speed. For this type of analysis, the $\frac{1}{10}$ real-time ability of the computer can reduce greatly the time required for scanning

Static control surface deflections and control system errors as functions of speed and foil depth provide a basis for evaluating the craft operation while probing a new operating region. The preceding quantities are monitored by the craft crew and by the ground station engineering personnel to detect any variation from the predicted values. By closely monitoring the static trim characteristics of the craft and comparing these with predicted values, it is possible to detect

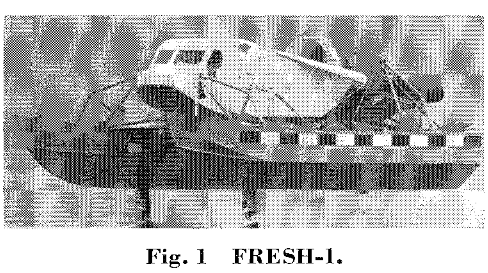

Fig. 1 FRESH-1.

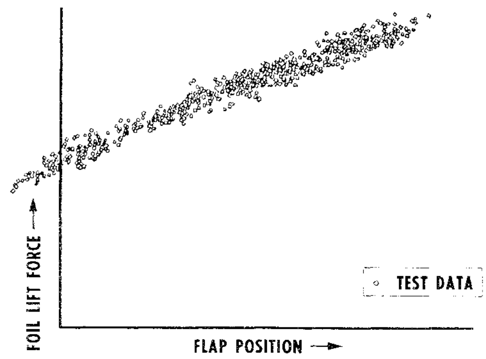

Fig. 2 Hydrodynamic data example.

abnormal operating conditions such as incorrect control gain settings or unusual foil flow. When such a condition is detected, the pilot is warned by radio and proper corrective action is taken. This may consist of discontinuing the probing operation or landing the craft until the unusual condition can be evaluated.

Foil Characteristics Measurement

The lift, drag, and side forces produced by a foil-strut assembly are measured by a force balance mounted between the strut and the attachment beam. The force balance is placed on one of the outboard foils so that the foil loading may be varied by performing turn maneuvers. The foil lift is displayed vs flap position on an *X-Y* plotter at the ground station, as described previously. The data reduction system allows this data to be plotted only when the test conditions match preset values. By watching the indicator lights of the data reduction device, a ground station operator can talk the pilot onto condition and keep him there while he does a gradual *S* turn maneuver. This maneuver will cause the loading of the test foil to vary from a minimum value when it is on the inside of the turn to a maximum when it is on the outside of the turn. During this maneuver, the ground station *X-Y* plotters produce plots of the foil lift vs flap angle over the range of flap angles encountered. An example of the type of data that is produced by this real-time data reduction system is shown in Fig. 2. If the desired foilborne condition was not achieved during the maneuver, it is known immediately and the test can be repeated to get the data. This is a distinct advantage over previous procedures where the results of the test were not known until several hours or days after the test when the onboard data were reduced.

The ground station data described previously are not the only or final form of hydrodynamic data on the test foils. The final form of the lift, drag, and side force data is obtained by digitizing the onboard data tape and correcting for interaction effects of the force balance. This also allows higher accuracy to be obtained since the digitzed data are automatically calibrated by a zero and standardize signal, which is impressed on each data channel at the beginning of each test run. In addition, calibrated pressure data are available from the craft data tape. A discussion of the various hydrodynamic phenomena that are being revealed by FRESH-1 operations is beyond the scope of this paper. A more detailed discussion of this area may be found in Ref. 2.

Step Response Measurement

A step response that provides a simple means for measuring certain transient characteristics of a hydrofoil craft can be obtained by making a sudden change in one of the pilot's control settings and recording the craft responses to this disturbance. By this means, the dynamic response of the craft to a known disturbance is obtained. This information is used by the dynamic analysist to predict the response of the craft to other more complex disturbances, such as waves

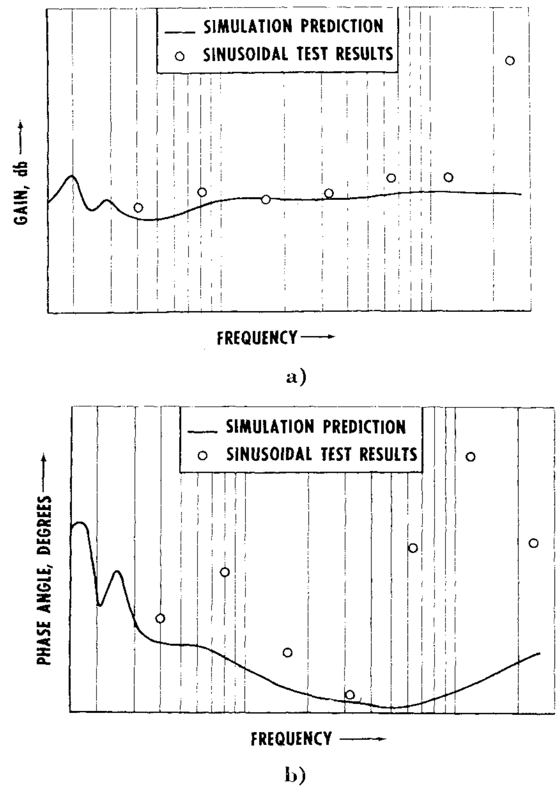

Fig. 3 Sinusoidal frequency response measurement.

The step response test requires very little foilborne time and no elaborate data reduction techniques. However, for a complex system such as a hydrofoil craft, the step response will be dominated by the low-frequency characteristics of the system. Thus, the higher frequency response characteristics of the hydrofoil craft will not be well defined by this method. Because of the nonlinearities involved in hydrofoil operation, the step response may vary with step amplitude, direction, and initial conditions. In spite of these shortcomings, the step response has been found to be a useful tool for rapidly evaluating low-frequency hydrofoil dynamic characteristics.

The analog simulation of FRESH-1 provides a convenient means for determining the cause of discrepancies between computer predictions and actual craft responses. In the high-speed repetitive mode, the computer can continually present a display of its calculated step response on a television-type picture tube. Along with the computer calculated step response, a second trace can show a copy of the actual craft response. Various parameters in the simulation then can be adjusted singly or in combinations, and the effect of each adjustment can be noted. In this way, one can evaluate rapidly the effect of numerous simulated craft parameters on the step response. The parameter that causes the simulated response to match the actual response, when adjusted to a new value, then may be remeasured on the actual craft. By this technique the analog simulation can be used to locate rapidly the cause of discrepancies between its predictions and actual craft step responses. When the true value of the craft parameter has been established, it is either modified to match the original design value or, if its effect is not detrimental, it is left unchanged and the simulation is modified to match the new craft configuration.

Frequency Response Measurement

Frequency response measurements provide a means of obtaining quantitative data on the dynamic characteristics of a hydrofoil system in the higher frequency range that is not accessible by the step response measurement. The frequency response of a dynamic system, like the step response, is a standard method by which the dynamic analysist measures the dynamic characteristics of a vehicle. Such a test consists of measuring the ratio of the amplitude of an input disturbance to the amplitude of the output response at various sinusoidal frequencies. In addition to this amplitude ratio, i.e., "gain," the phase angle between the input disturbance and the output response is measured as a function of sinusoidal frequency. These two functions of frequency, the gain and phase functions, provide the dynamic analysist with another measure of the information required to predict the response of the craft to more complex disturbances, such as waves. For a more complete description of dynamic response functions and their use see Ref 4.

The response at higher frequencies, say above 5 cps, contains information concerning structural flexibility and dynamic lags which are of importance to the control system design. To obtain a frequency response measurement, the FRESH-1 is flown to a particular foilborne condition of speed and foil depth and maintained there while test signals are applied to the craft through the control system to induce motion over the frequency range of interest. Two techniques of frequency response measurement have been used on FRESH-1; the first uses a sinusoidal test signal, and the other employs a statistical or random test signal

Sinusoidal Technique

A variable frequency signal generator on board the FRESH-1 provides a sinusoidal test signal that perturbs one of the foil control surfaces. This signal is successively set at different frequencies throughout the desired frequency range, and the amplitude of the signal is increased until a measurable signal level is attained at the craft motion sensors. The test signal amplitude is increased from zero at each frequency. A continuous frequency sweeping technique is not used, in order to avoid over-exciting any oscillatory modes that might be present. At each frequency, the test signal is left at its maximum amplitude for several cycles to assure that a steady-state condition has been achieved. As a result of this requirement, it is not possible to measure the frequency response at an arbitrarily low frequency since the time required for several cycles of the lower frequencies becomes excessive. Consequently, there is a lower bound on the frequencies that can be measured on the FRESH-1. With this lower frequency limit, it is possible to measure seven different frequencies on a single pass down the 6-mile test course. Water conditions during these and the other dynamic response tests are chosen to be very smooth to minimize this source of craft disturbances.

The sinusoidal test data have been reduced to standard gain and phase angle plots by manually reading signal level ratios and phase angles from oscillographs made from the onboard data tapes. The results of one such measurement are given in Fig. 3 which shows the response of a vertical accelerometer mounted over the starboard strut to starboard-foil flap position. The simulation's predicted frequency response also is shown for comparison. An automatic frequency response measuring scheme on the analog simulation will produce continuous gain and phase angle functions such as these in approximately 3 min. The simulation prediction and actual craft gain response are seen to be in good agreement except for one high-frequency point. The acceleration response in

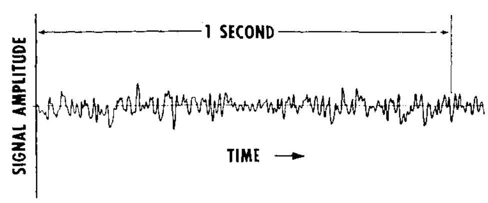

Fig. 4 Example of a white-noise test signal.

this frequency range is dominated by structural resonances that were not included in the simulation. However, frequency response measurements such as this one and those that follow, provide the quantitative information necessary to add such effects to the simulation. The phase angle measurements do not agree as well as those of gain. This is believed to be due in part to the inaccuracies of phase angle measurements made from oscillographs. Errors on the order of those shown in Fig. 3 were possible with the signal to noise ratios present in the sinusoidal data.

Statistical Technique

The second type of test signal used to measure the frequency response characteristics of FRESH-1 is a statistical white-noise signal; an example is shown in Fig. 4. This type of signal has a uniform power spectral density over the frequency range of interest and results in a continuous excitation of the hydrofoil at all of the frequencies in this range. Therefore, it is possible to obtain more detailed frequency response information with considerably less foilborne test time than with the sinusoidal technique. In order to obtain the desired gain and phase angle information from the test data, it is necessary to process the data through statistical spectrum analysis equipment.

Two methods are available for determining a transfer function gain from statistical test data. The simpler approach is the transmittance method by which the gain is determined as the ratio of the power spectral density function of the output signal to the power spectral density function of the input signal. This is stated mathematically in Eq. (1)

$$|G(f)|^2 = \Phi_{00}(f)/\Phi_{ii}(f) \tag{1}$$

where $|G(f)| \equiv$ the transfer function gain, $\Phi_{00}(f) \equiv$ the output signal power spectral density function, and $\Phi_{ii}(f) \equiv$ the input signal power spectral density function. A derivation of this equation is given in most books on statistical system analysis.[4] No phase angle information is available by this method, and errors may be introduced by extraneous noise appearing on either the input or output signals. However, a minimum amount of statistical analysis equipment is required by this method and it can provide a continuous gain vs frequency plot. Figure 5 shows the results of this type of measurement compared to the simulation prediction. It can be seen that the transmittance measurement defines the structural resonances in the higher frequency region in more detail than the sinusoidal measurement, and yet the foilborne test time required was less.

The second method of determining transfer functions from statistical test data utilizes the cross power spectrum of the input and output signals. Both the gain and phase angle of the transfer function are determined by this approach. Since this method involves a true correlation of the input and output signals, it is less sensitive to many noise sources that interfere with both the sinusoidal and transmittance methods.

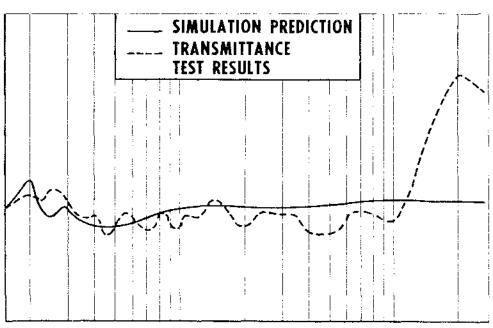

Fig. 5 Transmittance statistical frequency response measurement.

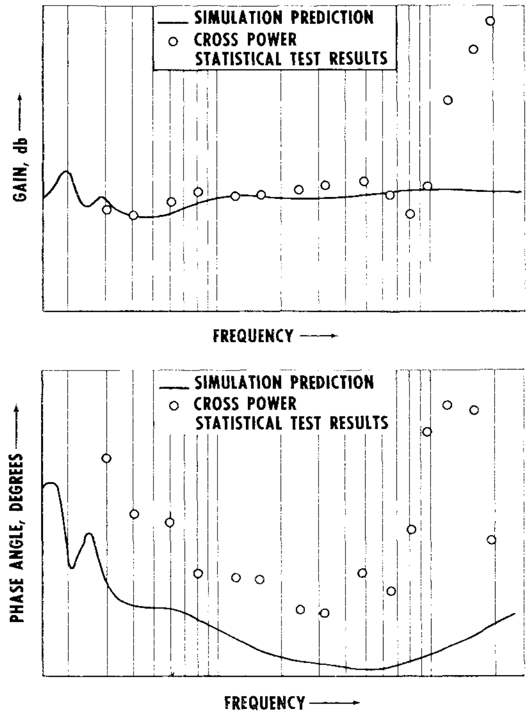

Fig. 6 Cross power statistical frequency response measurement.

A transfer function is a complex function of frequency normally given in polar form, as a magnitude (or gain) and (phase) angle. The cross power spectrum also is a complex function of frequency. The transfer function is related to the cross power spectrum and input signal power spectral density functions as given in Eq. (2)

$$G(f) = \Phi_{0i}(f)/\Phi_{ii}(f) \tag{2}$$

where $G(f) \equiv$ the complex transfer function of the system, and $\Phi_{0i}(f) \equiv$ the cross power spectrum of the output signal to input signal of the system. The cross power spectrum normally is measured in rectangular form as a real part and an imaginary part, designated cospectrum and quadspectrum, respectively. The gain and phase angle of the transfer function are related to the cospectra and quadspectra as given in Eqs. (3) and (4)

$$|G(f)| = [C_{0i}^2(f) + Q_{0i}^2(f)]^{1/2}/\Phi_{ii}(f) \tag{3}$$

$$\text{Angle } [G(f)] = \tan^{-1}[Q_{0i}(f)/C_{0i}(f)] \tag{4}$$

where Angle $[G(f)] \equiv$ the transfer function phase angle, $C_{0i}(f) \equiv$ the cospectrum of output signal to input signal, and $Q_{0i}(f) \equiv$ the quadspectrum of output signal to input signal.

Thus, the FRESH-1 statistical test data are analyzed, producing the cospectra, quadspectra, and power-spectra functions. The values of these functions at particular frequencies are substituted into Eqs. (3) and (4) to produce the gain and phase functions, such as those shown in Fig. 6. Although Fig. 6 shows gain and phase values at discrete frequencies, the spectral analysis functions are calculated continuously over the frequency range. Additional points may be obtained by substituting the values of these functions into Eqs. (3) and (4). Additional information, therefore, can be obtained without the expenditure of additional foilborne test time. Spectral analysis equipment is commercially available that will produce continuous gain and phase angle functions directly from statistical test data. However, lacking this equipment, the analysis may be performed as described previously. The results of the cross power method compare quite well with both the simulation predictions and the sinusoidal and transmittance method measurements.

The statistical analyses previously described are performed by analog-type equipment in which the test data are placed on a magnetic tape loop and repeatedly played back to the analyzer. In order to make the hydrofoil test data compatible with the analyzer, it is necessary to alter both the time and magnitude scales of the data. Throughout this process the calibration of the data is maintained by the use of zero and standardize signals. The primary problem encountered has been that of obtaining a satisfactory signal level for all of the signals to be analyzed. The ideal solution to this problem is to choose all signal transducers so that a satisfactory signal to noise ratio is obtained at the point of sensing the signal. If the signal level is not adequate at the sensor, it is difficult, if not impossible, to compensate for this by later signal amplification.

Only one transfer function has been shown previously as an example of the three methods of frequency response measurement used on FRESH-1. In order to describe completely a dynamic system as complex as a hydrofoil craft, many such transfer functions must be measured. Therefore, it is important to use measurement techniques that minimize the amount of test time required. The step response and statistical frequency response provide the means for obtaining a complete dynamic description of a hydrofoil with a minimum of foilborne test time.

Conclusions

The FRESH-1 provides the U. S. Navy with a unique test facility for gathering information on high-speed hydrofoil systems. This facility not only furnishes foil hydrodynamic information, but it also provides a means for studying the foil's control system. A test procedure for new foil systems has been developed which allows these systems to be investigated safely and thoroughly. The dynamic characteristics of the total hydrofoil system are measured by step response and frequency response tests. The step response tests provide a quick means of measuring the low-frequency portion of the dynamic characteristics. When coupled with a repetitive analog simulation, these tests provide a powerful tool for analyzing hydrofoil craft. Statistical frequency response measuring methods have been found to be very satisfactory and can provide a considerable reduction in the amount of foilborne time required to gather test data. In addition, the experience gained in analyzing and processing statistical data provides a useful background for the hydrofoil system designer since hydrofoil ships operate in a statistical environment, the sea.

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