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On-Line Analysis Capabilities Developed to Support the Active Flexible Wing Wind-Tunnel Tests

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A variety of on-line analysis tools were developed to support two active flexible wing (AFW) wind-tunnel tests. These tools were developed to verify control law execution, to satisfy analysis requirements of the control law designers, to provide measures of system stability in a real-time environment, and to provide project managers with a quantitative measure of controller performance. Descriptions and purposes of capabilities that were developed are presented in this article along with examples. Procedures for saving and transferring data for near real-time analysis, and descriptions of the corresponding data interface programs are also presented. Although much of the on-line analysis capabilities described herein are not technically new, the implementation for near real-time analysis to verify and evaluate controller performance is new, and is included in this special *Journal of Aircraft* issue for completeness in describing the AFW wind-tunnel testing. The on-line analysis tools worked well before, during, and after the wind-tunnel tests, and proved to be a vital and important part of the entire test effort.

Nomenclature

G = open-loop plant transfer matrix
H = open-loop controller transfer matrix
I = identity matrix
u = excitation
X = controller output transfer matrix
x = controller output
Y = plant output transfer matrix
y = plant output (sensors and strain gauges)
λ = eigenvalues
σ = singular values, $\sqrt{\lambda(A^*A)}$, for a given matrix A; σ are always non-negative real
$\bar{\sigma}$ = maximum singular value

Introduction

THE cooperative NASA/Rockwell International Active Flexible Wing (AFW) program[1] included wind-tunnel testing of an actively controlled aeroelastic wind-tunnel model that could be configured to roll. An important goal of the program was to test flutter suppression control laws and rolling maneuver control laws, first, independently, and then simultaneously above the open-loop flutter boundary. A digital controller system (DCS)[2] was developed to implement these various control law functions while accommodating various types and combinations of control law implementation. The DCS receives sensor outputs from the model, processes them through the control laws, sums the various control law actuator commands, and then sends these back to the model. Reference 1 contains a detailed description of the wind-tunnel model including instrumentation and test objectives.

In order to verify the execution of each control law during various stages of development of the DCS and to evaluate controller performance during the tests, it was necessary to generate time-history responses to excitations. These excitations could be added to either the control law inputs or outputs at various points in the execution loop and to perform analysis of individual control law performance. The DCS engineers needed these capabilities to debug the internal implementations and execution of the various control laws. The control law designers and the project managers all needed guarantees that control laws were being implemented properly both prior to and during wind-tunnel testing in order to protect the wind tunnel and model from damage.

Various analysis packages and computer systems were explored for their capabilities. An available Hewlett Packard analyzer had insufficient channel capability and the data acquired was not conveniently portable to other machines. Furthermore, a special code, which needed to be written to perform controller performance evaluation, could not be written and implemented on the analyzer. Another option investigated was an available Modcomp mainframe. The specialized operating system on the Modcomp required specialized programming support that was unavailable to develop code. The fast Fourier transform (FFT) package was also too slow for near real-time controller performance evaluation, and again, the data was not conveniently portable to other machines. The final options considered were Cyber mainframes. The data transfers to and from this computer were too slow for near real-time analysis, and insufficient funds prohibited the purchase of additional specialized hardware to perform on-line analysis capabilities. In summary, most of the options could not meet the requirements of the AFW program, either because of the unavailability of hardware, software, networking capabilities, programming support, or simply lack of computation speed.

Since all the signals required for analysis were already available within the DCS and digitized at the sampling frequency

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of the DCS, and since a second DCS system was available as a backup to the primary system, it was decided that the most expedient solution was to develop the required analysis tools on the backup DCS. This second DCS, which would be used as a backup only upon failure of the central processing unit in the primary DCS, could be hooked to the primary DCS via an Ethernet line for data transfer. It was considered a small investment that more cautious wind-tunnel runs might have to be accommodated in order to perform on-line analysis before each critical step in the testing.

To satisfy the analysis requirements of the AFW program, an extensive package of analysis capabilities was developed. Since the signals used were those digitized by the DCS and the analysis could be performed while the DCS was operating, the analysis capabilities are referred to herein as on-line capabilities. This package included data interface programs that converted integer data representing voltages to scaled signal data of selected signals. It included plotting routines that could provide time histories of all internally saved, digitized data from the DCS, and Fourier analysis tools that calculated transfer functions of any combination of output/input pairs of signals from any control law could be computed and plotted. In addition to these basic analysis tools, a controller performance evaluation (CPE) code[3] was also developed. The CPE code processed the matrix of transfer functions for the flutter suppression system (FSS) and the rolling maneuver load alleviation (RMLA) control laws to determine 1) closed-loop stability from open-loop measurements, 2) measures of stability for a closed-loop system, and 3) open-loop plant stability from closed-loop measurements.

Some capabilities were considered essential for safe testing of the model, whereas others provided additional analysis of data from the wind-tunnel test. These two classifications of capabilities, critical and supporting, are described in this article with emphasis on those capabilities that were considered critical. Details of data saving and transfer, and a description of the Fourier analysis program are also presented in this article.

Hardware

The primary and backup DCS were comprised of SUN 3/160 workstations configured with specialized hardware boards. One of these boards was a fast array processor, manufactured by SKY Computers, Inc. This board performed all the FFTs required to compute transfer functions within a time frame that would allow for near real-time processing. The first SUN workstation (designated SUN-1) was used for the primary DCS; and the second SUN workstation (designated SUN-2) was used as an on-line digital signal analyzer where data translation and near real-time analyses were performed. Signals were passed between the model and SUN-1. Selected data was saved automatically in binary form on SUN-1 and transferred as a binary data file, via the Ethernet line, from SUN-1 to SUN-2. It was recognized that if the SUN-2 system had to be used as a backup DCS, data would have to be analyzed between test runs, requiring more cautious testing and fewer test accomplishments while the SUN-1 system was being repaired. Since the SUN-2 would be required as a backup DCS only if the SUN-1 central processing unit itself crashed, it was decided that this was a small risk.

On-Line Analysis Requirements

Different types of active control wind-tunnel tests were performed in the AFW program. These included testing FSS and roll control laws. Several roll control laws were developed; a roll trim system (RTS), a roll rate tracking system (RRTS),[4] and an RMLA system.[5] In addition to operating each of these control laws individually, an FSS control law[6-9] could also be operated in combination with a rolling control law. Each type of testing had specific on-line analysis requirements associated with it. Table 1 is a summary of the types of on-line analysis requirements for each type of testing to be performed in the wind tunnel.

Execution of both types of control laws, FSS and roll, had to be verified in the DCS, first in a wind-off environment with just the DCS, and then in the wind-on environment with the model included. This was critical for safe wind-tunnel testing. This had to be done while each control law executed independently and in conjunction with other control laws. Evaluating total controller performance, both with feedback off [open loop (OL)] and feedback on [closed loop (CL)], was required while testing the model with the DCS in the loop. For the rolling control laws (RTS, RMLA, and RRTS), time-history plots were needed for the control law designers to evaluate the commands sent to the model and to evaluate the performance of the control laws. Although external signals could be seen on strip charts, the internal signals used by the control law as inputs and outputs could not. For the RMLA control laws as well as the FSS control laws, frequency-domain CPE was also required and essential for safe wind-tunnel testing.

For some control law designers, plant transfer functions were necessary for use in improving their control law designs.[7] There was also a requirement to predict the open-loop flutter boundary while operating closed loop. The plant transfer functions were also necessary in order to meet this need. Since not all signals could be saved while operating a control law, there was a requirement to obtain plant transfer functions both with and without a control law operating.

On-Line Analysis Capabilities

Fourteen on-line analysis capabilities were developed in conjunction with the AFW program in order to meet the five major analysis requirements listed in Table 1. These capabilities generally can be divided into time-domain and frequency-domain analyses. Table 2 is a summary of the requirements and the specific analysis capabilities that were developed to achieve these requirements. Reference 11 contains a flowchart of all the capabilities showing the data flow and how the capabilities are sequenced and run in order to meet the requirements.

The data used for the analyses was digitized by the DCS. In all the DCS modes of operation that involved wind-on testing, different blocks of time-history integer data representing signal voltages could be saved on a binary file, depending upon the mode of operation.[2] The length of each block was determined by the length of the excitation, or specified by the DCS operator. The exact data that was saved was a subset, selected by the control law designers, of the set of total possible signals. The first binary record of the data file contained a header that included the tunnel tab number and other parameters including Mach number, dynamic pressure, mode of operation, type of excitation, and whether the excitation was symmetric or antisymmetric. This header was printed out on the figures. In this article, all the figures containing wind-tunnel data serve as examples and, therefore, the actual header information on each figure has been replaced by "HEADER INFORMATION."

Binary data files were shipped to the SUN-2 computer via an Ethernet data line. Two data interface programs were written to convert the data into different formats. One program converted the time-history data into Matlab[10] format for use in plotting routines implemented in Matlab. The other converted the time-history data into a format required by a program written to calculate the transfer functions using the array processor. If the transfer functions were for FSS analysis, the interface program for transfer function data symmetrized or antisymmetrized the time-history data dependent on whether the excitation was a symmetric or antisymmetric excitation. The interface programs and analysis programs used the header information to determine the types of conversions and scaling required.

Table 1 On-line analysis requirements

	Type of testing									
	Wind-off (DCS only)			Wind-on (DCS + model)						
				Roll		FSS		FSS + roll		No control law
Requirements	Roll	FSS	FSS + roll	OL	CL	OL	CL	OL	CL	
Control law verification	√	√	√	√	√	√	√	√	√	
Time-domain controller performance evaluation					√	√	√	√	√	√
Frequency-domain controller performance evaluation						√	√	√	√	
Plant determination						√	√	√	√	√
Flutter boundary prediction						√	√	√	√	

Table 2 On-line analysis capabilities

	Requirements				
Capabilities	Control law verification	Time domain performance evaluation	Frequency domain performance evaluation	Plant determination	Flutter boundary prediction
Time domain					
Plot time histories	x	x			
Calculate rms values		x			
Plot rms values		x			
Calculate transfer functions	x		x	x	x
Generate overall transfer matrix	x		x	x	x
Extract plant transfer matrix			x	x	x
Extract controller transfer matrix	x		x		
Plot transfer functions	x			x	
Frequency domain					
Calculate singular values and determinants of return difference matrices			x		
Plot singular values and determinants of return difference matrices			x		
Calculate inverse maximum singular values of plant					x
Plot inverse maximum singular values of plant					x
Calculate peak-hold data					x
Plot peak-hold data					x

In order to generate transfer functions for frequency-domain analyses, a transfer function analysis program was developed. This program could perform overlapped averaging of all signals saved by the DCS, window the data with one of several selectable windowing functions, and generate FFTs using the array processor. The array processor was capable of calculating an FFT of 4K data blocks in 0.007 s. Transfer functions were generated for any pair of signals. This entire program took less than half a minute to calculate all the transfer functions required for each excitation. Postprocessors of this data were then developed to either plot the transfer functions, perform state-space analyses, generate the plant transfer matrix, or extract the open-loop control law transfer functions from a closed-loop system.

Control Law Verification

Control law verification was required to assure that the control law was loaded properly into the DCS and was the same as the designed control law. Time-domain and frequency-domain capabilities were developed and used to verify the correctness of control law implementation.

For time-domain analysis, time responses of the control law due to a specific input were plotted. For the FSS and RMLA control laws, the inputs were step functions. For the RRTS and RTS control laws, the input was a sine wave whose amplitude was large enough to encompass the entire range of the control law. The response time histories were compared directly with similar responses provided by the control law designer, and discrepancies were accounted for by either correcting the DCS, the scaling parameters, or the input data for the control law.

Since time-history comparisons do not clearly show discrepancies in frequency content and phasing, a frequency-domain method for verifying state-space control laws was developed to supplement the time-domain analyses. This frequency-domain method included a series of steps to determine the controller-only transfer functions between various points in the DCS, providing a stepwise control law verification scheme.

The first step in frequency-domain control law verification involved computing transfer functions of all the outputs of the control law with respect to each input. To provide data for this step, excitations were input into each control law corresponding to each sensor input. A Matlab program for generating digital excitations was developed to provide excitations. These excitation signals could be generated before testing and then loaded into memory at a specified time. The excitation options were a linear sine-sweep, log sine-sweep, and a periodic pseudo noise (PPN). The PPN was a specially designed excitation that provided high signal-to-noise ratios

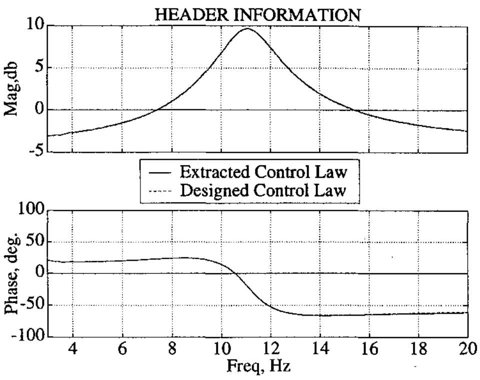

Fig. 1 Comparison of one designed control law transfer function with one extracted from a closed-loop system.

with a specified frequency resolution subject to constraints on control surface rates. It is not truly random and has a specified frequency content, generated by picking a block size that determines the frequency resolution.

Generation of all excitation types except the PPN was also possible by the DCS during execution. However, generating linear sine-sweeps, log sine-sweeps, and PPNs required several minutes of execution time. These excitations were, therefore, normally generated externally and saved on external files, so that desired excitations needed only to be loaded (not generated) by the DCS. This process saved valuable test time.

Digitized response data was saved and sent to the SUN-2 where transfer functions were calculated using the transfer function analysis program. Designer-supplied analytical frequency responses were also loaded and plots of the analytical transfer functions were superimposed to directly compare the digitized control law as generated by the DCS with the designed control law. This was repeated for all control law inputs. This capability was used to verify both the FSS control laws and the RMLA control laws.

The next step in frequency-domain control law verification involved extracting the control law transfer functions from a system that included the plant in one of five configurations. They were, extracting the control law transfer functions 1) from an open-loop system in which the excitations were added to the control law outputs, 2) from a closed-loop system in which the excitations were added to the control law outputs, 3) from an open-loop system in which the excitations were added to the final actuator commands, 4) from a closed-loop system in which the excitations were added to the final actuator commands, and 5) from a closed-loop system in which the excitations were added to the sensor inputs. A priori knowledge of the plant is not required for any of the above control-law extractions. An example of the transfer function plots resulting from control law extraction is shown in Fig. 1. Both the control law that was extracted and the designed transfer function match exactly, as they should. Reference 9 contains comparisons for control law verification.

Time-Domain Controller Performance Evaluation

Time-history plot capabilities were developed for use during rolling maneuvers to provide a means for the designer to evaluate whether the control law was operating as expected, to evaluate whether the command input was correct, and to assess the loads during the maneuver. Separate plotting functions were written to plot the data saved in any one of the rolling modes, RTS, RMLA, or RRTS. The control law designer chose 4 of 17 channels of saved data to be plotted during the test. The plot routines were optimized to require a minimum of intervention from the analyst providing the plots during wind-tunnel operation. Examples of two out of the four time-history plots that were generated on-line for an RRTS control law are shown in Fig. 2. In the upper plot, the solid line corresponds to the measured roll rate, PHIDM, and the dashed line corresponds to the commanded roll rate, PHID_c. In the lower plot, PHIM is the measured roll angle. References 4 and 5 contain actual wind-tunnel time-history results. Additional signals that were saved could also be plotted after a test run to gain greater insight or to further evaluate controller performance. Plot routines were also written to plot any of the 17 channels of time-history data saved during the FSS mode.

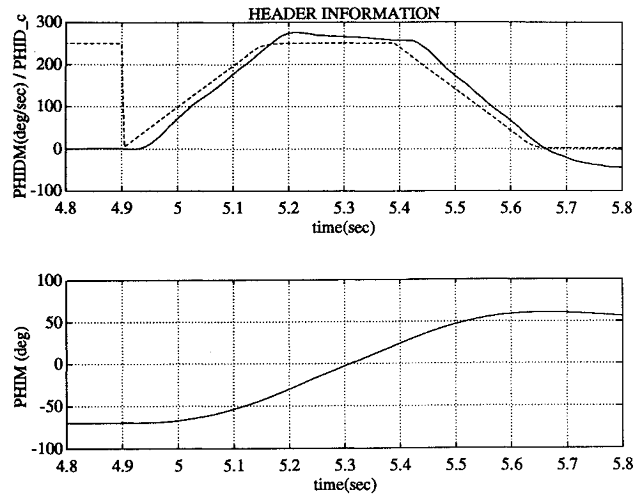

Fig. 2 Time-history plots of data during rolling maneuver with roll rate tracking system operating.

During the 1989 wind-tunnel test, calculation of the rms values of control surface commands and rates was required to evaluate FSS controller performance, since high rms values of control surface actuators would indicate saturation and impending closed-loop flutter. Consequently, the capability to calculate rms values, mean values, and maximum values of any saved data, including control-surface commands and rates, accelerations, and loads, was developed. The rms of symmetric and antisymmetric data were calculated for data saved during data acquisition for frequency-domain CPE in which excitations were either symmetric or antisymmetric, and those for right and left wing data were calculated for data saved during peak-hold data acquisition. The capability was also developed to save the calculated rms data and plot them as a function of dynamic pressure. Figure 3 is an example of the plots of rms control surface deflections, "delta" and rates, "delta dot" versus dynamic pressure q.

Since the model trip system worked so well in providing a measure of safety to the model and the frequency-domain controller performance capabilities proved to be substantially accurate, the rms calculating capability was used only as a secondary source for CPE during the 1991 wind-tunnel test entry.

Frequency-Domain Controller Performance Evaluation

Frequency-domain capabilities were developed as a primary source for evaluating controller performance.[3] Transfer functions were first calculated and combined into a transfer matrix, and the frequency range over which to execute the CPE code was selected. G and H, as well as the open-loop system transfer matrices at the plant input and the plant output points HG and GH, respectively, were then calculated or extracted, using equations presented in Ref. 3, for either an open-loop or a closed-loop system. Singular values of return-difference matrices at the plant input and output points, $\sigma(I + HG)$, $\sigma(I + GH)$ respectively, were calculated and $\sigma[H(I + GH)^{-1}]$ were calculated. From these, maximums, minimums, and inverse maximum values were calculated and plotted in order to evaluate the performance of FSS and RMLA control laws. Determinant values of $(I + HG)$ were also calculated and plotted.

One exception to the procedure described above was made for the FSS control law described in Ref. 7, which had more

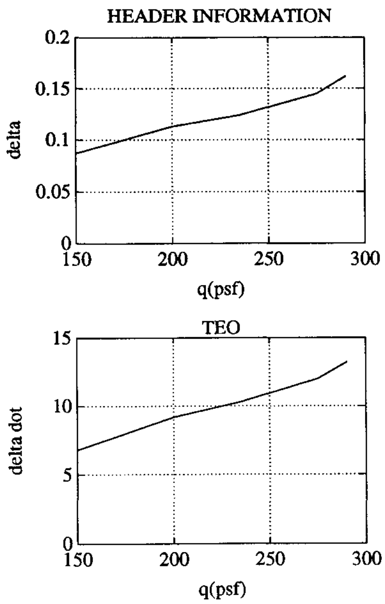

Fig. 3 Plots of rms of control surface deflections and rates.

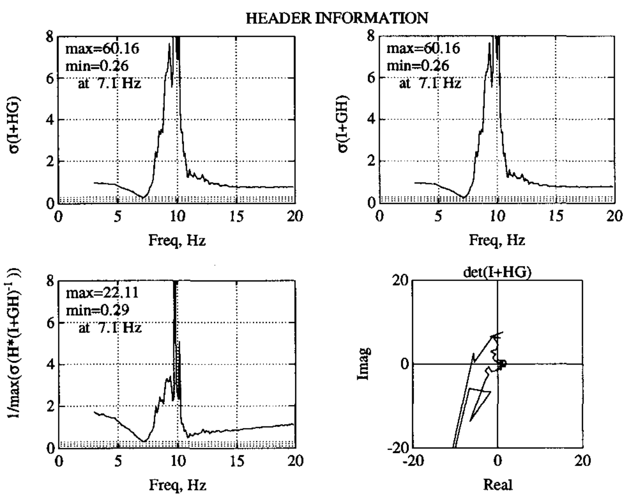

Fig. 4 Closed-loop CPE results of a symmetric control law (open-loop plant is unstable) for $M = 0.44$ and $q = 249$ psf.

sensor inputs than control law outputs. In order to reduce wind-tunnel testing time needed to extract the open-loop H from the closed-loop system as described in Ref. 3, H was analytically generated prior to the wind-tunnel test and loaded separately into the CPE code.

Figure 4 presents an example of actual output for CPE for a point above the open-loop flutter boundary. The upper plots in the figure are plots of the singular values of the return difference matrices. These provide measures of robustness with respect to multiplicative uncertainty at the plant input and plant output points, respectively. In the specific example shown, which is for a single-input/single-output system, both upper plots are identical. In general, however, for a multi-input/multioutput system, these would not be the same and, hence, both plots would be necessary for evaluating controller performance. The lower left plot, depicts a measure of robustness with respect to an additive uncertainty. The determinant plot in the lower right provides a means of checking open-loop stability. This plot is necessary to interpret the other three plots since knowledge of system stability is essential to interpreting robustness characteristics. References 6–8 contain results obtained from frequency-domain controller performance evaluation.

The capabilities to plot the determinant plot, separately, in order to better identify encirclements, and to generate a Nichols plot in order to view determinant data in a manner that not only showed encirclements, but also gave gain and phase information, were also developed.

Plant Determination

To determine the plant in the case when there is no control law operating, the plant transfer matrix can be derived directly from the calculated transfer functions. In the case when there was a control law operating, the plant had to be extracted from the closed-loop system. In either case, the purpose of plant determination was twofold. The first was to provide transfer function data to engineers for their use in redesigning control laws and the second purpose was to use the open-loop plant to evaluate open-loop plant stability. Some elements of the plant transfer matrix were extracted during CPE calculations; however, an additional capability was required to calculate the remaining elements of the plant transfer matrix.

Figure 5 shows a block diagram of the plant and controller. The ys are outputs from the plants corresponding to accelerometers and strain gauge sensors. The y_c is that subset of all the sensors that the control law designer has chosen to use in his control law. The y_e are the remaining sensors that he is not using in the control law and for which plant transfer functions are needed. The us are the commands to the control surfaces. The u_c correspond to commands to control surfaces used by the control law and u_e to those not used by the control law designer. Table 3 outlines the equations needed in order to calculate all the elements of the plant transfer matrix:

$$G = \begin{bmatrix} G_{cc} & G_{ec} \\ G_{ce} & G_{ee} \end{bmatrix}$$

In Table 3, X_c and X_e are the transfer functions of the control law outputs x, with respect to u_c and u_e, respectively.

Table 3 Basic plant equations[a]

Open-loop	Closed-loop
$G_{cc} = Y_{cc}$	$G_{cc} = ([I - X_c^T]^{-1} Y_{cc}^T)^T$
$G_{ec} = Y_{ec}$	$G_{ec} = ([I - X_c^T]^{-1} Y_{ec}^T)^T$
$G_{ce} = Y_{ce}$	$G_{ce} = Y_{ce} + G_{cc} X_e$
$G_{ee} = Y_{ee}$	$G_{ee} = Y_{ee} + G_{ec} X_e$

[a]All matrices are functions of ω.

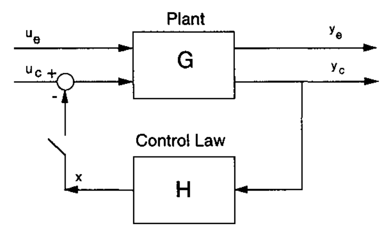

Fig. 5 Controller-plant diagram depicting the control problem with negative feedback.

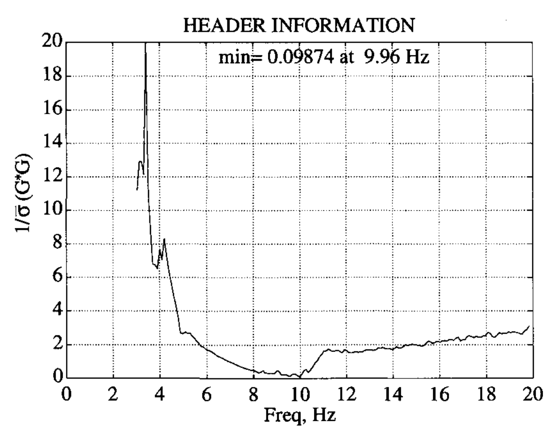

Fig. 6 Plot of inverse maximum singular value of the open-loop plant transfer matrix, $q = 230$ psf.

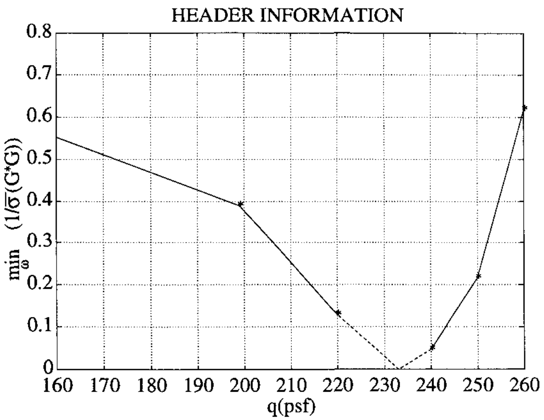

Fig. 7 Open-loop flutter prediction using closed-loop CPE results.

Y_{cc} and Y_{ce} are the transfer functions of the plant outputs y_c, with respect to u_c and u_e, respectively. Y_{ec} and Y_{ee} are the transfer functions of the plant outputs y_e, with respect to u_c and u_e, respectively.

Flutter Boundary Prediction

One of the purposes of the on-line analysis was to determine the open-loop plant stability from closed-loop data. The inverse maximum singular values of the plant were computed for many dynamic pressures. A plot of the inverse maximum singular values of the plant at one test condition is shown in Fig. 6. The point at which the inverse maximum singular values goes to zero is the point at which open-loop flutter is predicted to occur. A plot of these global minimum points is shown in Fig. 7. The curve is extrapolated to predict the open-loop flutter boundary. The predicted flutter boundary using this technique compared well with a hard flutter point that was determined from open-loop testing at the end of the wind-tunnel test entry.

In order to predict closed-loop flutter, the capability to perform peak-hold analysis was developed to determine the peak value at each frequency of the autospectra of a signal as it was calculated over a period of time using overlapped processing. Data due to random turbulence was saved by the DCS, and the capability of calculating and plotting the peak-hold data of multiple channels both symmetrically and antisymmetrically during the wind-tunnel test was developed. Any of the saved sensor data could be used to help determine the closed-loop flutter boundary during closed-loop testing. First, the maximum peak-hold data point was determined for each test point and the inverse maximum points were then plotted as a function of dynamic pressure. This curve was then extrapolated to zero to predict where closed-loop flutter would occur. Results from the peak-hold capability compared well with other sources.

Concluding Remarks

On-line capabilities, implemented using the DCS and its backup equipment, were developed to support the AFW wind-tunnel test. The purposes of the on-line analyses were to verify that control laws executed properly on the DCS, to provide control designers with a means to evaluate overall controller performance, and to provide guidance to the wind-tunnel test manager in determining the progress of the wind-tunnel test. The capabilities worked extremely well before, during, and after the wind-tunnel test, and proved to be a vital and important part of the test effort by providing on-line near real-time analysis capabilities.

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