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ON-LINE ANALYSIS CAPABILITIES DEVELOPED TO SUPPORT THE AFW WIND-TUNNEL TESTS

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Abstract

A variety of on-line analysis tools were developed to support two Active Flexible Wing 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 which were developed are presented in this paper 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. 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
X	controller output transfer matrix
y	plant output (sensors and strain gages)
Y	plant output transfer matrix
λ	eigenvalues
σ	singular values, $\sigma = \sqrt{\lambda(A^*A)}$, for a given matrix A; σ are always non-negative real.
$\bar{\sigma}$	maximum singular value

Subscripts

c	refers to control law elements
e	refers to elements external to control law

Notation

det($\cdot$)	determinant
$(\cdot)^*$	complex conjugate transpose
$(\cdot)^T$	matrix transpose

Acronyms

AFW	Active Flexible Wing

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CPE	Controller Performance Evaluation
CL	Closed Loop
DCS	Digital Controller System
FFT	Fast Fourier Transform
FSS	Flutter Suppression System
PPN	Periodic Pseudo Noise
RMLA	Rolling Maneuver Load Alleviation
RMS	Root Mean Square
RRTS	Roll Rate Tracking System
RTS	Roll Trim System
OL	Open Loop

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.

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. Most of these 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 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 which converted integer data representing voltages to scaled signal data of selected signals. It included plotting routines which could provide time histories of all internally saved, digitized data from the DCS and Fourier analysis tools which 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 FSS and 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 to safe testing of the model, while others were, simply, nice-to-have and provided additional analysis information from the wind-tunnel test. These two classifications of capabilities, critical and supporting, are described in this paper with emphasis on those capabilities which were considered critical. Details of data saving and data transfer and a description of the Fourier analysis program are also presented in this paper.

Hardware

The primary and backup DCS were comprised of SUN 3/160 workstations configured with similar hardware boards. One of these boards was a fast array processor,

manufactured by SKY Computers, Inc. This board performed all the Fast Fourier Transforms (FFT's) required to compute transfer functions within a time frame which would allow for near real-time processing. Figure 1 depicts the SUN workstation (SUN-1) which was used for the primary DCS and the second SUN workstation (SUN-2) which was used as an on-line digital signal analyzer where data translation and near real-time analyses were performed. It also depicts the signals passed between the model and SUN-1 as well as the Ethernet connection between the two computer systems. 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 flutter suppression systems (FSS) and roll control laws. Several roll control laws were developed; a roll trim system (RTS), a roll rate tracking system (RRTS)[4], and a rolling maneuver load alleviation system (RMLA)[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 law, 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 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

Table 1: On-line Analysis Requirements

REQUIREMENTS	TYPE OF TESTING									
	Wind-off (DCS only)			Wind-on (DCS + model)						
	Roll	FSS	FSS+Roll	Roll		FSS		FSS+Roll		No Control Law
				OL	CL	OL	CL	OL	CL	
Control Law Verification	√	√	√	√	√	√	√	√	√	
Time-Domain Controller Performance Evaluation					√	√	√	√	√	√
Frequency-Domain Controller Performance Evaluation						√	√	√	√	
Plant Determination						√	√	√	√	√
Flutter Boundary Prediction						√	√	√	√	

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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.

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 which were developed to achieve these requirements.

The data used for the analyses was digitized by the DCS. In all the DCS modes of operation which involved wind-on testing, different blocks of time-history integer

Table 2: On-line Analysis Capabilities

CAPABILITIES		REQUIREMENTS				
		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			
Frequency Domain	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	
	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

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 which 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 which 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.

Figure 2 shows a flowchart of the on-line capabilities. The capabilities are enclosed within rectangular boxes. Requirements are indicated by bold lettering. Arrows depict the flow of capabilities necessary to obtain data to satisfy each requirement. In each case, 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.

In order to generate transfer functions for frequency-domain analyses, a transfer function analysis program was developed. This program could perform overlapped

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averaging of all signals saved by the DCS, window the data with one of several selectable windowing functions, and generate FFT's using the array processor. The array processor was capable of calculating an FFT of 4K data blocks in 0.007 seconds. 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 step-wise 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 which provided high signal to noise ratios 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 which 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 PPN's required several minutes of execution time. These excitations were, therefore, normally generated externally and saved on external files so 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 which included the plant in one of five configurations. They were:

1) extracting the control law transfer functions from an open-loop system in which the excitations were added to the control law outputs
2) extracting the control law transfer functions from a closed-loop system in which the excitations were added to the control law outputs
3) extracting the control law transfer functions from an open-loop system in which the excitations were added to the final actuator commands
4) extracting the control law transfer functions from a closed-loop system in which the excitations were added to the final actuator commands
5) extracting the control law transfer functions from a closed-loop system in which the excitations were added to the sensor inputs.

An example of the transfer function plots resulting from control law extraction is shown in figure 3. Both the control law which was extracted and the designed transfer function match exactly, as they should.

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 four of seventeen 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 which were generated on-line for an RRTS control law are shown in figure 4. They are the measured roll rate and the measured roll angle. Additional signals which 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 seventeen channels of time-history data saved during the FSS mode.

During the 1989 wind-tunnel test, calculation of the Root Mean Square (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

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of any saved data, including control-surface commands and rates, accelerations, and loads, was developed. The RMS's 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 5 is an example of the plots of RMS control surface deflections and rates versus dynamic pressure.

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] A flowchart of the frequency-domain CPE capability is shown in figure 6. Transfer functions were first calculated and combined into a transfer matrix and the frequency range over which to execute the CPE code was selected. The open-loop plant transfer matrix, G, and controller transfer matrix, H, as well as the open-loop system transfer matrices at the plant output and the plant input points, HG and GH, respectively, were then calculated or extracted, using equations presented in reference 3, for either an open-loop or a closed-loop system. Singular values and/or determinant values of various return-difference matrices were then 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.

One exception to the procedure outlined in figure 6 was made for the FSS control law described in reference 7, having more sensor inputs than control law outputs. In order to reduce wind-tunnel testing time needed to extract the open-loop controller transfer matrix, H, from the closed-loop system as described in reference 3, H was analytically generated prior to the wind-tunnel test and loaded separately into the CPE code.

Figure 7 presents an actual output 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. The plots shown in figure 7 are for a single-input/single-output system, so, in this case, both plots are identical. The plot in the lower left 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.

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 which 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 two-fold. 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 8 shows a block diagram of the plant and controller. The "c" subscript refers to the control law elements. The "e" subscript refers to elements external to the control law tested. 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 the table, X_c and X_e are the transfer functions of the

Table 3. Basic Plant Equations*

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

* All matrices are functions of ω.

control law outputs, x, with respect to u_c (excitations of control surfaces used by the control law) and u_e (those not used by the control law). Y_{cc} and Y_{ce} are the transfer functions of the plant outputs, y_c, used by the controller with respect to u_c and u_e, respectively. Y_{ec} and Y_{ee} are

the transfer functions of the plant outputs, y_e, not used by the controller with respect to u_c and u_e, respectively.

Flutter Boundary Prediction

One of the purposes of the on-line analysis was to

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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 figure 9. 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 figure 10. 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 which 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 Digital Controller System 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 Digital Controller System, 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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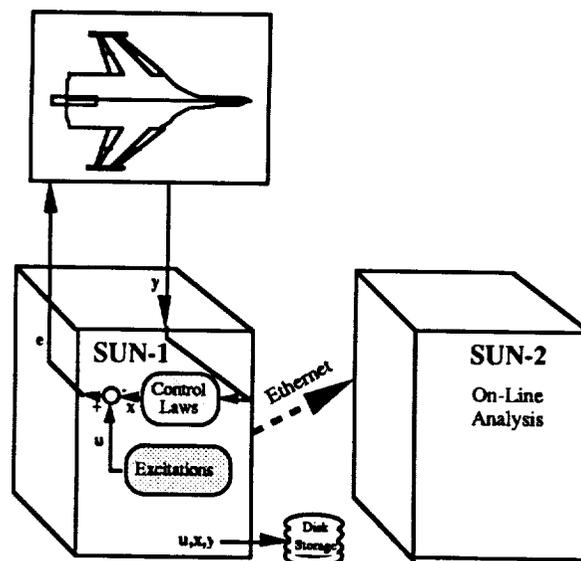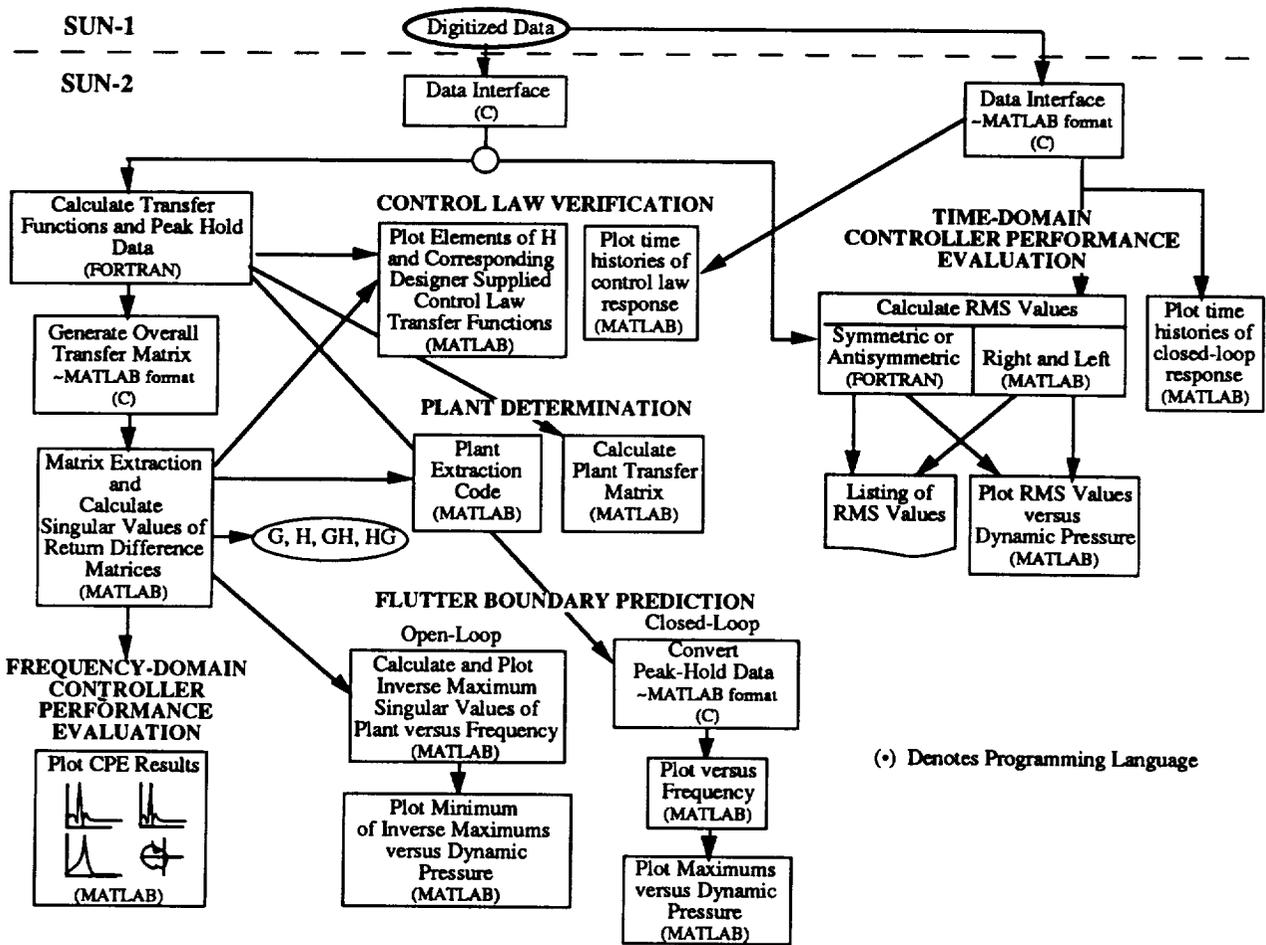
Figure 1.- Hardware involved in on-line analysis.

Digitized Data

Data Interface
(C)

Data Interface
~MATLAB format
(C)

Calculate Transfer
Functions and Peak Hold
Data
(FORTRAN)

CONTROL LAW VERIFICATION

Plot Elements of H
and Corresponding
Designer Supplied
Control Law
Transfer Functions
(MATLAB)

Plot time
histories of
control law
response
(MATLAB)

**TIME-DOMAIN
CONTROLLER PERFORMANCE
EVALUATION**

Calculate RMS Values

Symmetric or
Antisymmetric
(FORTRAN)

Right and Left
(MATLAB)

Plot time
histories of
closed-loop
response
(MATLAB)

Generate Overall
Transfer Matrix
~MATLAB format
(C)

PLANT DETERMINATION

Plant
Extraction
Code
(MATLAB)

Calculate
Plant Transfer
Matrix
(MATLAB)

Listing of
RMS Values

Plot RMS Values
versus
Dynamic Pressure
(MATLAB)

Matrix Extraction
and
Calculate
Singular Values of
Return Difference
Matrices
(MATLAB)

G, H, GH, HG

FLUTTER BOUNDARY PREDICTION

Open-Loop

Closed-Loop

**FREQUENCY-DOMAIN
CONTROLLER
PERFORMANCE
EVALUATION**

Plot CPE Results

(MATLAB)

Calculate and Plot
Inverse Maximum
Singular Values of
Plant versus Frequency
(MATLAB)

Convert
Peak-Hold Data
~MATLAB format
(C)

(•) Denotes Programming Language

Plot Minimum
of Inverse Maximums
versus Dynamic
Pressure
(MATLAB)

Plot versus
Frequency
(MATLAB)

Plot Maximums
versus Dynamic
Pressure
(MATLAB)

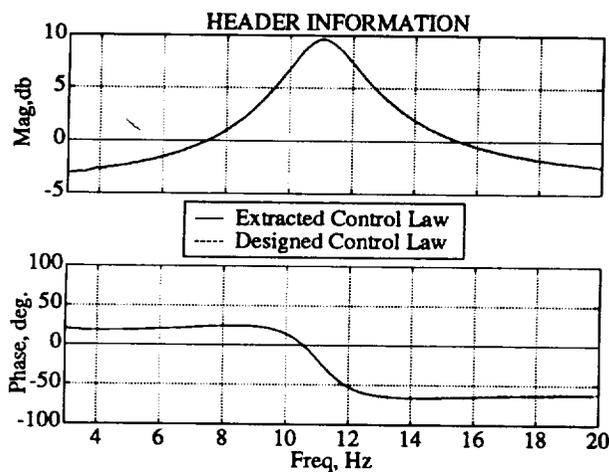Figure 2.- Flowchart of on-line analysis capabilities.

Figure 3.- Comparison of control law transfer function
extracted from a closed-loop system with one
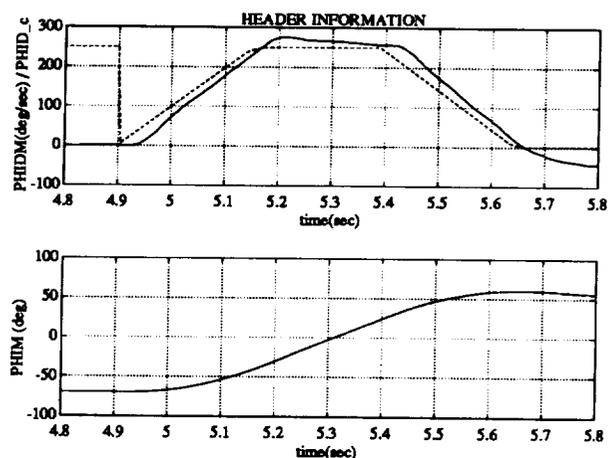supplied by control law designer.

Figure 4.- Time-history plots of data acquired during
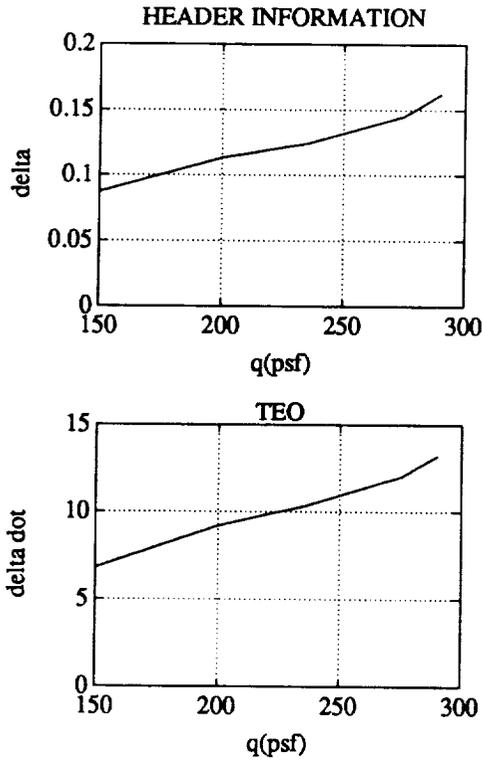rolling maneuver with RRTS operating.

HEADER INFORMATION

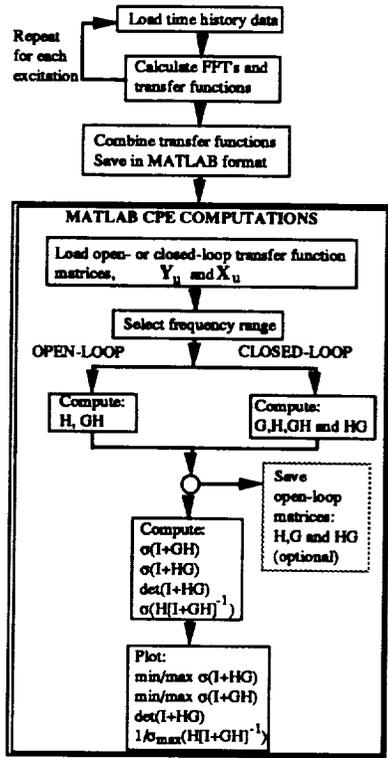Figure 5.- Plots of RMS values of control surface deflections and rates.

Figure 6.- Flowchart of frequency-domain CPE procedures.

HEADER INFORMATION

max=60.16
min=0.26
at 7.1 Hz

max=60.16
min=0.26
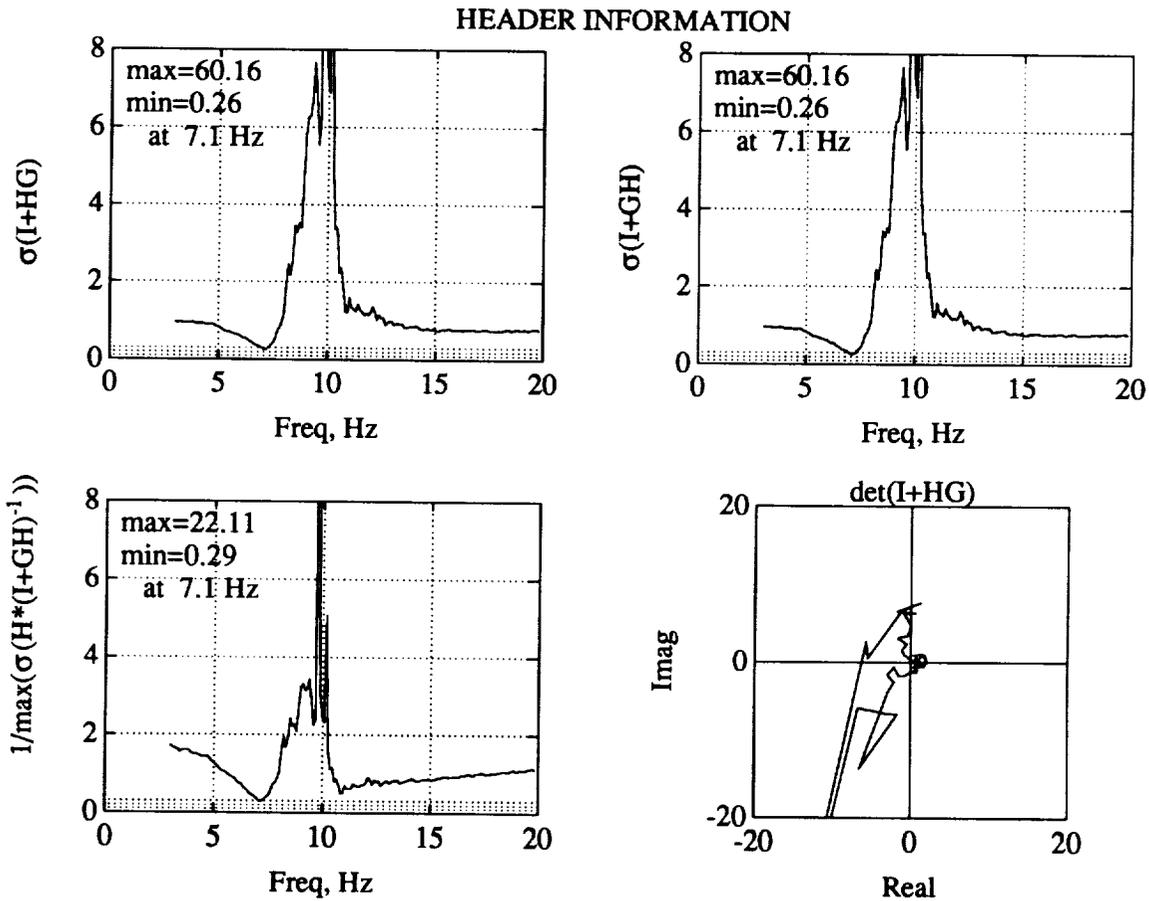at 7.1 Hz

max=22.11
min=0.29
at 7.1 Hz

det(I+HG)

Figure 7.- Closed-loop CPE results of a symmetric FSS control law for M=0.44 and q=249 psf.

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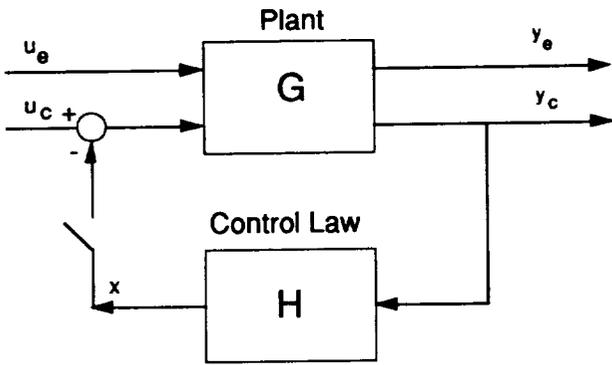
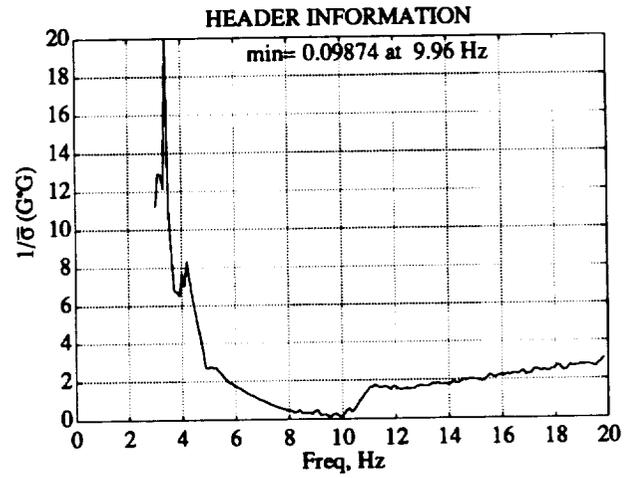Figure 8.- Controller-plant diagram depicting the control problem with negative feedback.

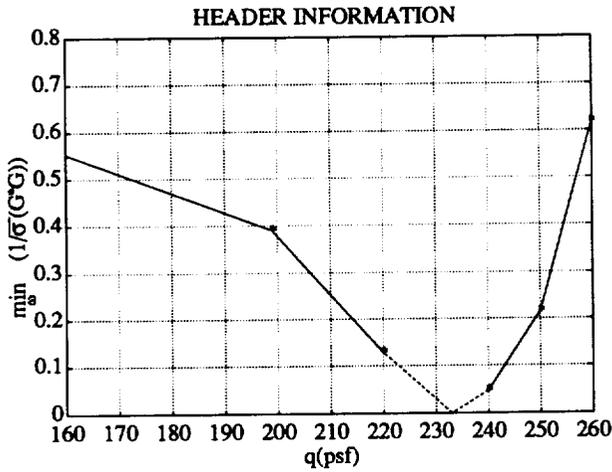Figure 9.- Plot of inverse maximum singular value of the open-loop plant transfer matrix, q=230 psf.

Figure 10.- Open-loop flutter prediction using closed-loop CPE results.

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)

A variety of on-line analysis tools were developed to support two Active Flexible Wing 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 which were developed are presented in this paper 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. 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.

14. SUBJECT TERMS

Analysis tools; controller performance; controller verification; data reduction; near real time; plot routines; software; wind-tunnel tests

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