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Versatile Software Package For Near Real-Time Analysis of Experimental Data

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VERSATILE SOFTWARE PACKAGE FOR NEAR REAL-TIME ANALYSIS OF EXPERIMENTAL DATA

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ABSTRACT

This paper provides an overview of a versatile software package developed for time- and frequency-domain analyses of experimental wind-tunnel data. This package, originally developed for analyzing data in the NASA Langley Transonic Dynamics Tunnel (TDT), is applicable for analyzing any time-domain data. A Matlab®-based software package, TDT_analyzer, provides a compendium of commonly-required dynamic analysis functions in a user-friendly interactive and batch processing environment. TDT_analyzer has been used extensively to provide on-line near real-time and post-test examination and reduction of measured data acquired during wind tunnel tests of aeroelastically-scaled models of aircraft and rotorcraft as well as a flight test of the NASA High Alpha Research Vehicle (HARV) F-18. The package provides near real-time results in an informative and timely manner far exceeding prior methods of data reduction at the TDT.

INTRODUCTION

A Matlab®-based software package, TDT_analyzer, was written to assist in the near real-time and post-test analysis and reduction of time-history data acquired during wind-tunnel tests of aeroelastically-scaled models of aircraft, rotorcraft and launch vehicles in the Transonic Dynamics Tunnel (TDT) at the NASA Langley Research Center. Near real-time reduction of dynamic wind-tunnel data and displays of results within seconds of data acquisition are paramount to assess requirements for subsequent test conditions and model configurations, thereby reducing test time and, in some cases, improving model safety. The software package is highly versatile and user friendly, taking advantage of the graphics capability of Matlab®. Although it requires Matlab® and two toolboxes to be installed and running, TDT_analyzer is a stand-alone package of Matlab® script routines that has evolved over the past eight years from the on-line, near real-time controller verification and controller performance evaluation package (ref. 1) developed for the NASA/Rockwell Active Flexible Wing program in 1989 and 1991 (refs. 2).

The TDT analysis package converts time-history data to engineering units and performs various time- and frequency-domain analyses including statistical analyses of the data. Plots of analysis results can be placed on a page in a user selectable layout. Outputs are provided to the engineers near real-time to 1) assist in determining effective model and tunnel test configurations, 2) to provide analyses of steady and unsteady aerodynamics, 3) to evaluate controller performance, and 4) assess data quality. Results can also be used for system identification to improve model simulation and control law design.

In addition to processing wind-tunnel data, TDT_analyzer can also process time history data generated by other sources, including simulations, after first providing the input time history and signal information used by the TDT_analyzer program in a standard Matlab® format. To this end, TDT_analyzer has a companion pre-processor program, TDT_interface, written in the C programming language that has also evolved over the past eight years. This pre-processor program converts data from a multitude of sources to the Matlab®-readable input file used by TDT_analyzer. TDT_interface provides a mechanism for integrating TDT_analyzer with most data acquisition systems and can be modified to read data from other sources as needed.

From its inception, TDT_analyzer was designed to perform on-line data analysis immediately after data were acquired. During the past few years its

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flexibility and capabilities have been enhanced to meet the data analysis requirements of engineers from many test programs conducted at the TDT and other NASA facilities. The TDT analysis package has maintained a user-friendly interactive environment, which can be exercised in a batch mode as well. It has been used in close conjunction with the TDT - Data Acquisition System (TDT-DAS) for the past three years, and has been used to provide near real-time, on-line and post-test analyses of wind-tunnel data during that time. Figure 1 depicts the flow of data from a wind-tunnel model through the Data Acquisition Unit (DAU) to computers running TDT_analyzer. Also depicted are some of the analysis options available with TDT_analyzer and samples of plot outputs which will be described in detail later.

The following sections present details of the capabilities of this package. Examples are shown which use data acquired during some of the tests performed at the TDT and elsewhere.

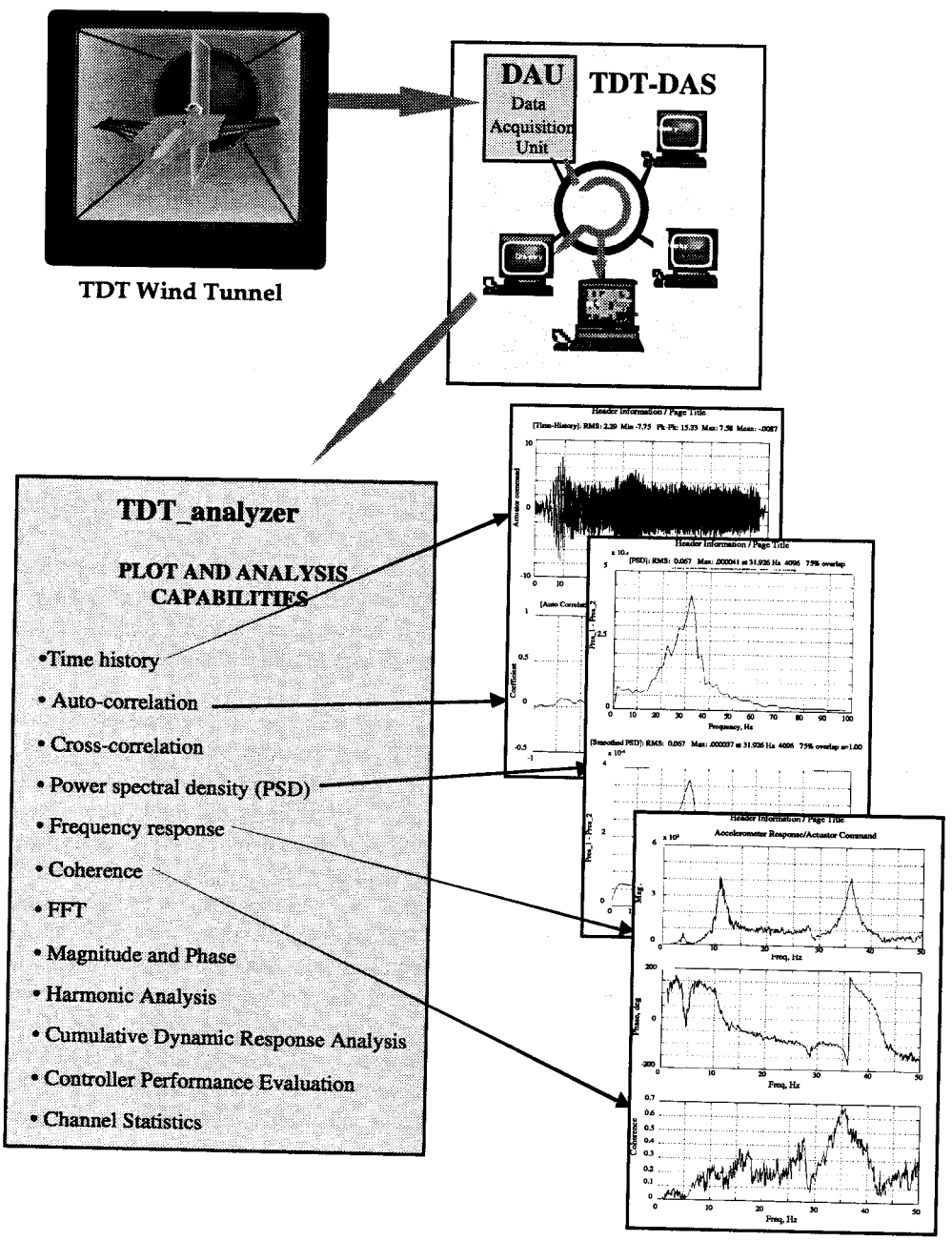

Figure 1.- Overview of TDT_analyzer capabilities depicting flow from data acquisition to final plots.

FEATURES

TDT_analyzer is a menu-driven package which uses standard Matlab® functions as well as some specially designed functions. This software can run on any computer where Matlab® and the required Controls and Signal Processing toolboxes are installed. This includes most UNIX workstations and personal computers.

During the running of TDT_analyzer, the user is first prompted for a file name which contains the data to be analyzed. The user then may input a specific title and header information that will be used on all plots. The user then selects the TDT_analyzer plot and analysis options. A list of the analysis options that are available in TDT_analyzer are listed and briefly described in Table 1. After the selection of the analysis options, the user is prompted for other general options available to all analyses. Then the user is prompted to input values of parameters which are specific to the types of analyses which have been selected. The user selects channels that s/he wants to analyze and if the option requires a reference channel, the user will be prompted at the appropriate time to input a signal number for the reference channel.

All the analysis options currently available in TDT_analyzer are described in this paper. Options general to all processing are described first.

General Options Applicable to All Analyses

Units conversion: Prior to data analysis, the user may select to use one of several units conversions. The raw data are typically in units of the data acquisition board, namely counts. If this is the case, options are provided to convert data to voltages or engineering units.

Signal selection and processing: The user can select a subset of available signals or even differenced pairs of signals to analyze. This differencing capability might be exercised, for example, to analyze antisymmetric acceleration by analyzing the difference of accelerometer data from signals on the right and left side of a full-span model. Differential pressures could be analyzed using the difference of upper and lower surface pressures. Some analyses in both the time- and frequency-domain require a reference signal. This reference signal may be either a single signal or a differenced pair of signals.

Decimation or resampling: The data can be 'n^{th}-pointed' before processing, meaning that every n^{th} point is selected for analysis. Appropriate digital filtering is automatically performed where necessary. The value of "n" is user selectable. The default is 1, which corresponds to selecting all points within the user-selected time interval of the data.

Plot page layout: Many of the analysis options provide graphical output. The user can select the number of plots vertically and horizontally on the page. Though there are no hard coded limits, the practical limit is 7 vertically and 3 horizontally. The analyses may be performed in any order and plots will be generated in sequence either vertically or horizontally, as selected by the user.

Repetitive Processing: One of the most convenient features of TDT_analyzer is the capability to easily repeat analyses by reexecuting the code in the same Matlab® session. Additional analyses can be performed on data previously processed or the same analyses can be performed on different time-history signals. During processing, the user input values are stored in temporary variables. During reexecution of the code, the user will be prompted for the values of these parameters. If s/he doesn't specify different values and just inputs a carriage return, the previously defined values will be used. This feature is what makes TDT_analyzer very convenient for repetitive processing. For example, if a user wants to repeat a frequency-domain analysis with a different block size, when prompted to input values for any other parameters s/he can just hit carriage returns and the previously defined values will be used. When prompted for the blocksize, s/he provides the new value which s/he wants to use during processing. This is the same procedure used for any one or multiple variables. All parameters except for the signal numbers can be kept constant thus resulting in the same analyses being performed on different data, or the values of the options can be changed while keeping the signal numbers the same resulting in the different analyses on the same time-history signals. Any combination of changes is available to the user.

Batch processing: To facilitate batch processing, TDT_analyzer automatically creates a command file which replicates all the user inputs generated during

Table 1. Summary of TDT_analyzer Analysis Options

Type of analysis	Domain	Description	Outputs
Time-history plot	Time	Plots any channel or multiple channels over a user-selected time segment. Overlays of time histories from several channels are available. Some channel statistics are included on the plots.	plots
Channel statistics	Time	Generates table of minimums, maximums, means, and root mean square calculated using standard Matlab® functions.	files with tables
Auto-correlation (normalized)	Time	Shows how well a signal is correlated with itself in time. Calculated using a standard Matlab® function.	plots
Cross-correlation (normalized)	Time	Shows how well a signal is correlated with another signal in time. Calculated using a standard Matlab® function.	plots
Power Spectral Density - standard - non-dimensionalized - normalized - smoothed standard - smoothed normalized	Frequency	Calculates PSD's using modified spectrum functions. The maximum and the frequency at which it occurs are included on the plots. For a purely oscillatory signal, the peak amplitude for a standard PSD is the square of the signal amplitude, while that of a normalized PSD is $\sqrt{2}$ times the amplitude. In TDT_analyzer, non-dimensionalizing is accomplished by dividing by q, dynamic pressure. This would most likely be used to non-dimensionalize pressure data. Other options for non-dimensionalizing could easily be incorporated in TDT_analyzer.	plots
Cross-spectrum - standard - smoothed	Frequency	Calculates cross-spectrum of two signals using a modified Matlab® function.	plots
Frequency Response - standard - smoothed standard - inverted - smoothed inverted	Frequency	Calculates frequency responses using built-in Matlab® functions. Additional processing is provided which uses the frequency-response functions generated by this option. They are listed and described in table 2. Frequency responses can be saved on file for any other desired post-processing, such as system identification in the frequency domain.	plots Matlab® output files tables
Coherence - standard - smoothed standard	Frequency	Measures the quality of the frequency responses. Calculated using built-in Matlab® functions	plots
Magnitude/Phase	Frequency	Generates tabular results with respect to a reference channel at a specific frequency calculated using a reference signal. The phase is referenced to the reference phase. The magnitude can be normalized by the reference magnitude. The magnitude and phase are calculated using a specialized single frequency discrete fourier transform function (SFDFT)	tables
FFT - standard - smoothed standard	Frequency	Calculates Fast Fourier Transforms using built-in Matlab® functions.	plots
Harmonic Analysis	Frequency	Calculates response harmonics with respect to an oscillatory signal. Used for rotor analysis to provide response at the harmonic frequencies.	plots tables
Cumulative Dynamic Response Analysis	Frequency	Determines the RMS over user-selected frequency bandwidths.	plots tables

an interactive session. This command file can then be used to generate a Matlab® input file to be used for example in a batch mode to perform the same calculations on a different set of experimental data. This file can be modified to add parameters to identify data points or other options. This capability facilitates the rapid setup of batch procedures for processing data acquired at different test conditions.

The following sections describe the time-domain, frequency-domain and extended function capabilities of TDT_analyzer. Examples of some of the capabilities are shown in the Sample Results section.

TIME-DOMAIN ANALYSIS CAPABILITIES

The types of time-domain analyses available within TDT_analyzer are listed in the beginning of Table 1. These include time-history plots, auto-correlation, cross-correlation, and tables of channel statistics: mean, minimum, maximum, root mean square, and peak-to-peak magnitude. A brief description of each time-domain analysis option is included in the Table 1. For all the options that are listed, the user can select the entire time history or select the initial and final times of a subset of the entire time history. The selected time interval is used for all the time-domain analyses performed by TDT_analyzer during a Matlab® session until changed by the user.

FREQUENCY-DOMAIN ANALYSIS CAPABILITIES

The types of frequency-domain analyses available in TDT_analyzer along with a brief description of each are also listed in Table 1. For all the options that are listed, the user can select the entire time history or select the initial and final times of a subset thereof for processing. The selected time interval will be used for all the frequency-domain analyses until changed by the user. This time interval is independent of that selected for time-domain analyses. This selection option allows the user to easily combine both time- and frequency-domain related plots on the same page without requiring the same time interval for both.

For all frequency-domain analyses, the user may select windowing, blocksize, and the percent of overlap used in averaging. The selected values will be used as default for all frequency-domain processing until changed by the user. Some of the details regarding the general options available to all frequency-domain analyses are summarized in the following section.

General Options for Frequency Domain

Windowing: The capability is provided to easily select the windowing option of the time history for frequency-domain processing. A user can select one of the following options: Hanning, Hamming, Rectangular, Triangular, Bartlett, Blackman, Chebyshev and Kaiser (reference 3). TDT-analyzer makes it easy to repeat analyses using different windows and plot the results on the same page for comparison.

Blocksize: The user can select any blocksize which is a power of two. If the user does not select a power of two, the closest power of two that fits the data will be calculated and used.

Overlap averaging: The user can select the percent overlap of time-history data for overlap averaging in frequency-domain analyses. There are no restrictions on the percent overlap as long as at least two averages are calculated. Error checking is provided to assure this restriction is met.

Frequency-domain units: Results for all of the frequency-domain analyses may be plotted over a user-specified frequency range in either Hertz or in radians per second. The axes for the dependent variable being plotted are automatically scaled. In the case of the PSD, the magnitudes are scaled for the specified frequency units.

Analysis Options for Frequency Domain

Standard Options: Frequency-domain analyses options include a standard, normalized, and non-dimensionalized Power Spectral Density (PSD), as defined in Table 1; frequency response (commonly referred to as "transfer function" within TDT_analyzer); coherence; auto- and cross-spectrum; and Fast Fourier Transform (FFT).

Inverted frequency responses can also be calculated and plotted. In TDT_analyzer, when the user requests frequency responses the desired output signals and then an input signal number are specified. The input signal is referred to as the reference signal. When the user requests an inverted frequency response the process is as follows. The user specifies the desired input signals and then an output signal

number. In this case, the output signal is referred to as the reference signal.

The option to calculate smoothed FFT's, PSD's, frequency responses, coherences and spectra using a specially-defined smoothing function based on methods described in reference 4 is also available.

Magnitude and Phase: Magnitude and phase of dynamic time-history data can be calculated with respect to an oscillatory reference signal at a specific frequency. This is useful for evaluating pressures at flutter, or the unsteady pressure responses due to control surface oscillatory motion. The reference signal is used to determine the oscillation frequency. First, the location of the peak of the reference signal PSD provides an estimate of the oscillatory frequency, which is then used as the starting point to zoom in on the actual frequency using a specialized peak-searching routine. Once this frequency is found, the magnitude and phase of the reference signal and all other requested signals are determined using a specialized function that calculates the single-frequency discrete Fourier transform (SFDFT) at the reference frequency. The reference phase is then subtracted from the phase of each requested signal. The magnitude of the signals can be normalized, if desired, by the magnitude of the reference signal. Tabular output files are generated.

Harmonic Analysis: Harmonic analysis is the calculation of magnitude and phase of signals at the fundamental frequency of a reference signal and at successive multiples thereof. The reference signal may be specified by the user, but for rotorcraft, specifically, the fundamental frequency is calculated from a one-per-revolution signal of a rotor blade. This fundamental frequency is calculated by identifying the starting point of each revolution and determining the difference in time between revolutions. Again, the magnitude and phase of the signals at the fundamental frequency and its multiples are calculated using SFDFT methods. The time-history of the signals can be reconstructed from these magnitudes and phases using a user-selected number of harmonics and then compared graphically with the original experimental data to display goodness of fit. A tabular output file is generated of the harmonic results.

Cumulative Dynamic Response Analysis: Cumulative dynamic response analysis corresponds to calculating the RMS over user-selected frequency bandwidths based on the PSD. The first step is to calculate the PSD and perform the cumulative integral of the PSD. The RMS is then calculated as the square root of the difference in the cumulative integral of the PSD at the two user-selected frequencies for each selected bandwidth. A table of the frequency limits and corresponding RMS values is generated.

Extended Analysis Options:

Frequency-response functions also serve as input to a number of extended analysis options as listed in Table 2. These sub-options are made available if any frequency response option is selected under the main menu.

One such extended option is Controller Performance Evaluation (CPE). The CPE analysis option is used to: (1) predict the closed-loop stability of a system while the system is open loop; and (2) assess the closed-loop stability and robustness when the system is closed loop. The details of the theory are documented in references 5 and 6. Both of these capabilities were critical in some of the wind-tunnel tests conducted in the NASA Langley Transonic Dynamics Tunnel to protect the wind tunnel and model from damage.

Another extended option enables the user to perform CPE using experimental data for the open-loop plant along with analytically generated control laws. The same graphical output that CPE produces is generated and predicts the performance of a control law prior to experimental testing.

The frequency-response functions of control law outputs with respect to sensor inputs can also be used for controller verification. This extended option verifies that the control law being executed matches the designed control law. It is performed by generating plots which overlay frequency responses calculated from an analytical control law with those calculated from the experimental data.

One of the byproducts of CPE is the extraction of the open-loop plant frequency responses for those actuators and sensors being used by the control law. The capability to extract frequency responses for other actuators and sensors not included in the control law is also an extended analysis capability available in TDT_analyzer. The additional actuators, however, must have been used to excite the model and the additional sensor time histories must have been measured.

Table 2. Summary of TDT_analyzer Extended Analysis Options which use the frequency responses.

Type of analysis	Description	Outputs
Controller performance evaluation (CPE)	Evaluate the performance of control laws	plots
CPE with loaded control-law and the open-loop plant	Predicts closed-loop performance of control law before experimental testing	plots
Controller verification	Compare experimental frequency responses and analytical frequency response using loaded control laws provided by control law designers	plots
Extraction of open-loop plant for additional sensors and/or control surfaces	Can be used for additional system identification for control law design with different actuators or sensors	plots
Comparison of experimental frequency response with analytical single-pole filter	Used for evaluating single-pole anti-aliasing filters.	plots
Magnitude and phase at selected frequencies	Assist in evaluating filter performance or control law performance	tables

A digital controller system used in the TDT for several active-control wind tunnel tests for flutter suppression, reducing maneuver loads and for gust load alleviation (reference 7), used single-pole anti-aliasing filters. In order to check these filters an option was added to TDT_analyzer to compare the frequency response calculated from experimental data to the frequency response of a single-pole filter generated analytically. The user is prompted for parameters defining the filter. Since many digital data acquisition systems require anti-aliasing filters, TDT-analyzer could easily be enhanced to include higher-order filters in this analysis option.

In addition to the graphical output of frequency responses, the magnitude and phase of the experimental frequency response can be calculated at user-selected frequencies and output on a tabular file. When evaluating the performance of anti-aliasing filters where the magnitude and phase of the anti-aliasing filters is known at selected frequencies, this tabular data is extremely helpful in making sure that the correct anti-aliasing filters have been chosen. This tabular data in combination with the graphical comparison of the experimental and analytical frequency-response functions can assist in determining whether the proper anti-aliasing filters are being used and whether the filters are working properly also.

SAMPLE RESULTS

During its evolution over the past 9 years, TDT_analyzer has been used on line on over 20 occasions. Without some of the capabilities of TDT_analyzer, some of the wind-tunnel tests could not have been performed as safely without putting the tunnel and model at great risk. The recent calibration of the TDT depended very heavily on TDT_analyzer. Two Langley tunnels have used TDT_analyzer and other tunnels around Langley are also starting to use TDT_analyzer. In addition to wind-tunnel tests, calibration tests, and flight tests, TDT was used to help diagnose and solve a pipe vibration problem at the TDT. Tests taken as a whole have exercised all options of TDT_analyzer and in fact have motivated continual enhancements of the software capability. A few examples are presented in this section.

Data analyzed using the TDT_analyzer software have been documented in numerous publications, conferences and meetings (refs. 5, 8-12). Example figures are described next which use data from some of the tests to show the versatility of TDT_analyzer. In all cases, plot titles and labels have been re-typed to permit readability, and signal names have been replaced with more generic terminology.

A typical time history plot of an actuator command signal from the Benchmark Active Controls Technology (BACT) model (refs. 9-10) test is shown at the top of figure 2 along with its auto-correlation at the bottom. This example shows the typical information plotted for two of the options available in TDT_analyzer. In addition to header information and a title on the figure, some channel statistics are also printed on each plot. For time history plots, the

following information about the time history are also included: the root mean square (RMS) value, the minimum value, peak-to-peak magnitude, the maximum value, and the mean. The subtitle of the auto-correlation plot displays the magnitude of the peak and the time at which it occurs. The user selects the range of the time (lag-lead) in seconds during processing.

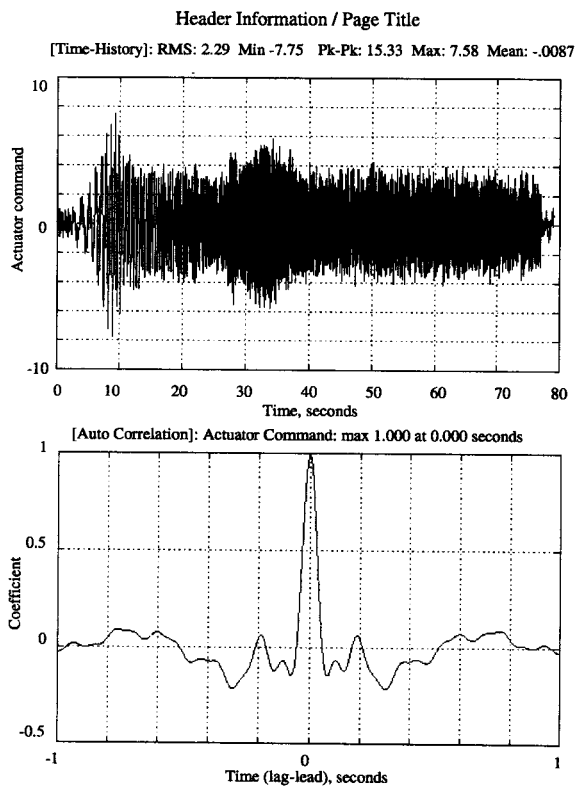

Figure 2. Time history and auto correlation of an actuator command acquired during testing of the BACT model.

A comparison of a standard and a smoothed standard PSD of the difference of two signals (differential pressure) from the ACROBAT F/A-18 buffet model (reference 11-13) test is shown in figure 3. These results show, first of all, that signals can be differenced. Labels on the dependent axis correspond to the actual signal identifiers and for differenced channels are generated from the individual signal names. In addition to header information, the RMS and the maximum of the PSD along with the frequency at which it occurs are documented on both PSD plots. The blocksize, in this case 4096, and percent overlap in processing these data are also included on the plots. The effect of using a special smoothing function (reference 4) available in TDT_analyzer is clearly shown at the bottom of figure 3. In this case, the smoothing coefficient used is equal to one as indicated by a = 1 on the subplot title. This parameter is user selectable and for this example was arbitrarily set to one to show the smoothing capability. When smoothing data, the peaks of the smoothed data tend to be rounded. In this case, this results in a 10% reduction in peak amplitude for the smoothed PSD. A user can very easily reprocess the data with different smoothing coefficients and compare the trade-off between smoothing and peak resolution.

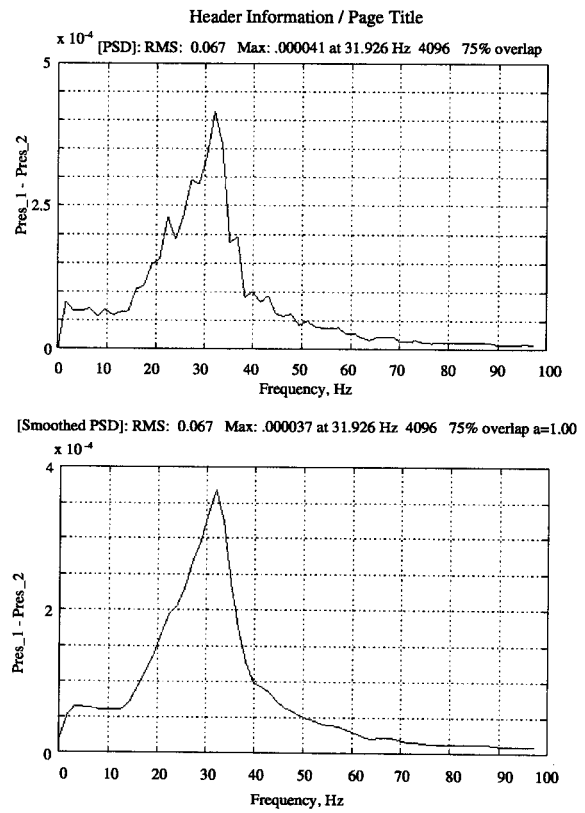

Figure 3. Comparison of a standard and a smoothed PSD of a difference of two signals (differential pressure).

The magnitude and phase of an accelerometer's frequency response for an accelerometer with respect to an excitation of a piezoelectric actuator, along with the corresponding coherence for data acquired during the Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI) test (reference 8) is shown in figure 4.

Frequency response results such as these are used

to experimentally identify the open-loop plant and are then employed in the design of active control laws. The coherence is a measure of the correlation between the input and output response time histories, and the quality of data acquired. For instance, presence of noise in the system, even with highly correlated signals, reduces the coherence in the measured data.

Controller performance evaluation (CPE) has been used in many tests in the Transonic Dynamic Tunnel. CPE results acquired during the first test of

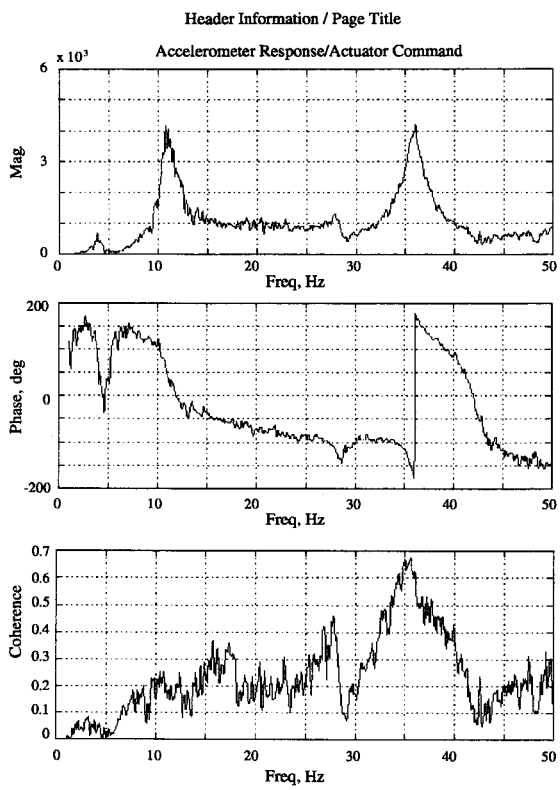

Figure 4. Frequency response of an accelerometer due to a piezoelectric actuator for the PARTI model.

the BACT model are shown in Figure 5. The upper two plots show the minimum singular value of the plant input and output return difference matrices. These are used to indicate the sensitivity of the plant to multiplicative perturbations at the plant input and output, respectively. The lower left plot indicates the sensitivity of the plant to additive perturbations of the plant. The minimum singular value is related to guaranteed gain and phase margins for multi-loop systems (references 5 and 6.) The three horizontal lines plotted on each singular value plot at values of 0.1, 0.2 and 0.3 are used to rapidly identify areas of decreased stability. A minimum singular value of 0.3 corresponds to approximately –2.3 and +2.8 db gain margins for zero phase margins, and for a 10 degree phase margin, the gain margins are –1.5 and +2.2 db, as derived in reference 14.

A plot of the determinant of the return difference matrix of the system, which corresponds to a Nyquist plot for a single-input single-output system, is shown in the lower right of the figure. Since encirclements of the critical point are important for determining system stability, this plot is automatically enlarged for the user, as shown in Figure 6. The user is prompted to supply a scaling value for the axes in order to expand the unit circle to better identify encirclements. A specialized function uses the resulting determinant to calculate the gain factors and the phase margins. The gain factors, shown in the plot title, are factors by which the gain can be multiplied to reach closed-loop instability. The possibility of two gain factors, greater and less than 1, which correspond to positive and negative gain margins, and two phase margins are possible. In this case in which there is no encirclement of the critical point, only the gain factor corresponding to the positive gain margin exists and is documented on the plot.

The coherence and cross-correlation shown in figure 7 along with the cross spectra, not shown, were used to assess the aerodynamics for the Active Control Reduction of Buffet-Affected Tails (ACROBAT) model (reference 11-13).

CONCLUDING REMARKS

TDT_analyzer, a versatile software package developed at NASA Langley's Transonic Dynamics Tunnel, has been used extensively to provide on-line, near real-time and post-test examination of measured data. The software package provides a compendium of analysis functions commonly required during wind-tunnel tests in a user-friendly, interactive and batch processing environment. It is a stand-alone package, but has a companion pre-processor, TDT_interface, which converts data from a multitude of sources to a Matlab®-readable input file used by TDT_analyzer. This preprocessor provides the mechanism for integrating the analysis package into any data acquisition system. The package has been integrated into the primary TDT-DAS as well as three other smaller data acquisition systems at the TDT. It has been ported to other platforms which support Matlab®, including personal computers.

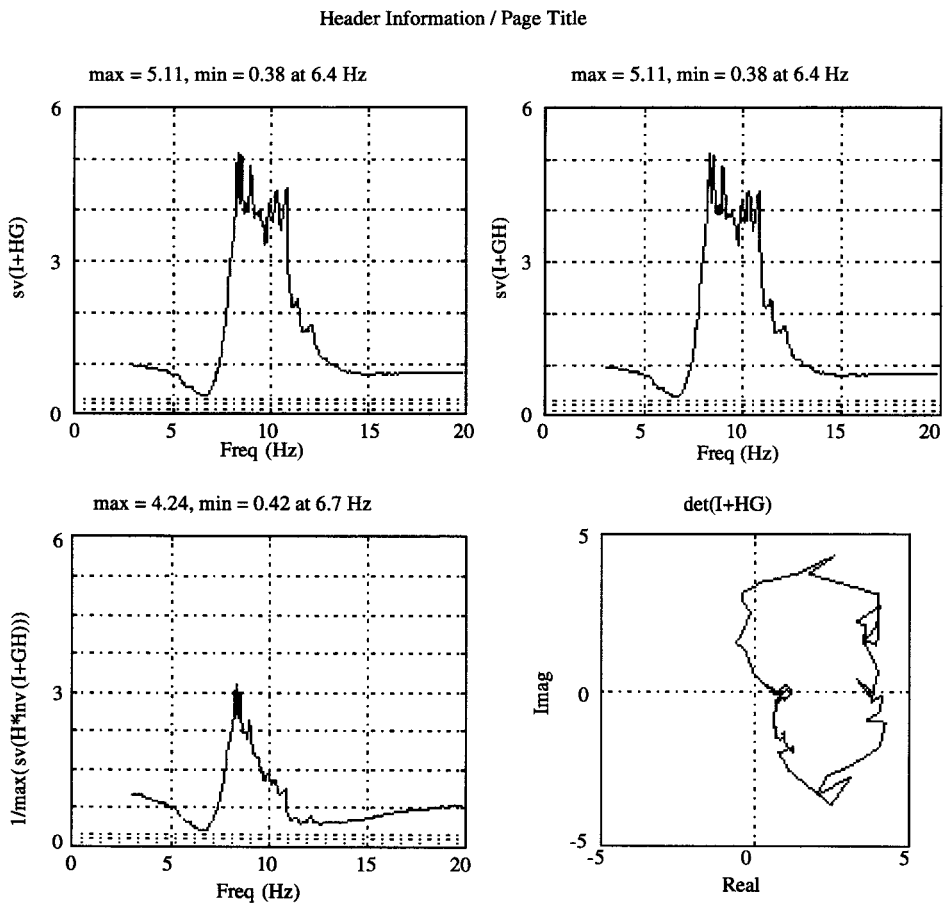

Figure 5. Output associated with CPE indicating stability and robustness.

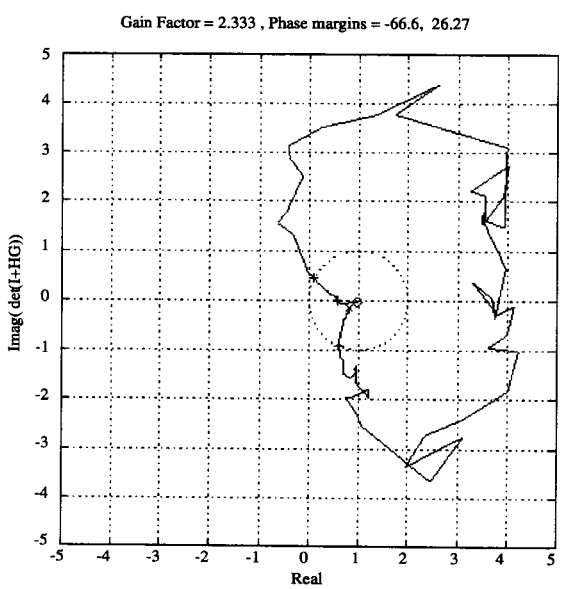

Figure 6. Enlarged determinant plot from figure 5.

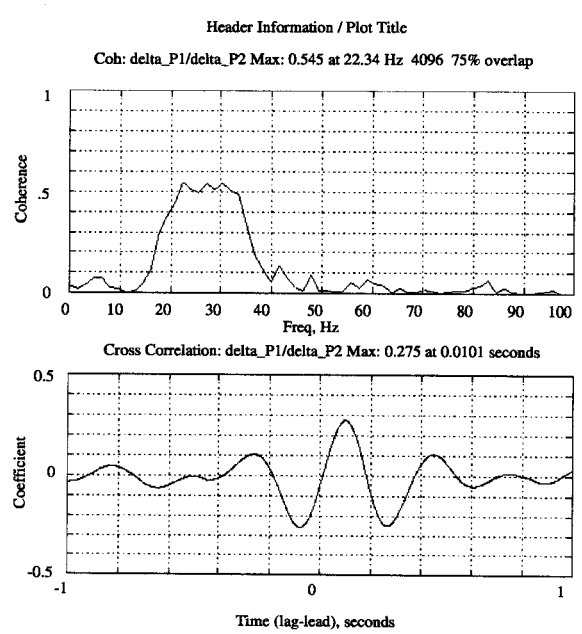

Figure 7. Results for assessing buffet aerodynamics.

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