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IMPROVED FLIGHT TEST PROCEDURES FOR FLUTTER CLEARANCE

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Abstract. Flight flutter testing is an integral part of flight envelope clearance. This paper discusses advancements in several areas that are being investigated to improve efficiency and safety of flight test programs. Results are presented from recent flight testing of the F/A-18 Systems Research Aircraft. A wingtip excitation system was used to generate aeroelastic response data. This system worked well for many flight conditions but still displayed some anomalies. Wavelet processing is used to analyze the flight data. Filtered transfer functions are generated that greatly improve system identification. A flutter margin is formulated that accounts for errors between a model and flight data. Worst-case flutter margins are computed to demonstrate the flutter boundary may lie closer to the flight envelope than previously estimated. This paper concludes with developments for a distributed flight analysis environment and on-line health monitoring.

Key words: Aeroelasticity, Structural Dynamics, Flutter, Wavelets, Robust Stability, Flight Test, Health Monitoring, Virtual Instruments, Distributed Computing

1. Introduction

Flight testing to clear a flight envelope of flutter instabilities is a costly and dangerous process [5]. Stability indicators are estimated at a series of test points based on flight data measurements of aeroelastic modal responses. Often these indicators are generated with little confidence so the envelope must be expanded in small increments to maximize safety of the pilot.

The aeroelastic community has identified several areas of research that are vital to improving the efficiency of flight flutter testing [3]. Three elements are specifically mentioned : excitation, data analysis, and flutter clearance. Each of these areas is targeted at increasing the usefulness of flight data for predicting stability boundaries.

NASA Dryden Flight Research Center is actively involved in research to improve the efficiency of flight flutter test programs. Several concepts are developed that may dramatically reduce the cost and risk associated with envelope expansion.

- enhanced excitation system
- wavelet processing of flight data
- robust flutter margins
- distributed environment for analysis

The first three research topics were utilized in a recent flight flutter test program with the F/A-18 Systems Research Aircraft. Results from this flight test program are briefly presented in this paper with a detailed analysis given in Reference [2].

The enhanced excitation system is based on a wingtip mechanism used with civilian and military aircraft [11, 12, 14]. This system excites modal responses better than control surface excitation. Wavelet processing introduces a powerful tool that avoids Fourier analysis assumptions which are violated by non-stationary and time-varying flight data [1]. Robust flutter margins account for flight data variations to replace the poorly behaved damping parameter as a predictor of instability [7].

Improvements in flight flutter test efficiency can be achieved by applying these three concepts to increase the value of flight data. Procedures are derived based on utilizing each concept at a series of test points to expand the flight envelope. Stability margins can be computed from the flight data which accurately reflect the true aircraft dynamics.

This paper concludes with a discussion of a distributed environment approach for low-cost and rapid implementation of on-line analysis algorithms. Such implementation tools are necessary to develop and evaluate on-line algorithms using real data. Novel automated approaches are rarely implemented on-line due to high development and maintenance costs associated with environments requiring usage of specific hardware platforms. A virtual instrument data server is introduced to disconnect the data source from analysis algorithms.

The concepts described in this paper directly address several concerns for flight flutter testing; however, they also represent significant advancements towards an on-line health monitoring ability which will be essential for maintaining aging commercial and military fleets. The general purpose on-line data server will facilitate demonstration of flight test procedures and analysis tools for both flutter testing and health monitoring applications.

2. F/A-18 SRA

The F/A-18 Systems Research Aircraft (SRA) is being flown at NASA Dryden Flight Research Center as a testbed for flutter testing, advanced actuator concepts, smart structures, and optical sensing systems. The SRA is a two seat configuration fighter with production engines as shown in Figure 1.

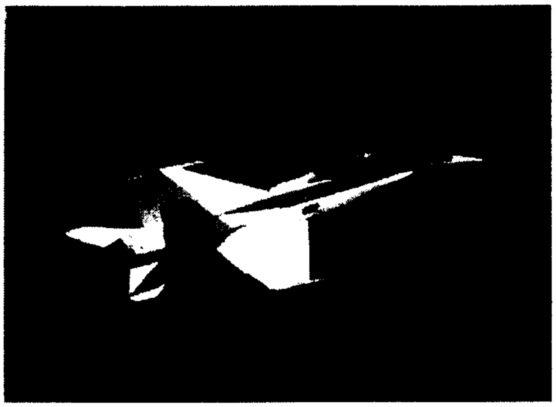

Figure 1. F/A-18 Systems Research Aircraft

Flutter testing was initiated on the SRA due to a major left wing structural modification to allow testing of several hydraulic and electromechanical aileron concepts. The increased size and weight of these ailerons required the replacement of a fitting called a 'hinge-half' supporting the aileron hinge, the actuator and a fairing with larger and heavier items. A total of about 35 lb was added to the wing.

A partial list of the calculated structural modal frequencies for the F/A-18 SRA after the modifications is given in Table 1.

Mode	Symm	AntiSymm
Wing 1^{st} Bending	5.59	8.84
Fuselage 1^{st} Bending	9.30	8.15
Stabilator 1^{st} Bending	13.21	12.98
Wing 1^{st} Torsion	13.98	14.85
Vertical Tail 1^{st} Bending	16.83	15.61
Wing 2^{nd} Bending	16.95	16.79
Wing Outboard Torsion	17.22	-
Fuselage 2^{nd} Bending	19.81	18.62
Trailing Edge Flap rotation	23.70	23.47
Fuselage Torsion	-	24.19
Wing 2^{nd} Torsion	29.88	29.93

Table 1 : Modal Frequencies in *Hz*

Aeroelastic research was performed on the F/A-18 SRA on 21 flights utilizing over 250 test points between September 1994 and February 1995 and during June and July of 1995.

3. Wingtip Excitation System

The F/A-18 SRA flight flutter test program utilized a wingtip excitation system developed by Dynamic Engineering Incorporated (DEI) [10]. The system consists of a wingtip exciter, avionics box in the instrumentation bay, and a cockpit controller.

Aerodynamic forces are generated by the wingtip exciter which consists of a small fixed aerodynamic vane forward of a rotating slotted hollow cylinder. Rotating the cylinder varies the pressure distribution on the vane and results in a wingtip force changing at twice the cylinder rotation frequency. The magnitude of the resulting force is determined by the amount of opening in the slot. The F/A-18 aircraft with a wingtip exciter is shown in Figure 2.

Figure 2. DEI Exciter Mounted in Aft Position on Left Wing

The cockpit controller commands sine sweeps to the rotating cylinder to determine the frequency and magnitude of the wingtip forces. The wingtip exciters are programmed to act in-phase (0 *degrees*) or out-of-phase (90 *degrees*) with each other to excite either symmetric or antisymmetric modes.

Sine sweeps were restricted to within 3 and 35 *Hz* with smaller ranges used to concentrate on a specific set of modes. Multiple sets of 1,2 or 4 linear or logarithmic sweeps were used with the sweep frequency increasing or decreasing.

The excitation force is not directly measured but rather a strain gage measurement is used to approximate this force. The strain gage records a point response at the exciter vane root which is considered representative of the distributed excitation force load over the entire wing surface. Vane root strain is assumed to be directly proportional to the vane airloads due to excitation [2].

Response data was measured from conditions throughout the flight envelope over the series of 21 flights. Exciter operation varied over a range of sweep frequencies and lengths, force magnitudes, symmetric or antisymmetric excitation, and exciter location being fore or aft on the launcher rail.

The DEI system is able to excite several aeroelastic modes. Figure 3 shows a power spectrum of the left wingtip accelerometer in response to a 60 *sec* symmetric excitation sweep from 3 to 35 *Hz* at Mach .85 and 10000 feet. The wing 1^{st} and 2^{nd} bending modes are strongly excited along with moderate excitation of the wing 1^{st} torsion mode.

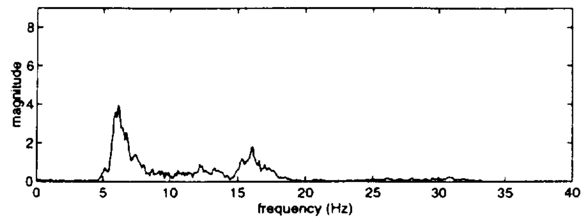

Figure 3. Power Spectrum of Left Wingtip Accelerometer for Mach=.85 and 10000 feet from DEI Excitation

Control surfaces do not excite the same level of modal responses. Figure 4 shows the power spectrum for the left wingtip accelerometer at the same flight condition using stick raps for excitation. A low frequency rigid body mode is strongly excited while only the wing 1^{st} bending and torsion modes are marginally excited.

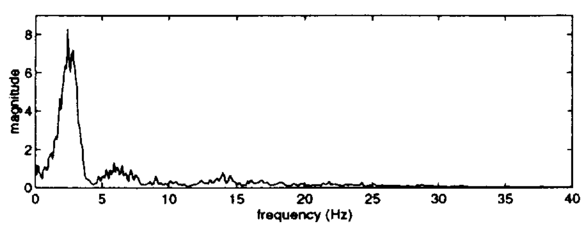

Figure 4. Power Spectrum of Left Wingtip Accelerometer for Mach=.85 and 10000 feet from Stick Rap Excitation

Several anomalies occurred during flight test of the DEI system [2]. The exciters displayed erratic behavior and phase errors at higher dynamic pressures due to binding in both the motor drive mechanism and rotating cylinders. Also, some data sets were nonrepeatable and varied with sine sweeps of increasing or decreasing frequency.

Flight test procedures can be implemented that maximize the effectiveness of the DEI system despite the noted anomalies. Utilizing multiple sweeps that include increasing and decreasing frequency sweeps has been shown to be more effective than single sweeps. Also, the exciters may be placed at differing positions to ensure a complete set of modes are excited.

The DEI system can be a valuable flight flutter test tool for exciting modal responses. Stronger motors are currently being evaluated to improve the performance at high dynamic pressures and reduce effects of poor phasing and nonrepeatibility.

4. Wavelet Processing

Flight test data is typically analyzed with signal processing algorithms to extract useful time and frequency domain information describing the aeroelastic dynamics of the aircraft. This information is used to estimate modal damping and natural frequencies and generate transfer functions.

Traditional signal processing methods are based on Fourier analysis which maps time domain data into the frequency domain. These methods are suspect due to the nature of flight data which violates the assumptions of linear, time-invariant, stationary data composed of sums of sinusoids. Discrete Fourier transforms with sliding windows attempt to avoid these violations but introduces "time smearing" which causes a loss of resolution.

Wavelets methods of signal processing provide more accurate flight data analysis [1]. Wavelets are versatile harmonic analysis tools which combine time and frequency representations into localized waveforms. Wavelets naturally characterize features of shape, size, and location present in the data and can identify transient and nonlinear behaviors. Wavelet analysis convolves these waveforms with the data to extract correlated features, or patterns, in the signal.

The Continuous Wavelet Transform (CWT) maps time domain signals into a time-frequency domain by projecting the signal onto a set of basis functions. The CWT can be viewed as processing the signal through a bank of filters.

The wavelet, which determines the basis of the CWT, must be chosen carefully to match desired features of the data. A particularly useful choice for transient aeroelastic data is the Morlet wavelet [4].

Analysis in the time-frequency domain allows intelligent filtering of the data signals. Often desired features of the data appear along with unwanted distortions and noise. A filtered wavelet map is obtained by masking wavelet coefficients corresponding to the unwanted components. Such feature extractions offer advantages to traditional band-pass filtering or thresholding techniques.

This filtering by feature extraction is useful for aeroelastic data obtained with the wingtip DEI excitation system which typically exhibited a primary harmonic along with other dynamics and noise. The primary harmonic represents a desired feature of the data that should be extracted to generate accurate transfer functions.

A time-frequency wavelet map for a typical strain gage measurement to approximate the DEI excitation force is shown in Figure 5a. The commanded linear sweep from 3 to 35 *Hz* is visible as the dark center diagonal stripe. Filtering around this primary feature eliminates undesired additional harmonics caused by poor measurements and improper exciter performance to result in Figure 5b.

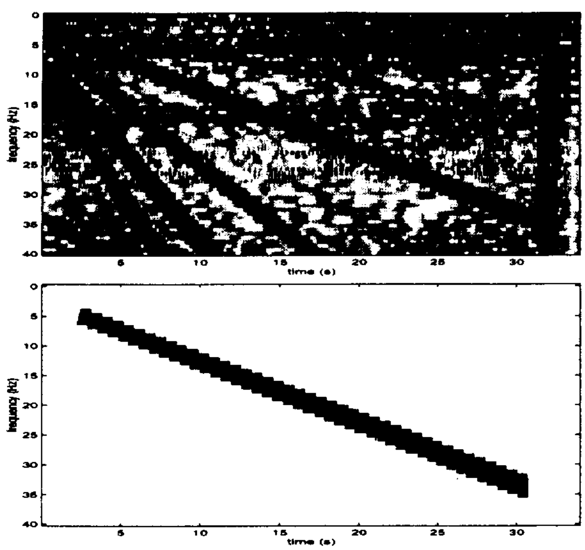

Figure 5. Time-frequency wavelet maps of F/A-18 SRA strain gage input measurement for DEI sweep from 3-35 *Hz* at M=.8 and 30 *kft* : unfiltered (a) and filtered (b)

The primary harmonic feature determined from the input data is also used to filter the sensor measurements. The wavelet map of accelerometer data in Figure 6a shows information around the desired feature along with additional harmonics and noise. Only this information is extracted by the filtering to result in Figure 6b.

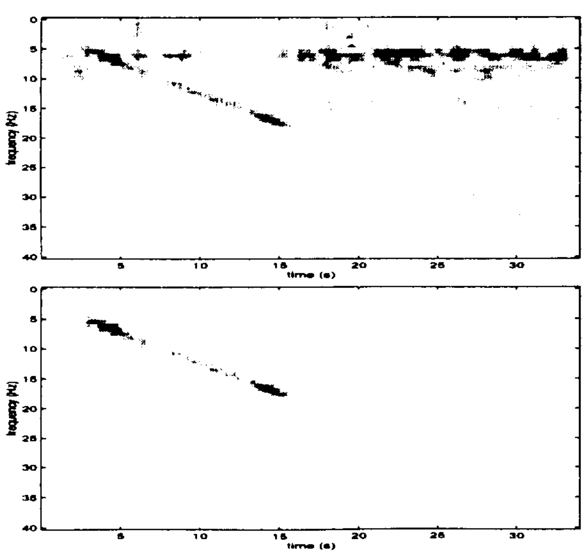

Figure 6. Time-frequency wavelet maps of F/A-18 SRA accelerometer measurement for DEI sweep from 3-35 *Hz* at M=.8 and 30 *kft* : unfiltered (a) and filtered (b)

Consider the transfer function in Figure 7 generated with Fourier analysis of the unfiltered data.

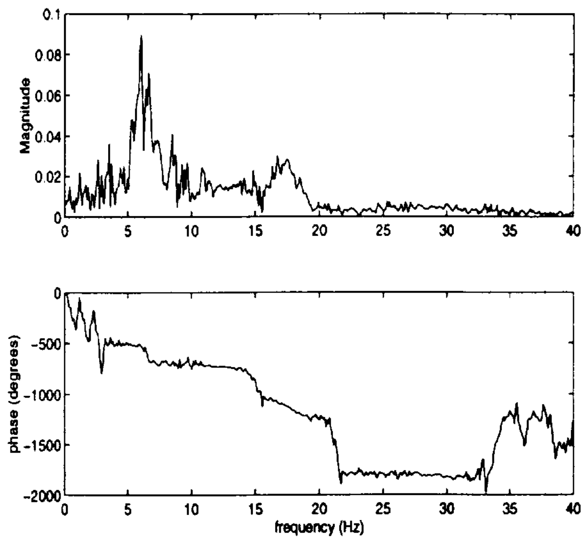

Figure 7. Transfer function from left wingtip exciter to accelerometer using Fourier analysis on original data

Figure 8 shows the transfer function generated by the filtered wavelet maps in Figure 5b and 6b.

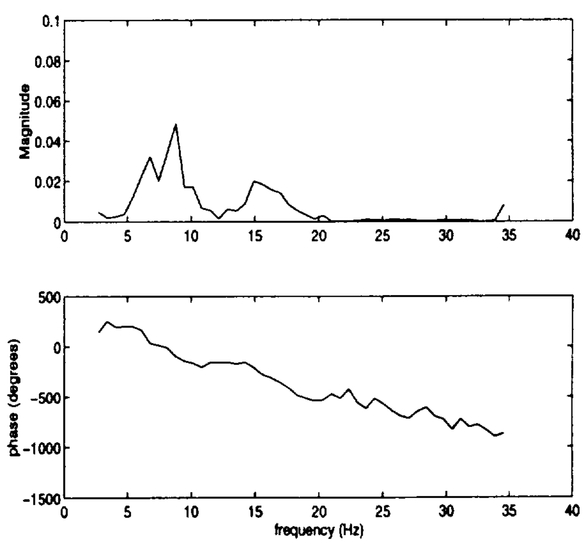

Figure 8. Transfer function from left wingtip exciter to accelerometer using wavelet methods on feature filtered data from Figures 5b and 6b

The transfer function in Figure 8 shows less effects of noise while the magnitude and phase characteristics are more indicative of a linear system. Linear state-space identification methods are able to obtain more accurate representations of the filtered data transfer function in Figure 8 than for Figure 7.

Wavelet processing can immediately be introduced to flight test programs. Signal processing at test points based on wavelets can be used to estimate modal damping and generate transfer functions to identify models and predict stability properties.

5. Robust Flutter Margins

The inefficiency of flight envelope clearance results in large part from the inability to generate confident flutter margins. Traditional pre-flight prediction methods, such as *p-k* , utilize a well developed model but do not account for inaccuracies. Traditional in-flight estimation methods, such as damping tracking, utilize flight data that describes the true aircraft dynamics but the estimates do not extrapolate to a flutter condition due to nonlinear behavior throughout the flight envelope.

A method to compute flutter margins is developed that uses the strengths of these traditional methods [7, 8]. This model-based approach utilizes flight data to generate uncertainty operators for the theoretical system that account for variations observed in the flight data. A robust stability measure, μ, computes a flutter margin that is worst-case with respect to the modeling uncertainty.

Worst-case flutter margins are computed for F/A-18 SRA using a nominal finite element structural model coupled with a state-space approximation to the unsteady aerodynamic forces [9]. This linear model contains 28 symmetric and 28 antisymmetric states for the structural model and 56 symmetric and 28 antisymmetric states for the unsteady aerodynamic forces.

Two uncertainty operators, Δ_A and Δ_{in}, are used to describe modeling errors in the linear system. An additional operator, $\delta_{\bar{q}}$, parametrizes the model around dynamic pressure so the analysis considers a range of flight conditions. Sensor noise is included with peak magnitude of 10% of the measurements.

The uncertainty operator Δ_A affects the state matrix of the nominal plant to model variations in both natural frequency and damping for each mode. Δ_A is a structured diagonal matrix with real scalar parameters as elements. Separate scalars are used to affect each modal response and time lag in the state matrix. A scalar associated with a modal response is repeated two times while each time lag uncertainty appears once on the diagonal.

The uncertainty affects the state matrix elements through scaling weights. The weighting W_ω describes the percent of variation allowed in natural frequency while W_ζ relates to damping and W_l is associated with time lags in the unsteady aerodynamic forces.

$$W_\omega = .05 \qquad W_\zeta = .15 \qquad W_l = .15$$

The uncertainty operator Δ_{in} is a complex multiplicative uncertainty on the excitation force. A weighting function, W_{in}, reflects the frequency varying levels of multiplicative uncertainty such as a large component at high frequency to indicate no dynamics above 40 *Hz* are included in the model.

$$W_{in} = 5\frac{s+100}{s+5000}$$

The block diagram for robust flutter margin analysis of the F/A-18 SRA, including the parametric variation in dynamic pressure $\delta_{\bar{q}}$ and uncertainties Δ_A and Δ_{in}, is given in Figure 9.

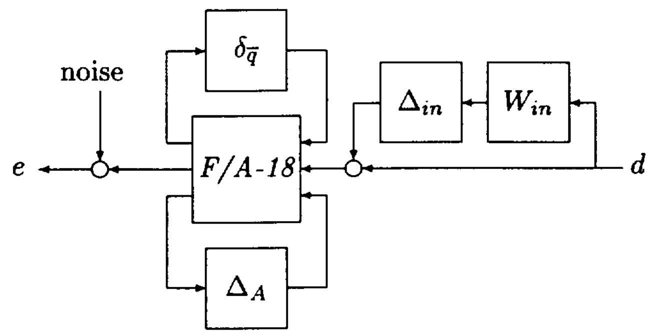

Figure 9. Robust Stability Model of the F/A-18 SRA

An example of observed modal variations is shown in Figure 10. The uncertainty description accounts for variations between the theoretical model and the range of time-varying aircraft dynamics observed throughout each flight test.

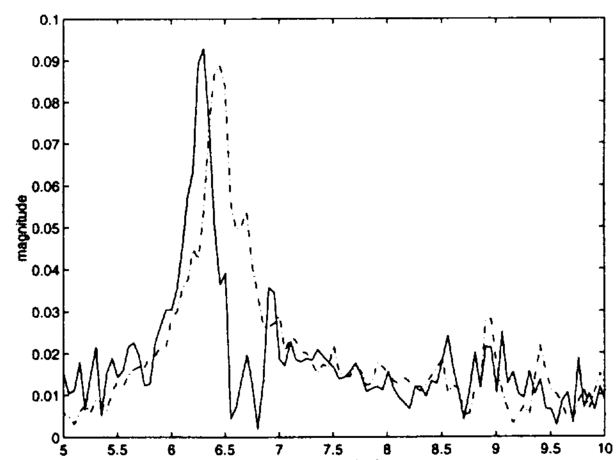

Figure 10. Flight Data Transfer Functions for Mach=.8 and 30000 feet Demonstrating Variation in Modal Frequency and Damping

Extensive flight data generated with the DEI excitation system from the 250 test conditions is used to determine the uncertainty levels in Figure 9. A model validation criterion is analyzed to ensure the measured flight data does not invalidate the robust model [6].

The dynamic pressures at which flutter occurs are converted into altitudes, commonly known as matched-point solutions, using standard atmospheric equations. These altitudes are plotted in Figures 11 and 12. The F/A-18 flight envelope is shown along with a 15% desired flutter boundary.

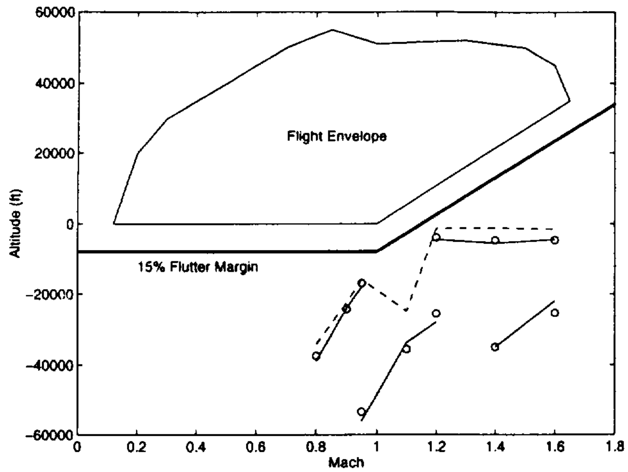

Figure 11. Matched Point Flutter Margins for Symmetric Modes : nominal *p-k* margin (—), nominal μ margin (o), robust μ margin (- - -)

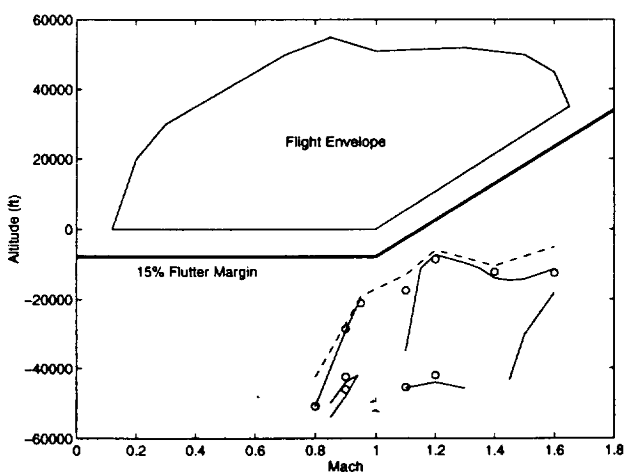

Figure 12. Matched Point Flutter Margins for Antisymmetric Modes : nominal *p-k* margin (—), nominal μ margin (o), robust μ margin (- - -)

Each short solid line indicates flutter margins due to a different unstable mode as computed by the *p-k* method [13]. Similarity of nominal μ and *p-k* margins demonstrates μ is an effective technique to characterize flutter dynamics. The μ method even detects the subcritical hump mode occurring for antisymmetric excitation at 0.9 Mach.

Approximate critical flutter frequencies for subsonic,transonic and supersonic flight are 7,12 and 28 *Hz* in Figure 11 and 9,28 and 30 *Hz* in Figure 12. The μ and *p-k* methods generated frequencies within 10% of each other.

The robust flutter margins have lower dynamic pressures, corresponding to higher altitudes, than the nominal margins which indicates the expected conservative nature of the robust computation. These robust margins are worst-case values to account for variations observed with flight data measured throughout the flight envelope.

The greatest deviation between μ and *p-k* solutions occurs at transonic conditions. Numerical sensitivity and inaccuracies in the transonic model are reflected by large differences in the nominal margins and highly conservative robust flutter margins. The robust flutter dynamic pressures are approximately 70% of the nominal μ margins.

The supersonic flight conditions show little variation in the nominal and robust flutter margins in Figure 11 due to little variation in the aeroelastic dynamics. A similar behavior is shown for the antisymmetric modes in Figure 12 excepting at Mach 1.6. The increased sensitivity at this point may indicate impending transition in flutter mechanism to the subcritical mode at high Mach.

The robust flutter boundaries indicate the *p-k* method may not accurately reflect the true flutter stability margins. In particular, the worst-case flutter margin for symmetric excitation at Mach 1.2 lies considerably closer to the boundary than the *p-k* method indicates. Also, the transonic margins may be significantly different than *p-k* predictions.

6. Improved Flight Test Procedures

The three concepts described in the previous sections may significantly increase efficiency of a flight flutter test program. The improved test procedure would utilize the new concepts at a series of test points to expand the flight envelope.

The basis for any on-line stability analysis is flight data. The DEI excitation system may be used to generate data that measures a rich set of modal responses. Wavelet processing can then be used for data analysis to characterize the true dynamics.

The objective at each test point is to confidently determine a stability margin for safe envelope expansion. The post-flight analysis of Figures 11 and 12 can be implemented on-line using a proposed flutterometer concept [8]. The confidence in these robust margins will be increased if strong modal responses are excited and the corresponding flight data is processed to accurately characterize the aeroelastic dynamics so realistic modeling uncertainty descriptions can be formulated.

7. Distributed Environments

In this section we address an implementation strategy for on-line aeroelastic and aeroservoelastic stability monitoring algorithms. A brief introduction describes the objectives and requirements which must be met. Then, a "middleware" software solution is described which provides the desired features.

On-line flight flutter testing is a type of health monitoring application in which the test engineer attempts to project measured data into stability metrics, leading to a series of decisions which, if erroneous, may result in catastrophic loss of machine and life. This danger is compounded by limited time and money in which to conduct flutter test clearance programs. The future will likely be characterized by fewer resources for flight test, and increasing risk from pushing various performance envelopes.

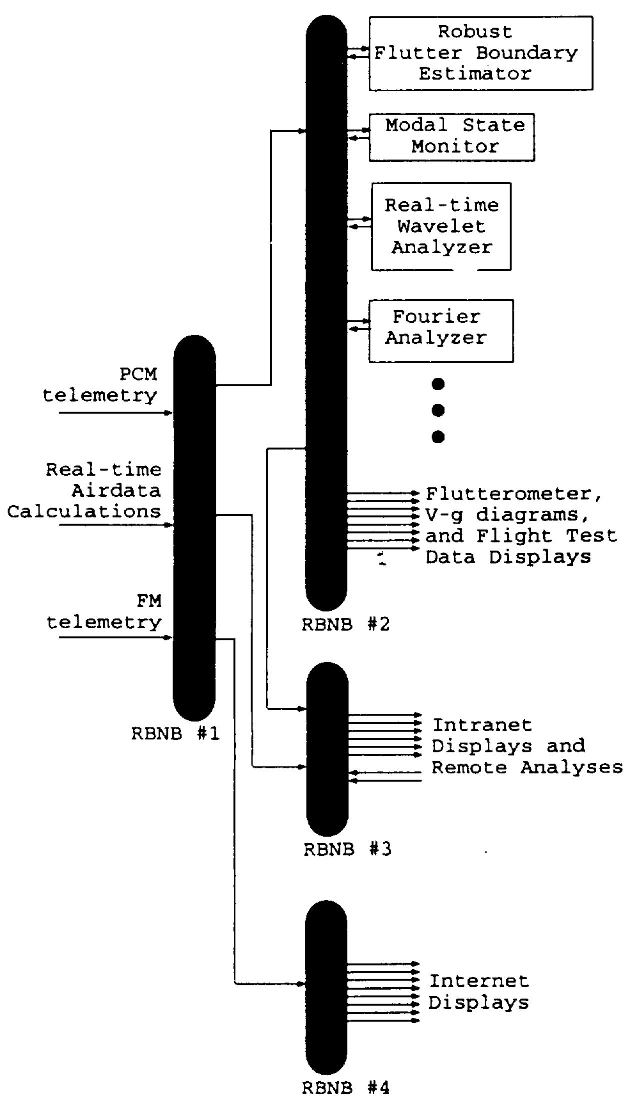

Figure 13. Distributed Environment for On-Line Analysis based on the Ring Buffered Network Bus

The goals addressed here originated with two ideas conceived approximately ten years ago. The first of these ideas was a rapid prototyping environment for speeding the evolution of on-line flutter data analysis algorithms. The second idea was that of a "flutter meter", or a fully autonomous vibration stability indicator in an aircraft cockpit. The combination of these ideas evolved toward a generally useful distributed signal processing environment applicable to both ground-based and airborne algorithms.

A useful environment must be able to manage and distribute multiple data sources to multiple algorithms running on multiple local and remote computers. This will be necessary for modular implementation of new algorithms and for merging results of several online algorithms. One or more of the participating algorithms may be geographically distant from the data sources. In addition, data queuing and archival services are required. For example, signal processing usually requires blocks of data at a guaranteed, constant sample interval (i.e. block transfer of data, not just current values). It also makes sense that accessing live data should be identical to the manner in which recorded data is accessed. This allows online algorithms to be developed in an online environment without necessarily requiring live data. For lowest cost and flexibility, communication over standard networks is required. In other words, a viable environment would allow algorithms running on low-performance computers over a wide area network via modems to coexist with real-time algorithms communicating over high speed local networks. Lastly, the number of programming languages permitted to interface with the environment should be maximized.

The enabling technology for this environment is currently being developed. Called the *Ring Buffered Network Bus* (RBNB), this solution is a modular and scalable virtual instrument data server. Its salient characteristics include a separation of data sources from data destinations and intelligent buffering which provides data storage and retrieval services. Within an RBNB server, a specific data source feeds information into a corresponding *Ring Buffer Object* (RBO), and requests for data are provided through a *Network Bus Object* (NBO). An RBO can contain a single data stream or thousands of channels. An RBO can be configured for deep storage, i.e. data can be streamed to disk for later playback. An NBO can select individual channels or several channels from one or more RBOs, and merges the requested data into a stream for export over the network to the recipient. An RBNB contains an arbitrary number of RBOs and NBOs. An NBO can also be a data source for a second server, thus allowing highly configurable data networking topologies and efficient data mirroring capabilities.

An example topology is shown in figure 13 which shows how the RBNB might be used in a flight flutter clearance test. The figure shows four RBNBs performing a variety of acquisition, routing, and processing tasks. Here it is assumed that real-time in-flight data will be available via telemetry. PCM data and FM data are converted to engineering units and streamed to RBNB #1, which in turn serves the data to the other servers. Data relevant to the flutter test is passed to RBNB #2 where several algorithms perform relevant on-line analyses and post results back to the same RBNB so that they can be displayed and archived. The real-time wavelet calculations require high performance dedicated processors, while the other algorithms might use standard workstation hardware and commercial analysis software.

The third and fourth RBNBs suggest uses for dedicated subnet servers. The "remote analyses" interfacing with RBNB #3 could be, for example, a new algorithm being tested by a university or industry partner. The fourth RBNB suggests a simple data display server, possibly existing as a site accessible from the World Wide Web. The added value of this server would be the capability to drive remote displays for people interested in the flight program but not required to be on site for the actual test - e.g. a program manager or supervisor, a classroom full of students, researchers at remote sites, etc.

8. Conclusion

Several concepts have been introduced to increase efficiency and reduce cost and risk associated with flight flutter testing. These concepts are associated with improving the quality of flight data to generate more confident flutter margins. Flight data recorded in response to a wingtip excitation is shown to measure a rich set of modal responses. Analysis of this flight data with wavelet processing eliminates noise and unwanted harmonics to generate clean transfer functions. A robust stability measure computes flutter margins that directly account for variations between the measured transfer functions and a theoretical model. A distributed environment approach is introduced to allow low-cost and rapid implementation of on-line algorithms for a flight flutter test program.

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