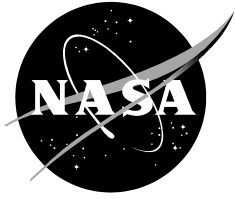


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Unsteady Aerodynamic Model Tuning for Precise Flutter Prediction

Chan-gi Pak

Dryden Flight Research Center, Edwards, California

April 2011

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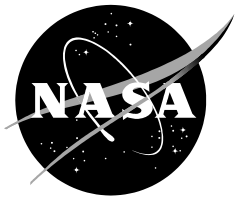
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Abstract

A simple method for an unsteady aerodynamic model tuning is proposed in this study. This method is based on the direct modification of the aerodynamic influence coefficient matrices. The aerostructures test wing 2 flight-test data is used to demonstrate the proposed model tuning method. The flutter speed margin computed using only the test validated structural dynamic model can be improved using the additional unsteady aerodynamic model tuning, and then the flutter speed margin requirement of 15 percent in military specifications can apply towards the test validated aeroelastic model. In this study, unsteady aerodynamic model tunings are performed at two time invariant flight conditions, at Mach numbers of 0.390 and 0.456. When the Mach number for the unsteady aerodynamic model tuning approaches to the measured fluttering Mach number, 0.502, at the flight altitude of 9,837 ft, the estimated flutter speed is approached to the measured flutter speed at this altitude. The minimum flutter speed difference between the estimated and measured flutter speed is -0.14 percent.

Nomenclature

a_{ij}	the i-th row and j-th column element of the real part of A
A	aerodynamic influence coefficient matrix
AIC	aerodynamic influence coefficient
ATW	aerostructures test wing
b_{ij}	the i-th row and j-th column element of the imaginary part of A
CG	center of gravity
DFRC	Dryden Flight Research Center
e_{ij}	design variable for a_{ij}
f	aeroelastic frequency, Hz
f_{ij}	design variable for b_{ij}
FEM	finite element model
FTF	flight test fixture
g	structural damping
GVT	ground vibration test
G(x)	constraints
m	number of degrees of freedom
n	number of modes
NASA	National Aeronautics and Space Administration
O3	object-oriented optimization
V	aircraft speed, KEAS
V_d	dive speed, KEAS
VFEM	test-validated-structural-dynamic finite element model

Introduction

The primary objective of this study is to reduce uncertainties in the unsteady aerodynamic model of an aircraft to increase the safety of flight. To this end, a new flutter analysis procedure using the validated aeroelastic model is proposed, and the block diagram of this new procedure is shown in figure 1.

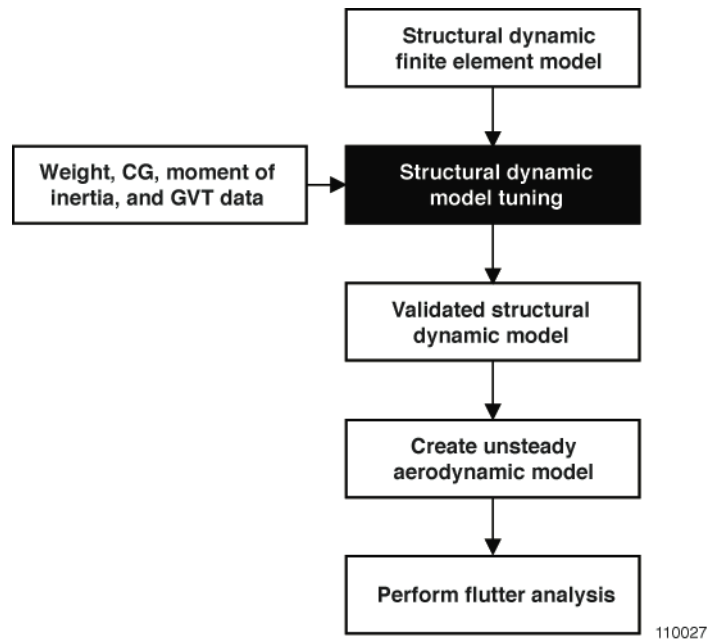


Figure 1a. Previous procedure.

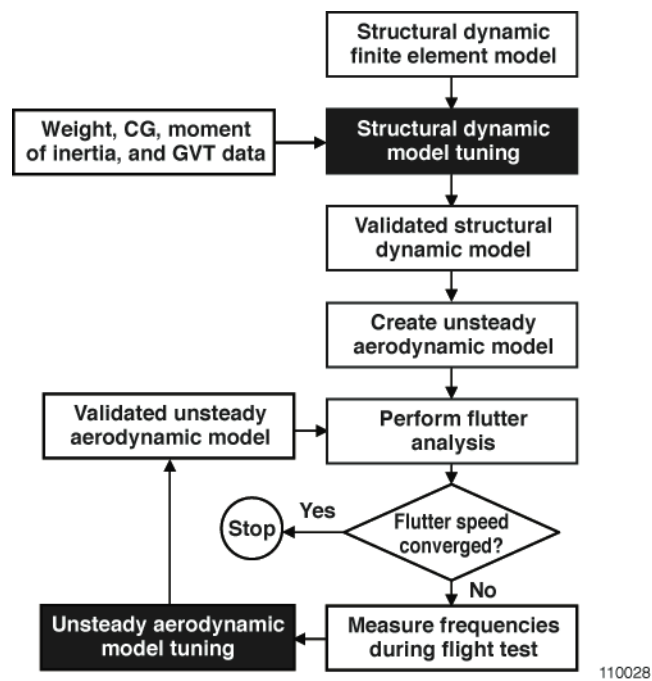


Figure 1b. Proposed new procedure.

Figure 1. Flutter analysis procedure at NASA Dryden Flight Research Center.

Significant efforts (refs. 1–3) have been made in developing corrections to linear aerodynamic models to improve correlation with steady-state wind tunnel and flight test data. There has been a limited amount of effort in the correction of unsteady aerodynamics for aeroservoelastic applications, which has been relatively sparse and ad-hoc when compared to the steady-state work that has been performed.

The aerostructures test wing (ATW) 2 test article, shown in figure 2, was developed and flown at the National Aeronautics and Space Administration (NASA) Dryden Flight Research Center (DFRC) on the F-15B (McDonnell Douglas, now The Boeing Company, Chicago, Illinois) test bed aircraft on December 15, 2009. To support the envelope expansion, a test-validated-structural-dynamic finite element model (VFEM) was used for the flutter analysis of the ATW2. Flutter boundaries of the ATW2, before and after the structural dynamic model tuning (ref. 4), are compared with the flight envelopes as shown in figure 3 (ref. 5). In this figure, the solid line bounds the ATW2 test envelope that is planned for flight, and the dashed line is the 15 percent margin of the ATW2 test envelope. This 15 percent margin line was designed to match the numerical flutter boundaries computed using the VFEM with the 3 percent structural damping, the solid line with circular marker. The solid line with the diamond marker represents flutter boundaries using the VFEM with the measured structural damping (ref. 5). The measured flutter point of the ATW2 is also shown in figure 3, using the x marker.



Figure 2. Aerostructures test wing 2 mounted on the F15-B pylon for flight-testing.

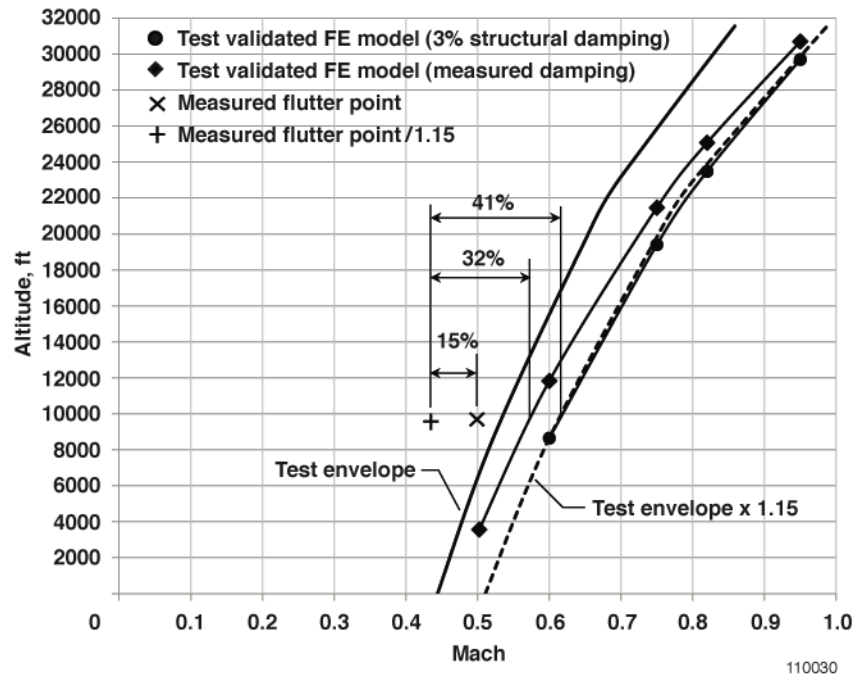


Figure 3. Flutter boundaries before and after structural dynamic model tuning.

Required flutter margins for the safety of flight were computed and summarized in table 1 and figure 3. It should be noted that the series of ground vibration tests (GVT) and structural dynamic model tuning has been performed (refs. 5–7) resulting in the computed flutter boundaries, based on the ATW2 configuration in figure 2 and the corresponding VFEM, shown in figure 3. The GVT for the final ATW2 configuration was performed while the ATW2 was mounted to the flight test fixture (FTF) (ref. 8) in the FTF ground handling cart as shown in figure 4. The FTF was sufficiently massive when compared to the ATW2 so that cantilevered boundary conditions were used. It may be concluded from table 1 and figure 3 that when only the structural dynamic model is validated with respect to GVT data, the flutter margin required for the flutter certification of the ATW2 should be approximately 40 percent. In addition to the historically stand-alone structural dynamic model, the unsteady aerodynamic model should also be validated with the test data to use the 15 percent flutter margin in the military specification (ref. 9).

Table 1. Required flutter margins for different types of structural dynamic models.

Flutter boundaries	Flutter margins
Measured/1.15 (= V_d)	0 %
Measured (= 1.15 V_d)	15 %
Test validated FEM; after model tuning with measured damping	32 %
Test validated FEM; after model tuning with 3% structural damping	41 %

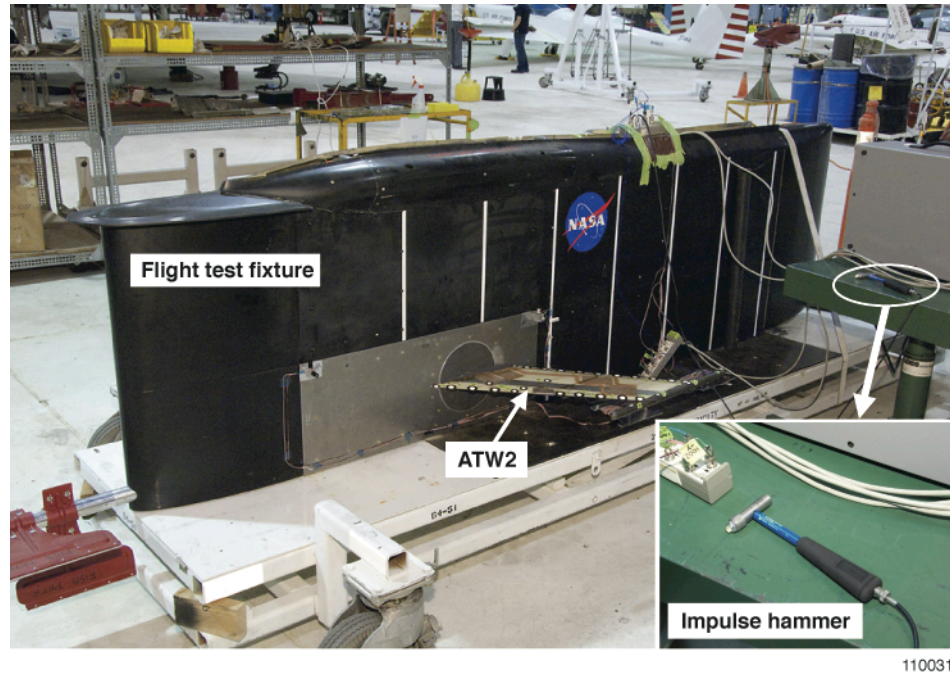


Figure 4. Flight test fixture and the ATW2 on a ground-handling cart.

Unsteady Aerodynamic Model Tuning Procedure

A simple technique has been proposed and developed to update unsteady aerodynamic models. The technique is based on matching the measured and numerical aeroelastic frequencies of an aircraft structure. In defining the optimization problem to match the measured aeroelastic frequencies, the variation of the unsteady aerodynamic force was selected as the design parameter. The unsteady aerodynamic force is a function of Mach number, reduced frequency, and dynamic pressure; which can be obtained based on any aerodynamic model. ZAERO (ZONA Technology Incorporated, Scottsdale, Arizona) (ref. 10) code is used in this study. If the Mach number is constant, the reduced frequency and dynamic pressure become variables for changing the unsteady aerodynamic force.

Supporting the Aeronautics Research Mission Directorate guidelines, NASA DFRC has developed an object-oriented optimization (O3) tool (ref. 11), which leverages existing tools and practices, and allows the easy integration and adoption of new state-of-the-art software. Unsteady aerodynamic model tuning used in this study is based on the minimization of the discrepancies in numerical and measured aeroelastic frequencies. A computer code for unsteady aerodynamic model tuning has been developed using the O3 tool together with the pre-processor, ZAERO, and post-processor codes shown in figure 5.

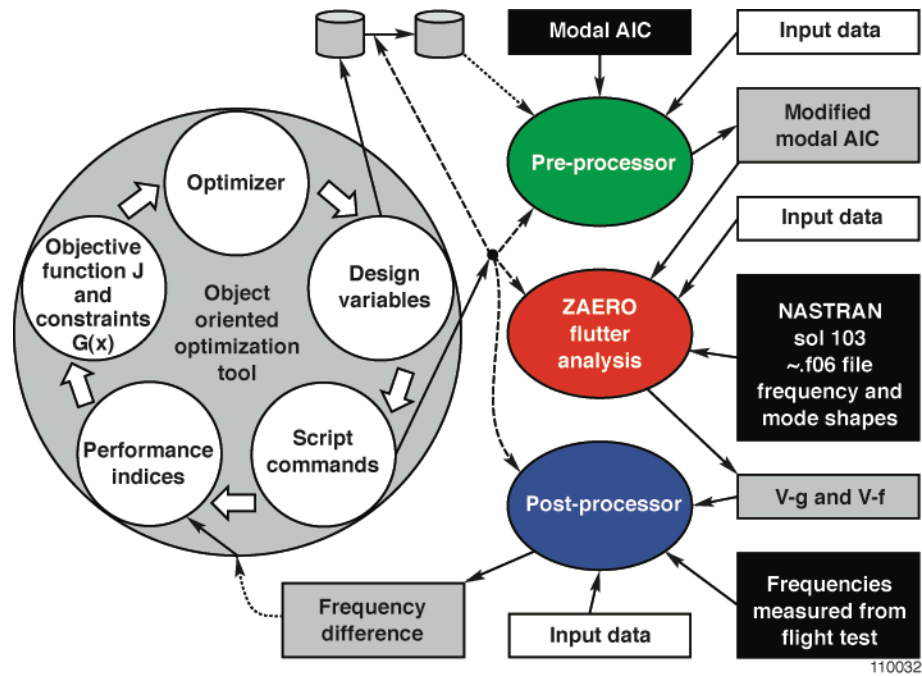


Figure 5. Unsteady aerodynamic model tuning using the object-oriented optimization tool.

Pre-processor code

This code reads in design variables generated by the O3 tool, and then reads modal aerodynamic influence coefficient (AIC) matrices that were computed and saved using ZAERO code. Modified modal AIC matrices are then created as shown in figure 6.

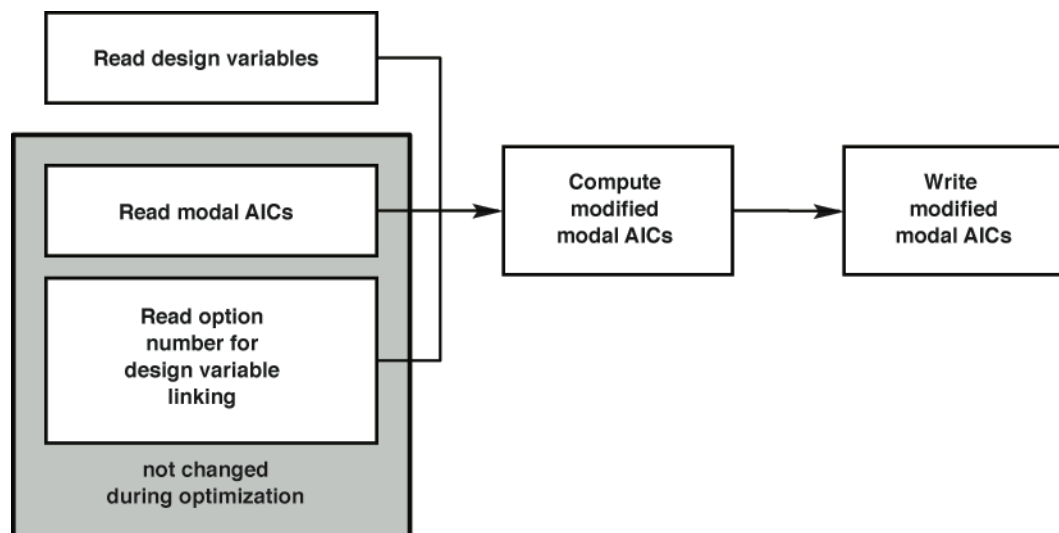


Figure 6. Flow chart of the pre-processor.

Design variables in this unsteady aerodynamic model tuning are scaling factors for each element in the AIC matrices. The AIC matrix at a reduced frequency can be written as:

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} + i \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \dots & b_{mn} \end{bmatrix}$$

Design variables, $e_{11}, e_{12}, \dots, e_{21}, e_{22}, \dots, e_{mn}, f_{11}, f_{12}, \dots, f_{21}, f_{22}, \dots, f_{mn}$ are defined as:

$$\begin{bmatrix} e_{11}a_{11} & e_{12}a_{12} & \dots & e_{1n}a_{1n} \\ e_{21}a_{21} & e_{22}a_{22} & \dots & e_{2n}a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{m1}a_{m1} & e_{m2}a_{m2} & \dots & e_{mn}a_{mn} \end{bmatrix} + i \begin{bmatrix} f_{11}b_{11} & f_{12}b_{12} & \dots & f_{1n}b_{1n} \\ f_{21}b_{21} & f_{22}b_{22} & \dots & f_{2n}b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1}b_{m1} & f_{m2}b_{m2} & \dots & f_{mn}b_{mn} \end{bmatrix}$$

The following design variable linking options are available for the unsteady aerodynamic model tuning.

Option 1: single design variable

$$d = e_{11} = e_{12} = \dots = e_{mn} = f_{11} = f_{12} = \dots = f_{mn}$$

Option 2: two design variables

$$d_1 = e_{11} = e_{12} = \dots = e_{mn}; \text{ real part}$$

$$d_2 = f_{11} = f_{12} = \dots = f_{mn}; \text{ imaginary part}$$

Option 3: columnwise the same design variables (total n design variables)

$$d_1 = e_{11} = e_{21} = \dots = e_{m1} = f_{11} = f_{21} = \dots = f_{m1}$$

$$d_2 = e_{12} = e_{22} = \dots = e_{m2} = f_{12} = f_{22} = \dots = f_{m2}$$

...

$$d_n = e_{1n} = e_{2n} = \dots = e_{mn} = f_{1n} = f_{2n} = \dots = f_{mn};$$

Option 4: columnwise the same design variables (total 2n design variables)

$$d_1 = e_{11} = e_{21} = \dots = e_{m1}$$

$$d_2 = e_{12} = e_{22} = \dots = e_{m2}$$

...

$$d_n = e_{1n} = e_{2n} = \dots = e_{mn}; \text{ real parts}$$

$$d_{n+1} = f_{11} = f_{21} = \dots = f_{m1}$$

$$d_{n+2} = f_{12} = f_{22} = \dots = f_{m2}$$

...

$d_{2n}=f_{1n}=f_{2n}=\dots=f_{mn}$; imaginary parts

Option 5: No design variable linking; total $2mn$ design variables.

ZAERO Flutter Analysis

Flutter analyses in this study are based on ZAERO code. This code acquires the modified modal AIC matrices and performs the matched flutter analysis as shown in figure 7. This computer simulation requires the natural frequencies and mode shapes of the aircraft, and in this study these modal data are computed using MSC/NASTRAN (MSC Software Corporation, Santa Ana, California) code (ref. 12). The V-g and V-f data are computed and saved for the next post-processing step.

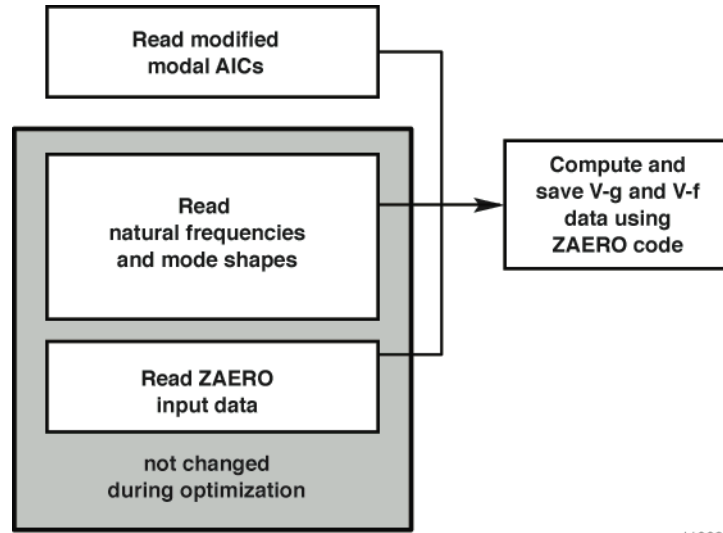
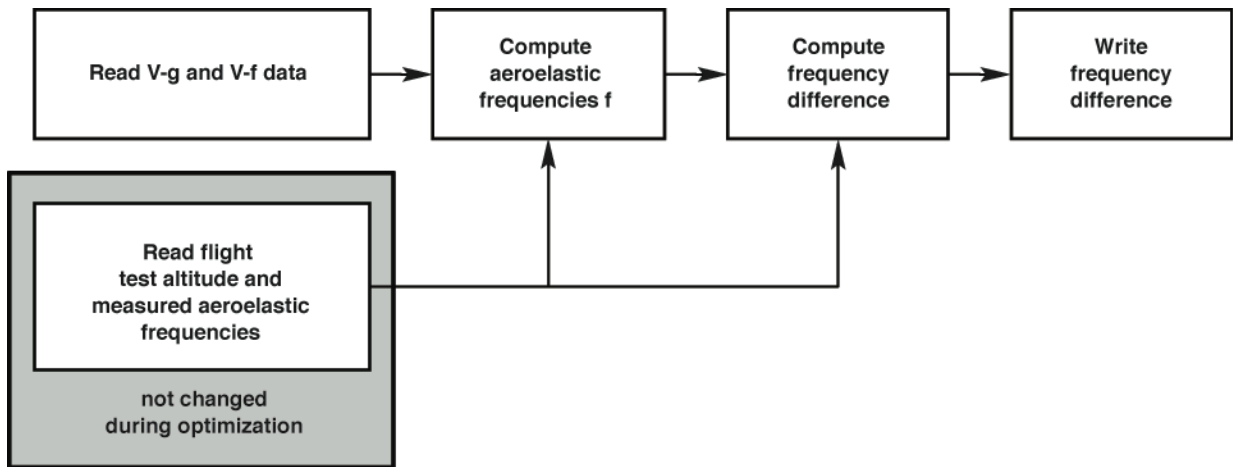


Figure 7. Flow chart of the flutter analysis procedure.

Post-processor code

This program reads in the V-g and V-f data and the target altitude where the flight test was performed. Based on the velocity information V in the V-g and V-f data, corresponding altitudes at fixed Mach numbers are computed. Numerical aeroelastic frequencies are computed from target and computed altitudes using the cubic splining procedure.

This program also computes the frequency difference between the numerical and measured aeroelastic frequencies. Frequency difference will be an objective function, which will be minimized through the use of the O3 tool. The proposed tuning technique is an unconstrained optimization problem that can be solved using a gradient based optimizer (ref. 13), a genetic algorithm (ref. 14), or a big-bang-big-crunch algorithm (refs. 15 – 17). A flow-chart of this post-processor code is shown in figure 8.



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Figure 8. Flow chart of the post-processor.

Application

During the flight test of the ATW2, a classical bending and torsion type of flutter, as shown in figure 9, was observed near a Mach number of 0.502 and a flight altitude of 9,837 ft. Measured Mach number, flight altitude, and acceleration at the middle and leading edge of the wing tip boom after take-off, near flutter, and during flutter are shown in figures 10 and 11, respectively. Measured aeroelastic frequencies during the flight test as well as natural frequencies computed using the VFEM and measured during GVT are shown in table 2.

Table 2. Numerical and measured frequencies (Hz) of the ATW2 during the flight test.

Mode	Natural frequencies		Measured aeroelastic frequencies		
	VFEM	GVT	After take off*	Near flutter**	During flutter***
1	17.45	17.45 (0.623)†			
2	43.48	43.72 (0.610)	40.45	38.99	37.69
3	82.98	83.66 (0.778)			
4	133.60	N/A			
5	153.80	142.30 (0.674)			

* Time steps 83,742 to 83,745 (Mach = 0.390; altitude = 9,934 ft; time invariant)

** Time steps 84,668 to 84,672 (Mach = 0.456; altitude = 9,858 ft; time invariant)

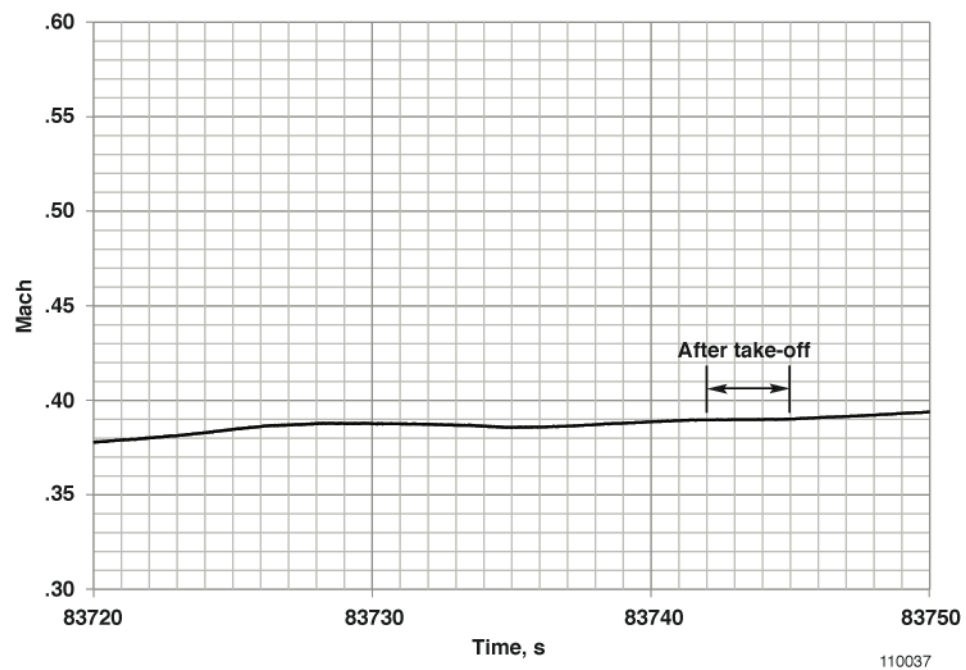
*** Time steps 84,683 to 84,684 (Mach = 0.502; altitude = 9,837 ft; time varying)

()† Measured damping (%)



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Figure 9. Classical bending and torsion flutter during flight test.



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Figure 10a. Mach number.

Figure 10. Measured Mach number, flight altitude, and acceleration at the middle and the leading edge of the boom after take off (time steps 83,720 s to 83,750 s).

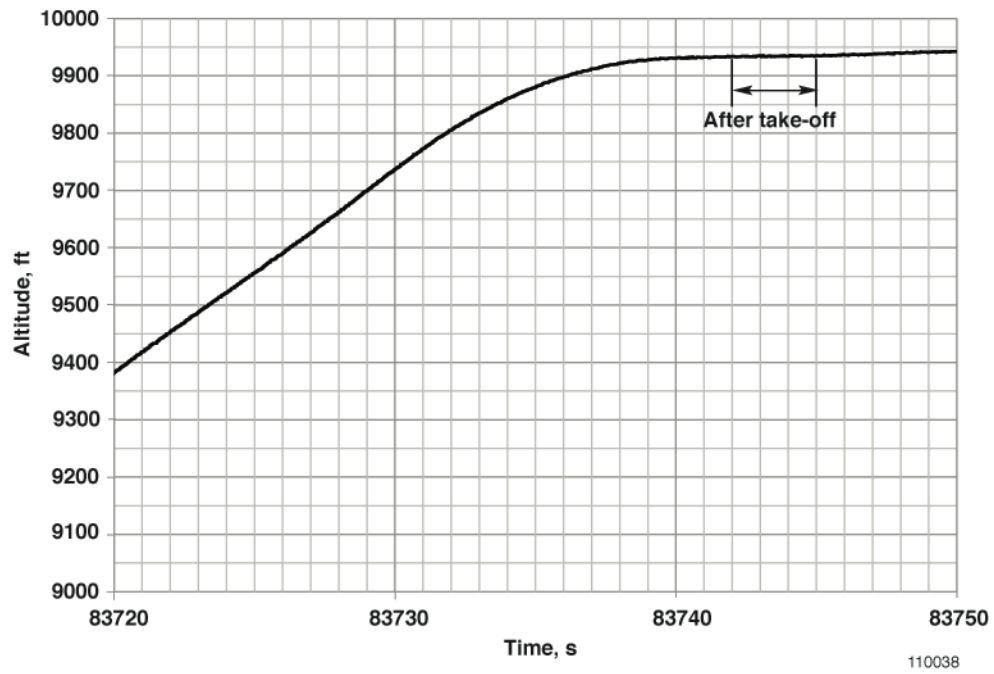


Figure 10b. Flight altitude.

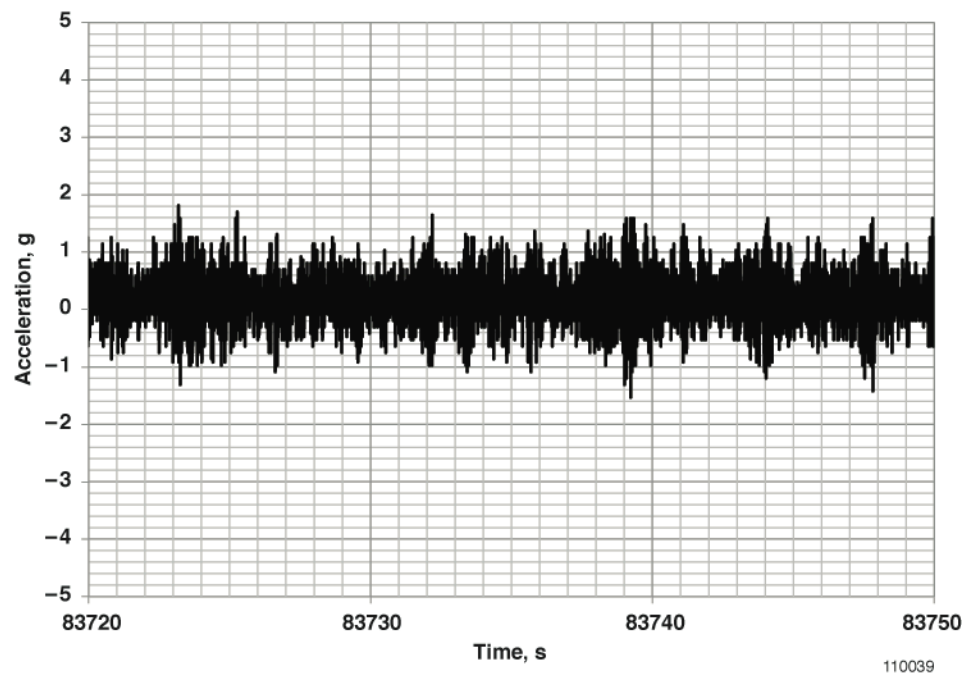


Figure 10c. Acceleration at middle of boom.

Figure 10. Continued.

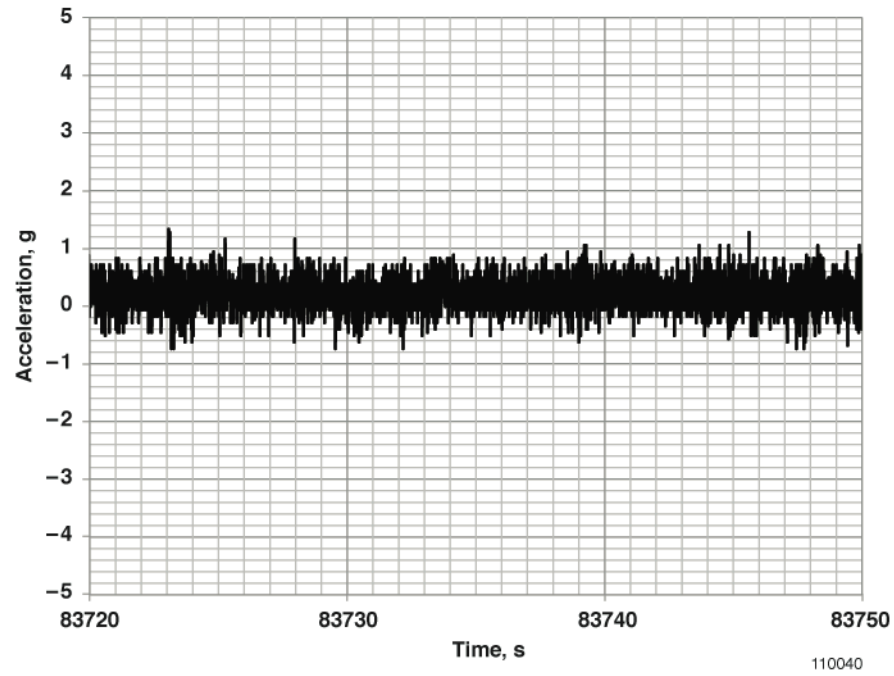


Figure 10d. Acceleration at leading edge of boom.

Figure 10. Concluded.

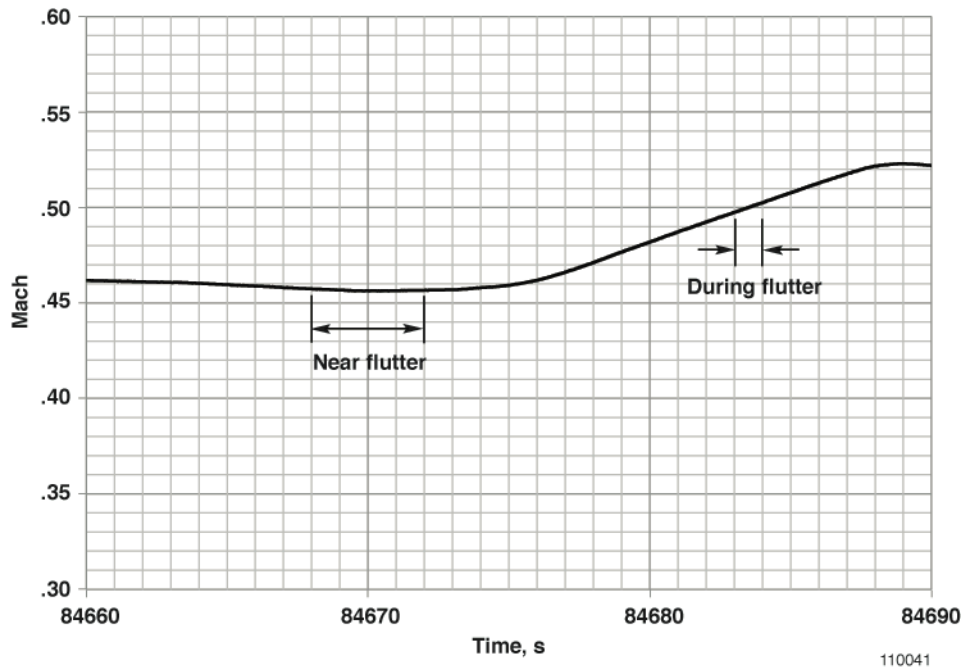


Figure 11a. Mach number.

Figure 11. Measured Mach number, flight altitude, and acceleration at the middle and the leading edge of the boom just before and during flutter (time steps 84,660 s to 84,690 s).

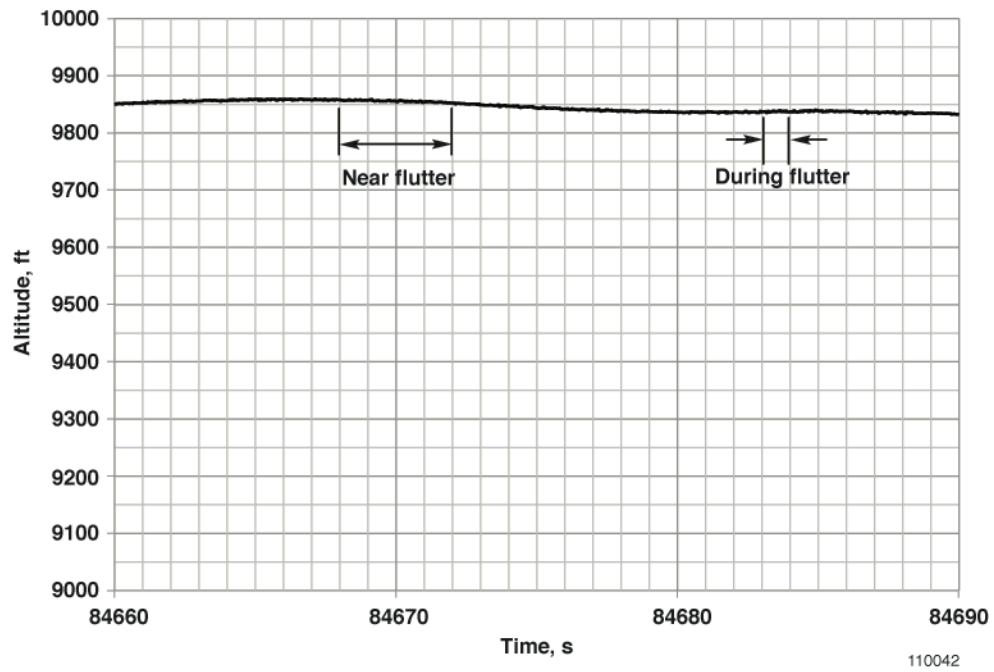


Figure 11b. Flight altitude.

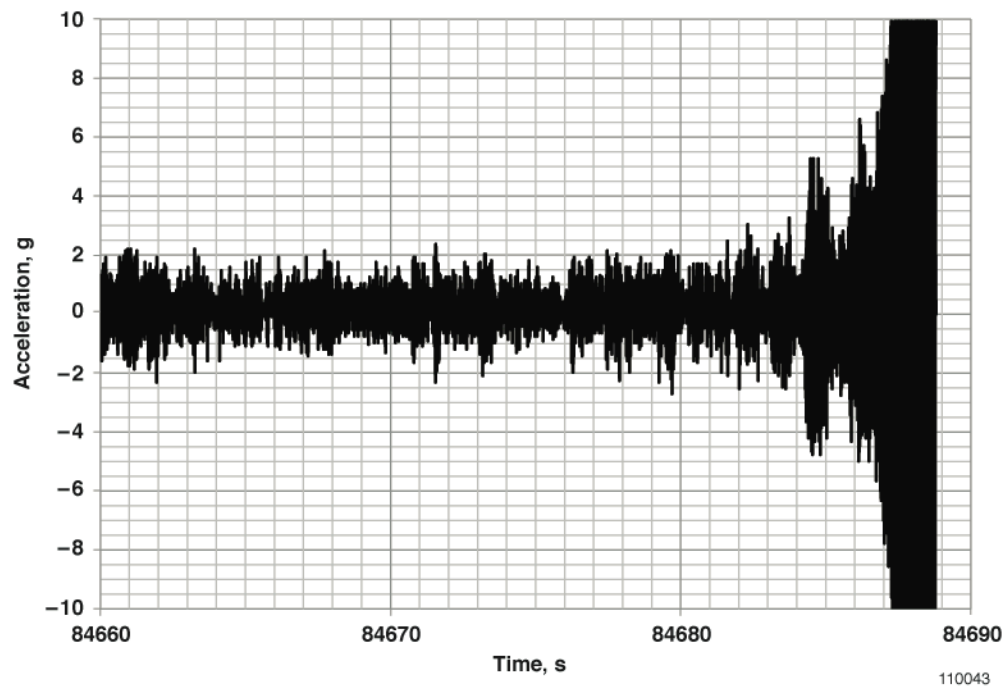


Figure 11c. Acceleration at middle of boom.

Figure 11. Continued.

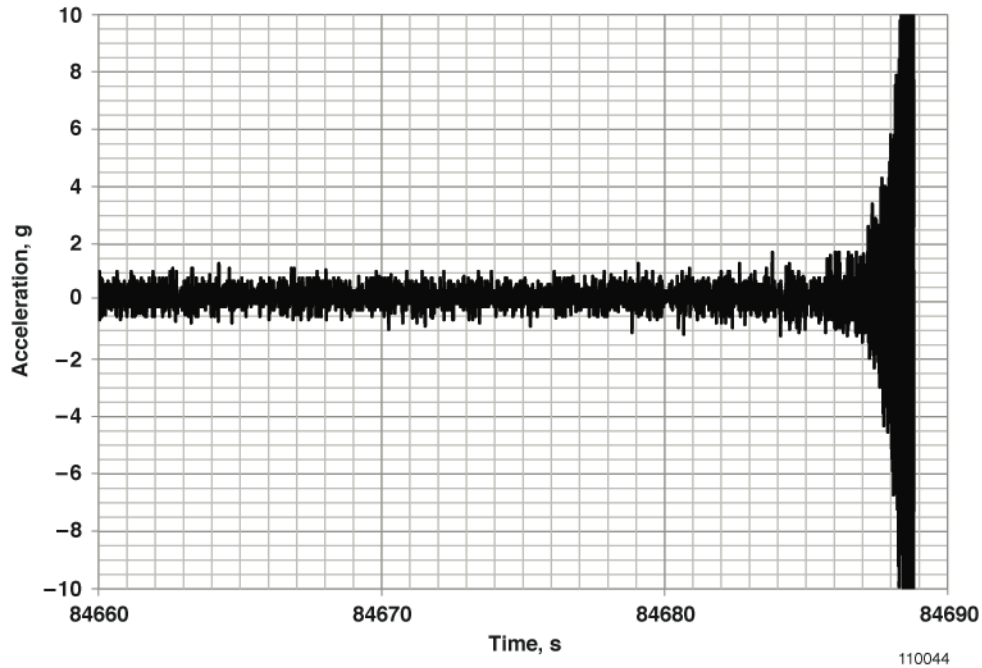


Figure 11d. Acceleration at leading edge of boom.

Figure 11. Concluded.

The first model tuning is performed using flight data after take-off, from 83,742 s to 83,745 s as shown in figure 10. The ATW2 in this time period is a time invariant system. The average flight Mach number and altitude during this time period were 0.39 and 9,934 ft, respectively. Unfortunately, measured acceleration data in figure 10 was noisy, and it was quite difficult to estimate the first and third aeroelastic frequencies because of high aerodynamic damping. The second measured aeroelastic frequency is 40.45 Hz as shown in table 2. An initial aeroelastic frequency of 41.12 Hz is computed using ZAERO code as shown in table 3.

Table 3. The second aeroelastic frequency before and after unsteady aerodynamic model tuning and corresponding scaling factors.

Mach	Measured (Hz)	Altitude (ft)	Before tuning (Hz)	Scaling factor (design variable)	After tuning (Hz)
0.390	40.45	9934	41.12	1.2579	40.45
0.456	38.99	9858	40.10	1.2719	38.99

In this model tuning procedure, the aeroelastic frequency difference in the second mode is minimized using the design variable linking option 1. The number of target aeroelastic frequencies to be matched is one, and therefore the simplest option is selected. In other words, there is an unconstrained optimization problem with a single design variable. After model tuning, the second aeroelastic frequency of 41.12 Hz becomes 40.45 Hz, and the corresponding scaling factor (single design variable) is 1.2579 as shown in table 3.

The saved AIC matrices at Mach = 0.502 is updated using the scaling factor of 1.2579, and the updated flutter boundary at this Mach number is summarized in table 4 and figure 12. The tuned flutter speed, corresponding altitude, and flutter frequency are 277.3 KEAS, 9,670 ft, and 37.69 Hz, respectively. It should be noted in table 4 that flutter speed and frequency difference after the unsteady aerodynamic model tuning are 0.33 percent and 0.00 percent, respectively.

Table 4. Measured and computed flutter boundaries at Mach = 0.502.

Comment	Scaling factor (design variable)	Flutter speed		Altitude, ft	Flutter frequency	
		KEAS	Difference %		Hz	Difference %
Measured	N/A	276.4	0.00	9836.9	37.69	0.00
Before tuning	1.0000	311.3	13.00	3561.5	37.67	-0.05
Use M = 0.390 aero	1.2579	277.3	0.33	9670.0	37.69	0.00
Use M = 0.456 aero	1.2719	276.0	-0.14	9912.5	37.68	-0.03

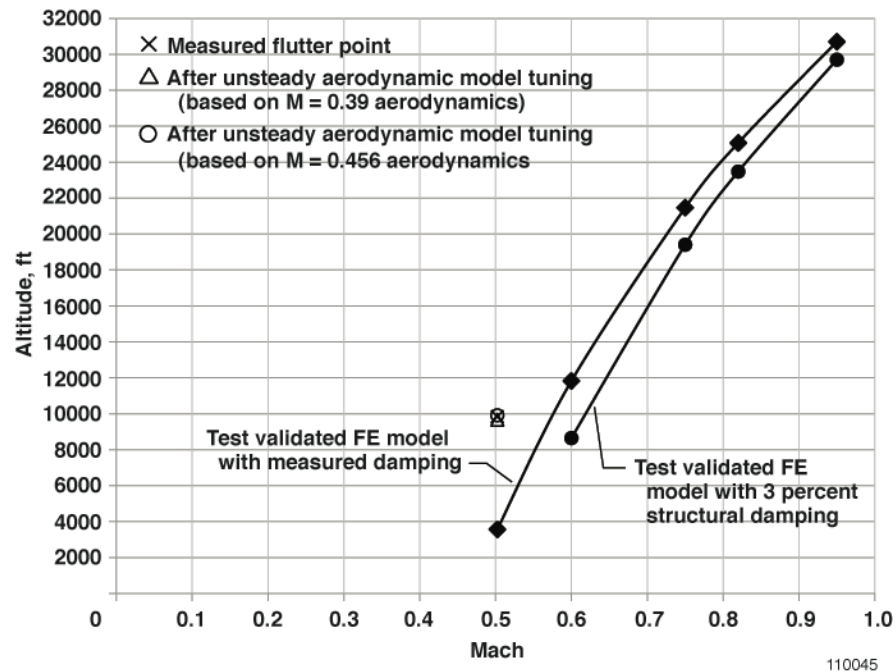


Figure 12. Flutter boundaries at Mach = 0.502 before and after unsteady aerodynamic model tuning.

The second model tuning is performed using another time invariant system, between time steps of 84,660 s and 84,690 s. Relatively flat time histories of flight Mach numbers and altitude, between time steps of 84,668 s and 84,672 s, are observed as shown in figure 11. In this time period, the average flight Mach number and altitude were 0.456 and 9,858 ft, respectively.

The second measured aeroelastic frequency in these time steps is 38.99 Hz as shown in table 2. The corresponding aeroelastic frequency computed from the ZAERO simulation with Mach 0.456 aerodynamics is 40.10 Hz as shown in table 3. Unsteady aerodynamic model tuning is performed using

these two numerical and measured frequencies, and a scaling factor of 1.2719 based on the design variable linking option 1, which is also given in table 3.

Flutter analysis at Mach 0.502 is performed using this new scaling factor, and the flutter speed and frequency are summarized in table 4 and figure 12. Flutter speed difference of 13 percent before the unsteady aerodynamic model tuning becomes -0.14 percent after tuning.

In case of the ATW2, computation time required for completing an unsteady aerodynamic model tuning based on option 1 was less than 7 min. Once the scaling factor (design variable) is computed, an additional 1 or 2 min is needed for the Fast Fourier Transformation, one more flutter analysis at a higher Mach number to compute the updated V-g and V-f data, and automatic computations of updated flutter speed and frequency. Therefore, less than 9 min are enough to predict more accurate flutter speed based on the current flight test data.

Conclusion

A simple unsteady aerodynamic model tuning based on the direct AIC modification is proposed in this study. The value of the unsteady aerodynamic model tuning procedure has been shown with the application to the ATW2 flight test data.

Flutter boundaries and the ATW2 flight test envelope were computed using the VFEM (ref. 5, 6). The flutter margins required for the safety of flight were approximately 40 percent when only the structural dynamic model was validated. Excellent flutter speed matching is accomplished when the simple unsteady aerodynamic model tuning is applied resulting in flutter speed differences of 0.33 and -0.14 percent. The flutter margin requirement of 15 percent in the military specification can now be used with the test validated aeroelastic model, that is test validated structural dynamic and unsteady aerodynamic models. The modeling uncertainties associated with the unsteady aerodynamics can be easily minimized through the use of the simple model tuning procedure proposed in this study.

Unsteady aerodynamic model tunings are performed at two time invariant flight conditions, at Mach numbers of 0.390 and 0.456. When the Mach number for the unsteady aerodynamic model tuning approaches to the measured fluttering Mach number, 0.502, at the flight altitude of 9,837 ft, the estimated flutter speed is approached to the measured flutter speed at this altitude. Therefore, we may conclude that the Mach number selected for the unsteady aerodynamic model tuning is closer to the measured fluttering Mach number at the same flight altitude, and we may get a more accurate scaling factor for the precise flutter prediction.

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14. ABSTRACT A simple method for an unsteady aerodynamic model tuning is proposed in this study. This method is based on the direct modification of the aerodynamic influence coefficient matrices. The aerostructures test wing 2 flight-test data is used to demonstrate the proposed model tuning method. The flutter speed margin computed using only the test validated structural dynamic model can be improved using the additional unsteady aerodynamic model tuning, and then the flutter speed margin requirement of 15 percent in military specifications can apply towards the test validated aeroelastic model. In this study, unsteady aerodynamic model tunings are performed at two time invariant flight conditions, at Mach numbers of 0.390 and 0.456. When the Mach number for the unsteady aerodynamic model tuning approaches to the measured fluttering Mach number, 0.502, at the flight altitude of 9,837 ft, the estimated flutter speed is approached to the measured flutter speed at this altitude. The minimum flutter speed difference between the estimated and measured flutter speed is -0.14 percent.						
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