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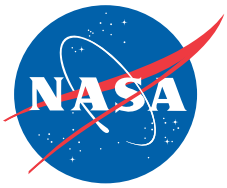

Updating the Finite Element Model of the Aerostructures Test Wing Using Ground Vibration Test Data

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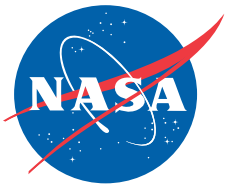

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ABSTRACT

Improved and/or accelerated decision making is a crucial step during flutter certification processes. Unfortunately, most finite element structural dynamics models have uncertainties associated with model validity. Tuning the finite element model using measured data to minimize the model uncertainties is a challenging task in the area of structural dynamics. The model tuning process requires not only satisfactory correlations between analytical and experimental results, but also the retention of the mass and stiffness properties of the structures. Minimizing the difference between analytical and experimental results is a type of optimization problem. By utilizing the multidisciplinary design, analysis, and optimization (MDAO) tool in order to optimize the objective function and constraints; the mass properties, the natural frequencies, and the mode shapes can be matched to the target data to retain the mass matrix orthogonality. This approach has been applied to minimize the model uncertainties for the structural dynamics model of the aerostructures test wing (ATW), which was designed and tested at the National Aeronautics and Space Administration Dryden Flight Research Center (Edwards, California). This study has shown that natural frequencies and corresponding mode shapes from the updated finite element model have excellent agreement with corresponding measured data.

NOMENCLATURE

AR	aspect ratio
ATW	aerostructures test wing
CG	center of gravity
DFRC	Dryden Flight Research Center
DOF	degrees of freedom
DPR	driving point residues
d	number of degrees of freedom
$\boldsymbol{E}$	effective independent matrix
EI	effective independence
F	original objective function
FE	finite element
FIM	Fisher information matrix
G	subscript for target values (or measured quantities)
GA	genetic algorithm
GVT	ground vibration test
g_i	inequality constraints
h_j	equality constraints
I_{XX}	computed x moment of inertia about the center of gravity
I_{XXG}	target x moment of inertia about the center of gravity
I_{xy}	computed xy moment of inertia about the center of gravity
I_{XYG}	target xy moment of inertia about the center of gravity
I_{YY}	computed y moment of inertia about the center of gravity
I_{YYG}	target y moment of inertia about the center of gravity
I_{YZ}	computed yz moment of inertia about the center of gravity
I_{YZG}	target yz moment of inertia about the center of gravity
I_{ZX}	computed zx moment of inertia about the center of gravity

I_{ZXG}	target zx moment of inertia about the center of gravity
I_{ZZ}	computed z moment of inertia about the center of gravity
I_{ZZG}	target z moment of inertia about the center of gravity
J_i	objective functions (optimization problem statement number i = 1, 2, … , 13)
$\mathbf{K}$	stiffness matrix
$\overline{\mathbf{K}}$	orthonormalized stiffness matrix
$\mathbf{KE}$	kinetic energy
KE_{ik}	kinetic energy associated with the *i*-th DOF in the *k*-th target mode
L	new objective function
l	number of modes
$\mathbf{M}$	mass matrix
$\overline{\mathbf{M}}$	orthonormalized mass matrix
MAC	modal assurance criterion
MDAO	multidisciplinary design, analysis and optimization
m	number of sensors (or number of measured degrees of freedom)
n	number of modes to be matched
q	number of inequality constraints
r	number of equality constraints
SEREP	system equivalent reduction expansion process
SMI	structural mode interaction
$\mathbf{T}$	transformation matrix
W	computed total mass
W_G	target total mass
X	x-coordinate of computed center of gravity
$\overline{\mathrm{X}}$	design variables vector
X_G	x-coordinate of target center of gravity
Y	y-coordinate of computed center of gravity
Y_G	y-coordinate of target center of gravity
Z	z-coordinate of computed center of gravity
Z_G	z-coordinate of target center of gravity
ε	small tolerance value for inequality constraints
λ	Lagrange multiplier
$\mathbf{\Phi}$	computed eigen-matrix ($m \times n$)
$\mathbf{\Phi_G}$	target eigen-matrix ($m \times n$)
$\overline{\mathbf{\Phi}}$	Reduced modal matrix ($d \times l$)
ϕ_i	i-th mode shape ($d \times 1$)
Ω_j	j-th computed frequency
ω_k	corresponding natural frequency

INTRODUCTION

A test article called the aerostructures test wing (ATW) was developed and flown at the National Aeronautics and Space Administration (NASA) Dryden Flight Research Center (DFRC) (Edwards, California) on the McDonnell Douglas NF15B test bed aircraft as shown in figure 1 for the purpose of demonstrating and validating flutter prediction methods during flight (ref. 1). The first aerostructures test wing (ATW1), flown in 2001, was originally developed to directly address requests for better flight flutter test techniques by providing a functional flight test platform. While the first series of tests was extremely successful, the minimum amount of instrumentation (structural accelerometers and strain gages) was chosen to satisfy the scope of the program. These sensors were limited in their capability to answer questions of aeroelastic interactions, sources of nonlinearity, physical mechanisms of aeroelastic coupling, and feedback dynamics between the structure and aerodynamics.

Figure 1. Aerostructures test wing mounted on the NF15B for flight flutter testing.

A second aerostructures test wing (ATW2), as shown in figure 2, was built for the demonstration of state-of-the-art sensor technologies for simultaneous; distributed; collocated measurement of shear stress (skin friction); steady and unsteady pressures; and structural strain and accelerations for mode shapes as well as other modal properties. Like the ATW1, the ATW2 was flown on the NF15B aircraft. In order to have a successful prediction of the onset flutter, the structural dynamics finite element (FE) model has to be robust and accurate. The ground vibration test (GVT) is used as one of the validation methods for robustness of the FE model.

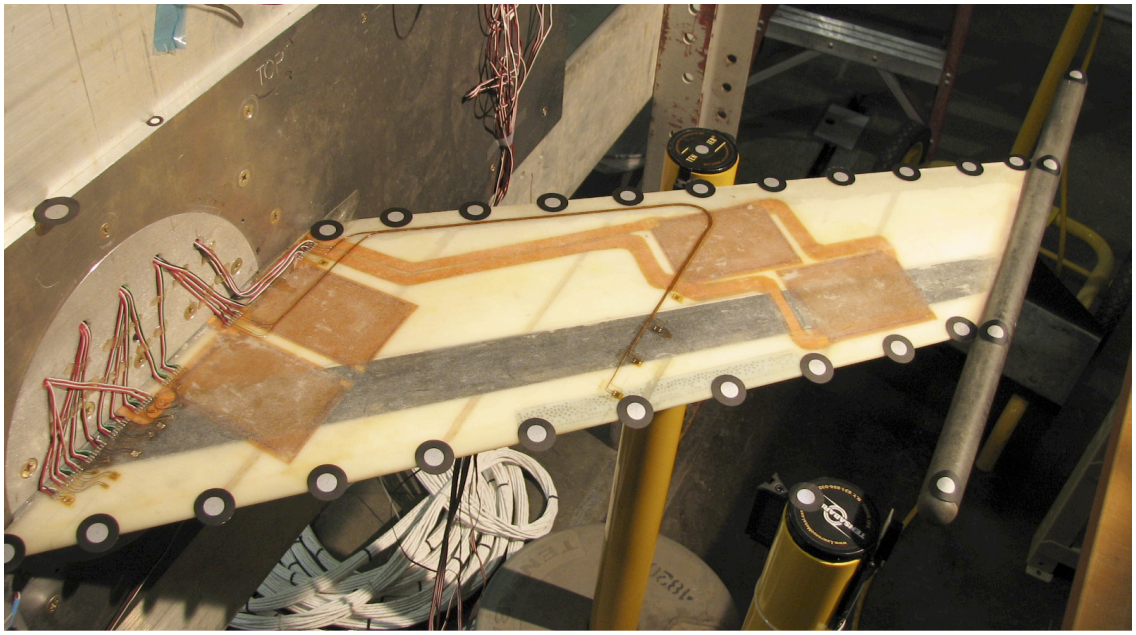

Figure 2. Aerostructures test wing 2.

The primary objective of this study is to obtain the GVT validated structural dynamics FE model for minimizing model uncertainties in the predicted flutter boundaries. Discrepancies are common between the test data and the analytical results. However, the FE model can be fine tuned through the use of the GVT data. Accurate and reliable GVT results are important to this adjusting process. Selection of measurement locations can be critical to the success of an experimental modal survey. So, different sensor and exciter placement algorithms for pre-test evaluations were investigated to ensure the quality of the modal test.

Manual trial-and-error methods provide an inefficient approach to correlate the FE model with test data. A more efficient approach is to use a mode matching technique for the model refinement of both ground and flight-based models. A model tuning technique utilized was NASA Dryden's multidisciplinary design, analysis, and optimization (MDAO) tool (ref. 2), which was used to adjust the structural properties so that the analytical results and the measured data were matched.

SENSOR/ACTUATOR PLACEMENT METHODS

It is important to assure that an adequate number of proper sensor locations are identified for the collection of data during the GVT. There are several existing techniques that can be used for the determination of measurement locations. These algorithms start with a full or selected set of finite element degrees of freedom (DOFs) with the desired number of mode shapes as shown in equation (1):

$$\overline{\Phi} = [\phi_1 \phi_2 \ldots \phi_l] \tag{1}$$

where $\overline{\Phi}$ is the reduced modal matrix ($d \times l$). Depending on the algorithm, the unwanted DOFs can be eliminated in one cycle or iteratively until the desired number of sensors is reached.

Effective Independence

The objective of the effective independence (EI) method is to select sensor locations that make the target modes linearly independent, while retaining as much information as possible. This procedure starts from a large set of candidate sensor locations in which the effective independence matrix ***E*** can be formed as shown in equation (2) (ref. 3).

$$\boldsymbol{E} = \overline{\Phi}\left(\overline{\Phi}^T\overline{\Phi}\right)^{-1}\overline{\Phi}^T \tag{2}$$

The DOF with the smallest value is removed and the ***E*** matrix is re-calculated for the new candidate set. The iterative process continues until the desired number of sensors is reached.

Genetic Algorithm

Selection of the sensor locations is a kind of optimization problem with discrete design variables. One of the solution methods for this optimization problem is the genetic algorithm (GA) (ref. 4). Using the determinant of the Fisher information matrix (**FIM**) as objective function, and sensor locations as design variables, the optimal sensor locations can be determined. The **FIM** is defined as shown in equation (3) (ref. 5).

$$\mathbf{FIM} \equiv \overline{\Phi}^T\overline{\Phi} \tag{3}$$

The sensor locations, which are based on the desired number of sensors, are randomly picked and the GA method will find the best set of locations that gives the maximum determinant value of the **FIM**. The determinant of the **FIM** indicates the amount of information in the data that is retained at the reduced set of coordinates. Maintaining a high value for this determinant is desired so that the **FIM** retains as much information as possible. The optimization problem statement can be written as:

Maximize the objective function $obj = \det(\mathbf{FIM})$ for any set of sensor positions with no constraint equations.

Kinetic Energy Sorting

The kinetic energy sorting technique involves an examination of each DOF's contribution of kinetic energy to each mode shape. The calculation of the kinetic energy in terms of the mode shapes can be expressed as shown in equation (4):

$$\mathrm{KE}_{ik} = \overline{\Phi}_{ik}\sum_j \mathrm{M}_{ij}\overline{\Phi}_{jk} \tag{4}$$

where KE_{ik} is the kinetic energy associated with the *i*-th DOF in the *k*-th target mode. The total kinetic energy for each DOF is the summation of the normalized kinetic energy of each DOF for each mode. Those DOFs having the greatest contribution or most kinetic energy can be identified and selected as sensor locations.

Guyan Reduction

The purpose of the Guyan reduction (ref. 6) is to remove the number of DOFs in a large FE model, but still maintain the characteristics of the original model at the lower frequencies. Higher frequency modes are neglected because these DOFs can be removed based on the fact that the inertia forces are

negligible compared with the elastic forces. This process involves examining the ratio of stiffness over mass for each DOF. If the ratio is small, then there are significant inertia effects associated with the DOF, and thus it should be retained. If the ratio is large, then the inertia effects are negligible and the corresponding DOF can be removed.

Iterative Guyan Reduction

Unlike the standard Guyan reduction, the iterative Guyan reduction (ref. 7) removes the DOF one at a time so that at each stage the effect of each DOF removed is redistributed to all of the remaining DOFs, resulting in greater accuracy than the non-iterative approach.

Driving Point Residues

Driving point residues (DPR) are equivalent to modal participation factors. They are proportional to the magnitude of the mode shapes. A driving point is a point in the structure where the excitation DOF and the response are equal. If the modal matrix is mass normalized, then the driving point residues for the DOF i of the mode shape k can be computed (ref. 8) as shown in equation (5):

$$DPR_k(i,i) = \frac{\bar{\Phi}(i) \otimes \bar{\Phi}(i)}{\omega_k} \tag{5}$$

where ω_k is the corresponding natural frequency and $\otimes$ is the element-by-element multiplication operator. The normalized DPR can then be used to calculate the average, minimum, maximum, and weighted modal displacement of all the target modes. The optimal sensor/exciter locations are then selected based on the values of the weighted driving point residue and the number of sensors/actuators available for the test. In this study, the weighted minimum was used for the selection of the sensor locations in order to opt out of those DOFs at the nodal point of a mode. The weighted minimum DPR was obtained as shown in equation (6).

$$DPR_{weighted}(i) = \min_{j=1}^{n} \overline{DPR}_j(i,i) \cdot \frac{1}{n} \sum_{j=1}^{n} \overline{DPR}_j(i,i) \tag{6}$$

The weighted maximum was used for the selection of the excitation locations so that those easily excited DOFs could be identified. The weighted maximum DPR can be expressed as shown in equation (7):

$$DPR_{weighted}(i) = \max_{j=1}^{n} \overline{DPR}_j(i,i) \cdot \frac{1}{n} \sum_{j=1}^{n} \overline{DPR}_j(i,i) \tag{7}$$

where $\overline{DPR}$ is the normalized DPR.

STRUCTURAL DYNAMIC MODEL TUNING PROCEDURE

Discrepancies in frequencies and mode shapes are minimized using a series of optimization procedures (refs. 9-11). There are two optimization algorithms adopted in NASA Dryden's MDAO tool: the traditional gradient-based algorithm (ref. 12) and the genetic algorithm. Gradient-based algorithms work well for continuous design variable problems, whereas GAs can handle continuous and discrete design variable problems easily. When there are multiple local minima, GAs are able to find the global

optimum results, whereas gradient-based methods may converge to a locally minimum value. In this research work, the GA was used for the solution of the optimization problem.

The GA is directly applicable only to unconstrained optimization; it is necessary to use some additional methods in order to solve the constrained optimization problem. The most popular approach is to add penalty functions in proportion to the magnitude of constraint violation to the objective function (ref. 13). The general form of the penalty function is shown in equation (8):

$$L(\bar{X}) = F(\bar{X}) + \sum_{i=1}^{q} \lambda_i g_i(\bar{X}) + \sum_{j=1}^{r} \lambda_{j+q} h_j(\bar{X}) \tag{8}$$

where $L(\bar{X})$ indicates the new objective function to be optimized, $F(\bar{X})$ is the original objective function, $g_i(\bar{X})$ is the inequality constraint, $h_j(\bar{X})$ is the equality constraint, λ_i are the Lagrange multipliers, $\bar{X}$ is the design variables vector, and q and r are the number of inequality and equality constraints, respectively.

The analytical mass properties, the mass matrix orthogonality, and the natural frequencies and mode shapes are matched to the target values based on the following three tuning steps.

Step 1: Tuning Mass Properties

The difference in the analytical and target values of the total mass, the center of gravity (CG) location, and the mass moment of inertias at the CG location are minimized to have the improved rigid body dynamics as shown in equations (9) through (18).

$$J_1 = (W - W_G)^2 / W_G^2 \tag{9}$$

$$J_2 = (X - X_G)^2 / X_G^2 \tag{10}$$

$$J_3 = (Y - Y_G)^2 / Y_G^2 \tag{11}$$

$$J_4 = (Z - Z_G)^2 / Z_G^2 \tag{12}$$

$$J_5 = (I_{XX} - I_{XXG})^2 / I_{XXG}^2 \tag{13}$$

$$J_6 = (I_{YY} - I_{YYG})^2 / I_{YYG}^2 \tag{14}$$

$$J_7 = (I_{ZZ} - I_{ZZG})^2 / I_{ZZG}^2 \tag{15}$$

$$J_8 = (I_{XY} - I_{XYG})^2 / I_{XYG}^2 \tag{16}$$

$$J_9 = (I_{YZ} - I_{YZG})^2 / I_{YZG}^2 \tag{17}$$

$$J_{10} = (I_{ZX} - I_{ZXG})^2 / I_{ZXG}^2 \tag{18}$$

Step 2: Tuning Mass Matrix

The off-diagonal terms of the orthonormalized mass matrix are reduced to improve the mass orthogonality as shown in equation (19):

$$J_{11} = \sum_{i=1, j=1, i \neq j}^{n} \left(\overline{\mathbf{M}}_{ij} \right)^2 \tag{19}$$

where n is the number of modes to be matched and $\overline{\mathbf{M}}$ is defined as shown in equation (20).

$$\overline{\mathbf{M}} = \Phi_G^T \mathbf{T}^T \mathbf{M} \mathbf{T} \Phi_G \tag{20}$$

In equation 20 above, the mass matrix **M** is calculated from the FE model, while the target eigen-matrix Φ_G is measured from the GVT. The eigen-matrix Φ_G remains constant during the optimization procedure. A transformation matrix **T** in the above equation is based on Guyan reduction, improved reduction system (ref. 14) or the system equivalent reduction expansion process (SEREP) (ref. 15). This reduction is required due to the limited number of available sensor locations and difficulties in measuring the rotational DOFs.

Step 3: Tuning Frequencies and Mode Shapes

Two different types of approach can be used for tuning the frequencies and mode shapes. In the first option, shown in equations (21) and (22), the objective function considered combines the normalized errors between GVT and computed frequencies with the total error associated with the off-diagonal terms of the orthonormalized stiffness matrix.

$$J_{12} = \sum_{i=1}^{n} \left(\frac{\Omega_i - \Omega_{iG}}{\Omega_i} \right)^2 \tag{21}$$

$$J_{13} = \sum_{i=1, j=1, i \neq j}^{n} \left(\overline{\mathbf{K}}_{ij} \right)^2 \tag{22}$$

The matrix $\overline{\mathbf{K}}$ is obtained from the matrix products as shown in equation (23):

$$\overline{\mathbf{K}} = \Phi_G^T \mathbf{T}^T \mathbf{K} \mathbf{T} \Phi_G \tag{23}$$

where the stiffness matrix, **K**, is calculated from the FE model.

In the second option, shown in equations (24) and (25), the error norm combines the normalized error between the GVT and computed frequencies with the total error between the GVT and computed mode shapes at given sensor points.

$$J_{12} = \sum_{i=1}^{n} \left(\frac{\Omega_i - \Omega_{iG}}{\Omega_i} \right)^2 \tag{24}$$

$$J_{13} = \sum_{i=1}^{m} \sum_{j=1}^{n} \left(\Phi_{ij} - \Phi_{ijG} \right)^2 \tag{25}$$

In this study, the second option for tuning frequencies and mode shapes was employed since the definition of the objective function is much simpler than in the first option for this application. Any errors in both the modal frequencies and the mode shapes are minimized by including an index for each of these in the objective function. For this option, a small number of sensor locations can be used at which errors between the GVT and computed mode shapes are obtained. Any one of J_1 thru J_{13} can be used as the objective function with the others treated as constraints. This gives the flexibility to achieve the particular

optimization goal while maintaining the other properties at as close to the desired target value as possible. The optimization problem statement can be written as:

Minimize J_i
Such that $J_k \leq \varepsilon_k$, for k = 1 thru 13 and $k \neq i$

where ε_k is a small value which can be adjusted according to the tolerance of each constraint condition.

TEST ARTICLE

The ATW2 was used to demonstrate NASA Dryden's MDAO tool through the process of ground vibration testing and the model tuning technique. This test article was a small-scale airplane wing comprised of an airfoil and wing tip boom as shown in figure 3, based on the ATW1 design. This wing was formulated based on a NACA-65A004 airfoil shape with a 3.28 aspect ratio. The wing had a half span of 18 in. with root chord length of 13.2 in. and tip chord length of 8.7 in. The total area of this wing was 197 in^2. The wing tip boom was a 1-in. diameter hollow tube of 21.5 in. length. The total weight of the wing was 2.66 lb.

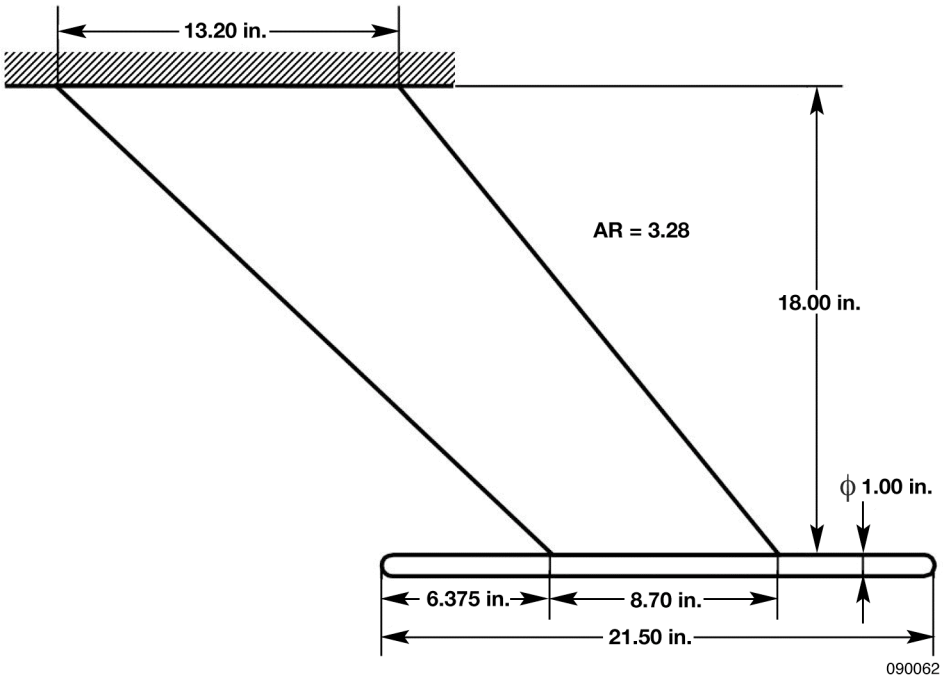

Figure 3. Dimension of the ATW2.

Since the ATW was attached to the F15B flight test fixture, the construction of the wing was limited to lightweight materials with no metal, due to safety concerns. The wing and spar were constructed from fiberglass cloth, the boom was constructed from carbon fiber composite, the wing core was constructed from rigid foam, and the components were attached by epoxy. The wing skin was made of three plies of fiberglass cloth, each about 0.01 in. thick. The internal spar located at the 30% chord line was composed of 10 plies, 0.05 in. thick of carbon at the root but decreases to 1 ply, 0.005 in. thick at the tip.

TEST SETUP

Ground vibration tests were performed to determine the dynamic modal characteristics of the ATW2. In the test set up, the ATW2 was clamped on to a circular plate, which was bolted to a mounting panel, and then installed into a small strong back called the ground test fixture in the NASA Dryden Flight Loads Laboratory. The PONTOS photogrammetry optical measuring system (Gesellschaft für Optische Messtechnik, Braunschweig, Germany), as shown in figure 4, was used to measure output displacement/acceleration at the sensor points. For the excitation method, an impact hammer with an impedance head was used to excite the ATW2's natural frequencies and mode shapes as well as to measure input forces.

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Figure 4. The PONTOS photogrammetry optical measuring system.

PONTOS is a non-contact optical 3D measuring system. It analyzes, computes, and documents object deformations, rigid body movements, and the dynamic behavior of a measuring point (ref. 16). The PONTOS system provides an alternative for complex sensor technology like laser sensor, draw-wire sensors or accelerometers, which are commonly used in GVTs for measuring responses of the structure. The features of the PONTOS system include:

- Unlimited number of sensors. The sensor markers are weightless, and a large number of sensors can be used at the same time without altering the total weight or the mode shapes of the structure.
- Non-contact acquisition of the precise 3D position of any number of measuring points.
- Mobility and flexibility due to an easy and compact measuring system.
- Easy and quick adaptation to different measuring volumes and measuring tasks.

The limitations of the PONTOS system include:

- Measuring structural vibration up to 250 Hz.
- Measuring frame rate up to 500 Hz at 1280x1024 pixels.
- Measuring volume up to 1700x1360x1360 mm^3.
- Applying the sensors on a plane or slightly curved surface.

SENSOR PLACEMENT DISCUSSION

Only a small number of sensors were placed on the wing for the GVT compared to the full FE model DOFs. The selection of sensor locations were based on the sensor placement algorithms previously discussed in Section II. In order to compare different sensor placement algorithms, the determinant of **FIM** was calculated for different sets of sensor locations. Results are summarized in table 1 and the corresponding sensor locations are shown in figure 5.

Table 1. Comparison of the determinant of FIM for different sensor placement algorithm.

Sensor placement algorithms	det(FIM) (30 sensors, 3 modes)
Effective independence	753.1
Genetic algorithm*	753.1
Kinetic energy	303.6
Iterative Guyan reduction	59.5
Non-iterative Guyan reduction	8.6
Model configuration (25 sensors)	50.0
Driving point residue	97.0

* Based on 150 populations and 500 generations

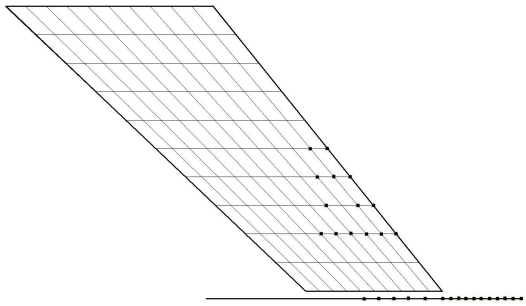


Figure 5a. DPR method.

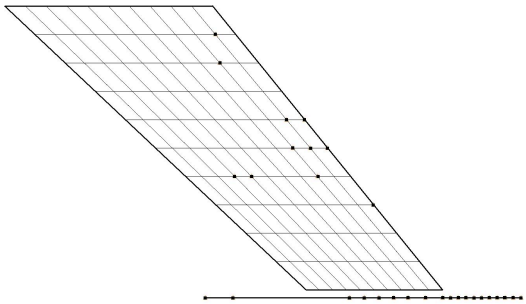


Figure 5b. KE method.

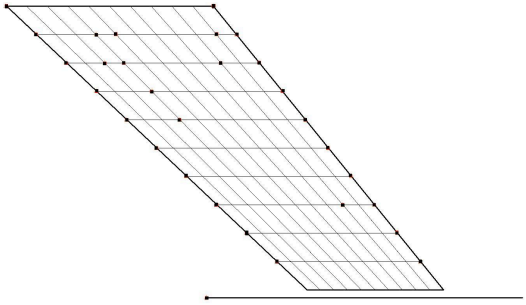


Figure 5c. Guyan reduction method.

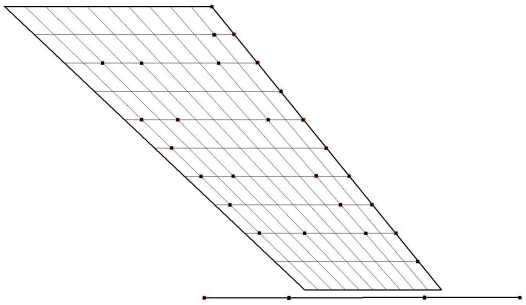


Figure 5d. Iterative Guyan reduction method.

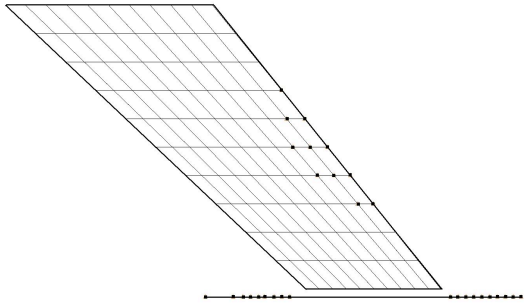


Figure 5e. Effective independence method.

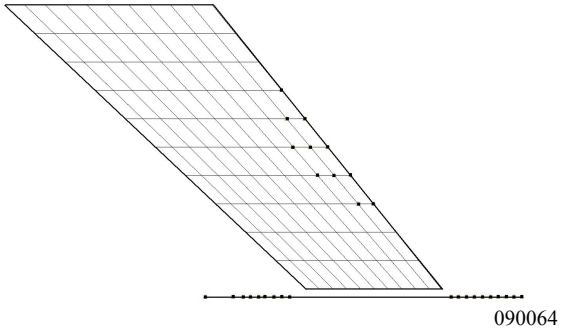


Figure 5f. Genetic algorithm.

Figure 5. Sensor locations from different sensor placement algorithms.

In table 1, the EI and GA methods have the same determinant of **FIM** value. This is due to the fact that the EI method is also an optimization process. In this application, both the EI and GA methods found the globally optimal value. The sensor locations with higher determent of **FIM** value were used for the GVT response measurement locations.

For the excitation point selection, the weighted maximum driving point residue method was used to determine the excitation locations. The predicted sensor locations and excitation point based on the FE model of the ATW2 is shown in figure 6 and the corresponding coordinates are given in table 2.

At the time of this ATW2 research work, only the GVT results with the sensor placements based on the model configuration were available. Therefore, these data were used for the FE model tuning process.

The sensor locations and excitation point of this GVT are shown in figure 7, and its coordinates are listed in table 3. Figure 8 shows the typical time history and frequency response curves of the ATW2 ground vibration tests.

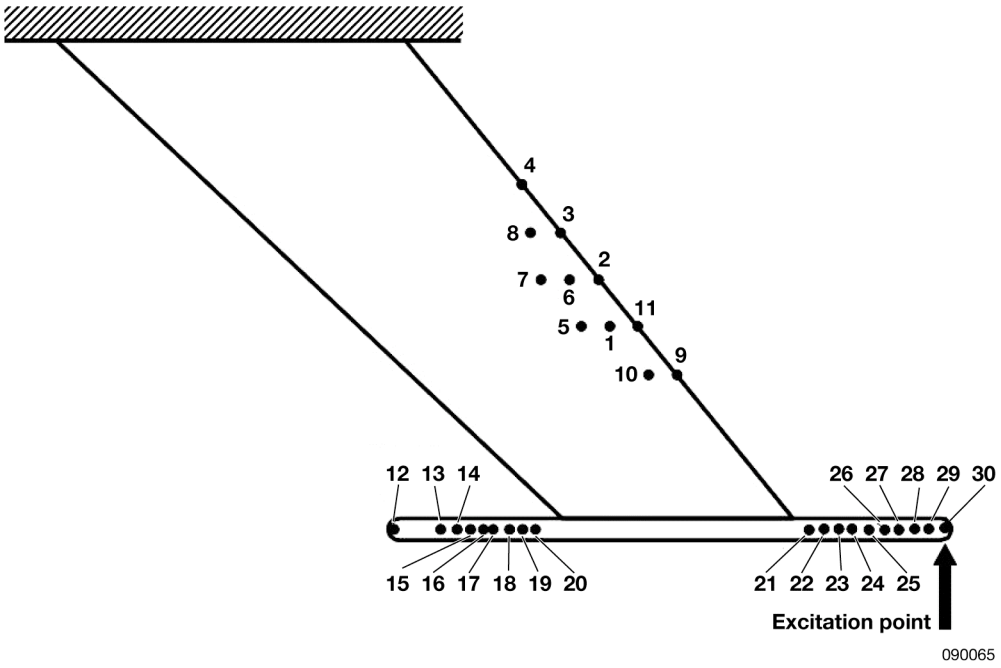


Figure 6. Predicted sensor/excitation locations.

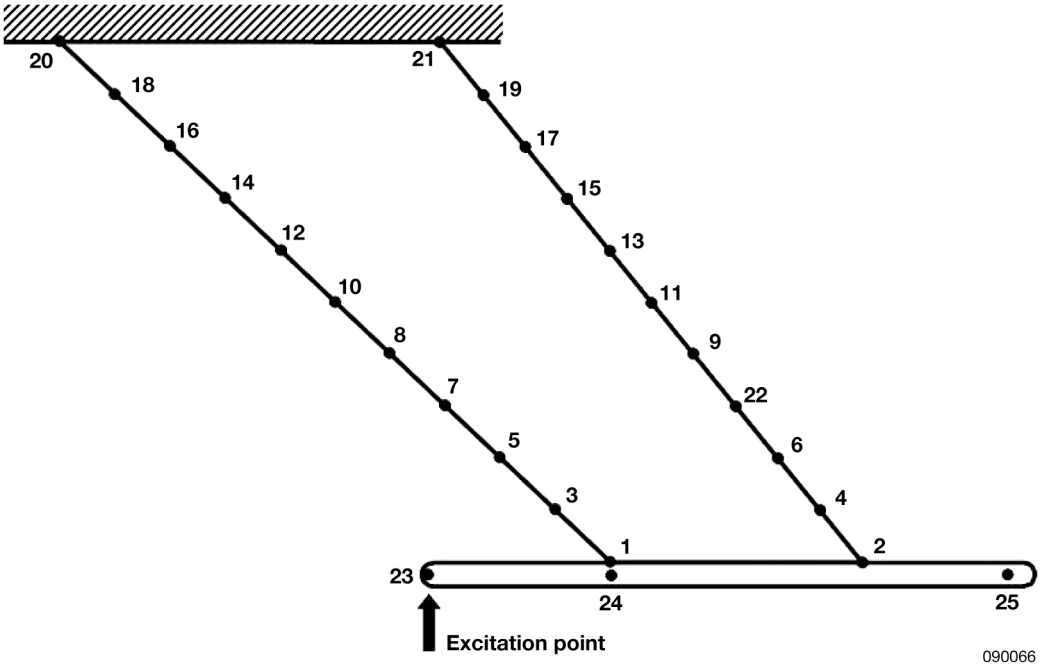


Figure 7. GVT sensor/excitation locations.

Table 2. Sensor locations for Figure 6.

Sensor point	Coordinates (inch)		
	X	Y	Z
1	20.9244	-10.80	-0.05
2	21.9750	-10.80	0
3	19.0499	-7.20	0
4	17.5875	-5.40	-0.001
5	19.8735	-10.80	0.1016
6	19.4167	-9.00	0.0537
7	18.3209	-9.00	0.1059
8	17.9092	-7.20	0.0559
9	23.4375	-12.60	0
10	22.4317	-12.60	0.0493
11	21.9750	-10.80	0
12	12.7500	-18.50	0
13	14.5000	-18.50	0
14	15.1250	-18.50	0
15	15.6250	-18.50	0
16	16.1250	-18.50	0
17	16.5000	-18.50	0
18	17.1250	-18.50	0
19	17.6250	-18.50	0
20	18.1250	-18.50	0
21	28.3250	-18.50	0
22	28.8250	-18.50	0
23	29.3250	-18.50	0
24	29.8250	-18.50	0
25	30.3250	-18.50	0
26	30.8250	-18.50	0
27	31.3250	-18.50	0
28	31.8250	-18.50	0
29	32.3250	-18.50	0
30	32.8250	-18.50	0

Table 3. Sensor locations for Figure 7.

Sensor point	Coordinates (inch)		
	X	Y	Z
1	19.125	-18.00	0
2	27.825	-18.00	0
3	17.212	-16.20	0
4	26.362	-16.20	0
5	15.300	-14.40	0
6	24.900	-14.40	0
7	13.387	-12.56	0
8	11.475	-10.80	0
9	21.975	-10.80	0
10	9.5625	-9.00	0
11	20.5125	-9.0	0
12	7.65	-7.2	0
13	19.0499	-7.2	0
14	5.7375	-5.4	0
15	17.5875	-5.4	0
16	3.825	-3.6	0
17	16.125	-3.6	0
18	1.9125	-1.8	0
19	14.6625	-1.8	0
20	0	0	0
21	13.2	0	0
22	23.4375	-12.6	0
23	12.75	-18.5	0
24	19.125	-18.5	0
25	32.825	-18.5	0

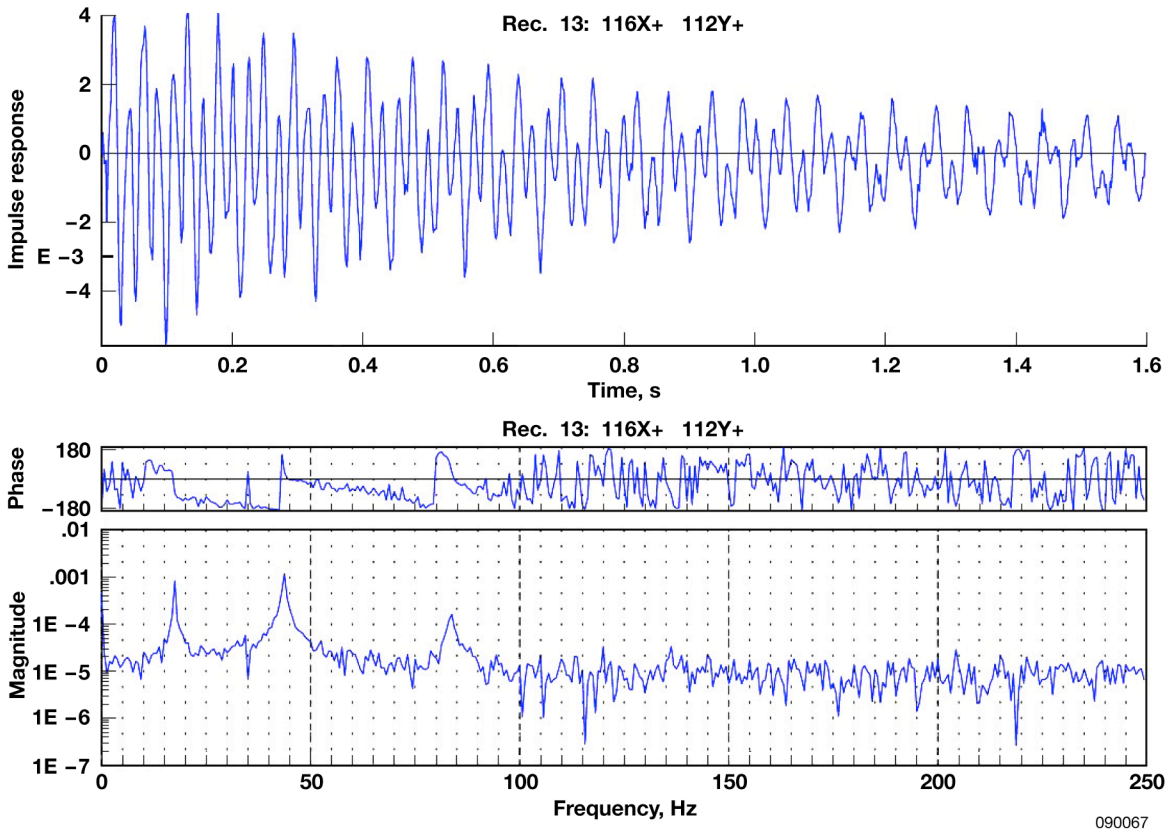


Figure 8. Typical time history and frequency response GVT results for the ATW2.

MODEL TUNING

The frequencies and mode shapes of first bending, first torsion and second bending modes; and total mass from the GVT are listed in table 4. The measurements of table 4 were based on the time history responses data collected by the PONTOS system at each of the sensor points. The eigensystem realization algorithm routine, which was developed by Juang and Pappa (ref. 17) at NASA Langley Research Center (Hampton, Virginia), was then used to identify the frequencies and mode shapes of the system.

Table 4. Measured frequencies and mode shapes (Z direction).

Sensor point	Mode 1 (17.24 Hz)	Mode 2 (44.10 Hz)	Mode 3 (84.00 Hz)
1	0.481	-0.398	-0.325
2	0.755	0.409	-0.187
3	0.386	-0.390	-0.149
4	0.670	0.353	0.142
5	0.311	-0.408	0.088
6	0.589	0.254	0.455
7	0.214	-0.320	0.113
8	0.139	-0.252	0.157
9	0.368	0.082	0.912
10	0.085	-0.177	0.131
11	0.281	0.036	1.000
12	0.047	-0.116	0.140
13	0.196	0.021	0.917
14	0.018	-0.067	0.053
15	0.157	0.018	0.870
16	0.006	0.022	-0.012
17	0.081	0.026	0.587
18	0.008	0.007	0.006
19	0.035	0.025	0.345
20	0.010	0.008	0.017
21	0.014	0.022	0.125
22	0.451	-0.111	0.765
23	0.312	-1.000	-0.582
24	0.518	-0.432	-0.523
25	1.000	0.962	-0.196

Corresponding numerical FE model frequencies and mode shapes computed using MSC/NASTRAN (MSC. Software Corporation, Santa Ana, California) (ref. 18) are shown in figure 9. The FE model in the MSC/NASTRAN format is provided in the appendix. The frequency differences between the GVT and the numerical results before model tuning (shown in table 5) were 53% in the second mode and 12% in the third mode, both of which greatly exceed the 3% limitation for the primary modes allowed by military specifications (refs. 19, 20). Therefore, the FE model needs to be updated for a more reliable flutter analysis.

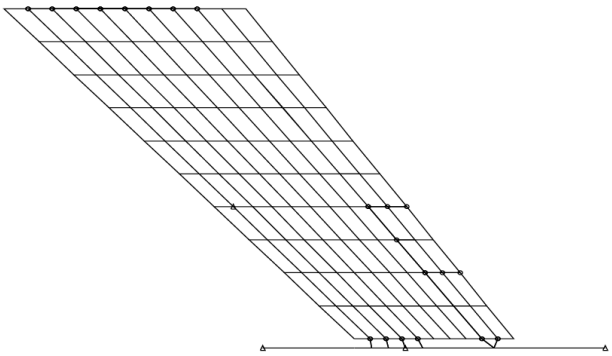


Figure 9a. MSC/NASTRAN FE model.

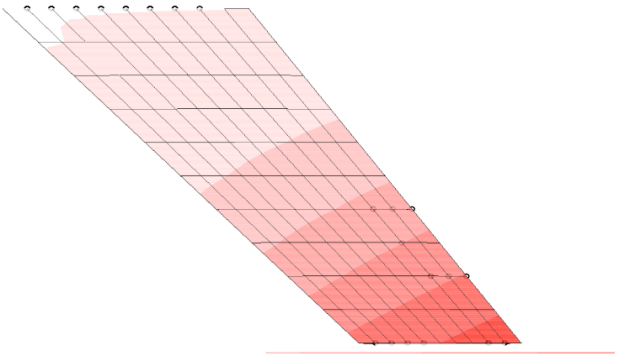


Figure 9b. Mode 1 (1st bending): 17.7048 Hz.

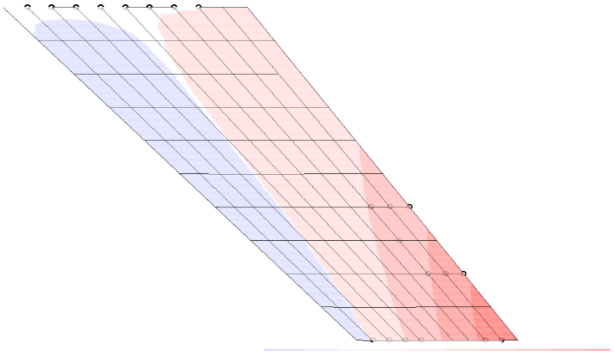
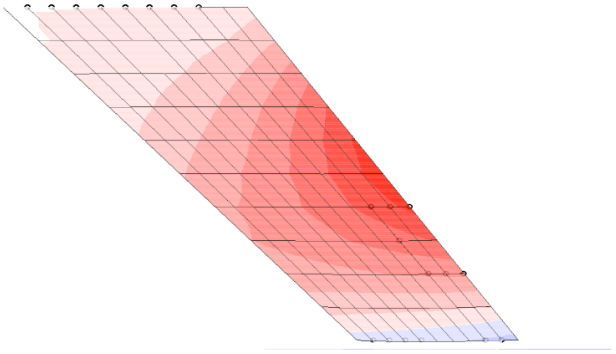


Figure 9c. Mode 2 (1st torsion): 20.9207 Hz.



090068

Figure 9d. Mode 3 (2nd bending): 88.3203 Hz.

Figure 9. Finite element model and mode shapes before tuning.

Table 5. Frequencies and total weight of the ATW2 before and after model tuning.

	GVT (Hz)	Before		After	
		MSC/NASTRAN (Guyan/Full; Hz)	Error (%)	MSC/NASTRAN (SEREP/Full; Hz)	Error (%)
Mode 1	17.24	17.71/17.70	2.72/2.68	17.79/17.79	3.19/3.19
Mode 2	44.10	20.93/20.92	-52.5/-52.6	44.71/44.71	1.38/1.38
Mode 3	84.00	93.91/88.32	11.80/5.14	84.33/84.33	0.39/0.39
Total weight (lb)	2.66	2.77	4.13	2.72	2.25

Since Guyan reduction is a static condensation, it is only accurate for lower modes. For higher modes, the errors become too large as shown in table 5. Unlike the Guyan reduction, the SEREP process preserves the dynamic character of the original full system model for selected modes of interest. Therefore the dynamic characteristics of the reduced model were virtually the same as the full model shown in table 5. Therefore, the SEREP model reduction process was used in this ATW2 model update application.

Using frequency difference as an objective function; and mass properties, mass orthogonality, and mode shapes as constraint equations; the frequencies before and after model tuning are presented in table

5. Dramatic improvement was noted, in that after model tuning, the frequencies difference was reduced to 1.38% in the second mode and 0.39% in the third mode.

Table 6 shows the center of gravity, moment of inertia, orthonormalized mass matrix, and modal assurance criterion (MAC) values of the ATW2 before and after model tuning. The off-diagonal terms of the orthonormalized mass matrix, maximum of 37% before model tuning, were minimized in the second tuning step. The maximum off-diagonal term of 7.4% after model tuning is observed in table 6, and this off-diagonal term of the orthonormalized mass matrix satisfies the 10% limitation allowed by military specifications. Model correlation with the test data prior to model tuning was poor and unacceptable to proceed with flight. The MAC values of 0.52 and 0.73 for modes 2 and 3 before model tuning become 0.97 and 0.95, respectively. Therefore, we can conclude that excellent model correlation with the test data was achieved after model tuning, which lead to a more reliable flutter speed prediction.

Table 6. Summary of center of gravity, moment of inertia, orthonormalized mass matrix and MAC values for the ATW2 before and after model tuning.

		Before tuning			After tuning		
C.G. (X,Y,Z)		14.22, -11.86, -0.011			13.089, -7.61, -0.0080		
Ixx		73.44			97.52		
Iyy		74.74			118.13		
Izz		148.1			215.5		
Ixy		-43.03			-85.55		
Ixz		0.032			0.0286		
Iyz		-0.02			0.0956		
Orthonormalized mass matrix		1	2	3	1	2	3
	1	1	25.0%	4.6%	1	4.0%	-5.7%
	2	0.2467	1	37.0%	0.0395	1	-7.4%
	3	0.0463	0.3681	1	-0.0565	-0.0743	1
MAC	Mode 1	0.90			0.99		
	Mode 2	0.52			0.97		
	Mode 3	0.73			0.95		

CONCLUDING REMARKS

This paper describes the ground vibration test (GVT) and model tuning procedures for the second aerostructures test wing (ATW2), which was developed at the National Aeronautics and Space Administration Dryden Flight Research Center (Edwards, California) for demonstrating flutter and advanced aeroelastic test techniques. In the sensor locations selection process, it was found that the effective independence (EI) and the genetic algorithm (GA) gave a higher determinant value of the Fisher information matrix (**FIM**) and thus, should be used for determining the sensor locations.

The finite element (FE) model tuning process was a challenging task, which depended not only on the accuracy of the experimental data, but also required a good prediction of the design variables for the optimization. After tuning the FE model, the frequency differences between GVT and the numerical results were within 3%, and the off-diagonal terms of the orthonormalized mass matrix were within 10%, both of which satisfy the military specifications. Excellent mode shape correlations were also achieved through the high modal assurance criterion (MAC) value (greater than 95%). With the updated FE model, the accuracy of flutter analysis can be improved and the flutter boundary prediction will be more reliable.

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APPENDIX
THE FE MODEL IN THE MSC/NASTRAN FORMAT

```
$ NASTRAN input file created by the MSC MSC.Nastran input file
$ translator ( MSC.Patran 13.1.116 ) on December  13, 2007 at 08:05:41.
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ASSIGN OUTPUT4='atw2c_kaa.op4',UNIT=31,STATUS=UNKNOWN,FORM=FORMATTED
SOL 103
$ Direct Text Input for Executive Control
$============================
$ DMAP ALTER SOL 103
     COMPILE SEMODES SOUIN=MSCSOU LIST REF$
     ALTER 315$
     OUTPUT4 MAA///30/2//9$
     OUTPUT4 KAA///31/2//9$
     ENDALTER
$============================
CEND
SEALL = ALL
SUPER = ALL
TITLE = ATW2
$ECHO = SORT
$ Direct Text Input for Global Case Control Data
SUBCASE 1
$ Subcase name : ATW2C
   SUBTITLE=ATW2C
   METHOD = 1
   SPC = 2
$   VECTOR(PLOT,SORT1,REAL)=ALL
   DISP=ALL
GPKE = ALL
BEGIN BULK
PARAM   POST    -1
PARAM   AUTOSPC YES
PARAM   WTMASS  .002588
PARAM   GRDPNT  0
PARAM   NOCOMPS,-1
PARAM,   USETPRT, 10
EIGRL    1                      10      0                       MAX
$ Direct Text Input for Bulk Data
$ Elements and Element Properties for region : pbar.700
PBAR     700     701    .5      .1      .1
$ Pset: "pbar.700" will be imported as: "pbar.700"
CBAR     300     700     303     308    -.061556-.998102.0018318
CBAR     301     700     9       124    -.061556-.998102.0018318
$ Elements and Element Properties for region : pcomp.500
$ Composite Property Record created from P3/PATRAN composite material
$ record : pcomp.500
$ Composite Material Description :
PCOMP    500    .01                                0.      0.
         501    .01     45.      YES     501    .01     -45.     YES
$ Pset: "pcomp.500" will be imported as: "pcomp.500"
CQUAD4   500     500     229     240     113     102     0.      0.
CQUAD4   501     500     218     229     102     91      0.      0.
```

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CQUAD4   502     500     207     218     91      80      0.      0.
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CQUAD4   506     500     163     174     47      36      0.      0.
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PELAS    1       50.
$ Pset: "celas2.ca6.cb6" will be imported as: "pelas.1"
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PELAS    4       1.+8
$ Pset: "celas2.ca4.cb4" will be imported as: "pelas.4"
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$ Pset: "celas2.ca3.cb3" will be imported as: "pelas.5"
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$ Pset: "celas2.ca2.cb2" will be imported as: "pelas.6"
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$ Elements and Element Properties for region : celas2.ca1.cb1
PELAS    7       1.+6
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CQUAD4   604     600     237     238     115     116     0.      0.
CQUAD4   605     600     236     237     116     117     0.      0.
CQUAD4   606     600     235     236     117     118     0.      0.
CQUAD4   607     600     234     235     118     119     0.      0.
```

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CQUAD4   618     600     211     212     97      98      0.      0.
CTRIA3   619     600     99      211     98      0.      0.
CTRIA3   620     600     197     67      68      0.      0.
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CQUAD4   637     600     168     169     52      53      0.      0.
CQUAD4   638     600     310     311     305     306     0.      0.
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CTRIA3   640     600     153     23      24      0.      0.
CQUAD4   641     600     152     153     24      25      0.      0.
CQUAD4   642     600     151     152     25      26      0.      0.
CQUAD4   643     600     150     151     26      27      0.      0.
CQUAD4   644     600     149     150     27      28      0.      0.
CQUAD4   645     600     148     149     28      29      0.      0.
CQUAD4   646     600     147     148     29      30      0.      0.
CQUAD4   647     600     146     147     30      31      0.      0.
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CQUAD4   653     600     128     129     4       5       0.      0.
CQUAD4   654     600     127     128     5       6       0.      0.
CQUAD4   655     600     126     127     6       7       0.      0.
CQUAD4   656     600     125     126     7       8       0.      0.
CQUAD4   657     600     124     125     8       9       0.      0.
CQUAD4   658     600     123     124     9       10      0.      0.
CTRIA3   659     600     11      123     10      0.      0.
CQUAD4   660     600     145     146     31      32      0.      0.
CTRIA3   661     600     33      145     32      0.      0.
CQUAD4   662     600     167     168     53      54      0.      0.
CTRIA3   663     600     55      167     54      0.      0.
$ Elements and Element Properties for region : pshell.608
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PSHELL   608     601    .06      601             601
$ Pset: "pshell.608" will be imported as: "pshell.608"
CQUAD4   700     608     309     311     305     304     0.      0.
CQUAD4   701     608     308     309     304     303     0.      0.
CQUAD4   702     608     31      42      157     146     0.      0.
CQUAD4   703     608     42      53      168     157     0.      0.
$ Elements and Element Properties for region : psolid.300
PSOLID   300     301     0
$ Pset: "psolid.300" will be imported as: "psolid.300"
CHEXA    200     300     13      2       3       14      142     131
         130     141
CHEXA    201     300     14      3       4       15      141     130
         129     140
CHEXA    202     300     24      13      14      25      153     142
         141     152
CHEXA    203     300     15      4       5       16      140     129
         128     139
CHEXA    204     300     25      14      15      26      152     141
         140     151
CHEXA    205     300     35      24      25      36      164     153
         152     163
CHEXA    206     300     16      5       6       17      139     128
         127     138
CHEXA    207     300     26      15      16      27      151     140
         139     150
CHEXA    208     300     36      25      26      37      163     152
         151     162
CHEXA    209     300     46      35      36      47      175     164
         163     174
CHEXA    210     300     17      6       7       18      138     127
         126     137
CHEXA    211     300     27      16      17      28      150     139
         138     149
CHEXA    212     300     37      26      27      38      162     151
         150     161
CHEXA    213     300     47      36      37      48      174     163
         162     173
CHEXA    214     300     57      46      47      58      186     175
         174     185
CHEXA    215     300     18      7       8       19      137     126
         125     136
CHEXA    216     300     28      17      18      29      149     138
         137     148
CHEXA    217     300     38      27      28      39      161     150
         149     160
CHEXA    218     300     48      37      38      49      173     162
         161     172
CHEXA    219     300     58      47      48      59      185     174
         173     184
CHEXA    220     300     68      57      58      69      197     186
         185     196
CHEXA    221     300     19      8       9       20      136     125
         124     135
CHEXA    222     300     29      18      19      30      148     137
         136     147
CHEXA    223     300     39      28      29      40      160     149
         148     159
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CHEXA    224     300     49      38      39      50      172     161
         160     171
CHEXA    225     300     59      48      49      60      184     173
         172     183
CHEXA    226     300     69      58      59      70      196     185
         184     195
CHEXA    227     300     79      68      69      80      208     197
         196     207
CHEXA    228     300     20      9       10      21      135     124
         123     134
CHEXA    229     300     30      19      20      31      147     136
         135     146
CHEXA    230     300     40      29      30      41      159     148
         147     158
CHEXA    231     300     50      39      40      51      171     160
         159     170
CHEXA    232     300     60      49      50      61      183     172
         171     182
CHEXA    233     300     70      59      60      71      195     184
         183     194
CHEXA    234     300     80      69      70      81      207     196
         195     206
CHEXA    235     300     90      79      80      91      219     208
         207     218
CHEXA    236     300     31      20      21      32      146     135
         134     145
CHEXA    237     300     41      30      31      42      158     147
         146     157
CHEXA    238     300     51      40      41      52      170     159
         158     169
CHEXA    239     300     61      50      51      62      182     171
         170     181
CHEXA    240     300     71      60      61      72      194     183
         182     193
CHEXA    241     300     81      70      71      82      206     195
         194     205
CHEXA    242     300     91      80      81      92      218     207
         206     217
CHEXA    243     300     101     90      91      102     230     219
         218     229
CHEXA    244     300     304     303     313     300     309     308
         314     302
CHEXA    245     300     52      41      42      53      169     158
         157     168
CHEXA    246     300     62      51      52      63      181     170
         169     180
CHEXA    247     300     72      61      62      73      193     182
         181     192
CHEXA    248     300     82      71      72      83      205     194
         193     204
CHEXA    249     300     92      81      82      93      217     206
         205     216
CHEXA    250     300     102     91      92      103     229     218
         217     228
CHEXA    251     300     112     101     102     113     241     230
         229     240
CHEXA    252     300     305     304     300     306     311     309
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         302     310
CHEXA    253     300     63      52      53      64      180     169
         168     179
CHEXA    254     300     73      62      63      74      192     181
         180     191
CHEXA    255     300     83      72      73      84      204     193
         192     203
CHEXA    256     300     93      82      83      94      216     205
         204     215
CHEXA    257     300     103     92      93      104     228     217
         216     227
CHEXA    258     300     113     102     103     114     240     229
         228     239
CHEXA    259     300     64      53      54      65      179     168
         167     178
CHEXA    260     300     74      63      64      75      191     180
         179     190
CHEXA    261     300     84      73      74      85      203     192
         191     202
CHEXA    262     300     94      83      84      95      215     204
         203     214
CHEXA    263     300     104     93      94      105     227     216
         215     226
CHEXA    264     300     114     103     104     115     239     228
         227     238
CHEXA    265     300     75      64      65      76      190     179
         178     189
CHEXA    266     300     85      74      75      86      202     191
         190     201
CHEXA    267     300     95      84      85      96      214     203
         202     213
CHEXA    268     300     105     94      95      106     226     215
         214     225
CHEXA    269     300     115     104     105     116     238     227
         226     237
CHEXA    270     300     86      75      76      87      201     190
         189     200
CHEXA    271     300     96      85      86      97      213     202
         201     212
CHEXA    272     300     106     95      96      107     225     214
         213     224
CHEXA    273     300     116     105     106     117     237     226
         225     236
CHEXA    274     300     97      86      87      98      212     201
         200     211
CHEXA    275     300     107     96      97      108     224     213
         212     223
CHEXA    276     300     117     106     107     118     236     225
         224     235
CHEXA    277     300     108     97      98      109     223     212
         211     222
CHEXA    278     300     118     107     108     119     235     224
         223     234
CHEXA    279     300     119     108     109     120     234     223
         222     233
CPENTA   280     300     2       1       131     13      12      142
CPENTA   281     300     13      12      142     24      23      153
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CPENTA   282     300     24      23      153     35      34      164
CPENTA   283     300     35      34      164     46      45      175
CPENTA   284     300     46      45      175     57      56      186
CPENTA   285     300     57      56      186     68      67      197
CPENTA   286     300     68      67      197     79      78      208
CPENTA   287     300     79      78      208     90      89      219
CPENTA   288     300     90      89      219     101     100     230
CPENTA   289     300     21      22      134     10      11      123
CPENTA   290     300     101     100     230     112     111     241
CPENTA   291     300     32      33      145     21      22      134
CPENTA   292     300     300     301     302     313     312     314
CPENTA   293     300     306     307     310     300     301     302
CPENTA   294     300     65      66      178     54      55      167
CPENTA   295     300     76      77      189     65      66      178
CPENTA   296     300     87      88      200     76      77      189
CPENTA   297     300     98      99      211     87      88      200
CPENTA   298     300     109     110     222     98      99      211
CPENTA   299     300     120     121     233     109     110     222
$ Elements and Element Properties for region : conm2
CONM2    400     500     0       0.475   0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    401     513     0       0.      0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    402     529     0       0.075   0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    406     68      0       0.03    0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    407     57      0       0.03    0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    408     46      0       0.03    0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    409     35      0       0.03    0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    410     24      0       0.03    0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    412     91      0       0.0638  0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    413     97      0       0.0638  0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    414     103     0       0.0638  0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    415     109     0       0.0638  0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    416     212     0       0.0638  0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    417     218     0       0.0638  0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    418     228     0       0.0638  0.      0.      0.
         0.      0.      0.      0.      0.      0.
CONM2    419     222     0       0.0638  0.      0.      0.
         0.      0.      0.      0.      0.      0.
$ Elements and Element Properties for region : pbar.39
PBAR     39      901    .097314 .011411 .011411 .022821
        .5                      .5      -.5                     -.5
$ Pset: "pbar.39" will be imported as: "pbar.39"
CBAR     800     39      501     500     0.     -1.      0.
CBAR     801     39      502     501     0.     -1.      0.
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CBAR     802     39      503     502     0.      -1.      0.
CBAR     803     39      504     503     0.      -1.      0.
CBAR     804     39      505     504     0.      -1.      0.
CBAR     805     39      506     505     0.      -1.      0.
CBAR     806     39      507     506     0.      -1.      0.
CBAR     807     39      508     507     0.      -1.      0.
CBAR     808     39      509     508     0.      -1.      0.
CBAR     809     39      510     509     0.      -1.      0.
CBAR     810     39      512     511     0.      1.       0.
CBAR     811     39      513     512     0.      1.       0.
CBAR     812     39      514     513     0.      1.       0.
CBAR     813     39      515     514     0.      -1.      0.
CBAR     814     39      516     515     0.      -1.      0.
CBAR     815     39      517     516     0.      -1.      0.
CBAR     816     39      518     517     0.      1.       0.
CBAR     817     39      519     518     0.      -1.      0.
CBAR     818     39      520     519     0.      -1.      0.
CBAR     819     39      521     520     0.      -1.      0.
CBAR     820     39      522     521     0.      -1.      0.
CBAR     821     39      523     522     0.      -1.      0.
CBAR     822     39      524     523     0.      -1.      0.
CBAR     823     39      525     524     0.      -1.      0.
CBAR     824     39      526     525     0.      -1.      0.
CBAR     825     39      527     526     0.      -1.      0.
CBAR     826     39      528     527     0.      -1.      0.
CBAR     827     39      529     528     0.      -1.      0.
CBAR     828     39      530     510     0.      -1.      0.
CBAR     829     39      511     530     0.      1.       0.
$ Elements and Element Properties for region : pcomp.41
$ Composite Property Record created from P3/PATRAN composite material
$ record : pcomp.10
$ Composite Material Description :
PCOMP    41      -.13            8000.    HOFF    0.      0.
         201     .11     0.      YES      202     .02     45.      YES
$ Pset: "pcomp.41" will be imported as: "pcomp.41"
CQUAD4   1002    41      228     239      240     229     4        0.
CQUAD4   1003    41      227     238      239     228     4        0.
CQUAD4   1012    41      217     228      229     218     4        0.
CQUAD4   1013    41      216     227      228     217     4        0.
CQUAD4   1202    41      102     113      114     103     4        0.
CQUAD4   1203    41      103     114      115     104     4        0.
CQUAD4   1212    41      91      102      103     92      4        0.
CQUAD4   1213    41      92      103      104     93      4        0.
$ Elements and Element Properties for region : pcomp.42
$ Composite Property Record created from P3/PATRAN composite material
$ record : pcomp.20
$ Composite Material Description :
PCOMP    42      -.09            8000.    HOFF    0.      0.
         201     .075    0.      YES      202     .015    45.      YES
$ Pset: "pcomp.42" will be imported as: "pcomp.42"
CQUAD4   1022    42      206     217      218     207     4        0.
CQUAD4   1023    42      205     216      217     206     4        0.
CQUAD4   1032    42      195     206      207     196     4        0.
CQUAD4   1033    42      194     205      206     195     4        0.
CQUAD4   1222    42      80      91       92      81      4        0.
CQUAD4   1223    42      81      92       93      82      4        0.
CQUAD4   1232    42      69      80       81      70      4        0.
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CQUAD4   1233    42      70      81      82      71      4       0.
$ Elements and Element Properties for region : pcomp.43
$ Composite Property Record created from P3/PATRAN composite material
$ record : pcomp.30
$ Composite Material Description :
PCOMP    43     -.073           8000.    HOFF    0.      0.
         201    .058     0.      YES     202    .015    45.      YES
$ Pset: "pcomp.43" will be imported as: "pcomp.43"
CQUAD4   1042    43      184     195     196     185     4       0.
CQUAD4   1043    43      183     194     195     184     4       0.
CQUAD4   1052    43      173     184     185     174     4       0.
CQUAD4   1053    43      172     183     184     173     4       0.
CQUAD4   1242    43      58      69      70      59      4       0.
CQUAD4   1243    43      59      70      71      60      4       0.
CQUAD4   1252    43      47      58      59      48      4       0.
CQUAD4   1253    43      48      59      60      49      4       0.
$ Elements and Element Properties for region : pcomp.44
$ Composite Property Record created from P3/PATRAN composite material
$ record : pcomp.40
$ Composite Material Description :
PCOMP    44     -.038           8000.    HOFF    0.      0.
         201    .023     0.      YES     202    .015    45.      YES
$ Pset: "pcomp.44" will be imported as: "pcomp.44"
CQUAD4   1062    44      162     173     174     163     4       0.
CQUAD4   1063    44      161     172     173     162     4       0.
CQUAD4   1072    44      151     162     163     152     4       0.
CQUAD4   1073    44      150     161     162     151     4       0.
CQUAD4   1262    44      36      47      48      37      4       0.
CQUAD4   1263    44      37      48      49      38      4       0.
CQUAD4   1272    44      25      36      37      26      4       0.
CQUAD4   1273    44      26      37      38      27      4       0.
$ Elements and Element Properties for region : pcomp.45
$ Composite Property Record created from P3/PATRAN composite material
$ record : pcomp.50
$ Composite Material Description :
PCOMP    45     -.03            8000.    HOFF    0.      0.
         201    .015     0.      YES     202    .015    45.      YES
$ Pset: "pcomp.45" will be imported as: "pcomp.45"
CQUAD4   1082    45      140     151     152     141     4       0.
CQUAD4   1083    45      139     150     151     140     4       0.
CQUAD4   1092    45      129     140     141     130     4       0.
CQUAD4   1093    45      128     139     140     129     4       0.
CQUAD4   1282    45      14      25      26      15      4       0.
CQUAD4   1283    45      15      26      27      16      4       0.
CQUAD4   1292    45      3       14      15      4       4       0.
CQUAD4   1293    45      4       15      16      5       4       0.
$ Elements and Element Properties for region : pcomp.46
$ Composite Property Record created from P3/PATRAN composite material
$ record : pcomp.200
$ Composite Material Description :
PCOMP    46     -.0165          8000.    HOFF    0.      0.
         202    .0033   45.     YES     202    .0033   -45.     YES
         202    .0033   45.     YES     202    .0033   -45.     YES
         202    .0033   45.     YES
$ Pset: "pcomp.46" will be imported as: "pcomp.46"
CQUAD4   1000    46      230     241     111     100     4       0.
CQUAD4   1001    46      229     240     241     230     4       0.
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CQUAD4   1004    46      226     237     238     227     4       0.
CQUAD4   1005    46      225     236     237     226     4       0.
CQUAD4   1006    46      224     235     236     225     4       0.
CQUAD4   1007    46      223     234     235     224     4       0.
CQUAD4   1008    46      222     233     234     223     4       0.
CQUAD4   1009    46      110     121     233     222     4       0.
CQUAD4   1010    46      219     230     100     89      4       0.
CQUAD4   1011    46      218     229     230     219     4       0.
CQUAD4   1014    46      215     226     227     216     4       0.
CQUAD4   1015    46      214     225     226     215     4       0.
CQUAD4   1016    46      213     224     225     214     4       0.
CQUAD4   1017    46      212     223     224     213     4       0.
CQUAD4   1018    46      211     222     223     212     4       0.
CQUAD4   1019    46      99      110     222     211     4       0.
CQUAD4   1020    46      208     219     89      78      4       0.
CQUAD4   1021    46      207     218     219     208     4       0.
CQUAD4   1024    46      204     215     216     205     4       0.
CQUAD4   1025    46      203     214     215     204     4       0.
CQUAD4   1026    46      202     213     214     203     4       0.
CQUAD4   1027    46      201     212     213     202     4       0.
CQUAD4   1028    46      200     211     212     201     4       0.
CQUAD4   1029    46      88      99      211     200     4       0.
CQUAD4   1030    46      197     208     78      67      4       0.
CQUAD4   1031    46      196     207     208     197     4       0.
CQUAD4   1034    46      193     204     205     194     4       0.
CQUAD4   1035    46      192     203     204     193     4       0.
CQUAD4   1036    46      191     202     203     192     4       0.
CQUAD4   1037    46      190     201     202     191     4       0.
CQUAD4   1038    46      189     200     201     190     4       0.
CQUAD4   1039    46      77      88      200     189     4       0.
CQUAD4   1040    46      186     197     67      56      4       0.
CQUAD4   1041    46      185     196     197     186     4       0.
CQUAD4   1044    46      182     193     194     183     4       0.
CQUAD4   1045    46      181     192     193     182     4       0.
CQUAD4   1046    46      180     191     192     181     4       0.
CQUAD4   1047    46      179     190     191     180     4       0.
CQUAD4   1048    46      178     189     190     179     4       0.
CQUAD4   1049    46      66      77      189     178     4       0.
CQUAD4   1050    46      175     186     56      45      4       0.
CQUAD4   1051    46      174     185     186     175     4       0.
CQUAD4   1054    46      171     182     183     172     4       0.
CQUAD4   1055    46      170     181     182     171     4       0.
CQUAD4   1056    46      169     180     181     170     4       0.
CQUAD4   1057    46      168     179     180     169     4       0.
CQUAD4   1058    46      167     178     179     168     4       0.
CQUAD4   1059    46      55      66      178     167     4       0.
CQUAD4   1060    46      164     175     45      34      4       0.
CQUAD4   1061    46      163     174     175     164     4       0.
CQUAD4   1064    46      160     171     172     161     4       0.
CQUAD4   1065    46      159     170     171     160     4       0.
CQUAD4   1066    46      158     169     170     159     4       0.
CQUAD4   1067    46      157     168     169     158     4       0.
CQUAD4   1070    46      153     164     34      23      4       0.
CQUAD4   1071    46      152     163     164     153     4       0.
CQUAD4   1074    46      149     160     161     150     4       0.
CQUAD4   1075    46      148     159     160     149     4       0.
CQUAD4   1076    46      147     158     159     148     4       0.
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CQUAD4   1077    46      146     157     158     147     4       0.
CQUAD4   1080    46      142     153     23      12      4       0.
CQUAD4   1081    46      141     152     153     142     4       0.
CQUAD4   1084    46      138     149     150     139     4       0.
CQUAD4   1085    46      137     148     149     138     4       0.
CQUAD4   1086    46      136     147     148     137     4       0.
CQUAD4   1087    46      135     146     147     136     4       0.
CQUAD4   1088    46      134     145     146     135     4       0.
CQUAD4   1089    46      22      33      145     134     4       0.
CQUAD4   1090    46      131     142     12      1       4       0.
CQUAD4   1091    46      130     141     142     131     4       0.
CQUAD4   1094    46      127     138     139     128     4       0.
CQUAD4   1095    46      126     137     138     127     4       0.
CQUAD4   1096    46      125     136     137     126     4       0.
CQUAD4   1097    46      124     135     136     125     4       0.
CQUAD4   1098    46      123     134     135     124     4       0.
CQUAD4   1099    46      11      22      134     123     4       0.
CQUAD4   1200    46      100     111     112     101     4       0.
CQUAD4   1201    46      101     112     113     102     4       0.
CQUAD4   1204    46      104     115     116     105     4       0.
CQUAD4   1205    46      105     116     117     106     4       0.
CQUAD4   1206    46      106     117     118     107     4       0.
CQUAD4   1207    46      107     118     119     108     4       0.
CQUAD4   1208    46      108     119     120     109     4       0.
CQUAD4   1209    46      109     120     121     110     4       0.
CQUAD4   1210    46      89      100     101     90      4       0.
CQUAD4   1211    46      90      101     102     91      4       0.
CQUAD4   1214    46      93      104     105     94      4       0.
CQUAD4   1215    46      94      105     106     95      4       0.
CQUAD4   1216    46      95      106     107     96      4       0.
CQUAD4   1217    46      96      107     108     97      4       0.
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CQUAD4   1219    46      98      109     110     99      4       0.
CQUAD4   1220    46      78      89      90      79      4       0.
CQUAD4   1221    46      79      90      91      80      4       0.
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CQUAD4   1225    46      83      94      95      84      4       0.
CQUAD4   1226    46      84      95      96      85      4       0.
CQUAD4   1227    46      85      96      97      86      4       0.
CQUAD4   1228    46      86      97      98      87      4       0.
CQUAD4   1229    46      87      98      99      88      4       0.
CQUAD4   1230    46      67      78      79      68      4       0.
CQUAD4   1231    46      68      79      80      69      4       0.
CQUAD4   1234    46      71      82      83      72      4       0.
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CQUAD4   1238    46      75      86      87      76      4       0.
CQUAD4   1239    46      76      87      88      77      4       0.
CQUAD4   1240    46      56      67      68      57      4       0.
CQUAD4   1241    46      57      68      69      58      4       0.
CQUAD4   1244    46      60      71      72      61      4       0.
CQUAD4   1245    46      61      72      73      62      4       0.
CQUAD4   1246    46      62      73      74      63      4       0.
CQUAD4   1247    46      63      74      75      64      4       0.
CQUAD4   1248    46      64      75      76      65      4       0.
CQUAD4   1249    46      65      76      77      66      4       0.
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CQUAD4   1250    46      45      56      57      46      4       0.
CQUAD4   1251    46      46      57      58      47      4       0.
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CQUAD4   1255    46      50      61      62      51      4       0.
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CQUAD4   1260    46      34      45      46      35      4       0.
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CQUAD4   1267    46      41      52      53      42      4       0.
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CQUAD4   1287    46      19      30      31      20      4       0.
CQUAD4   1288    46      20      31      32      21      4       0.
CQUAD4   1289    46      21      32      33      22      4       0.
CQUAD4   1290    46      1       12      13      2       4       0.
CQUAD4   1291    46      2       13      14      3       4       0.
CQUAD4   1294    46      5       16      17      6       4       0.
CQUAD4   1295    46      6       17      18      7       4       0.
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CQUAD4   1299    46      10      21      22      11      4       0.
$ Elements and Element Properties for region : pshell.47
PSHELL   47      601    .02      601             601
$ Pset: "pshell.47" will be imported as: "pshell.47"
CQUAD4   1068    47      302     310     311     309     4       0.
CQUAD4   1069    47      301     307     310     302     4       0.
CQUAD4   1078    47      314     302     309     308     4       0.
CQUAD4   1079    47      312     301     302     314     4       0.
CQUAD4   1268    47      304     305     306     300     4       0.
CQUAD4   1269    47      300     306     307     301     4       0.
CQUAD4   1278    47      303     304     300     313     4       0.
CQUAD4   1279    47      313     300     301     312     4       0.
$ Referenced Material Records
$ Material Record : mat1.301
$ Description of Material :
MAT1     301    13100.          .499     .0027
$ Material Record : mat1.601
$ Description of Material :
MAT1     601    2.67+6          .483333  .068
$ Material Record : mat1.701
$ Description of Material :
MAT1     701    2.+7            .3
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$ Material Record : mat1.901
$ Description of Material :
MAT1     901    2.+7            .3       .058
$ Material Record : mat8.201
$ Description of Material :
MAT8     201    1.58+7  1.5+6   .28      1.+6                      .058
                                218000.  247000.  5850.    35700.  10000.
$ Material Record : mat8.202
$ Description of Material :
MAT8     202    2.67+6  2.67+6           500000.                   .068
                                43000.   45000.   43000.   45000.  10000.
$ Material Record : mat8.501
$ Description of Material :
MAT8     501    2.67+6  2.67+6  .3       500000.                   .068
$ Multipoint Constraints of Group : left_wing
RBE2     303     304     123     42
RBE2     304     303     123     31
RBE2     421     403     123456  112      113      114      115      116
         117     118     119     234      235      236      237      238
         239     240     241
RBE2     4429    518     123456  9        10       123      124
RBE2     4430    511     123456  2        131
RBE2     4431    512     123456  3        130
RBE2     4432    513     123456  4        129
RBE2     4433    514     123456  5        128
RBE2     4434    305     123     53
RBE2     5000    307     123456  55
RBE2     5001    312     123456  33
RBE2     5002    167     123456  310
RBE2     5003    54      123456  306
RBE2     5004    145     123456  314
RBE2     5005    32      123456  313
RBE2     5006    146     123456  308
RBE2     5007    168     123456  311
$ Nodes of Group : left_wing
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GRID     3               20.8561 -18.     -.142824 3
GRID     4               21.7274 -18.     -.164471 3
GRID     5               22.5989 -18.     -.173716 3
GRID     6               23.4706 -18.     -.170052
GRID     7               24.3419 -18.     -.151726
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GRID     18              22.6993 -16.2    -.159573
GRID     19              23.6154 -16.2    -.128362
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GRID     21              25.447  -16.2    -.044854
GRID     22              26.3624 -16.2    -8.22-4
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GRID     523            29.825  -18.5   3.43-7
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$ Displacement Constraints of Load Set : spc1.100
SPC1     100     123456  402
$ Referenced Coordinate Frames
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        -.707107.707107 3.079-8
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01-04-2009	Technical Memorandum	

4. TITLE AND SUBTITLE
Updating the Finite Element Model of the Aerostructures Test Wing Using Ground Vibration Test Data

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

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14. ABSTRACT

Improved and/or accelerated decision making is a crucial step during flutter certification processes. Unfortunately, most finite element structural dynamics models have uncertainties associated with model validity. Tuning the finite element model using measured data to minimize the model uncertainties is a challenging task in the area of structural dynamics. The model tuning process requires not only satisfactory correlations between analytical and experimental results, but also the retention of the mass and stiffness properties of the structures. Minimizing the difference between analytical and experimental results is a type of optimization problem. By utilizing the multidisciplinary design, analysis, and optimization (MDAO) tool in order to optimize the objective function and constraints; the mass properties, the natural frequencies, and the mode shapes can be matched to the target data to retain the mass matrix orthogonality. This approach has been applied to minimize the model uncertainties for the structural dynamics model of the aerostructures test wing (ATW), which was designed and tested at the National Aeronautics and Space Administration Dryden Flight Research Center (Edwards, California). This study has shown that natural frequencies and corresponding mode shapes from the updated finite element model have excellent agreement with corresponding measured data.

15. SUBJECT TERMS
Aerostructures test wing, Ground vibration test, Multidisciplinary design, analysis, and optimization, Structural dynamic model tuning, Sensor/Actuator placement

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