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DAMAGE DETECTION IN AIRCRAFT STRUCTURES USING DYNAMICALLY MEASURED STATIC FLEXIBILITY MATRICES

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ABSTRACT

Two methods for detecting the location of structural damage in an aircraft fuselage using modal test data are presented. Both methods use the dynamically measured static flexibility matrix, which is assembled from a combination of measured modal vectors, frequencies, and driving point residual flexibilities. As a consequence, neither method requires a mode-to-mode correlation, and both avoid tedious modal discrimination and selection. The first method detects damage as a softening in the point flexibility components, which are the diagonal entries in the flexibility matrix. The second method detects damage from the disassembled elemental stiffnesses as determined using a presumed connectivity. Vibration data from a laser vibrometer is used to measure the modal mechanics of a DC9 aircraft fuselage before and after induced weakening in a longitudinal stringer. Both methods are shown to detect the location of the damage, primarily because the normal stiffness of the reinforced shell of the fuselage is localized to a few square centimeters.

INTRODUCTION

In the development and maintenance of aerospace and civil structures, the ability to evaluate the integrity of the structure is an increasingly important technology. Commercial aircraft, for instance, are remaining in service long past their designed lifetime because replacement costs are impractical. For this reason, structural inspection must be done at regular intervals but with minimal impact on the operation of the aircraft. Consequently, inspection techniques which require little or perhaps no dissection of the aircraft are important to maintaining their safety.

Assessing the structural condition without removing the individual structural components is known as non-destructive evaluation (NDE) or non-destructive inspection (NDI). Many NDE methods have been developed, and a good overview of the various techniques is presented by Witherell [1]. Examples of these techniques include visual inspection of cracks and dye-penetrant inspection of cracks. While techniques such as these directly detect damage as discontinuities in the physical properties of the structure, they are time consuming and labor intensive because they are highly localized measurements. To address these problems, researchers have been recently developing an entirely different set of techniques based on the interpretation of measured changes in the global mechanical properties of the structure. These more global methods of damage detection can potentially reduce the required number of locations which must be inspected by the highly localized direct NDE methods.

The use of modal test data to locate structural damage is one approach for determining changes in the global mechanical properties of a structure. This is primarily because modal techniques for data re-

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duction and analysis are well developed for other applications, so existing modal test facilities and methods can be utilized for NDE. Also, modern data acquisition systems allow the acquisition, processing, storage, and analysis of hundreds or thousands of channels of data. Since it is desirable to assess the condition of a structure in its operating environment, the ability to make modal measurements remotely and quickly minimizes the impact on the operation of the structure.

One particular method for detecting damage using optimal matrix update is called Minimum Rank Perturbation Theory (MRPT). This technique models the changes to the structure as rank-one updates of the mass, damping and stiffness matrices. This method was developed by Zimmerman and Kaouk [2], [3], [4], and has been used extensively for damage detection, primarily in truss structures. For examples of applications of this technique to NDE problems, see Zimmerman and Simmermacher [5], Zimmerman, et. al. [6], and Kim and Bartkowicz [7].

Another class of methods for FEM update which has been used for NDE is known as sensitivity-based matrix update. A sensitivity-based method which computes the sensitivity of the global structural mass and stiffness matrices at the structural element level has been developed by Hemez and Farhat [8], [9] and applied by Doebling, et. al. [10], [11]. Also, a method that was originally developed for control design, known as the eigenstructure assignment approach, has also been applied to NDE using modal test data. This technique has been applied to the damage detection problem by Zimmerman and Kaouk [12] and Lim and Kashangaki [13], [14], [15].

The above techniques share a common problem in that in some form they all require the correlation of modal vectors from one damage condition to another. This can sometimes lead to ambiguous results, especially when the damage causes very large changes in the modal vectors. The research described in this paper is attempting to avoid this problem through the use of the measured static flexibility matrix. By combining all of the measured modes, frequencies, and residual flexibility coefficients, it contains a complete set of data to describe the static behavior of the structure. Thus, there is no need to find a correspondence between the measured modes of different data sets, since all the modes are used in each case. The theoretical basis for this approach to measuring flexibility is presented in References [16] and [17].

In this paper, the dynamically measured static flexibility matrix is used with two different techniques to find damage in a stringer of a DC9 aircraft fuselage. In the first method, damage is indicated by changes in the point flexibility of the structure. Point flexibilities are the diagonal components of the flexibility matrix, and they are physically the deflection in a measured degree of freedom (DOF) due to a unit force at the same DOF. The second method uses an algebraic disassembly of the flexibility matrix along a presumed finite element connectivity pattern. Both of these techniques are shown to indicate the location of the damage in the aircraft fuselage structure.

This paper is organized into three additional sections. The theoretical development section explains how the measured flexibility matrix and the calculated residual flexibility are collected into a complete flexibility matrix. Then, the experimental configuration and procedures are explained, followed by a presentation and discussion of the results.

THEORETICAL DEVELOPMENT

Experimental Measurement of Static Flexibility

The flexibility matrix, $[G]$, relates the static displacement vector, $\{u\}$, of a structure to the static force loading vector, $\{F\}$, according to

$$\{u\} = [G]\{F\}. \tag{1}$$

For a restrained structure, the columns of $[G]$ represent the displacements of the structure under a static unit load applied at that column's DOF. For an unrestrained structure, the columns of $[G]$ are inertia relief modes of the structure due to a static unit load at the corresponding DOF.

Measuring the flexibility matrix using static test methods is impractical because of difficulties applying static loads under the proper boundary conditions. It has long been recognized that modal data can be used to form an approximation to the static flexibility using the measured modes. In this manner, $[G]$, may be approximated as,

$$[G] = [\Phi_n][\Lambda_n]^{-1}[\Phi_n]^T + [G_r] \tag{2}$$

where $[\Lambda_n]$ and $[\Phi_n]$ represent the measured eigenvalue and mass-normalized eigenvector matrices, respectively, and $[G_r]$ is the residual flexibility of modes outside the test set. In some situations, $[G_r]$ will be small. However, as shown in [16] and [17], this depends on the richness of the test set and also the subspace spanned by the input locations. When the residual flexibility is significant, References [16] and [17] provide several methods for approximating $[G_r]$.

Damage Detection Using Measured Point Flexibilities

Once the complete flexibility matrix is approximated, the point flexibilities can be used to find damage locations. Point flexibilities are the diagonal of the flexibility matrix:

$$\{G_p\} = diag[G]. \qquad (3)$$

Physically, point flexibilities are the static deflection in a measured DOF caused by a unit force input at the same DOF. Damage is located by a "softening" in the point flexibility of a DOF. This method is most applicable to plate-like structures with simple (i.e. localized) connectivity.

Damage Detection Using Disassembled Elemental Flexibilities

Another method for finding the damage in the aircraft is to use the algebraic disassembly of the flexibility matrix. A connectivity must be assumed to apply this method, and its success largely depends on the accuracy of that presumed connectivity. The flexibility matrix is disassembled using the algebraic direct disassembly formulation given in Reference [18]. In this approach, the following linear algebra problem is solved for unknown elemental stiffnesses:

$$\begin{aligned} &\sum_{\beta=1}^{n} p_\beta(\{A_\alpha\}^T[G]\{A_\beta\}\{A_\beta\}^T[G]\{A_\alpha\}) \\ &\qquad = \{A_\alpha\}^T[G]\{A_\alpha\} \end{aligned} \qquad (4)$$

in which A_α are elemental stiffness eigenvectors corresponding to elemental stiffness parameters p_α. Damage is detected by averaging the disassembled p_α over individual elements and then compared before and after damage. Again, a "softening" of the averaged stiffness of an element indicates damage.

EXPERIMENTAL CONFIGURATION AND PROCEDURE

Test Article and Data Acquisition System

The forward fuselage of a DC9 aircraft was used as the test article for a series of induced damage tests on an actual structure. This test article contains many of the experimental uncertainties and nonlinearities seen in practical field modal testing (see Figure (1)). A Zonic LAZON system was used to acquire and process the test data for all tests. This system consisted of two major hardware components: an Ometron Scanning Laser Vibrometer and a Zonic Workstation 7000. The Workstation 7000 is a multichannel, real time, FFT-based analyzer and data acquisition system. The system also included the following software: Zonic A&D Engineering and Test Analysis (ZETA) and LSI. Zeta is a general data acquisition and real time analysis package. LSI is a user interface to ZETA written specifically for use with the scanning laser vibrometer.

The Workstation 7000 used three analog output channels. Channels one and two were used to drive the x and y position of the laser beam. Channel three provided a random output signal to drive a 50lb electrodynamic shaker. An accelerometer and load cell were place at the force input location to allow a driving-point Frequency Response Function to be measured. Three analog input channels were also used. The first channel acquired data from the load cell. The second acquired all driving-point accelerometer data. Redundant driving-point data sets were acquired for each laser scan point. The third input channel acquired all laser data.

The force was input to the skin of the DC9 fuselage through an aluminum pad and dental cement. The force was continuous, random excitation with a lower frequency bound of 50Hz and an upper frequency bound of 1250Hz. The maximum force inputs were 5 pounds or less. Data was acquired from a grid of 38 inches by 14 inches on a 1 inch spacing for a total of 585 measurement points. The laser head was positioned on a tripod at a working distance of 75 inches from the surface. The System 7000 calculated FRF's and coherence functions in real-time and saved these functions for detailed post-test analysis at a later time. A Hanning window was used in the band of 0-1250 Hz with 10 measurements ensembles and a block-size of 1024. The acquisition mode was continuous with a 50% overlap. The data acquisition took approximately 1.5 hours for a complete scan.

The laser scan area covered a stringer which had been previously cut, as shown in Figure (2). For the "undamaged" data collected in this paper, the stringer was "repaired" using metal plates as shown in Figure (3).

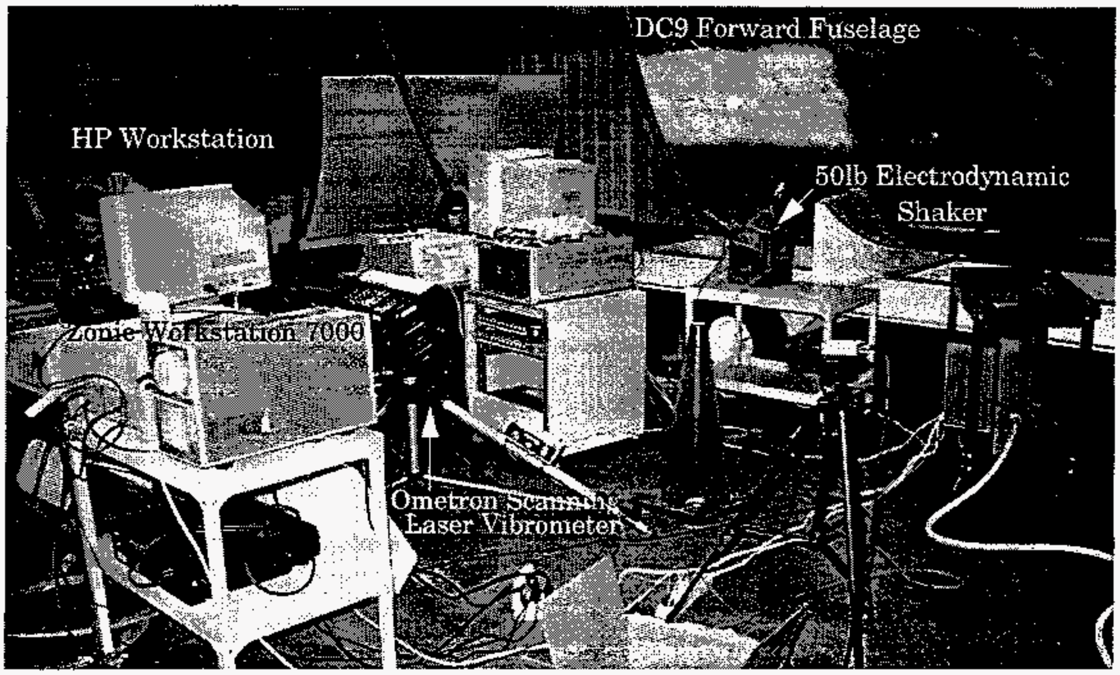


Figure 1. Photograph of DC9 Test Article and Data Acquisition System

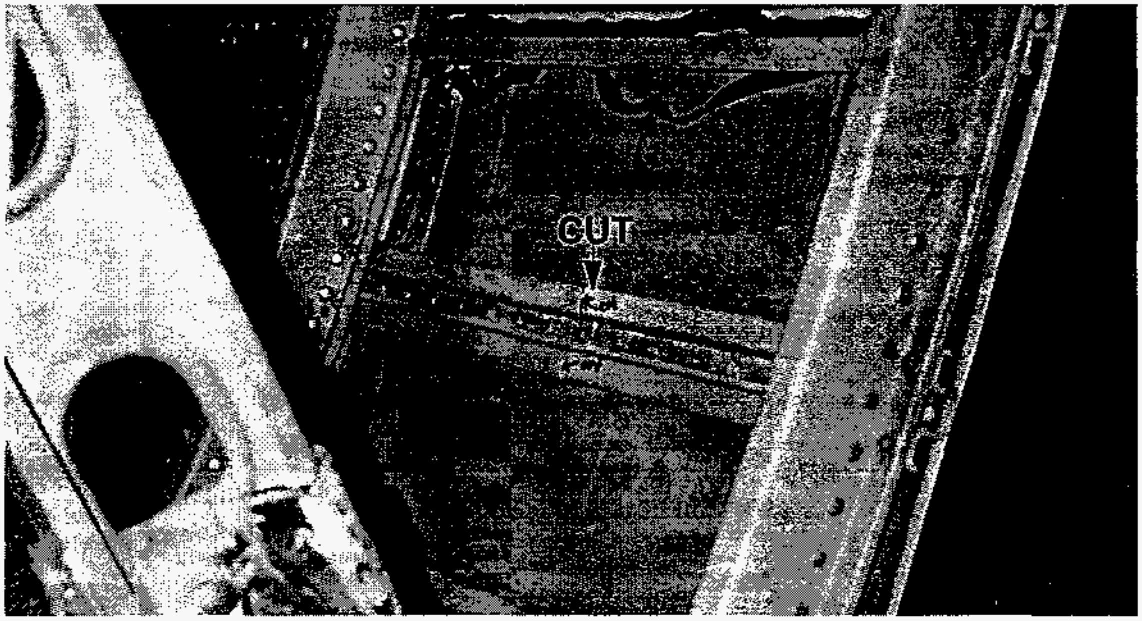
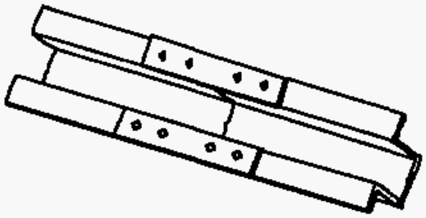


Figure 2. Photograph of Damaged Stringer

Undamaged Configuration



Damaged Configuration

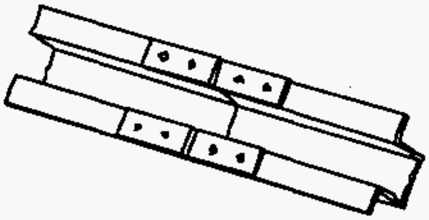


Figure 3. Repair of Previously Damaged Stringer to Simulate Damaged and Undamaged Configuration

RESULTS

Modal Analysis Procedure

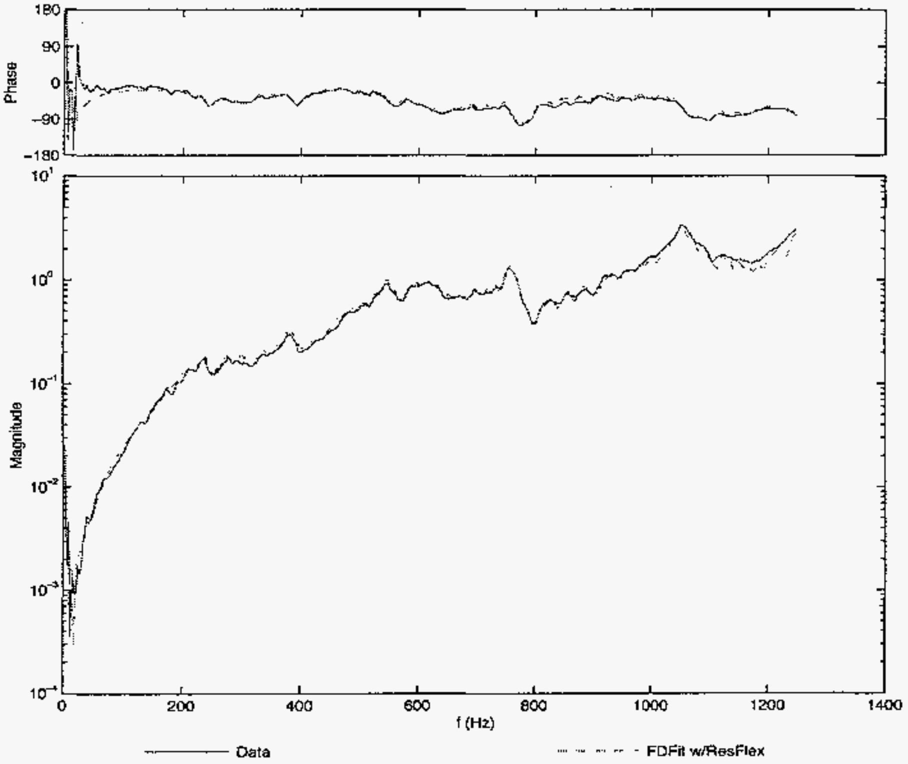
The FRF's were estimated using IDEAS. The ERA/DC method of analysis was applied to a 23,400 x 500 Hankel matrix. Details of the particularly efficient algorithm used in this procedure can be found in Reference [19]. A frequency domain curve fit was performed on the data, as described in Reference [20]. The curve fit obtained for the undamaged driving point FRF is shown in Figure (4). The model includes approximately 80 modes, which means that the data is "over identified," meaning there are more modes identified than actually exist in the measured frequency spectrum. This was done to save time on modal identification, and to demonstrate the insensitivity of the measured flexibility matrix to spurious noise modes remaining in the modal set. Total modal analysis time was less than twenty minutes.

Damage Detection Using Point Flexibilities

The flexibility matrix was calculated from the data as explained above. In the first method examined in this research, damage was indicated by a local softening of the aircraft skin as measured by the point flexibilities. The damage is located on a horizontal stringer midway between two vertical frames. Figure (5) shows that the point flexibilities found the damaged area of the aircraft structure. Frames are located on the right and left sides and also down the middle of the test section. Stringers are located on the top, bottom, and middle of the test section. Notice that the reduced flexibility over the stringers and frames reflects the geometry of the structure. Also note that the skin between stringers and frames is much more flexible. The two plots on the right side of Figure (5) plot the point flexibility as a vertical displacement. In both figures, the vertical scale is the same, and the measurement DOF over the skin panels have been omitted for clarity.

Damage Detection Using Disassembled Elemental Flexibilities

In this approach, only nodes along the damaged stringer were used for the connectivity. Nineteen six piece spring elements were used (see Figure (6)). The damage is located at element ten. As shown in Figure (7), the element stiffness of element ten is much lower for the damaged case than for the undamaged case.



MATLAB Version 4.2c

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Figure 4. FRF for the Undamaged Driving Point Curve Fit

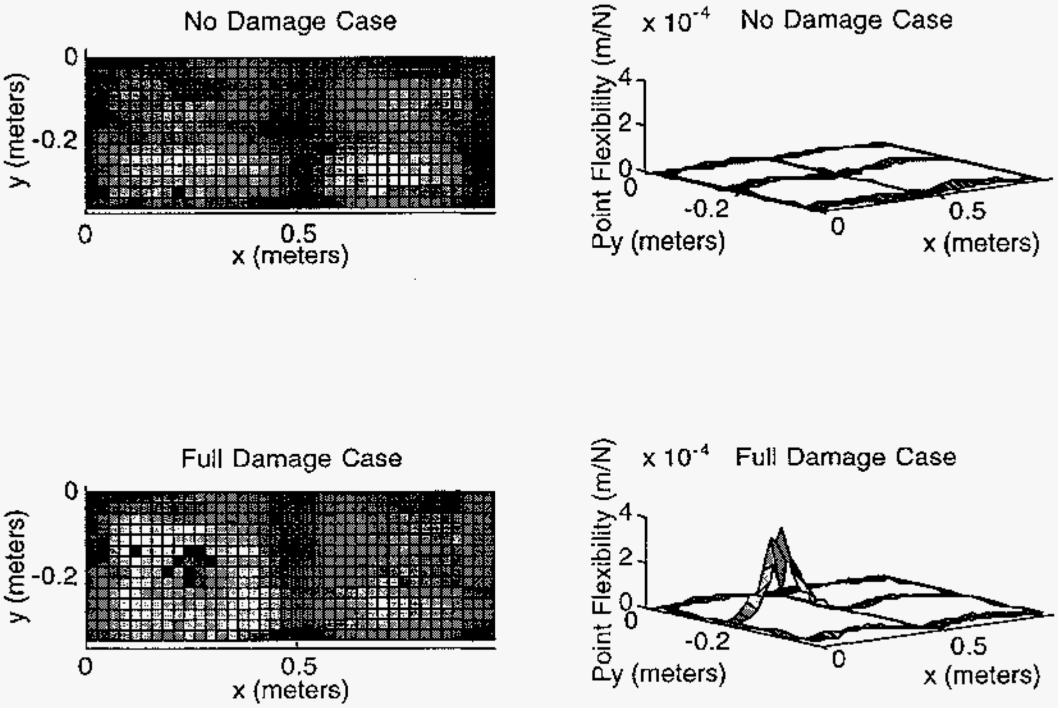

Figure 5. Point Flexibility Plots for Undamaged and Full Damaged Cases

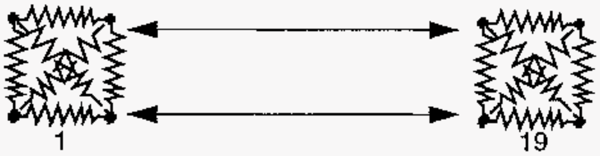

Figure 6. Six-Piece Spring Element Connectivity Distributed Along Damaged Stringer

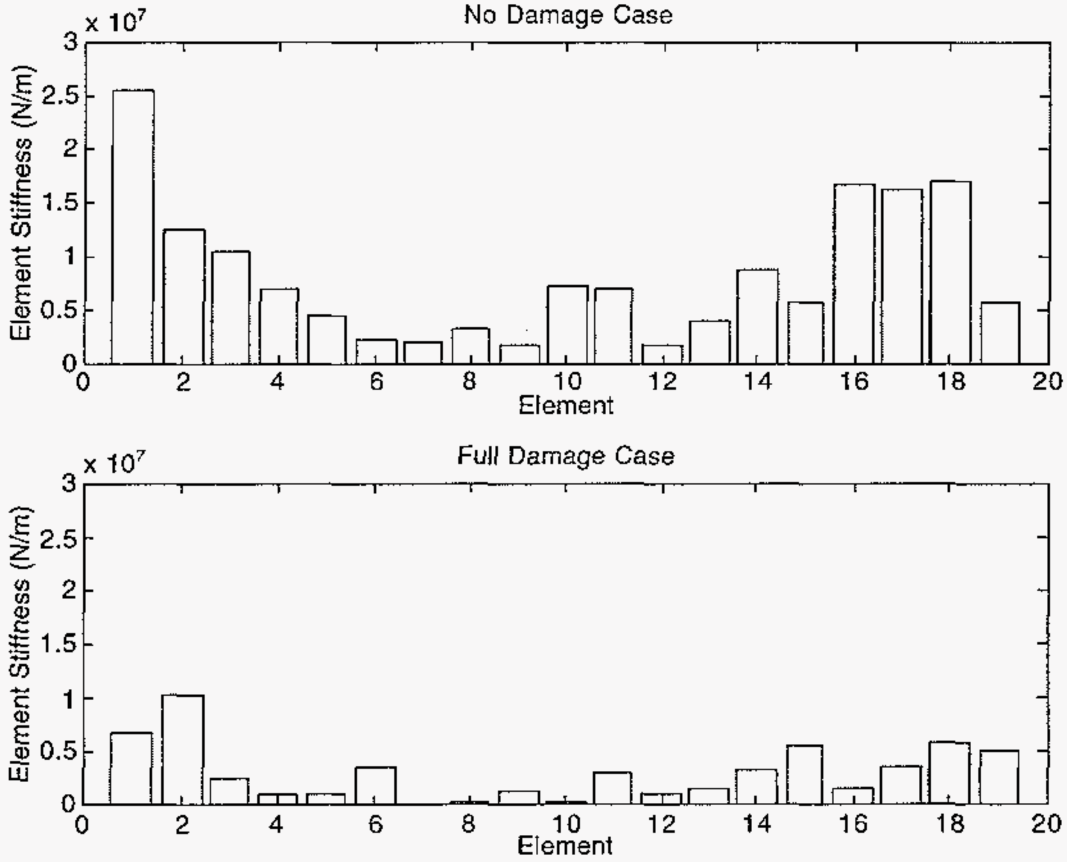

Figure 7. Element Stiffness Plot for Undamaged and Damaged Data

CONCLUSIONS

Two methods for damage detection in aircraft fuselages using modal test data have been introduced and experimentally applied. Both methods use the dynamically measured static flexibility matrix, which is assembled from a combination of measured modal vectors, frequencies, and driving point residual flexibilities. As a consequence, neither method requires a mode-to-mode correlation, and both avoid tedious modal discrimination and selection. This leads to a tremendous savings in modal analysis time, because semi-automated modal discrimination can be applied. Any remaining noisy or numerical modes apparently have little impact on the final flexibility matrix.

The first damage detection method detects damage as a softening in the point flexibility components, which are the diagonal entries in the flexibility matrix. The second method detects damage from the disassembled elemental stiffnesses as determined using a presumed connectivity. Vibration data from a laser vibrometer was used to apply these methods to a DC9 aircraft fuselage in which damage was artificially induced in a longitudinal stringer. In these results, the point flexibility method successfully and unambiguously locates the damaged stringer. The disassembly results are less successful. This is largely due to the inadequacy of the presumed elemental connectivity used in applying the disassembly method, and because the measured flexibility is not statically complete.

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REFERENCES

[1] Witherell, C.E., *Mechanical Failure Avoidance: Strategies and Techniques*, McGraw-Hill, New York, 1994.

[2] Zimmerman, D.C. and Kaouk, M., "Structural Damage Detection Using A Subspace Rotation Algorithm," AIAA-92-2521-CP, Proceedings of the 33rd Structures, Structural Dynamics and Materials Conference, Dallas, TX, April 1992.

[3] Kaouk, M. and Zimmerman, D.C., "Structural Damage Assessment Using a Generalized Minimum Rank Perturbation Theory," AIAA-93-1483-CP, Proceedings of the 34th Structures, Structural Dynamics and Materials Conference, La Jolla, CA, April 1993.

[4] Kaouk, M. and Zimmerman, D.C., "Evaluation of the Minimum Rank Update in Damage Detection: An Experimental Study," Proceedings of the 11th International Modal Analysis Conference, Orlando, FL, February 1993.

[5] Zimmerman, D.C. and Simmermacher, T., "Model Refinement and System Health Monitoring Using Data From Multiple Static Loads and Vibration Tests," AIAA-94-1714-CP, Proceedings of the 35th Structures, Structural Dynamics and Materials Conference, April 1994.

[6] Zimmerman, D.C., Smith, S.W., Kim, H.M., and Bartkowicz, T.J., "An Experimental Study of Structural Damage Detection Using Incomplete Measurements," AIAA-94-1712-CP, Proceedings of the 35th Structures, Structural Dynamics and Materials Conference, April 1994.

[7] Kim, H.M. and Bartkowicz, T.J.,"Damage Detection and Health Monitoring of Large Space Structures," AIAA-93-1705-CP, Proceedings of the 34th Structures, Structural Dynamics and Materials Conference, La Jolla, CA, April 1993.

[8] Hemez, F.M., *Theoretical and Experimental Correlation Between Finite Element Models and Modal Tests in the Context of Large Space Structures*, Ph. D. Dissertation, University of Colorado, Boulder, CO, 1993.

[9] Farhat, C. and Hemez, F.M., "Updating Finite Element Dynamic Models Using an Element-by-Element Sensitivity Methodology," AIAA Journal, Vol. 31, No. 9, September 1993.

[10] Doebling, S.W., Hemez, F.M., Barlow, M.S., Peterson, L.D., and Farhat, C., "Damage Detection in a Suspended Scale Model Truss via Modal Update," Proceedings of the 11th International Modal Analysis Conference, Orlando, FL, February 1993.

[11] Doebling, S.W., Hemez, F.M., Barlow, M.S., Peterson, L.D., and Farhat, C., "Selection of Experimental Modal Data Sets for Damage Detection via Model Update," AIAA-93-1481-CP, Proceedings of the 34th Structures, Structural Dynamics and Materials Conference, La Jolla, CA, April 1993.

[12] Zimmerman, D.C. and Kaouk, M., "Eigenstructure Assignment Approach for Structural Damage Detection," AIAA Journal, Vol. 30, No. 7, July 1992.

[13] Lim, T.W., "Structural Damage Detection of a Planar Truss Structure Using a Constrained Eigenstructure Assignment," AIAA-94-1715-CP, Proceedings of the 35th Structures, Structural Dynamics and Materials Conference, April 1994.

[14] Lim, T.W. and Kashangaki, T. A.-L., "Structural Damage Detection of Space Truss Structures Using Best Achievable Eigenvectors," AIAA Journal, Vol. 32, No. 5, May 1994, pp. 1049-1057.

[15] Kashangaki, T. A.-L., *Damage Location and Model Refinement for Large Flexible Space*

Structures Using a Sensitivity Based Eigenstructure Assignment Method, Ph. D. Dissertation, University of Michigan, Ann Arbor, MI, 1992.

[16] Doebling, S.W., Peterson, L.D., and Alvin, K.F., "Measurement of Static Flexibility Matrices for Experiments with Incomplete Reciprocity," Proceedings of the 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April, 1995, AIAA-95-1092.

[17] Doebling, S.W., "Measurements of Structural Flexibility Matrices for Experiments with Incomplete Reciprocity," CU-CAS-95-10, Center for Aerospace Structures, University of Colorado, Boulder, Colorado, April, 1995.

[18] Peterson, L.D., Alvin, K.F., Doebling, S.W., "Experimental Determination of Local Structural Stiffness by Disassembly of Measured Stiffness Matrices", AIAA-95-1090-CP, Proceedings of the 36th Structures, Structural Dynamics and Materials Conference, New Orleans, LA, April 1995.

[19] Peterson, L.D. "Efficient Computation of the Eigensystem Realization Algorithm" *J. Guidance, Control and Dynamics*, Vol. 18, No. 3, May-June 1995, pp 395-403.

[20] Peterson, L.D. and Alvin, K.F., "A Time and Frequency Domain Procedure for Identification of Structural Dynamic Models" AIAA-CP-94-1731 Proceedings of the *35th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Hilton Head, April 1994.