A98-31626

ICAS-98-R,5,1

ON-LINE HEALTH MONITORING OF AERONAUTICAL STRUCTURES USING A VIBRATION BASED METHOD

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Abstract

The aim of this paper is to apply to a typical aeronautical structure a Vibration Based Method which detects damage in structures when a 'description of normality' is provided. A model of the primary structure of a wing is developed such that damage of different extent and type can be introduced. Despite the only slight modification of the dynamic behaviour of the wing due to the presence of the fault, numerical simulations demonstrate that damage of moderate extent in spar-flanges can be detected using this technique even if the dynamic characteristics vary due to changes in the mass of the fuel.

Introduction

In the aerospace industry, one fundamental problem that must be addressed concerns the monitoring of the condition of aircraft structures. Maintenance checks are expensive and inspection for structural damage is usually performed at regular intervals following a specified number of flight hours. As such the monitoring of the integrity of the structure is not continuous: the aircraft is taken out of service and one or more non-destructive ground tests are conducted. Clearly, from this point of view, it would be extremely advantageous to develop techniques which permit the aircraft to be monitored continuously in-service when operating normally.

The capacity for rapid detection of damage in mechanical, aerospace and civil structures is becoming increasingly important, such that a variety of Non Destructive Evaluation methods have been developed.
Most of these techniques are capable of detecting small defects close to the surface of the structure and near the sensor position. Vibration Based Inspection is currently receiving increased attention, mainly due to the capability of detecting faults at unmeasured locations by monitoring, during the lifetime, the dynamic characteristics of the structure under test. The concept behind this category of techniques is based on the analysis of the dynamic response and observing the variations in its spectrum [1] [2].

During recent years, several algorithms have been introduced to relate changes in the spectrum to the location and size of the damage: some perform a pattern-recognition task while others refer to the modal characteristics of the structure. In order to permit a comparison between different techniques, Rytter [3] proposed the following classification:

- Level 1: to indicate qualitatively that damage might be present in the structure (detection).
- Level 2: to provide information about the probable location of the damage (localisation).
- Level 3: to quantify the extent of the damage (assessment).
- Level 4: to evaluate the actual safety of the structure in a certain state of damage (consequences).

Generally, techniques of level 2 and 3 can be applied only in particular types of structures, due to their need for an accurate mathematical model both of the structure under test and of the damage to be detected; it is evident that such models may be developed only for relatively simple structures. As a consequence there is a need for more general techniques, ie. of level 1, which may detect a damage in any type of structure by comparing the current response characteristics with measurements made previously at the same locations. Furthermore, even if a level 1 technique does not give any information on the geometrical properties of the damage, the development of a good level 1 technique is nevertheless a key feature for damage identification procedures of higher levels; indeed, damage can be identified only if it is detected.

In this article a method, recently proposed by Ruotolo and Surace [4] [5] and based on the application of the Singular Value Decomposition Technique to analyse dynamic response data measured from the structure under examination, is utilised for monitoring the condition of structures. Unlike other methods of damage detection based on vibrations which require an accurate mathematical model of the undamaged structure, the new technique described relies only on a 'description of normality' which is defined in terms of features measured in operational conditions when the

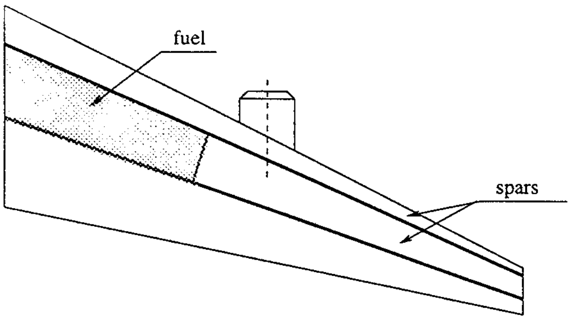

Figure 1: The wing under study

structure is known or assumed to be fault-free. For this reason the method can be applied even to very complex stuctures which operate in a range of conditions with a corresponding variation in the dynamic characteristics of the structure. For the case of an aircraft in flight, examples are decrease in the effective mass due to a reduction in fuel and a change in the flight speed.

To demonstrate the validity of the method for the primary structure of a typical transport aircraft (see figure 1), a finite element model of a wing was developed. Several mass configurations have been considered, corresponding to varying amount of fuel, together with different levels and types of structural damage. Using the results obtained it has been possible to assess the sensitivity of the method to structural alterations and analyse the influence of measurements noise on its effectiveness.

Description of the SVD-Based Technique

This method was originally proposed in ref. [4] as a means for detecting the presence of a fault in a structure even if the dynamic behaviour varies during normal operational conditions, eg. an offshore platform which changes in mass: methods which consider only the comparison of natural frequencies [6] [7] are not able to detect damage, since a change in mass of the structure results in an alteration of the dynamic behaviour even if the structure is undamaged.

For each operating condition both in undamaged and damaged states, it is possible to introduce a feature vector $\{v\}$ in which a particular characteristic of the structure is represented, eg. individual natural frequencies, modeshapes, frequency response functions, transmissibilities etc. Due to the effect of damage on the dynamic behaviour of the inspected structure, it is assumed that a fault will alter the vibrational response and, as a consequence, also the feature vectors. Hence, the problem of damage detection can be addressed by comparing the feature vectors $\{v\}$ in order to discover any significant deviation, which cannot be ascribable to noise, from the given configurations; at this point it is necessary to verify that:

$$\{v\}_c \neq \{v\}_i \qquad \forall\, i \in [1, n], \tag{1}$$

where $\{v\}_i$ is related to a normal operational configuration and $\{v\}_c$ to the current condition, which may correspond to a damaged state.

The feature vectors $\{v\}$ can be arranged in a matrix $[\ P\ ]$ in the following way:

$$[\ P\ ] = [\{v\}_1\{v\}_2 \ldots \{v\}_n\{v\}_c],$$

such that condition (1), which can be used to determine whether or not a structure is damaged, can be checked by estimating the rank of the matrix $[\ P\ ]$. Indeed, if the structure is undamaged, the feature vector $\{v\}_c$ will be equal to one of the feature vectors $\{v\}_1 \ldots \{v\}_n$ and the rank of the matrix $[\ P\ ]$ will be equal to n. On the other hand, if the structure under test is damaged, the rank of the matrix $[\ P\ ]$ will be equal to $n+1$.

As a consequence, a straightforward way of investigating the structural integrity is by evaluating the rank of the matrix $[\ P\ ]$, which is built up by acquiring and analysing the dynamic response of the structure. Usually this computation is carried out by a Gaussian elimination but, in practice, the rows of a matrix are neither exactly orthogonal nor parallel, such that it may be difficult to estimate the rank after performing this numerical procedure. On the other hand, it is well known that a good way of evaluating the rank is by using SVD, expecially if the matrix is large or complex.

This method can be extended simply to the case in which p feature vectors can be associated to each operational condition, eg. in the case in which for each configuration p functions are acquired. As a consequence, a feature matrix $[\ V\ ]_i$ with p columns can be introduced, where the jth column is a previously defined feature vector $\{v\}_i^{(j)}$. By following the same procedure previously outlined, matrix $[\ P\ ]$ will be:

$$[\ P\ ] = [[\ V\ ]_1[\ V\ ]_2 \ldots [\ V\ ]_n[\ V\ ]_c],$$

which has $p\cdot(n+1)$ columns. If the structure is undamaged and the acquired functions are linearly independent, for example when transmissibilities are acquired, the rank of matrix $[\ P\ ]$ will be $p \cdot n$, while if the structure is damaged the rank will be greater than $p \cdot n$ and less than or equal to $p \cdot (n+1)$.

Effect of Measurement Noise

When dealing with experimental data, it is necessary to consider the influence of measurement noise; as a consequence the previous considerations about the rank of matrix $[\ P\ ]$ have to be re-considered. Firstly,

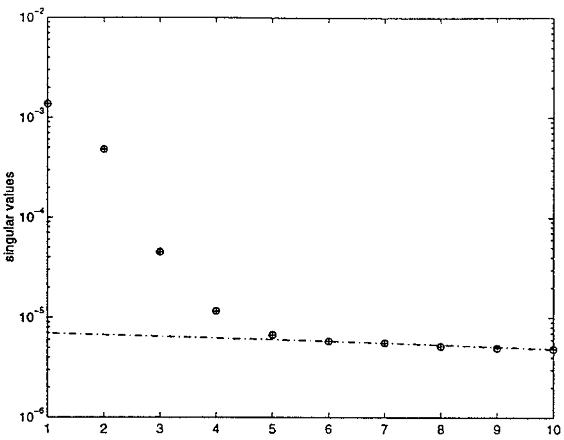

Figure 2: First ten singular values for an undamaged beam (four values greater than the threshold given by the dash-dot line) [4]

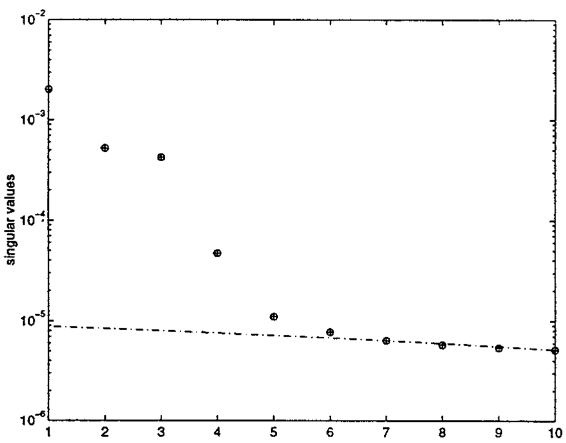

Figure 3: First ten singular values for a damaged beam (five values greater than the threshold given by the dash-dot line) [4]

the evaluation of the rank of an experimental determined matrix will be more accurate using SVD than a Gaussian elimination. Secondly, if the difference between a theoretically evaluated [P] matrix and the corresponding experimentally determined matrix [P_n] depends only on measurement noise, the rank of these two matrices should be equal. Furthermore, as opposed to the case of matrix [P], all the singular values of matrix [P_n] will be greater than zero. Consequently, in order to distinguish between singular values related to the noise from those related to the state of the structure, a threshold level for the singular values related to the noise is introduced, such that any singular value greater than this threshold can be related to the state of the structure.

When a real structure is monitored using this technique and the singular values of the matrix [P_n] are evaluated, it should be possible in principle to decide whether the structure is damaged or not by looking at the number of singular values greater than the threshold due to the measurement noise. By performing this task periodically, an increase of the number of singular values related to the state of the structure should provide an indication that the structure under investigation has altered its dynamic behaviour, ie. undergone damage. Of course, as described above, any change of operating conditions does not alter this number, such that the method would be insensitive to a switching between different operating conditions. An example is shown in figures 2 and 3, which corresponds to a simple cantilever beam with a concentrated mass at the free end [4]. Figure 2 is related to the structure without damage, while figure 3 is related to the beam with a damaged element. Frequency response functions have been used as feature vectors polluted by additive noise, giving the threshold level indicated by the dash-dot line of figures 2 and 3, ie. singular values related to the additive noise are almost flat. It is possible to see that when the structure is undamaged just 4 singular values are greater then the threshold level (figure 2), while 5 singular values are greater than this threshold when the structure is damaged (figure 3).

The procedure to decide whether or not the structure is damaged has some problems to be applied to experimental data, as described in [5], mainly because experimental data are often corrupted by noise which is at least partially multiplicative in nature. In this case the noise is coloured, meaning that peaks in noise correspond to peaks in the data, such as singular values related to the noise are no longer flat. As a consequence, it is very difficult to introduce a threshold level that permits the separation of singular values related to the state of the structure from singular values related to the noise.

To deal with this situation and in order to increase the distance between singular values related to the state of the structure and those related to the noise, it is advisable to introduce into matrix [P] more feature matrices [V]$_i$ for each operational configuration; this procedure could be seen as means of averaging the various measurements performed on the structure under test at the same configuration. By collecting l measurements for each one of the n configurations, matrix [P] will be:

$$[P] = [[V]_1^{(1)} \cdots [V]_1^{(l)} \; \cdots \; [V]_n^{(1)} \cdots [V]_n^{(l)} \; [V]_c^{(1)} \cdots [V]_c^{(l)}].$$

Moreover, it is possible to take advantage of a property of singular values [5] of matrix [P]. In order to assist in the diagnosis of damage, the following damage index can be formulated:

$$D_i = \alpha \left(\prod_{k=1}^{r+1} \sigma_k([\ P\ ]) \right), \qquad (2)$$

where [P] is the matrix with multiple measurements for each operational configuration, σ_k([P]) is the kth singular value of this matrix, r is the number of singular values greater than the threshold due to noise related to the undamaged structure and α is a constant properly selected to normalise the index. The main characteristic of damage index D_i is that it varies slightly by switching to a different normal operational condition and, for a given configuration, it increases when the structure is damaged.

Model of the Wing

The mathematical model of the wing has been developed according to the method proposed by Kapania and Castel [8], which allows to build a one-dimensional model of a wing with composite upper and lower panels. The first step is to isolate a typical segment of the wing, eg. from rib to rib, and then to transform it into a wing-box element, shown in figure 4. This element is considered as a beam, with a cross section which can vary from one end to the other, as well as geometric properties of stringers and skins. The builtup structure consists of curved bottom and top laminated skins, four webs and eight stringers as in figure 4. According to the classical empirical rules of aeronautical engineering, webs are assumed to support only shear stresses, while skins are subjected only to axial stresses. Both transverse shear, according to Timoshenko theory, and a correction factor which takes into account the warping restraints induced by the boundary conditions, are included in the formulation. Furthermore, the code permits properties of members which are not present in the layup, eg. webs or stringers, to be set to zero.

The wing model considered in this study has the following properties:

- wing span of 26.6 m;
- chord of 5.223 m at root and 1.272 m at tip;
- sweep angle of -24^o (backward);
- two webs;
- eight stringers;
- aluminium is used for all the elements of the structure;
- one engine with mass M_E = 2000 kg is located in the middle of the wing.

Configurations and Cases of Damage

In order to simulate real operational conditions, the change in fuel mass stored in the wing is assumed to be a free parameter, such that it introduces a variation in the dynamic behaviour of the wing, ie. different operational configurations. In particular, 10 different configurations were considered: in the first configuration, a fuel mass of 4111.1 kg is stored in the wing, while in the tenth configuration the fuel mass is of 4384.0 kg. As a consequence, the difference in mass between two adjacent configurations is of 0.62%, referred to 4384.0 kg, which is sufficiently low to consider these ten configurations as a continuous variation in the mass of the structure.

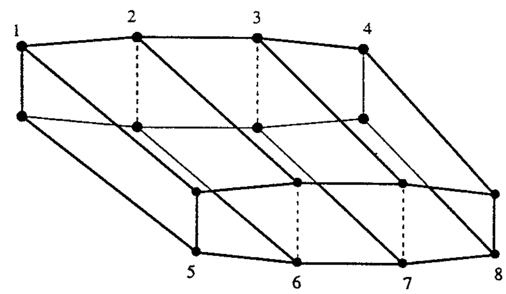

Figure 4: The wing-box element

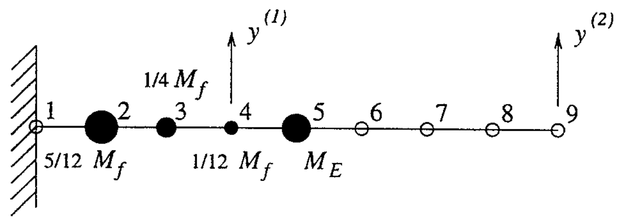

Figure 5: Positions of concentrated masses and sensors on the model of the wing

The wing is discretised using eight elements, as shown in figure 5, and the fuel mass is introduced as concentrated masses without rotational inertia at nodes no. 2, 3 and 4, with a value of $5/12M_f$, $1/4M_f$ and $1/12M_f$ respectively, where M_f is the mass of the fuel.

The finite element method allows the evaluation of the mass $[\ M\ ]$ and stiffness $[\ K\ ]$ matrices of the following equation:

$$[\ K\ ](1+\mathrm{i}\eta)\{\ y\ \}+[\ M(M_f)\ ]\{\ \ddot{y}\ \}=\{\ F\ \}, \quad (3)$$

where $\eta = 0.02$ introduces a structural damping. The previous equation highlights that the dynamic behaviour of the structure is a function of the fuel mass M_f; figure 6 shows the modeshape for the first four modes of the wing in configuration 1, ie. when M_f = 4111.1 kg.

The variation in natural frequencies of the wing due to the change of mass fuel during the flight, is shown in table 1. It is possible to observe that the frequency of the first mode does not change with the variation of the fuel mass, while the other modes have a relative variation in frequency which is 1.4%, 2.2% and 2.3% for the second, third and fourth mode respectively. As a consequence, the modification in the dynamic be-

	Configuration no.									
	1	2	3	4	5	6	7	8	9	10
f_1 [Hz]	2.353	2.353	2.353	2.353	2.353	2.353	2.353	2.353	2.353	2.353
f_2 [Hz]	8.833	8.825	8.816	8.807	8.798	8.790	8.781	8.772	8.764	8.755
f_3 [Hz]	19.428	19.397	19.366	19.335	19.305	19.275	19.245	19.215	19.186	19.157
f_4 [Hz]	33.365	33.308	33.252	33.197	33.142	33.088	33.034	32.981	32.929	32.877

Table 1: First four natural frequencies of the wing for the various configurations

Damage in the web			Damage in the spar-flange		
A	B	C	D	E	F
10%	20%	30%	10%	20%	30%

Table 2: Stiffness reduction for the various damage cases

haviour of the structure can be approximated with a continuous variation, as well as previously stated for the mass variation.

In order to investigate on the effect of different type of damage on the dynamic behaviour of the structure under test, two kind of faults have been considered:

1. reduction of the stiffness of one web of the element nearest to the clamped end of the wing;
2. reduction of the stiffness of the stringer no.1 (see figure 4) for the element nearest to the clamped end of the wing (this case is equivalent to decrease the stiffness of the spar-flange).

Each damage is entered by taking advantage of the possibility of introducing directly the Young's modulus for webs, stringers and skins. As a consequence, a reduction in stiffness of a given percentage is obtained by decreasing the Young's modulus of the same percentage. Moreover, damage of varying extent is introduced into the web and the stringer, as shown in table 2.

In table 3 the first four natural frequencies of the wing in configuration 1, ie. with the minimum amount of fuel, and damaged according to table 2 are presented. It is possible to see that all the damage scenarios give rise to a slight variation in natural frequencies; in particular, damage in the web modifies only slightly natural frequencies for modes 3 and 4, while damage in the spar-flange affects all the four modes. Nevertheless, it is necessary to highlight that the maximum variation in natural frequencies for this kind of damage is equal to -0.883% for mode no.3 and damage case F. This variation is very low and therefore extremely difficult to detect by just comparing natural frequencies.

Application of the Technique

To apply the formulation described above to the case considered, feature vectors were constructed using the amplitude of frequency response functions $H^{(1)}(\omega)$ and $H^{(2)}(\omega)$ of the structure related to the position of the two sensors shown in figure 5 for a force applied at the free end of the wing. As a consequence, feature matrix $[\ V\ ]_i$ has $p = 2$ columns:

$$[\ V\ ]_i = [\ \{H^{(1)}\}_i\ \{H^{(2)}\}_i\ ].$$

A first analysis was performed without noise on the 'measurements'. Matrix $[\ P\ ]$ is constructed by using the feature matrix $[\ V\ ]_i$, with two columns for each operational configuration, and for the current condition. Each $\{H^{(k)}\}_i$ is a vector obtained by evaluating the amplitude of $H_i^{(k)}(\omega)$ in 241 equally spaced frequency points in the range from 6 to 30 Hz, resulting in a matrix $[\ P\ ]$ of dimensions 241 × 22.

Figures 7 and 8 show the values of the damage index D_i evaluated according to (2) in which r is set to 5. In order to simulate a real-time monitoring of the structure, in figures 7 and 8 measurements are 'acquired' 8 times for each operational configuration. Furthermore, in figures 7 and 8 dashed lines highlight the change in operational configuration; at each time the current configuration is indicated at the top of the figure, with the label N_D, where N refers to the configuration number, and D to the damage case. When the wing is undamaged D is equal to 0.

In figures 7 and 8 it is possible to see that the transition from configuration 1_0 to 1_A and from 1_0 to 1_D is characterised by an increase in the index, meaning that damage occurred. Moreover, these figures show also that an increase of the extent of the damage without a change in configuration, ie. mass of the fuel, is characterised by an increase in the damage index. Finally, both damage in the web and damage in the spar-flange are detected.

To deal with a more realistic situation, multiplicative noise is added to the frequency response functions. According to the procedure described in the previous sections, in this case in matrix $[\ P\ ]$ more feature matrices $[\ V\ ]_i$ for each operational condition are introduced in order to average the noise. Matrix $[\ P\ ]$ is constructed by using 5 feature matrices related to the structure at the initial stage and for each operational configuration; as a consequence if the current condition is not taken into account, 100 columns are introduced in matrix $[\ P\ ]$: 2 frequency response functions × 10 configurations × 5 measurements for each configuration. In order to give a similar importance to the current condition, 25 feature matrices $[\ V\ ]_c$ obtained performing on-line 'measurements', ie. related to the current condition, are stored in $[\ P\ ]$.

Figures 9 and 10 show the damage index evaluated for the damage in the web (cases A, B and C) and in the spar-flange (cases D, E and F) respectively, when the level of multiplicative noise is of 1%. Even if the level of noise is relatively low, it is possible to see in figure 9 that no sharp increase in the damage index occurs, ie. damage is not detected even at the highest extent. On the other side, results shown in figure 10 demonstrate that damage in the spar-flange can be detected also at the lowest level of 10% reduction in stiffness. Similar results are shown in figures 11 and 12 for a multiplicative noise of 2%.

Conclusions

In this paper a Vibration Based Method for detecting structural damage in structures with different operating conditions is applied to diagnose damage in the primary structure of a typical wing of a transport aircraft. The technique uses a description of 'normality' of the structure, ie. it needs that some features of the structure are acquired before the onset of damage. Two types of damage are analysed: a reduction in the stiffness of one of the two webs, and a reduction in the stiffness of a stringer (equivalent to a damage in the spar-flange). Both types of damage are introduced close to the clamping end of the wing.

This method allows to detect the damage in the spar-flange even if the noise in the 'measured' data is relatively high (2% of multiplicative noise), while damage in the web is undetectable also with a lower level of noise. Finally, it should be remembered that in this case any direct comparison of natural frequencies is impractical, mainly due to the presence of different operating conditions and to the noise on the measurements.

Acknowledgements

The authors would like to thank Mr Fabio Ruta for helping in developing the finite element code under Matlab© environment. The research has been funded by the *Italian National Research Council* (CNR).

References

[1] S.W. Doebling, C.R. Farrar, M.B. Prime and D.W. Shevitz 1996 *Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics: a Literature Review.* Report no. LA-13070-MS, Los Alamos National Laboratory.

[2] R. Ruotolo 1997 *Vibration-Based Techniques for Identifying Structural Damage* (in italian). Doctoral dissertation, Politecnico di Torino.

[3] A. Rytter 1993 *Vibrational Based Inspection of Civil Engineering Structures.* Ph.D. Thesis, University of Aalborg.

[4] R. Ruotolo, and C. Surace 1997 *Proceedings DAMAS '97*, Sheffield, UK, 87-96. Damage Detection using Singular Value Decomposition.

[5] R. Ruotolo and C. Surace 1998 *Proceedings XVI International Modal Analysis Conference.* The Use of SVD to Detect Damage in Structures with Different Operating Conditions.

[6] R.N. Coppolino and S. Rubin 1980 *Proceedings of the Offshore Technology Conference* 101-110. Detectability of Structural Failures in Offshore Platforms by Ambient Vibration Monitoring.

[7] R. Ruotolo and C. Surace 1997 *Proceedings PACAM '97* Puerto Rico. A Statistical Approach to Damage Detection Through Vibration Monitoring.

[8] R.K. Kapania and F. Castel 1990 *AIAA Journal* vol.28, no.2, 329-337. A Simple Element for Aeroelastic Analysis of Undamaged and Damaged Wings.

	Damage cases					
	A	B	C	D	E	F
f_1 [Hz]	2.353	2.353	2.353	2.351	2.348	2.344
f_2 [Hz]	8.832	8.831	8.830	8.810	8.784	8.755
f_3 [Hz]	19.413	19.397	19.382	19.403	19.376	19.346
f_4 [Hz]	33.326	33.287	33.246	33.342	33.317	33.289

Table 3: First four natural frequencies of the wing for the various damage cases

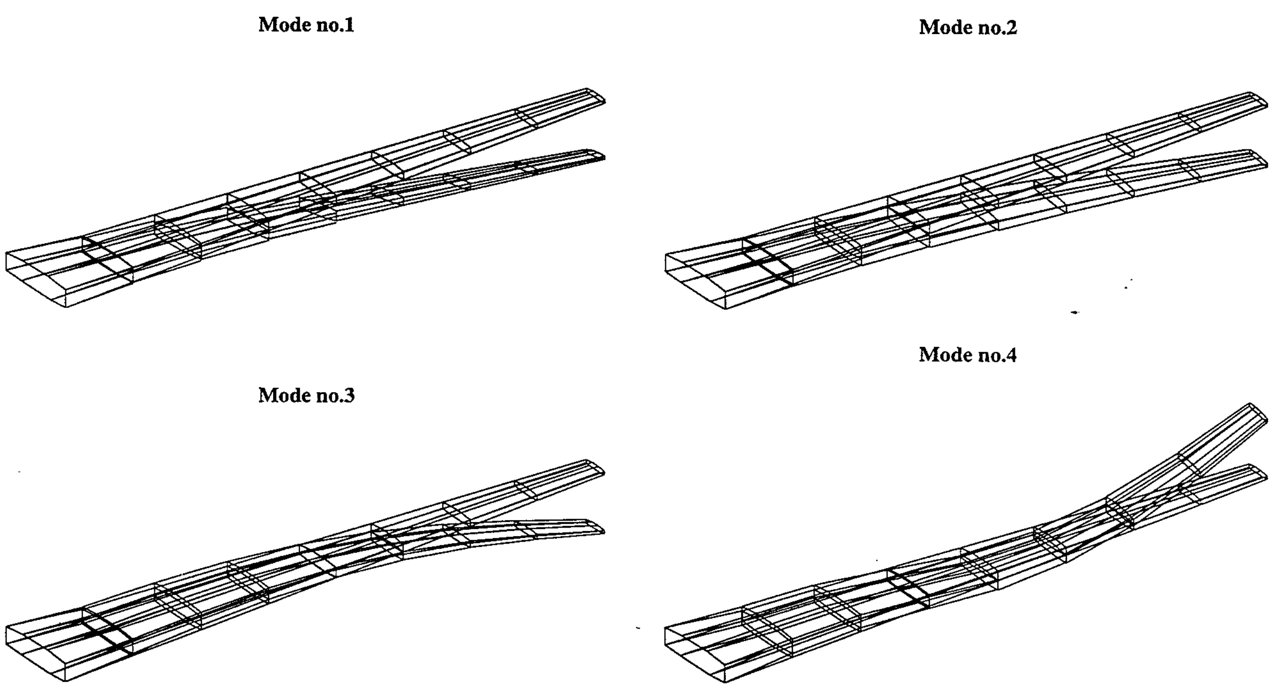

Figure 6: Modeshapes for first 4 modes of the analysed wing

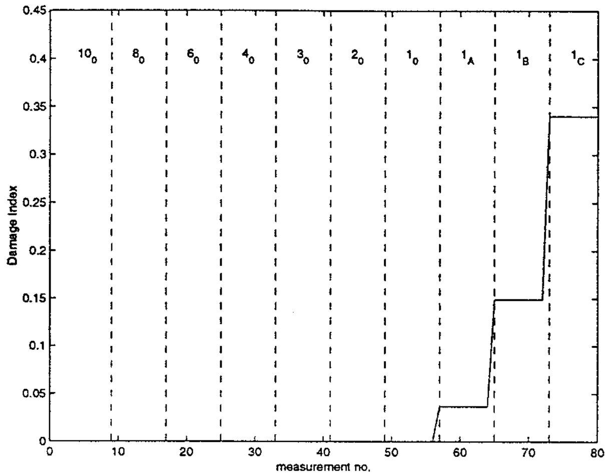

Figure 7: Damage cases A, B and C; no noise

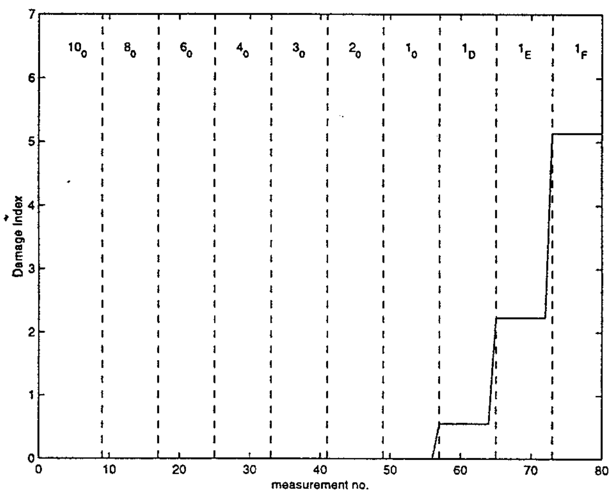

Figure 8: Damage cases D, E and F; no noise

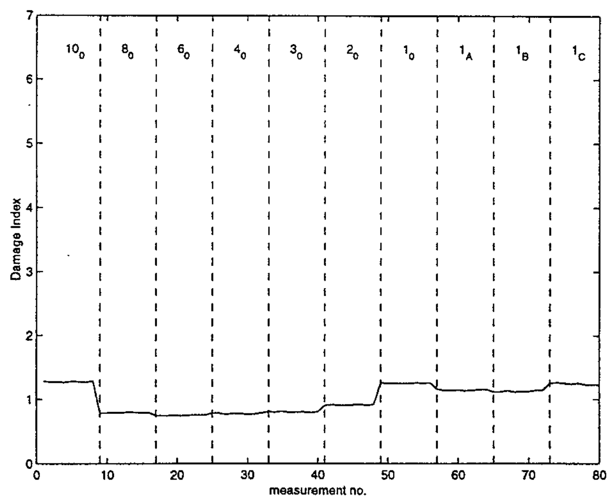

Figure 9: Damage cases A, B and C; 1% noise

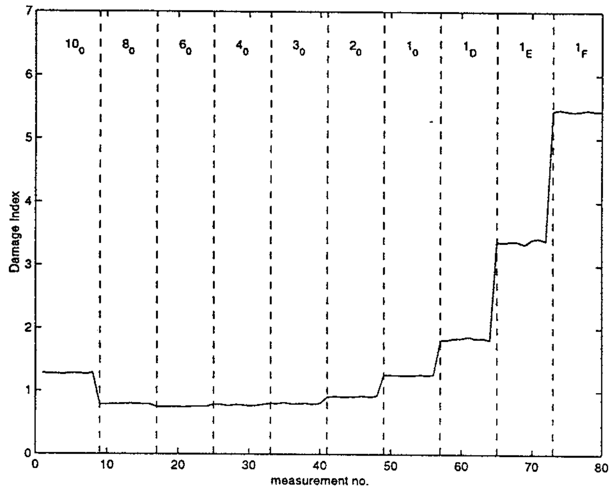

Figure 10: Damage cases D, E and F; 1% noise

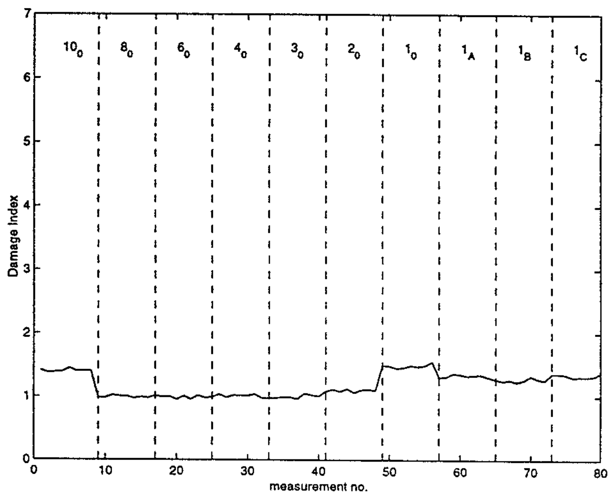

Figure 11: Damage cases A, B and C; 2% noise

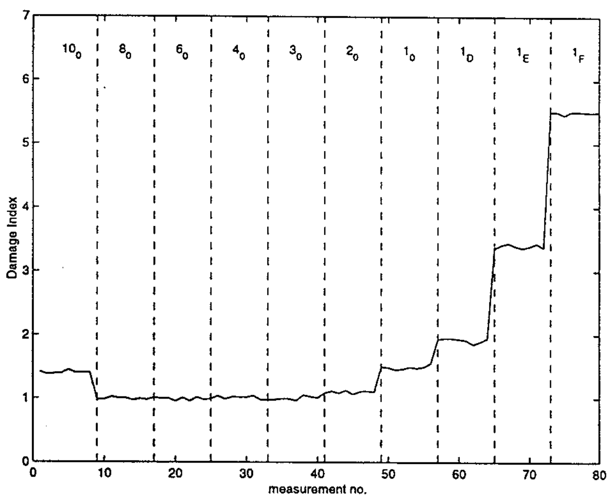

Figure 12: Damage cases D, E and F; 2% noise