FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION

DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA

Invited Paper

ENHANCED PARAMETER IDENTIFICATION FOR DAMAGE DETECTION IN AEROSPACE STRUCTURES USING "TWIN" STRUCTURES CONCEPT

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ABSTRACT

For safety and economic reasons, it is important for many aerospace, maritime, mechanical and civil engineering structures to have reliable and efficient methods enabling damage identification and their health monitoring. The research investigates a promising new approach to damage detection and structural integrity assessment for aerospace, mechanical and civil engineering structures, which, in contrast to the existing techniques, enables the engineer to step outside the "closed space" of limited data available using current conventional approaches and to develop a detection strategy which provides fresh new data which, in principle, is simple to generate. The new method is based on existing frequency sensitivity techniques, but it is radically enhanced by the inclusion of data from "twin" structures, a novel concept in this context.

Numerical investigations of the proposed method have yielded exceptionally encouraging results, and demonstrated the potential advantages of simplicity (hence lower costs), improved reliability and wider applicability when compared with current techniques. The feasibility of the method is demonstrated using a wide range of structural systems as examples: spring-mass systems; 2D and 3D complex truss structures; beam and frame models. Multiple damage sites have been successfully identified and quantified. The method has been shown to perform well. This technology can be especially efficient for large elastic truss and frame space structures.

1. INTRODUCTION

The design, control and maintenance of aircraft, spacecraft, future large space structures, bridges, high-rise buildings, offshore platforms, etc. offers many new and different challenges for engineers and scientists, for example, the development of a rapid and remote damage structural identification methods. This task is especially important and difficult for the complex aerospace structures, such as an orbiting space station, where damage is possible during orbital manoeuvres, docking operations, on-orbit assembling process, as well as collisions with space debris. In view of the variety of possible damage sources, the damage may occur at several locations and at any position. Therefore, the method of damage detection in the mentioned cases should be of a global nature, admitting the occurrence of damage in any of many design parameters of the structure. It should also be applicable to both - small and large damages.

Although successful damage detection investigations have been reported, they are mainly limited to simplified and very specific laboratory cases and do not include the global identification. This is because in the most practical applications, when conventional damage detection techniques are applied, a conflict between the unknowns in the analytical problem formulation and the available experimental data usually arises: the first number is usually large, and the data is usually inadequate for a unique solution [1].

For example, in the case of large space structures the only partial modal data can be measured; also, the desired accurate modal test data is not available periodically during the lifetime of the structure. At the same time, these high cost and safety-critical systems requiring the in-situ determination of damage are characterised with a huge number of design parameters, which is in contrast with the highly limited data available.

2. GLOBAL DAMAGE IDENTIFICATION PROBLEM FORMULATION

Difficulties with the global damage identification process, where all main design parameters of the structure are involved in the analysis, can be easily explained by the example of the 1-DOF mass-spring system shown in Fig.1a. The global damage identification task in the selected example is the problem of finding two unknowns - possible changes Δm and Δk to the original mass m and stiffness k of the system. To solve the problem analytically, an experimentally measured change in the natural frequency of the system can be used to formulate a mathematical equation for the two unknowns $\Delta p_1 = \Delta m$ and $\Delta p_2 = \Delta k$. The examined system has 1-DOF, thus the comparison of the natural frequencies for the undamaged and damaged system can bring one equation only. But this single equation in two unknowns can not be solved without ambiguity.

Similar contradiction between the required number of equations and available number of equations may take place also in the more general case of the N-DOF system with M design parameters. If the conventional sensitivity analysis technique is employed [2], the frequency sensitivity matrix $[S]$ can be calculated and the comparison of the natural frequencies ω_i $(i = 1,2,\ldots,N)$ of the undamaged and damaged "original" (so called "unmodified") configurations then can be used to formulate at most N algebraic equations in M unknowns (in the case of the complex structure the actual number of equations is much less, than N, because only partial modal data can be measured), providing that Δp are all small:

$$\{\Delta\omega\}_{N\times 1} = [S]_{N\times M}\{\Delta p\}_{M\times 1} \tag{1}$$

If the number of unknowns M is greater than the number of equations N, the designed system of equations yields an infinite number of solutions. However, for the precise identification of the damage, a unique solution is required.

3. THE PROPOSED SOLUTION - "TWIN" STRUCTURES METHOD

3.1 Generation of Additional Equations with New "Twins"

In many conventional damage detection techniques, the number of unknowns is truncated in order to reduce it to the number of available equations. On the contrary, our approach [3] is to step outside the "closed" space of the experimental data and to generate required extra number of equations. This method is based on the finite element modeling of the flexible structure. It proposes to utilise a conventional sensitivity analysis [2] and involves generation of extra equations by artificial modifications of the analysed structure. In this process the "unmodified" structure (so called "twin" with zero modifications) is used as the basis for producing the sets of new "modified" (so called "***twin***") structures. The selected modifications should be temporarily applied to the system twice (before the damage and after the damage) and should be identical in these two cases.

A large variety of "twins" can be easily obtained, for example, by: ① submerging the original structure as a substructure in the larger structure; ② introduction of known mass and/or stiffness modifications to the original structure; ③ embedding into the structure additional structural members or mechanisms with controllable stiffness and/or mass distribution properties; ④ changing the boundary conditions for the original structure, even without any its structural modifications. For example, the 2nd way can be efficient in space applications, when a twin for the space station can be obtained after the docking to it of a space vehicle, like the Space Shuttle, Hope or X-33. It can be also applied to bridges, where the known mass can be temporarily placed on the structure. The 4th way may be applied, for example, to the bridge structures, where additional supports can be installed temporarily for two natural frequencies measurements on undamaged and damaged structures.

For *each* of the newly created "modified" systems, comparison of natural frequencies for the *undamaged* and *damaged* configurations can generate at most N new equations. The whole set of these equations or its part only can be simply added to the system of equations (1) because the new set of the equations is formulated in terms of the same vector $\{\Delta p\}$.

3.2 Geometric Interpretation of the Proposed Method

To give a graphical illustration of the method, let us consider a 1-DOF system, shown in Fig.1a and consisting from the mass m=10 kg and the spring k=1000 N/m. The natural

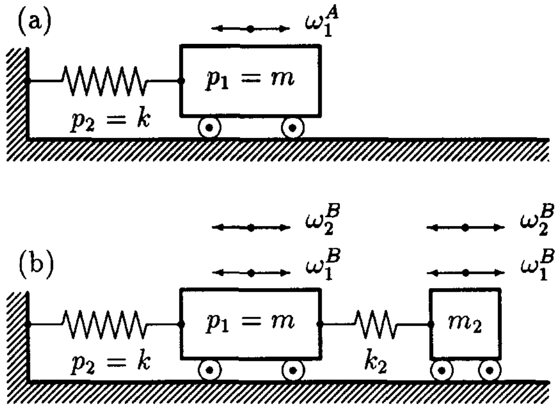

Figure 1: (a) 1-DOF mass-spring vibrating system; (b) Example of it's "twin".

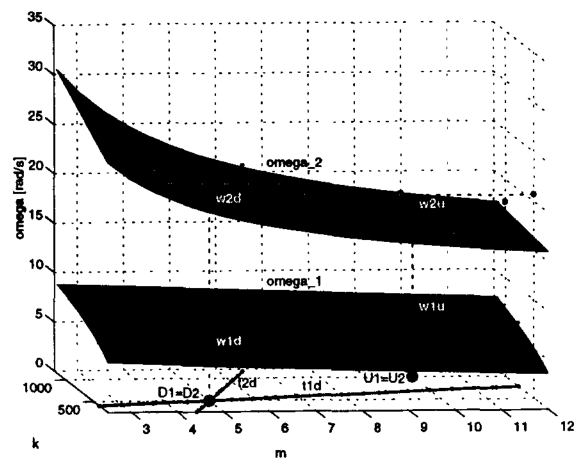

Figure 2: Geometric interpretation of damage detection procedure, using "twins".

frequency ω of the undamaged system can be calculated as $\omega = \sqrt{k/m}$ =10 rad/s. Let assume now, that the damage in the system, with so far unknown changes Δm and Δk in m and k, does not lead to any changes in ω. From this information the damage can not be identified precisely. Let us apply the "twin" structures method now, employing the technique No.① to create the twin (we will call it as "Twin B") by temporarily attaching to the original damaged structure, for example, a spring with the known stiffness of 1000 N/m and a weight with the known mass of 6 kg as shown in Fig.1b. For the introduced "twin" it is possible to calculate two frequency surfaces *omega-1* and *omega-2*, shown in Fig.2. Assume, that the measured natural frequencies of the system (damaged "Twin B") are ω_1=6.2 and ω_2=20.7 rad/s correspondingly. The projection *t1d* of the contour line *w1d* for ω=6.2 comprises the point *D1*, corresponding to the new m and k for the damaged system, but the point *D1* can not be identified precisely from the ω_1 data only. Also, the projection *t2d* of the contour line *w2d* for ω=20.7 comprises the point *D2*, corresponding to the new m and k for the damaged system, but the point *D2* can not be identified precisely from the ω_2 data only. The problem presented here can be solved if we combine together two sets of incomplete information: the point of intersection between *t1d* and *t2d* gives us the required solution.

For the particular figures used in this illustrative example, we can find that damage in the system is characterised with the reductions in mass m and stiffness k by Δm= –5 kg and Δk= –500 N/m correspondingly.

3.5 Major Advancement Resulting from this Approach: Selection of the Working Modes

During practical modal measurements on the real structure, some of the natural frequencies may not be clearly recognised, furthermore, some of them are very close to other natural frequencies, some of them can not be precisely measured, and many of them can not be measured at all! The method proposed in this paper, offers the possibility of generating new sets of equations, therefore it brings an obvious flexibility: during damage detection it is possible to select from *experiment, the preferred frequencies for the following numerical calculations.* This proposition is illustrated in Fig.5 for the damage detection in an 11-DOF system, taken as an example and shown in Fig.3.

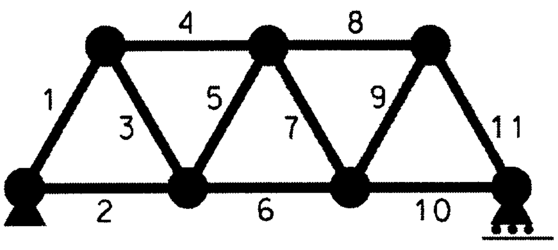

Figure 3: 11-degree-of-freedom planar truss structure.

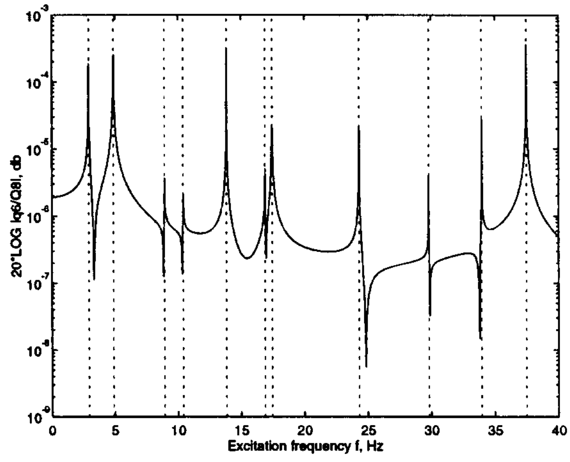

Figure 4: FRF for the 11-DOF "Twin *A*".

In this testing example damage in 7 out of 11 structural elements was imitated. To do this the 20%, 15%, 40%, 60%, 25%, 30% and 50% reduction in stiffness in the 1st, 2nd, 3rd, 6th, 8th, 9th and 10th elements correspondingly was applied to the original (undamaged and unmodified) system. The new frequencies were calculated from the finite element model for all twins of the system and were then used as the frequencies, "measured" on the damaged structure.

To apply the proposed method to damage identification in the structure, a set of appropriate twins must be introduced and active modes for each of the twins must be specified. As one of the possibilities, we use the following twins:

❶ *Twin-A*: original unmodified structure; active modes: 1-6;

❷ *Twin-B*: original modified structure with twice increased stiffness for the element 10; active modes: 1-3, 6, 8. The last modification can be easily done by clamping an identical rod to the existing element 10.

The frequency response function for one of the twins is presented in Fig.4. As the active frequencies we take, for example, frequencies No. 1, 2, 3, 4, 5, 6 (Twin *A*) and frequencies No. 1, 2, 3, 6, 8 (Twin *B*). This process of selecting natural frequencies is not unique and is based on some practical considerations. For example, the 7th natural frequency for Twin *A* is too close to the 6th natural frequency and consequently it was abandoned. Also, all highest frequencies for both Twins were not selected as active because they are more difficult to measure.

Practical implementation of the damage identification procedure for small parameter variation is shown in detail in the Appendix. The sensitivity based procedure, applicable to the cases with small parameter variation, has been extended to the cases with *large parameters variation* by employing an iterative method to solve the nonlinear problem. To perform this, a special numeric technique was developed and implemented in computer code.

Damage identification results for the 20-step iteration procedure are presented in Fig. 5 & 6.

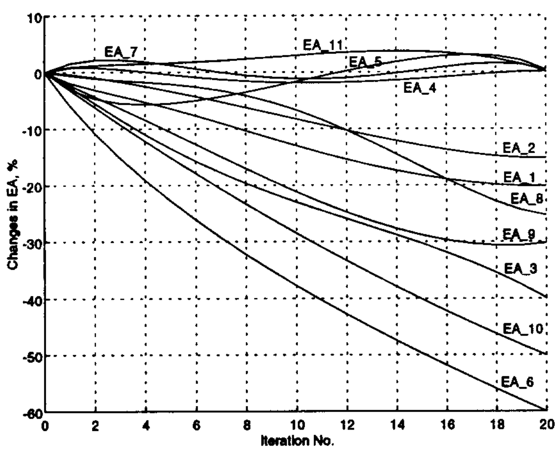

Figure 5: Damage identification in the 11-DOF truss structure.

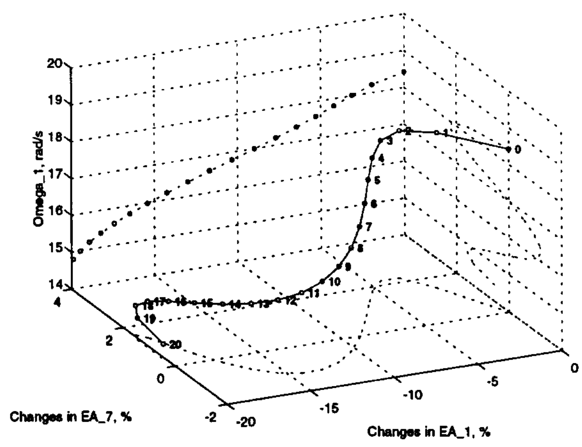

Figure 6: Iteration trajectory in the EA_1 - EA_7 - ω_1 space.

As Fig.5 shows, new method was able to very accurately locate (point out the numbers of the finite elements, serving here as the addresses of the damage) and quantify (calculate percentage change) combine damage in all damaged elements of the model. Results are quite accurate even for a 10-step iteration procedure.

4. APPLICATION OF THE "TWIN" STRUCTURES METHOD

4.1 Results for the 40-DOF 2D Truss Structure

The "Twin Structures" method is illustrated with the damage identification in a 40-DOF system, shown in Fig.7.

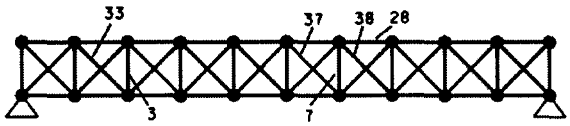

Figure 7: 40-DOF planar truss structure.

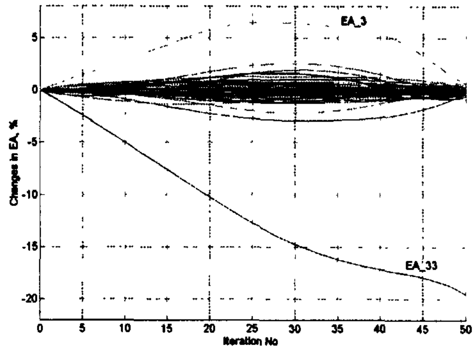

Figure 8: Iterative procedure.

In this global identification experiment, all 51 member stiffnesses were included in the analysis. For this example the following "twins" were used:

❶ *Twin-A*: original unmodified structure; active modes: 1-20;

❷ *Twin-B*: original modified structure with reduced by 50% stiffness for the element 7; triple stiffness for the element 28; active modes: 1-20;

❸ *Twin-C*: original modified structure with increased by 50% stiffness for the element 37; completely removed element 38; active modes: 1-11.

The method was able to identify a 20% damage (reduction in the *EA*) in the element 33. The convergence of the damage identification iteration procedure is illustrated with Fig.8.

4.2 Results for the 3D Space Truss Structure

In 1988, NASA began examining options for performing on-orbit system identification experiments with Space Station Freedom. Known as the Space Station Structural Characterisation Experiment, the intent is to use the Space Station as a research testbed to study techniques for determining the dynamic characteristics of large space structures [4]. Following this tradition, this structure (see Fig. 9) has been used to test the proposed method. Results of the damage identification are presented in Fig 10. In the test numerical experiment presented, damage (reduction in stiffness *EA*) was introduced to the following elements of the structure: 5%, 15% and 20% for elements 38, 24 and 31 respectively.

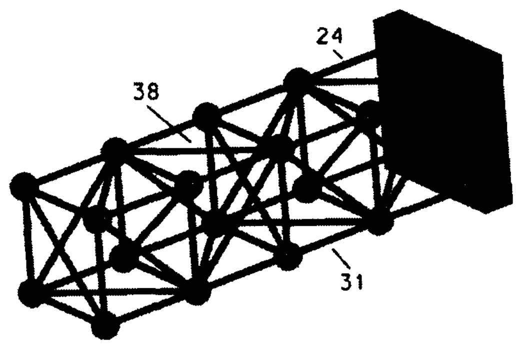

Figure 9: 48-DOF model of a four-bay segment of the Space Station Freedom.

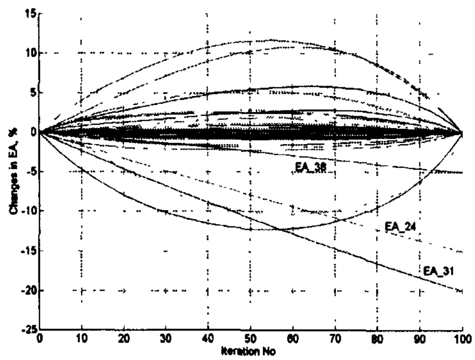

Figure 10: Multiple damage identification in the 48-DOF truss.

4.3 Results for the 3D Wing-Like Frame Structure

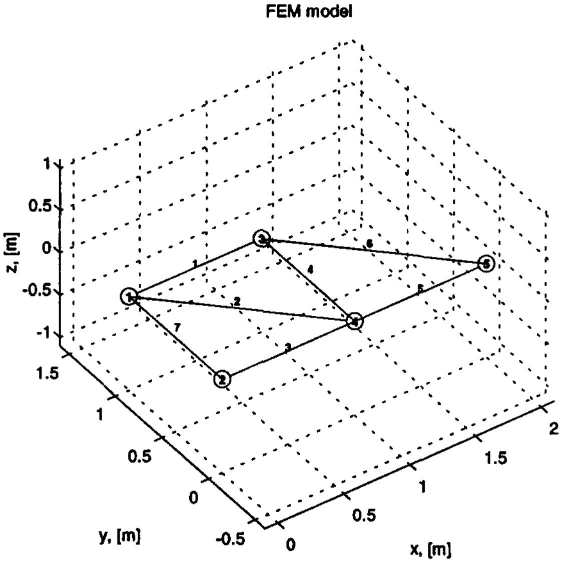

Figure 11: The simplified model of a wing.

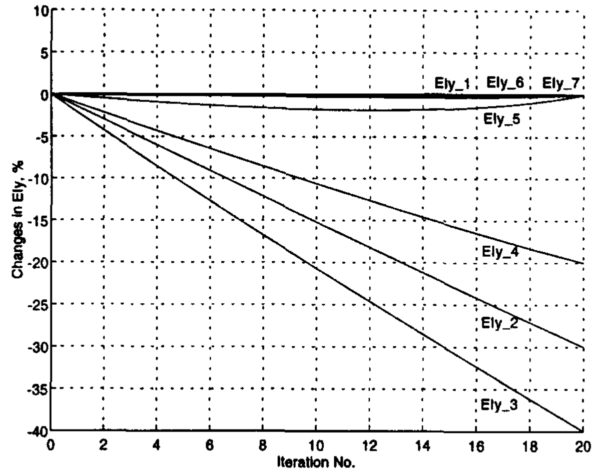

Figure 12: Damage identification for the frame 19-DOF model.

As Fig.12 shows, a "Twin Structures" method has been proved to be also a very efficient tool in the global damage identification for a frame structure (6-DOF per node), shown in Fig.11. The accuracy in the identification of 20%, 30% and 40% damage (reduction in bending stiffness) for elements 4, 2, and 3 respectively, is perfect.

5. MAIN RESULTS AND CONCLUSIONS

The new method to detect the geometric *location* of the damage in large flexible structures and to *quantify* the severity of the damage has been developed and implemented in a set of computer programs. The method requires comparison of vibration characteristics of undamaged and damaged structures for the unmodified (or "original") and/or modified (or "twin") structures. The main features of the method are:

- it allows *global damage* and *parameter* identification in structures with *many* members;
- it allows detection of *multiple* damage sites occurring simultaneously in any number of members of the structure;
- it allows identification of damage using *few modes only*;
- in conjunction with the developed numerical algorithms, this method can be used to detect *large damage* in structures, in other words it is applicable to the highly nonlinear problems;
- it gives a *single solution*, i.e. for the selected model it identifies the damage "precisely";
- it is *simple* to implement experimentally: it requires a minimum number of sensors and therefore it is electronically more *reliable and accurate.*

Feasibility of the method is demonstrated at the examples: 3-DOF spring-mass system; 2D 40-DOF truss; the model of a four-bay suspended segment of the Space Station Freedom 3D truss structure; and the wing-like frame structure. The method has been shown to perform well. This technology can be especially efficient for large elastic truss and frame space structures.

6. REFERENCES

[1] Deobling, S.W., Farrar, C.R., Prime, M.B., and Shevitz, D.W. *Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in Their Vibration Characteristics: A Literature Review.* LA-13070-MS UC-900, Los Alamos National Laboratory, May 1996.

[2] **Johnson, D.A,** and **Jen, C.W.** *Sensitivity Analysis of Robot Modal Properties Using Low-Order Component Mode Synthesis.* - Proc. of the 8th International Modal Analysis Conference, Vol.1, January 29-February 1, 1990, pp.241-247.

[3] **Trivailo, P.M,** and **Plotnikova, L.A.** *A Method of Damage Identification in Vibrating Aerospace Flexible Structures: "Twin" Structures Approach.* - Proc. of The International Aerospace Congress 1997. Sydney, Australia, 25-27 February 1997. - 17 pp.

7. APPENDIX: Main stages in the "Twin Structures" method at the example of 11-DOF truss