ISSN 1392 - 1207. MECHANIKA. 2008. Nr.5(73)

Incremental strategy for damage detection in structures

F. Asma
Université Mouloud Mammeri BP 17 RP 15000 Tizi-Ouzou, Algeria, E-mail: asma7farid@yahoo.fr

1. Introduction

Many mechanical structures worsen because of age, abuse, and sometimes of repair lack or maintenance. In order to prevent incidents which are likely to occur, one must evaluate deteriorations and quantify them. Structural damage is considered as a weakening of the structure which affects its normal behaviour negatively. Damage can also be defined as any modification of the geometrical structure or initial material properties which can cause undesirable shocks or vibrations. Several phenomena can be at the origin of this damage like: cracks, welding, corrosion, fatigue…

The visual inspection was for a long time one of the most common methods used to detect this damage in structures. The larger size and the complexity of today's structures can reduce the effectiveness of the visual inspections. The conventional visual inspection can be very expensive in time and money, particularly when disassembling is necessary to give access to the elements to inspect. Moreover, these techniques of visual inspection are often unsatisfactory to identify the status of the structure where the damage is invisible with the naked eye.

The dynamic identification methods have a dominating role in defects detection of mechanical structures. Reference [1] gives the advantages of these methods as a nondestructive testing. In this context we propose a damage localisation and quantification method based on the principle of visual inspection. Finite element method is used to characterize the behaviour of the structure and damage is expressed by a reduction of the stiffness. A correlation function is used to compare predicted and measured behaviours (what replaces the eye of the visual inspection).

Several damage detection methods exist and can be classified in three categories:

- detection methods;
- detection – localization methods [1, 2];
- inverse calculation or direct correction methods [3, 4, 5];
- simultaneous detection-correction methods.

The proposed method is of the third type.

Many methods exists for identifying and locating damages in structural and mechanical systems, such as updating methods [6, 7], genetic algorithms [8], statistical methods [9], and wavelet analysis [10]. The proposed method is an incremental strategy based on correlation function.

2. Problematic

Let us consider the case of a dissipative structure in forced mode whose dynamic behaviour is governed by the differential system equations

$$M_A\ddot{y}(t) + B_A\dot{y}(t) + K_A y(t) = f(t) \tag{1}$$

where M_A is the mass matrix $\in R^{N,N}$, B_A is the damping matrix $\in R^{N,N}$, K_A is the stiffness matrix $\in R^{N,N}$, $y(t)$ is the response vector $\in R^N$, and $f(t)$ is the force vector $\in R^N$.

For harmonic excitation the particular solution of the equation (1) is

$$\left[s_\nu^2 M_A + s_\nu B_A + K_A\right] y_\nu = f \tag{2}$$

with $\nu = 1,\ldots,N$.

The solution of this equation depends on the precision of M_A, B_A and K_A matrices.

The correction method then consists in finding new matrices K_X, and M_X which define the real structure. Considering a proportional damping, we have $B=\alpha M+\beta K$. Considers the following parametrisation for the possible errors

$$\begin{cases} K_X^{(e)} = (1+k_i)K_{Ai}^{(e)} \\ M_X^{(e)} = (1+m_i)M_{Ai}^{(e)} \end{cases} \tag{3}$$

with

$$\begin{cases} K_X = \sum_{i=1}^{Ne} K_{Xi}^{(e)} \\ M_X = \sum_{i=1}^{Ne} M_{Xi}^{(e)} \end{cases} \tag{4}$$

The problem consists then in determining the k_i and m_i coefficients.

3. Choice of correlation function

To implement the suggested method we must have a correlation function between predicted and real structural measurements.

Several functions can be used. Liu et al. [11] use the residual force matrix and the sensitivity matrix of the structure. Burton et al. [12] have choose the Ritz damaged vector to locate the defect combined with an iterative diagram based on these residues to estimate the extent of the defect by variation of the dynamic stiffness. Dutta et al. [13] observed variations of the normal frequencies between the real and measured model, and the localization of the defect fear being quantified by considering the eigenmodes themselves; statistical functions can also be used [2]. Richardson [1] uses the modal correlation function MAC (Modal Criterion Insurance) to quantify the defect, Marwala and Heyns [3] use in addition to this criterion another correlation function COMAC (Modal Co-ordinate Criterion Insurance) which is a correlation between the measured eigenmodes and analytical ones for the same degree of freedom.

For the method suggested, we use the correlation frequency in frequency domain FRAC (Frequency Response Assurance Criterion) defined by [14]

$$FRAC(i,j)=\frac{\left|\{H_{Ajk}\}^T\{H_{Xjk}\}^*\right|^2}{\left(\{H_{Ajk}\}^T\{H_{Ajk}\}^*\right)\left(\{H_{Xjk}\}^T\{H_{Xjk}\}^*\right)}$$

with $H_{Ajk}(\omega)$ being the analytical frequency response of the degree of freedom j according to an excitation to the degree of freedom k, and $H_{Xjk}(\omega)$ the corresponding experimental frequency response function.

That gives FRAC = 1 in the perfect case, and $0 \leq$ FRAC ≤ 1 elsewhere.

The FRAC value is more close to 1 that the analytical frequency response functions are close to the measured ones; this gives us an influence of approaching or moving away the solution. The problem then consists in determining the values of k_i which as close as possible bring FRAC to 1.

4. Proposed method

The method is based on a comparison of the FRAC value in undamaged and damaged beams. It should be noted that any damage occurring in any element will affect the FRAC global value.

The method presented here consists of building the values of k_i and m_i by incrementing and/or decrementing of value ε according to the following algorithm.

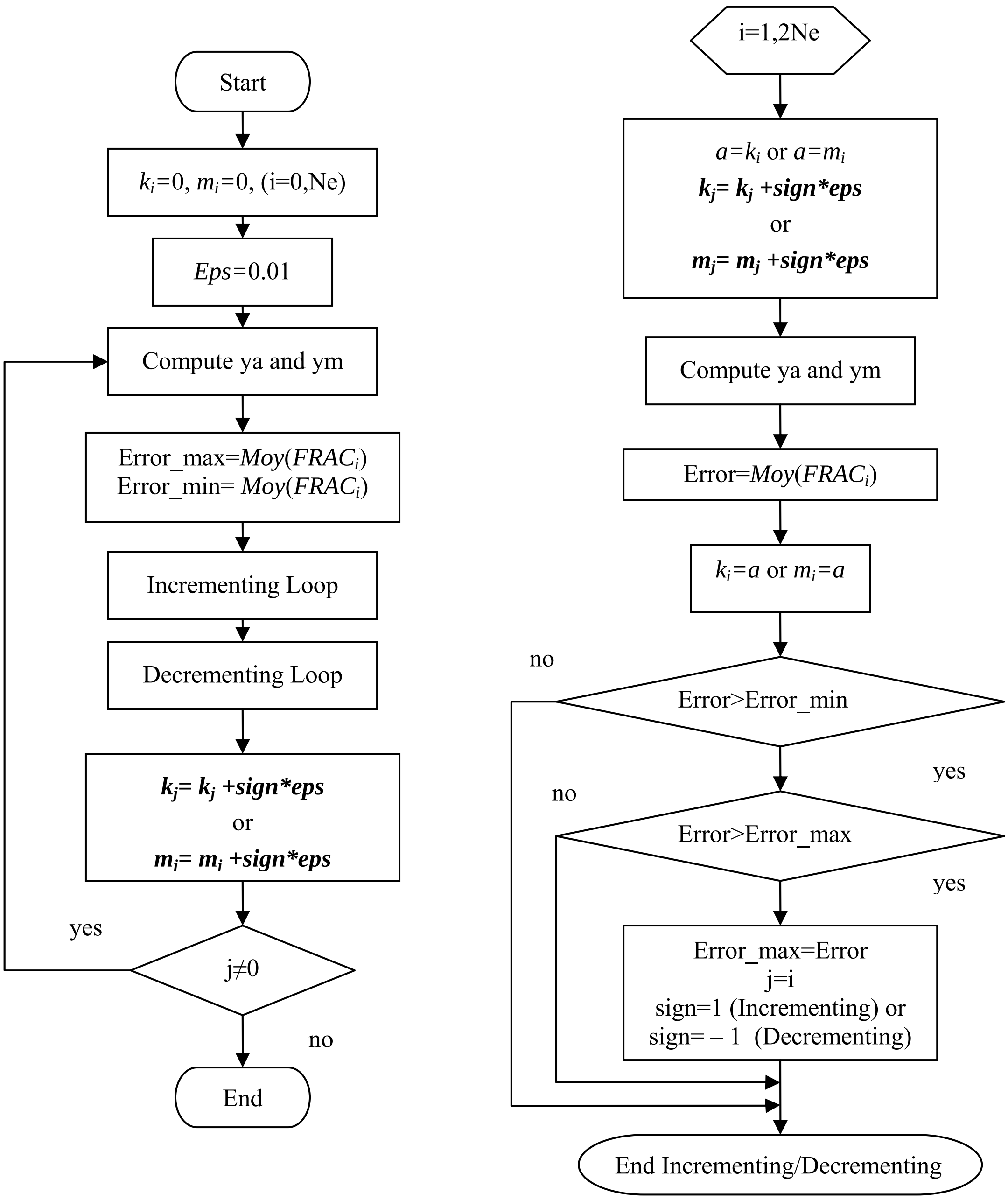

Fig. 1 Global method with the incrementing – decrementing loops diagrams

Let $k = [k_1,\ldots,k_{Ne}]^T$, $m = [m_1,\ldots,m_{Ne}]^T$
Assign a value to ε
Repeat
I = 1 to 2N
$k_i = k_i+\varepsilon$, *Compute* $FRACk_i = FRAC$
$k_i = k_i-\varepsilon$, *Compute* $FRACk_{Ne+i} = FRAC$
$m_i = m_i+\varepsilon$, *Compute* $FRACm_i = FRAC$
$m_i = m_i-\varepsilon$, *Compute* $FRACm_{Ne+i} = FRAC$
Mfrac1 = Max(FRACk) and j_k *his index*
Mfrac2 = Max(FRACm) and j_m *his index*
If Mfrac1 > Mfrac2
Then $k_j = k_j \pm\varepsilon$ *(+ or – case* j_k*)*
Else $m_j = m_j\pm\varepsilon$ *(+ or – case* j_m*)*
Delta = correction value of FRAC
Until Delta < ε
End

That is translated with more details according to the diagrams (Fig. 1).

5. Application

In our case, to simulate a measurement, random noise is added according to the model:

$$y^{(s)}(i,\omega_t) = (1 + r.d.n\%)y^{(s)}(i,\omega_t)$$

where r is a random value equalizes to 1 or –1, d is a random value between 0 and 1, and n is the introduced noise percentage.

Simulation was led until the rate of n = 5%.

Consider the plane lattice structure made up of 30 welded beams (Fig. 2). The structure is discretised into 30 finite elements and 39 degrees of freedom, with E = 2.1e11 N/m^2, and ρ = 7800 kg/m^3. The model simulating the structure is built by introducing defects of +20% and +30% to the stiffness respectively of elements 2, 14 and defects of -15% and -20% to the mass respectively of elements 18 and 26 adding 5% of random noise. Measurements are taken according to the degrees of freedom 8, 14, 20, 26 and 32 of the structure.

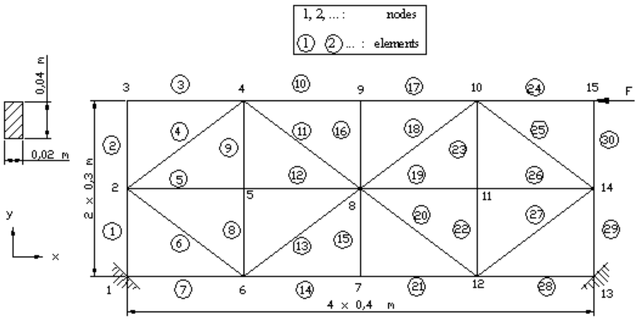

Fig. 2 Experimental lattice structure

The results show that the developed method detects and corrects the introduced defects. Indeed, we see on Fig. 3 that the frequency response function of the corrected model (curve in indents) is obviously confused with the response of the experimental structure (continuous curve) by correcting the analytical model (curve in dotted lines).

Table

Updating results

Elements	Simulated stiffness defects	Updating Stiffness results	Simulated mass defects	Updating mass results
1	0	0.90	0	0
2	**20**	**15.00**	0	0
3	0	2.00	0	0.60
4	0	-0.70	0	0
5	0	1.00	0	0
6	0	0	0	0
7	0	0.10	0	0
8	0	-0.10	0	0.60
9	0	0	0	0
10	0	0.20	0	0.20
11	0	1.10	0	3.60
12	0	0	0	-2.50
13	0	3.20	0	0
14	**30**	**20.00**	0	**7.50**
15	0	1.00	0	3.80
16	0	-0.20	0	1.90
17	0	0	0	-1.00
18	0	0.60	**-15**	**-13.40**
19	0	**8.10**	0	-7.20
20	0	1.00	0	0
21	0	-1.60	0	-5.00
22	0	1.10	0	0
23	0	0.40	0	0
24	0	-1.30	0	0
25	0	0.70	0	1.20
26	0	-2.70	**-20**	**-10.00**
27	0	0	0	0.20
28	0	0.90	0	0
29	0	0.80	0	1.10
30	0	1.20	0	0

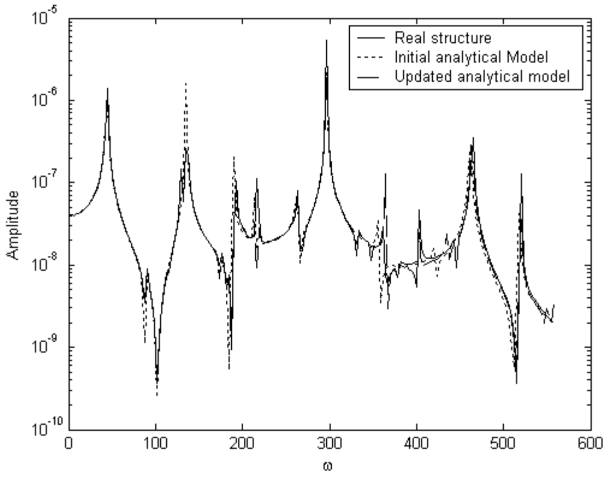

Fig. 3 Frequency response comparison of dof 20

Table also shows that the simulated defects are localised and quantified for noise ratio going up to 5% and a reduced number of measurements (6 degrees of freedom of vertical displacement are measured on nodes 4, 6, 8, 10 and 11). A good choice of the measurement points could make the method even more effective.

Note that unmeasured degrees of freedom are replaced by their analytical counterparts, this lead to a reduction technique of the analytical model to the measured degrees of freedom.

6. Conclusions

A damage detection method in mechanical structures based on the finite elements model correction was proposed. This is an incremental correction strategy which proceeds by correction increment on the element detected using the correlation function in frequency domain FRAC which materializes the convergence check by correlating the predicted and measured frequency response functions. The method thus presented, shows a good numerical stability.

The tests carried out on a truss structure shows very interesting qualities of detection and correction in term of quantification, localization and convergence speed by avoiding bad conditioning problems which often poses an abrupt divergence in the case of inverse problems. The technique has been applied to detect damages in many others simulated 2D structures, this gives an accurate estimation of the extent of the damages.

The effect of introducing noise in frequency measurements does not affect the reliability of the proposed method.

The effectiveness of the suggested method could be ameliorated using an appropriate choice of the measurement points.

References

1. **Richardson, M.H., Mannan, M.A.** Remote detection and location of structural faults using modal parameters.-Int. Modal Analysis Conference, 1992, p.502-507.
2. **Richardson, M.H., Mannan, M.A.** Detection and location of structural cracks using FRF measurements. -Int. Modal Analysis Conference, 1990, p.512-518.
3. **Marwala, T., Heyns, P.S.** A multiple-criterion method for determining structural damage.-AIAA Journal, 1998, v.36(8), p.1494-1501.
4. **Marwala, T., Hunt, H.E.M.** Fault localization using finite elements models and neural networks.-Mechanical System and Signal Processing, 1999, v.13(3), p.475-490.
5. **Ren, W.X., De Roeck, G.** Structural damage identification using modal data: Simulation verification.-J. of Structural Engineering, ASCE 128 (1), 2002, p.87-95.
6. **Asma, F., Bouazzouni, A.** Finite element model updating using FRF measurements.-Shock and Vibration Journal, 2005, 12 (5), p.377-388.
7. **Asma, F., Bouazzouni, A.** Finite element model updating using variable separation.-European Journal of Mechanics, A/Solids 26, 2007, p.728-735.
8. **Friswell, M.I., Penny, J.E.T., Garvey, S.D.** A combined genetic and eigensensitivity for the location of damage in structures.-Computers and Structures, 1998, 69, p.547-556.
9. **Xia, Y., Hao., H**. Statistical damage identification of structures with frequency changes.-J. of Sound and Vibration, 2003, 263, p.853-870.
10. **Djebala. A., Ouelaa. N., Hamzaoui. N., Chaabi. L.** Detecting mechanical failures inducing periodical shocks by wavelet multiresolution analysis. Application to rolling bearing faults diagnosis.-Mechanika.-Kaunas: Technologija, 2006, Nr. 2(58), p.44-51.
11. **Liu, X., Li J., Xu, Y., Peng, Z.** Location and modification of errors in structural dynamics models.-Int. Modal Analysis Conference, 1995, p.1763-1769.
12. **Burton, T.D., Farrar, C.R., Doebling, S.W.** Two methods for model updating using damage Ritz vectors. -Int. Modal Analysis Conference, 1998, p.973-979.
13. **Dutta, A., Talukdar, S.** Damage detection in bridges using accurate modal parameters.-Finite Elements in Modal Analysis and Design, 2004, v.40, p.287-304.
14. **Fosch, D., Ewins, D.** Application of the MAC in the frequency domain.-Int. Seminar on Modal Analysis, 2000, p.1225-1231.

F. Asma

KONSTRUKCIJŲ PAŽEIDIMŲ NUSTATYMAS TAIKANT PRIEAUGIO STRATEGIJĄ

R e z i u m ė

Paprastai, norint aptikti pakenkimus konstrukcijų pažeidimus, sudaromas nepažeistos mechaninės konstrukcijos matematinis modelis, kuris naudojamas kaip šablonas išmatuotų rezultatų nuokrypiams nuo idealių nustatymui. Kad konstrukcijų pažeidimus būtų galima nustatyti ankstyvoje jų radimosi stadijoje, analitinio modelio dinaminės charakteristikos lyginamos su realiomis. Ar yra defektų nustatoma fiksuojant gautų analitinių ir išmatuotųjų duomenų tarpusavio skirtumus. Tikrasis pažeidimų mastas nustatomas atlikus keletą analitinio modelio korekcijų. Pažeidimų nustatymo metodai skirstomi į tris kategorijas: aptikimo ir po to einančio atitaisymo metodas, atvirkštinio atitaisymo metodas ir akimirkinio aptikimo ir atitaisymo metodas.

Siūlomas metodas yra trečiojo tipo: jis pertvarko standumo matricą proporcingai slopinimui. Dažnio koreliacinė funkcija naudojama dažnio charakteristikos jautrumą defektams, imituojamiems iš eilės kiekvienam konstrukcijos elementui, įvertinti. Ši funkcija, kuri kinta intervale nuo 0 iki 1, informuoja mus apie imituotų pažeidimų įtaką konstrukcijos dažnių charakteristikai. Kai ji artima vienetui, esami pažeidimai įvertinami. Ši funkcija parodo, ar priartėjama, ar tolstama nuo sprendinio, kai daroma prielaida, kad elementas pažeistas. Šiuo atveju sunku nustatyti standumo korekciją, kuri artima konstrukcijos dažnio charakteristikai, nustatytai analitiškai ir eksperimentiškai.

Aprašomas metodas susideda iš standumo korekcijos dydžio nustatymo, jį didinant ar mažinant žingsniu ε, iki kiek galima tikslesnio priartėjimo prie analitinių duomenų. Sukurtas metodas, pritaikytas rėminėms konstrukcijoms modeliuoti, parodė šios atitaisymo strategijos efektyvumą ir tikslumą.

F. Asma

INCREMENT STRATEGY FOR DAMAGE DETECTION IN STRUCTURES

S u m m a r y

Usually, for defects detection in structures, it is necessary to establish a mathematical model for the undamaged mechanical structure to pose a template from which deviations can be measured. The dynamic behaviours of the analytical model and the real structure considered are compared in order to detect any appearance of defect at its early stage. The presence of defects results in a difference between the measured behaviour and that given by the analytical model. The extent of the damage is obtained after some correction stages of this analytical model. Damage detection methods can be classified into three categories: methods of detection then correction, inverse correction methods, and simultaneous detection – correction methods.

The proposed method is of the third type: it rebuilds the stiffness matrix considering proportional damping. A frequency correlation function is used to evaluate the sensitivity of the frequency response to a defect simulated successively into each element of the structure. This function which varies in the interval [0, 1] informs us about the influence of a simulated defect on the frequency response of the structure. When this one is close to the unity, the defects then are located and quantified. This function indicates if one approaches or moves away from the solution when a defect is supposed in a given element. The problem then consists in determining the stiffness corrections which as close as possible bring the frequency responses of the analytical model and those of the experimental structure.

The method presented here consists of determining the stiffness corrections by incrementing and/or decrementing of a step ε until as close as possible bringing the analytical model to the structure. The method thus obtained, applied to simulated measures for a lattice structure, shows the effectiveness and the precision of this correction strategy.

Ф. Асма

СТРАТЕГИЯ ПРИРАЩИВАНИЯ ДЛЯ ОБНАРУЖЕНИЯ ПОВРЕЖДЕНИЙ В КОНСТРУКЦИЯХ

Р е з ю м е

Обычно, для обнаружения дефектов в конструкциях, необходимо создать математическую модель для неповрежденной механической конструкции, которая позже используется как шаблон для установления отклонений измеренных результатов от идеальных. С целью установления повреждений в конструкциях в ранней стадии их появления, динамические характеристики аналитической модели сравниваются с реальными. Наличие дефектов характеризуется при фиксации разности аналитических данных с измеренными. Действительный масштаб повреждений устанавливается после нескольких коррекций аналитической модели. Методы установления повреждений подразделяются на три категории: метод обнаружения с последующим исправлением, метод обратного восстановления и метод мгновенного обнаружения и исправления.

Предположенный метод относится к третьему типу: он переустраивает матрицу жесткости пропорционально демпфированию. Функция корреляции частоты используется для оценки чувствительности частотной характеристики к имитируемым дефектам поочередно каждому элементу конструкции. Эта функция изменяется в интервале от 0 до 1 и информирует нас о влиянии имитируемых повреждений в конструкции на ее частотную характеристику. При ее приближении к единице, существующие повреждения оцениваются. Эта функция указывает приближаемся ли мы или отдаляемся от решения при предпосылке, что указанный элемент поврежден. В этом случае возникают проблемы при установлении коррекции жесткости, которая близка к частотной характеристике, установленной аналитически и экспериментально.

Предположенный метод основан на определении величины коррекции жесткости при ее увеличении или уменьшении величиной ε до возможно точного его приближении к аналитическим данным. Созданный метод, приспособлен к моделированию рамных конструкций, показал высокую эффективность и точность стратегии восстановления.

Received April 25, 2008

DOI: 10.5755/j02.mech.15151