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Damage Detection of a Cantilever Beam by Topology Optimization Using Modal Parameter

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***Abstract*— In the present work a new methodology has been developed using the concepts of topology optimization to detect the damage regions in a structure based on the vibration parameters such as natural frequency and mode shapes. The method involves correlating a local loss of stiffness and change in modal parameters to the damages in structures. This methodology serves as the Non Destructive test method for analyzing the structures.**

A cantilever plate made of Aluminium material is considered for the validation of the methodology. The method involves finding the natural frequencies for an undamaged and damaged specimen experimentally and utilizing these in the topology optimization routine of the finite element package to identify the damage locations in the structure. Hypermesh is used as a pre-processor and post-processor and Optistruct is used as a solver.

The initial excitation is given to the specimen by means of controlled low energy impacts. Natural frequencies of damaged specimens are compared with the natural frequencies of undamaged specimen. The changes in the natural frequencies indicate loss in the stiffness of material and also indicate the presence of damage in the specimen.

Keywords—Topology optimization; Modal parametrs; Frequency; Aluminium cantilever plate; DAQ Lab view setup; Hypermesh optistruct.

I. INTRODUCTION

In this approach, the topology optimization variable is now applied to the design domain of a finite element model that is based on the undamaged structure. By optimizing the system's stiffness and mass matrix towards those of the damaged structure by matching modal parameters, the correct location and geometry can be found in terms of elements with a lower density. In this case, the localization of damage is done by estimating the most probable equivalent damage (local loss of rigidity) which leads to a minimization of the norm between the baseline (undamaged) FRF and experimental FRFs of different damage states.

In the presented work, a rectangular plate of dimensions 200mm×50mm×1mm is considered for validating the Topology optimization method. The left end of the plate is fixed and subjected to free vibration at the other end thus it resembles like a cantilever plate. The first three natural frequencies are considered for the analysis.

A similar test is carried out on a damaged cantilever plate specimen, which gives changes in the natural frequencies compared to the undamaged specimen this change in the natural frequencies indicates the positive loss in the material and loss in the stiffness of material and also indicate the presence of damage in the specimen.

The natural frequencies obtained from the undamaged specimens are used as objective functions for the topology optimization method to find the positive location of damage. The optimization is carried out using Hypermesh optistruct solver. The damaged regions obtained from the Topology optimization are compared with the actual damaged specimen for the validation.

The experimental work is carried out on an undamaged and damaged aluminum rectangular plate, using labview setup. It consists of DAQ, accelerometer, impact hammer. An accelerometer is used to measure output response of the system and impact hammer is used to give an input to the test specimen in terms of low impact energy. DAQ is used to acquire the vibration signals and it converts these signals into digital signals. Experimentally obtained values are compared with numerical values obtained by analysis software.

II. EXPERIMENTAL PROCEDURE

The Experiment is carried out, on both undamaged and damaged cantilever plate to determine the natural frequencies.

The specimen is fixed to the table at one end so that the specimen resembles the cantilever plate: another end is left free for loading. An accelerometer is used to measures the output response of the system and excitation force is applied through impact hammer. The impact hammer is used to give only the free excitation DAQ will acquire the signals from the output and input sensors i.e. the accelerometer and impact hammer and converts analog signals into digital signals. The

results are stored in lab view software. The accelerometer is fixed at the desired position and force is applied at the different positions on the plate using impact hammer, the readings are taken over the particular time interval. The force and accelerometer readings are used in MATLAB software, to obtain a graph of FRF magnitude verses frequency to determine the natural frequency. The experiment is repeated for different impact load positions to determine the corresponding natural frequencies. The Fig 1 shows the experiment set up with lab view software.
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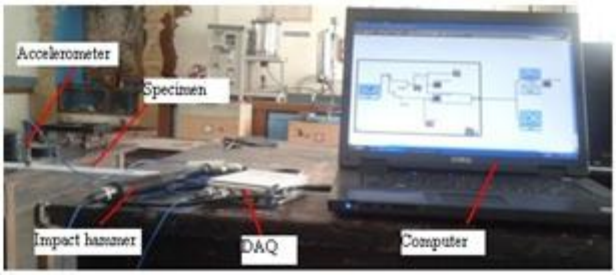

Fig 1: Lab view set up for the experimentation

The Damage is introduced in the aluminum test plate by removing the metal piece of 10×25mm, 25 mm away from the free end of the cantilever plate. A similar experimental procedure as in the case of undamaged cantilever plate is followed to determine the natural frequencies of a damaged cantilever

III. FINITE ELEMENT ANALYSIS OF CANTILEVER PLATE FOR DAMAGE DETECTION

The modal analysis is carried out on undamaged cantilever plate to determine the natural frequencies and then topology optimization is carried out to determine the damage location. Based on the optimization results the elements are removed to induce local loss of stiffness in the FE model for analysis of damaged cantilever plate

A cantilever plate test model with homogeneous isotropic material properties is shown in Fig 2 which is meshed with iso-parametric membrane-bending shell elements. On the free end of the plate, modal frequency-dependent excitation force with constant amplitude is applied and constraints are applied at the rear end.

Fig 2: Finite element model of a cantilever plate with applied forces and constraints

The Fig 2 shows the aluminum plate of length 200mm, width 50mm and thickness 1mm is modeled in hypermesh optistruct. The plate is meshed with shell elements of size 5mm each and about 400 elements are created. The frequency response analysis is carried out to find the natural frequencies for five modes of vibration over band width of 0-500Hz.

Topology optimization is carried out on undamaged cantilever plate using density method. Frequency and volume fraction are used as responses with frequency as an objective function and volume fraction as a constraint. The solution as converged after eight iterations
Based on the above topology optimization results, damage is created in the model by deleting ten elements in the lower density region as shown in Fig 3. The modal analysis is carried out, on the damaged specimen for five modes of vibration.

Fig 3: Finite element model of damaged cantilever plate with applied forces and constraints

IV. RESULTS AND DISCUSSIONS

The modal analysis is performed on the undamaged cantilever plate to extract the natural frequencies through experiments and finite element analysis. Fig 4 and 5 represent the FRF plots of the undamaged cantilever plate obtained in experiment and finite element analysis respectively. The natural frequencies are extracted from the FRF plots and are shown in table 1**.**

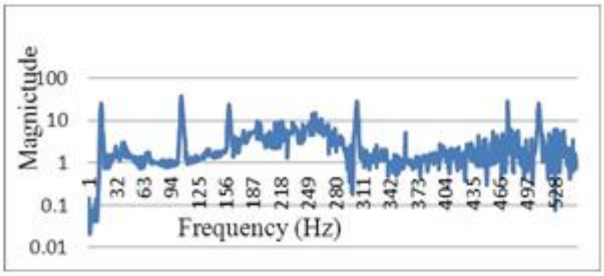

Fig 4: FRF plot for the undamaged cantilever plate

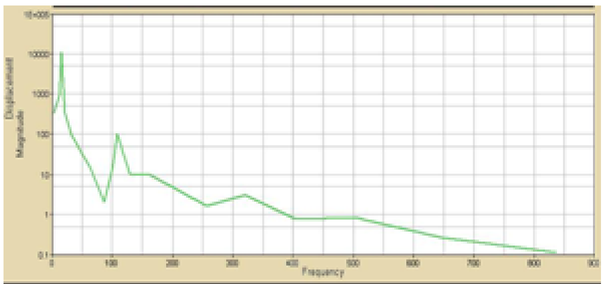

Fig 5: FRF plot for the undamaged cantilever plate

Table 1: Natural frequencies of undamaged cantilever plate

Mode	Natural frequencies(Hz) (Experiment)	Natural frequencies(Hz) (FEA)	Error (%)
1	15	15.46518	3.101
2	106	108.4123	2.276
3	160	161.8037	1.127
4	305	319.7226	4.827
5	475	499.0687	5.067

From table 1, it can be observed that the error involved in the natural frequencies is less than 3 percent up to third mode of vibration and less than 5 percent for the next two modes of vibration. The errors indicate that PSHELL element can be used for modal analysis of the cantilever plate with a maximum deviation of 5.067 percent from experimental frequencies. Based on these results PSHELL element is utilized in the topology optimization routine to detect the damage location of the cantilever plate.

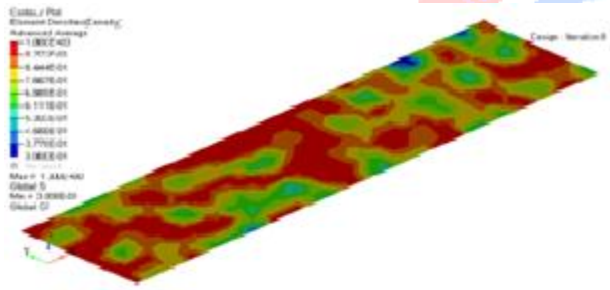

Fig 6: Density plot for the undamaged specimen (Eighth iteration)

Table 2: Natural frequencies of undamaged cantilever plate by experiment and topology Optimization

Mode	Natural frequencies(Hz) (Experiment)	Natural frequencies(Hz) (Topology optimization)
1	15	16.1970
2	106	106.3261
3	160	160.4848
4	305	298.3714
5	475	428.6338

The table 2 shows the Natural frequencies of undamaged cantilever plate obtained by experiment and topology Optimization. It can be observed that there is a variation in the natural frequencies obtained from topology optimization routine compared with the experimental values of natural frequencies. This variation is due to the local loss of stiffness and mass in the material; represented by lower values (Blue) of densities as shown in Fig 6. This region of lower density values indicates the possible location of damage in the material

Fig 7: Finite element model of damaged cantilever plate

The Fig 7 shows the finite element model for modal analysis of the damaged cantilever plate. The damage is introduced in the specimen based on the density plots by removing the lower density regions. Table 3 shows the optimized, experimental and FEA frequencies for the damaged cantilever plate. The values are in close correlation with experimental frequencies with a maximum deviation of 5.6 percent

Table 3: Natural frequencies for the damaged cantilever plate

Mode	Natural frequencies(Hz) (Topology optimization)	Natural frequencies(Hz) (Experiment)	Natural frequencies(Hz) (FEA)	Error (%)
1	16.1970	17	15.81970	4.7
2	106.3261	112	104.6001	5.06
3	160.4848	170	162.7848	5.6
4	298.3714	294	292.0814	1.46
5	428.6338	429	425.4136	0.80

IV. CONCLUSIONS

Finite element analysis and the experimental validation of the results for a cantilever plate show that there will be a measurable change in the modal parameters like natural frequency when the structure is damaged. The change in the modal parameters is due to the loss of stiffness and mass of a structure at the damage locations. This characteristic of the structure can be utilized in the formulation of topology optimization problems to identify the damage location in the structure.

Topology optimization routine can be used as a non destructive test method for identifying the damage locations in a structure. The observations indicate that the results are accurate for first three modes of vibration with a maximum deviation of 5 percent This method can be effectively used for various mechanical components to detect the damage regions, which obey plane stress conditions.

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