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Finite Element Model Updating Approach for Structural Health Monitoring of Lightweight Structures Using Surface Response Optimization

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Abstract. Mechanical defects in the structure changes it's vibration response. There is a wide variety of methods that examine changes in measured vibration response to detect, locate, and characterize damage in structural and mechanical systems. One method to evaluate the structural changes and to analyse their causes is the Finite Element Model Updating (FEMU). The objective of this research is to investigate the FEMU procedure for mechanical damage identification and to propose an experimental-computational SHM method for lightweight structures. The structural dynamic response to impact excitation of a structure with and without defects are collected from transient and modal analysis using Ansys FE software. Afterwards, FEMU algorithm using Ansys Surface Response Optimization is investigated for its applicability to damage identification. Obtained results revealed the possibility to use this algorithm with having minimum discrepancy between parameters obtained from experiments and finite element modelling.

1. Introduction

Structural health monitoring (SHM) is tracking static or dynamic characteristics of a structure to identify and localize damage, monitor its evolution, and decides inspection and repair intervals in order to avoid the structural collapse. Mechanical changes caused by defects in mechanical structure changes it's vibration response. There are wide variety of methods that examine changes in measured vibration response to detect, locate, and characterize defects in structural and mechanical systems [1-5]. The basic idea behind this technology is that modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness) [6-8]. Therefore, changes in the physical properties will cause detectable changes in the modal properties. One of the method to evaluate this changes and to find what causes these changes is Finite Element Model Updating (FEMU), which could be used in wide variety of applications: Computational FEMU algorithms for damage identification based on experimental measurements of the structural dynamic response [9], as applied to multi-response structural parameters estimation for bridges; Convolutional Neural Network based FEMU approach for the prediction of various types of damage in composite laminates based on low frequency structural vibration outputs [10]; applied to damage detection in helicopter blade based on experimental data from laser scanning vibrometery [11]; applied to structural damage detection based on measured time domain vibration response [5]; FEMU feasibility applied for the suspension bridges assessment [12]. In most of the research FEMU process is carried out using specific Matlab programming codes [13], classical mathematical calculations using FEM matrixes or Ansys APDL codes [12]. In this research a novel procedure for FEMU using Ansys FE software combined with Ansys Surface Response Optimization is proposed and investigated for the defect identification in aluminium plate. Proposed procedure could be used in significantly complex structures for SHM purposed in lightweight composites structures such as wind turbine blades, aeroplane wing, automobile frames, etc.

2. FEMU Algorithm using Ansys Response Surface optimization software

Principal scheme of proposed FEMU algorithm is presented in Fig. 1.

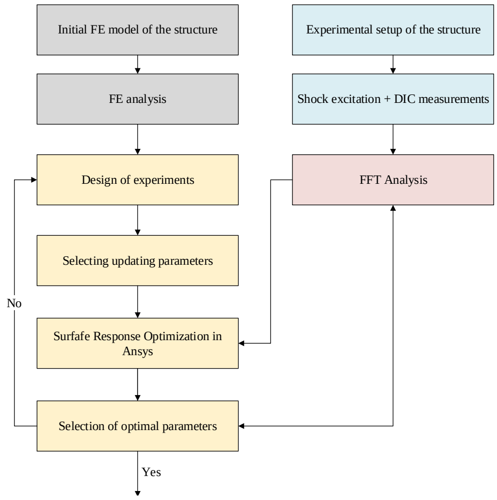

Figure 1. Principal scheme of FEMU algorithm

As it is shown in Fig. 1, at the beginning initial finite element model of the structure is created and finite element analysis in order to obtain natural frequencies, mode shapes or other required parameters is carried out. In parallel experimental setup of the same structure and contact, i.e. accelerometers, or non-contact measuring technology, i.e. digital image correlation (DIC), 3D laser vibrometry, etc. with impact type excitation or FFT analysis on demand of obtained results should be carried out. These results are compared with results obtained from FE analysis and if there are some shifts, i.e. caused by defects, between frequencies or other parameters, surface response optimization by selecting updating parameters using design of experiments tool is carried out. This procedure is repeated by iterations until difference between results obtained from experiments and FE analysis are minimized. Afterwards parameters, which were used in optimization and caused minimum difference between experimental results and FE modeling are used to identify and describe defect in the structure. For validation of proposed method for damage identification, two different cases using virtual experiments with aluminium plate with and without defects were carried out and presented in next section.

3. Damage identification using proposed FEMU algorithm

Finite element model updating procedure were carried out using Ansys R19.2 software in combination with response surface optimization tool. FE analysis was carried out with Transient and Modal analysis.

3.1. Finite element modelling of the investigated structure

FEMU in this research was conducted with two different types (stages) of virtual experiments and data sets. In the first stage Modal analysis of the plate were carried out with the health and damaged aluminum plate (two different locations of defects, i.e., 2 cases) having same geometric conditions. Defect was modelled as 20x20 mm through hole on the structure and its location varied depending on simulation case. Geometry of the investigated plate are presented in Fig. 2 and geometric dimensions and properties of the material together with FEM numerical simulation data of both stages – modal and transient analysis are collected and presented in table 1.

During both modal and transient analysis aluminium plate was fully fixed on the one surface area of 150 x 150 mm size (white zone in Fig. 2). During modal analysis 20 resonant frequencies with damaged and undamaged plate were calculated. During transient analysis excitation was applied by adding 10 N force for 0.022 s on the excitation surface *A* thus generating excitation impulse, presented as green zone in Fig. 2. Noticed, that there could be 15 different excitation surfaces *A-M* in this structure for further investigation. Transient analysis results were vertical displacement of measurement points 1-24, measured for 3 s period from the excitation. Noticed, that these measurements points can be the same used for real experimental investigation, e.g. DIC or laser vibrometry measurements.

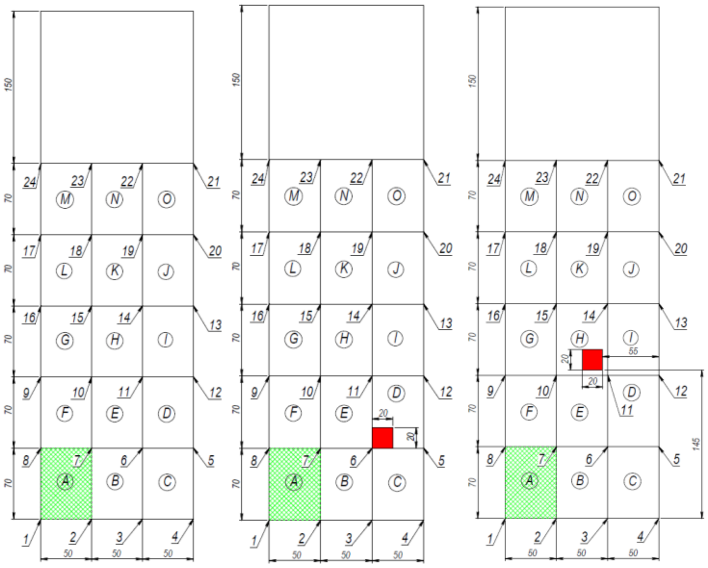

Figure 2. Geometry of the investigated aluminium plate: left side – undamaged structure, middle – with defect Case 1, right side – with defect Case 2.

Table 1. Properties, geometric dimensions of the aluminium plate and FEM numerical simulation data

Parameter	Unit	Value
length x width x thickness	mm	500 x 150 x 3
Young's modulus of aluminium alloy	GPa	71
Poisson's ratio of aluminium alloy	-	0.33
Density of aluminium alloy	kg/m^3	2770
number of finite elements without defect	-	3000
number of nodal points without defect	-	6262
number of finite elements with defect	-	2984
number of nodal points with defect	-	6244
excitation impulse time for transient analysis	s	0.022
excitation impulse for transient analysis	N	10
fixture surface area length x width	mm	150x150

Modal analysis results – natural frequencies of modes 1-8 with and without defect in the aluminium plate is presented in table 2.

Table 2. Modal analysis results

Mode number	Natural frequency, undamaged, Hz	Natural frequency, defect case 1, Hz	Difference between undamaged and case 1, Hz	Natural frequency, defect case 2, Hz	Difference between undamaged and case 2, Hz
1	20.5	20.64	0.14	20.50	0.00
2	99.54	99.80	0.27	99.04	-0.49
3	127.77	127.23	-0.54	126.69	-1.08
4	319.76	317.40	-2.36	318.43	-1.33
5	359.33	355.84	-3.49	358.53	-0.80
6	600.11	597.23	-2.88	598.34	-1.77
7	697.29	693.04	-4.25	691.59	-5.70

Mode number	Natural frequency, undamaged, Hz	Natural frequency, defect case 1, Hz	Difference between undamaged and case 1, Hz	Natural frequency, defect case 2, Hz	Difference between undamaged and case 2, Hz
8	766.16	753.61	-12.55	757.09	-9.07

As it is seen from presented results, damage decreases the natural frequency of the structure and significant differences between undamaged and damaged structures begins from mode no. 4, what means that in FEMU process is better to use higher modes of the investigates structure.

Transient analysis results, as for example measurement point no. 1 displacement versus time in 3s period is presented in Fig. 3, and measurement points 1-12 minimum vertical displacement, which as numerical value will be used for FEMU process, in the same time period is presented in table 3.

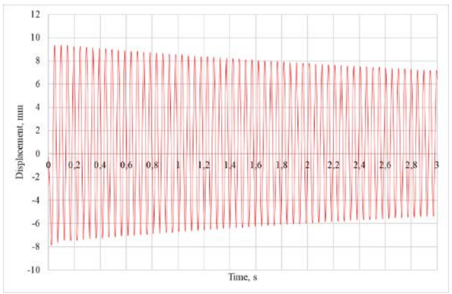

Figure 3. Measurement point no. 1 displacement in 3s period of undamaged structure

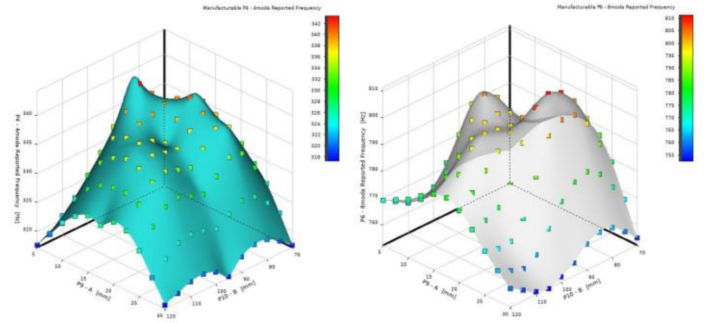

Figure 4. Response surfaces of the 4th and 8th modes for case 1

Table 3. Transient analysis results

Measurement point number	Minimum vertical displacement without defect, mm	Minimum vertical displacement defect case 1, mm	Difference between undamaged and case 1, mm	Error, %
1	7.8638	7.9228	0.0590	0.75
2	7.8027	7.8585	0.0558	0.72
3	7.7252	7.7778	0.0526	0.68
4	7.6410	7.6900	0.0490	0.64
5	5.4503	5.4700	0.0197	0.36
6	5.4998	5.5281	0.0283	0.51
7	5.5568	5.5917	0.0349	0.63
8	5.5922	5.6258	0.0336	0.60
9	3.4757	3.4901	0.0144	0.41
10	3.4761	3.4937	0.0176	0.51
11	3.4593	3.4680	0.0087	0.25
12	3.4353	3.4280	0.0073	0.21

As it is seen from presented results, damage change values of displacement, thus changing structure's response to the same excitation conditions. Noticed, that the most relevant results are up to 20th point, because points 21-24 are almost fixed.

3.2. Finite element modelling updating

In this section two different FEMU process is demonstrated to validate proposed algorithm, presented in Fig. 2: using modal and transient analysis results for FE modelling and virtual experiments results as parameters required for updating process.

FEMU process using Modal analysis data: The central composite design approach was used to perform the design of experiments. Horizontal distance of damage from the right corner and vertical distance of damage from the bottom were used as updating parameters. The interval of horizontal distance varied

from 5 to 30 mm and vertical – from 70 to 120 mm for case 1. For case 2 horizontal distance varied from 50 to 80 mm and vertical – from 140 to 190 mm. Updating values were divided into 13 and 11 parts (by incremental size equal to 2,5 and 5 mm) of horizontal and vertical distance respectively for both cases. A total of 17 design points as centre point were created and calculated. The natural frequencies of the 1st, 4th, 7th and 8th modes were selected as output parameters.
The genetic aggregation approach is used to generate response surface. Fig. 4 presents response surface as example for the 4th and 8th modes of the case 1.
After creating response surface, optimization using surface response optimization tool and Moga optimization method was carried out. For this purpose, natural frequencies obtained from virtual experiments, presented in the 3rd and 5th column in table 2 were used as objective values for algorithm to seek this target. Table 4 presents the optimization of design variables for horizontal and vertical distance and natural frequencies of 2 candidate points for case 1 and case 2.

Table 4. Optimization results for FEMU using modal analysis

Parameter		Virtual experiment		Candidate 1		Error, %		Candidate 2		Error, %	
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Defect location, mm	Horizontal distance	30	55	30	50	0.00	3.45	5	140	0.00	3.45
	Vertical distance	70	145	70	140	0.00	9.09	70	80	83.33	45.45
Natural frequencies, Hz	Mode 1	20.64	20.5	20.61	20.51	0.15	0.04	20.64	20.41	0.00	0.44
	Mode 4	317.40	318.43	317.62	318.27	0.07	0.05	317.42	318.30	0.01	0.04
	Mode 7	693.04	691.59	693.64	692.14	0.09	0.08	696.60	690.60	0.51	0.14
	Mode 8	753.61	757.09	753.31	757.21	0.04	0.02	764.13	756.29	1.40	0.11
Average						0.06	2.12			14.21	8.27

As it is seen for the obtained results, candidate no 1 fits case 1 with average error 0.06 % and has error factor 2.12 % for case 2. However, to measure higher modes of the investigated structure might be a challenge, thus similar procedure was tested using transient analysis results and modelling thus imitating excitation of the first mode only and measuring displacement of the surface when excitation condition is known and remains the same for all tests.

FEMU process using Transient analysis data: The initial updating parameters and intervals were the same as described in 3.2.1 chapter for case 1. The minimum vertical displacement in 3s time of measurement points 1, 6, 11 and 12 together with the 1st natural frequency of the structure were selected as output parameters. For optimization minimum vertical displacement of measurement points 1, 6, 11 and 12 obtained from virtual experiments, presented in the 3rd column in table 3 were used as objective values for algorithm to seek this target. Table 5 presents the optimization using transient analysis results of 3 candidate points for case 1.

Table 5. Optimization results for FEMU using transient analysis

Parameter		Virtual experiment	Candidate 1	Error, %	Candidate 2	Error, %	Candidate 3	Error, %
Defect location, mm	Horizontal distance	30	29.5	1.67	30	0.00	5	83.33
	Vertical distance	70	69.8	0.29	82	17.14	78	11.43
Natural frequency, Hz	Mode 1	20.64	20.63	0.05	20.623	0.08	20.621	0.09
Minimum vertical displacement, mm	Point 1	7.9228	7.9221	0.01	7.924	0.02	7.936	0.17
	Point 6	5.5281	5.5275	0.01	5.5284	0.01	5.5287	0.01
	Point 11	3.468	3.46	0.23	3.4674	0.02	3.4696	0.05
	Point 12	3.428	3.423	0.15	3.4251	0.08	3.4275	0.01

Parameter	Virtual experiment	Candidate 1	Error, %	Candidate 2	Error, %	Candidate 3	Error, %
Average			0.34		2.48		13.58

Obtained results showed that the candidate 1 fits optimization scope and thus identifies defect with average error up to 0.34 %. Candidate no 2 can be considered as well due to error up to 2.48% while candidate no 3 is not relevant in this case.

4. Conclusions

Finite element modelling updating technique using surface response optimization were proposed and investigated. Obtained results showed that using this method it is possible to identify and locate damage by using two different measurement and data acquisition techniques. It is necessary to measure at least 4 natural frequencies of modes 1, 4, 7 and 8 of investigated structure to identify defect with accuracy up to 99.94%. Since measurements of higher modes natural frequencies are complicated in real application, the methodology was tested with measuring surface displacement and the first natural frequency only. Obtained results revealed the possibility to identify defect in the structure with accuracy up to 99.66 %. Noticed, that this algorithm can be applied with various updating and objective parameters, such as elastic modulus, stiffness, damping ratio, etc.

5. References

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Acknowledgments

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