437. Application of macro-fiber composite (MFC) as a piezoelectric actuator

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Abstract. The aim of the present work is to investigate the use of Macro Fiber Composite (MFC) actuator for modal analysis of composite plate. Efficiency of application of MFC as an actuator in comparison with the impact hammer, PZT actuator and modal shaker has been investigated. POLYTEC laser Vibrometer operating on the Doppler principle and measuring back-scattered light from a vibrating panel has been used to determine its vibration velocity and displacement. Modal analysis is subsequently applied to extract natural frequencies and mode shapes.

Keywords: macro-fiber composite actuator, modal analysis, laser vibrometer

Introduction

Modal analysis has been appreciated as an important part of the engineering investigation. It is commonly used to determine the natural frequencies and mode shapes of a structure and ensure that design structure will not stay in the vicinity of resonant frequencies [1]. The resonant (natural) frequency, which depends on the mass distributions and stiffness of the structure, as well as mode shapes are used to validate all types of structures such as automotive structures, aircraft structures, and spacecrafts. Modal analysis can also be found as a part of an identification of material properties of advanced composite materials which is based on vibration tests. Recently, an application of modal analysis in damage detection became very wide, especially in composite materials due to its flexibility of measurement and relatively low cost. A good and easy validation of the real structure with finite element model makes modal analysis useful tool for structure design. Although, the application of modal analysis is very broad, the description of its advantages cannot be given exactly because it is beyond the scope of the paper.

Nowadays, there are many variations for exciting a structure in experimental modal analysis. The present study deals with application of four devices for modal analysis of the laminated composite plate, namely, impact hammer, PZT actuator, modal shaker and piezocomposite actuator (MFC). Brief description of all four devices is provided below.

Impact testing by hammer has been developed during the late 1970s, and has become the most popular modal testing method used nowadays. It is a fast, convenient, and low cost procedure of finding the modes of machines and structures. However, not all structures can be forced by hammer. If they have a delicate surface, limited frequency range or low energy density over a wide spectrum, the impacting force will be not sufficient to adequately excite the modes of interest. In such case the modal shaker is attached to the structure for modal test. A stinger (long slender rod) is usually used in order to connect modal shaker with structure under investigation so that the shaker will transmit only force to the structure along the axis of the stinger. A load cell is then attached between the structure and the stinger to measure the excitation force.

The use of piezoelectric actuators for modal analysis has been demonstrated extensively over the past few years.

Piezoelectric actuators are devices that produce a small displacement with a high force capability when voltage is applied. Piezoceramics can be used as both actuators and sensors, named piezo-actuators and piezo-sensors, due to its respective attributes of inverse piezoelectric effect and direct piezoelectric effect. One of the application fields of the piezoceramics is active vibration and noise control.

The aim of this work is to investigate the use of Macro Fiber Composite (MFC) actuator for modal analysis of the laminated composite plate and determine its advantages in comparison with aforementioned exciters, which application has been described in [2]. The results of experimental measurements have been compared with finite element simulations with discrete model of the laminated composite plate performed in ANSYS environment.

The Macro Fiber Composite

The MFC has been developed at NASA Langley Research Center [3]. It is an innovative, low-cost piezoelectric device designed for controlling vibrations, noise, and deflections in composite structural beams and panels. It has been created for use on helicopter blades and airplane wings as well as for the shaping of aerospace structures. The major advantages of a piezofiber composite actuator are higher performance, flexibility, and durability in comparison with traditional piezoceramic actuators.

The MFC actuator consist of polyamide films with interdigitated electrodes patterns that are bonded on the top and bottom of piezoceramic fibers (PZT 5A) (Fig. 1,2). The interdigitated electrodes are placed perpendicular to the fibers and are used for poling and actuation. The poling of fibers and in-plane voltage actuation allows the MFC to create the d_{33} piezoelectric effect, which is stronger than the d_{31} effect used by the traditional PZT actuators with poling and voltage actuation through the thickness. Also, the polymer matrix can protect piezoceramic fibers against the impact and make piezocomposite materials flexible. Therefore, they can conform to the curved surface easily. These advantages of piezocomposite materials can be applied to more practical applications of smart structure technology. Further, piezocomposite materials can produce a twisting actuation due to the anisotropic characteristics, difficult to achieve using typical piezoceramic actuator.

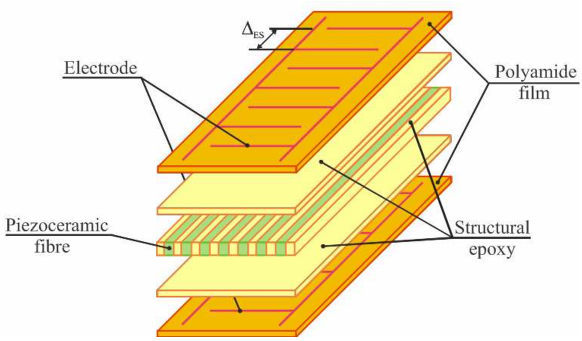


Fig. 1. MFC actuator construction

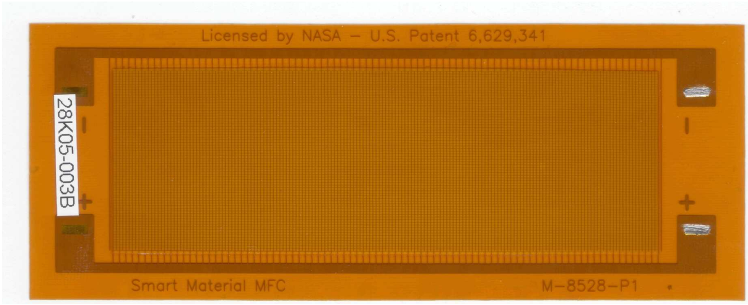


Fig. 2. MFC actuator

The MFC has different dimensions of active part and a constant distance between electrodes equal to 0.5 mm. Maximum operational voltages is from -500 V to +1500 V. This voltage allows using this actuator not only for structural vibration but also for shape form control.

The design, manufacture and testing of the MFC actuator has been presented by Wilkie et al [4]. Williams et al [5] investigated the mechanical properties of a MFC using the classical lamination theory. Nonlinear mechanical behavior of the MFC was studied by experiment and the linear mechanical properties of the MFC were compared with the result of the analytical method [6]. In addition, Williams et al [7] measured the nonlinear actuation properties of a MFC under various loads. There have been some studies related with application of the MFC to a structure. Azzouz et al [8] studied the finite element modeling of an MFC actuator and compared the performance of the MFC with that of a traditional PZT actuator. His results demonstrate that the MFC actuator outperformed the typical piezoceramic actuator. Ruggerio et al [9] used several MFCs as both actuators and sensors to measure the dynamic behavior of an inflatable satellite structure. The flexibility of the MFC made for convenient attachment to the curved surface outperformed the other actuators. Jha and Inman [10] researched optimal sizes and placements of the MFC actuator for the inflatable toroidal structure. Sodano, Park, and Inman [11] experimentally investigated the suitability of using the MFC for structural vibration applications. Ground testing and active vibration control of an inflated Kapton torus was performed using MFC. They demonstrated that MFC devices can be used as sensor and actuator to find modal parameters of an inflatable structure and reduce vibration of this inflated object. Schultz and Hyer [12] studied the snap-through behavior of an unsymmetrical laminate using MFC. Another study of application of MFC is active twist concept [13]. The goal of this idea is reduction of helicopter noise and vibration. In this case MFC actuators are implemented in the form of active plies within the composite skin of the rotor blade with orientation at 45^0 to the blade axis to maximize the shear deformations in the laminated skin producing a distributed twisting moment along the blade. The change of shape form rotor blade allows decreasing noise and vibration of helicopter during forward flight.

Experimental set-up

The use of the laser Doppler vibrometer for non-contact vibration response measurement enabled elimination of effect of added mass caused by i.e., accelerometers, and therefore, only the influence of the excitation devices over the dynamic characteristic of the structure became necessary to assess [2].

The general experimental set-up of the POLYTEC PSV-400-B scanning laser vibrometer consists of a PSV-I-400 LR optical scanning head equipped with high sensitivity vibrometer sensor (OFV-505), an OFV-5000 controller, PSV-E-400 junction box, an amplifier

Bruel&Kjaer type 2732, and a computer system with data acquisition board and PSV Software. The system requires definition of the geometry of the object and definition of scanning grid. 130 points have been taken to cover a rectangular panel with regular grid. The test panel has been excited by an input periodic chirp signal generated by the internal generator with a 1100 Hz bandwidth through a macro-fiber composite. As a result of this excitation the panel starts to vibrate within the frequency band of the input signal. After the measurement is performed in one point, the vibrometer automatically moves the laser beam to another point of the scan grid and measures the response using the Doppler principle and validates the measurement with the signal-to-noise ratio. The procedure is repeated until all scan points have been measured. The frequency spectrum of the panel is then obtained by taking the Fast Fourier Transform of the response signal.

Fig. 3 shows experimental set-up for modal test of the laminated composite plate with MFC. Free-free boundary conditions have been simulated by hanging up the panel with two thin threads bonded in two top corners of the plate.

A rectangular, symmetrically laminated $[0/90]_{4S}$ composite plate with dimensions 200x300 mm and thickness 2.4 mm has been used in the present investigation. The mechanical properties of the plate are as follows:

E_1 = 65,11 GPa, E_2 = 39,1 GPa, G_{12} = 4.12 GPa,

υ_{12} = 0.3, ρ = 1478 kg/m^3

The MFC actuator has been attached to the surface of the plate at the centre of the bottom edge.

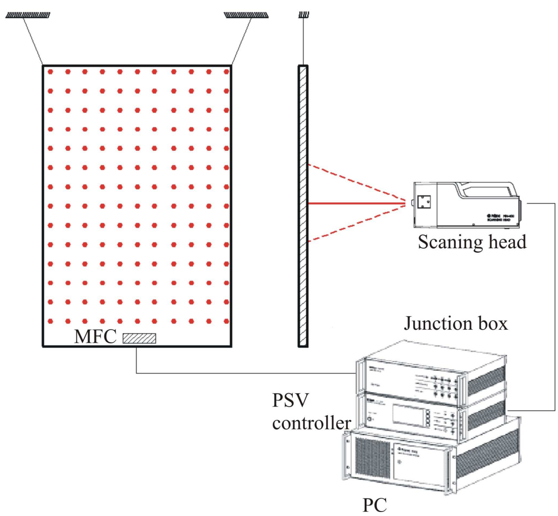


Fig. 3. Experimental set-up with MFC

Results and discussion

In order to validate experimental results, a comparison has been made with the numerically obtained results of the discrete model of the laminated composite plate. Ten first natural frequencies have been expanded and compared with numerical results (Table 1) [2].

The frequency response function (FRF) of the composite plate with MFC as an exciter has been obtained and presented in Fig. 4. The mode shapes for 1^{th} and 7^{th} frequencies of the composite plate are compared with numerically calculated shapes in Fig. 5.

TABLE 1. Natural frequencies of the tested composite plate.

Mode no.	Frequency (Hz)		Δ%
	FEM[2]	MFC	
1	72.70	71.60	***1.54***
2	174.02	176.50	***1.41***
3	230.15	230.50	***0.15***
4	301.70	302.50	***0.26***
5	331.61	334.00	***0.72***
6	490.07	497.50	***1.49***
7	533.04	542.00	***1.65***
8	821.88	827.60	***0.69***
9	860.58	857.50	***0.36***
10	1028.10	1016.00	***1.19***

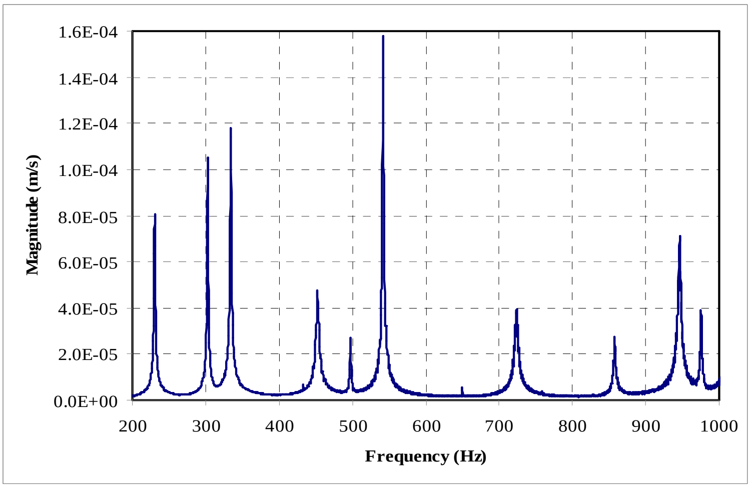
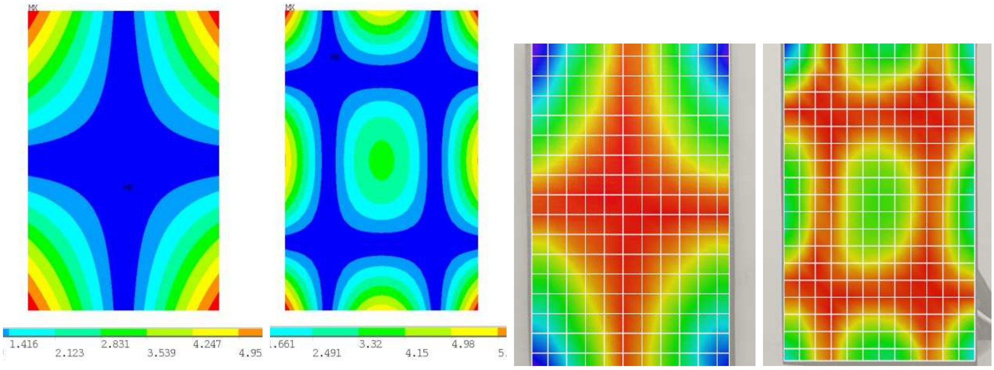


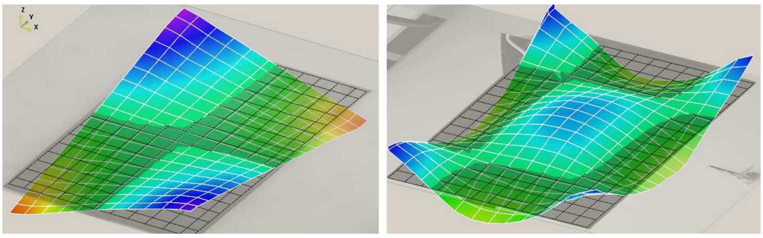
Fig. 4. Frequency response function of the laminated composite plate with application of the MFC

All results obtained with application of the MFC have been compared with the application of impact hammer, modal shaker, and PZT. Table 2 shows the resonant frequencies of the laminated composite plate obtained by application of the above mentioned devices.

As it can be noticed, the application of the MFC does not cause any additional discrepancies in comparison with PZT or impact hammer. Obviously, the application of modal shaker is not recommended for a light structure such as composite plates. It causes a significant difference in resonant frequencies, makes them lower in comparison with PZT, hammer or MFC (Fig.6). The reason of that can be found in additional mass and structural damping added to the plate. However, the advantage of the MFC regarding to the impact hammer can be found in practical application. The greatest difficulties in using a modal hammer to excite a structure is to ensure that each impact is essentially the same as all previous hits, not only in magnitude, but also in position and orientation to the normal to the surface. In addition, it is very important to avoid "double hit" which results when the hammer bounces against the surface. Double hit causes significant signal changes.



a)



b)

Fig. 5. Mode shapes of the laminated composite plate: a) numerical results [2]; b) experimental results

TABLE 2. Natural frequencies (Hz)

Mode no.	Frequency (Hz)			
	MFC	**PZT[2]**	**Hammer[2]**	**Shaker[2]**
1	71.60	71.50	71.30	70.10
2	176.50	176.00	176.30	171.00
3	230.50	231.00	230.00	221.60
4	302.50	301.00	300.00	291.40
5	334.00	328.00	327.50	317.80
6	497.50	490.00	490.00	472.30
7	542.00	541.00	541.30	512.40
8	827.60	827.40	828.00	813.30
9	857.50	853.80	856.30	843.30
10	1016.00	1012.40	1016.50	1000.40

It seems from the results presented in Table 3 that the application of PZT and MFC for a modal analysis results in the same frequency response and the choice depends on the test performer. However, as it was already mentioned in the present paper, the application of MFC takes advantage when the shape control or high voltage is required. The mode shapes obtained with application of MFC in comparison with the corresponding mode shapes obtained from numerical calculation are in good agreement. It allows us to carry out further studies for active vibration and noise control using shape changes of the structure.

TABLE 3. Relative error.

Mode no.	MFC/PZT	MFC/Hammer	MFC/Shaker
	Δ%		
1	0.14	0.42	2.14
2	0.28	0.11	3.22
3	0.22	0.22	4.02
4	0.50	0.83	3.81
5	1.83	1.99	5.10
6	1.53	1.53	5.34
7	0.18	0.13	5.78
8	0.02	0.05	1.76
9	0.43	0.14	1.68
10	0.36	0.05	1.56
Average	***0.55***	***0.55***	***3.44***

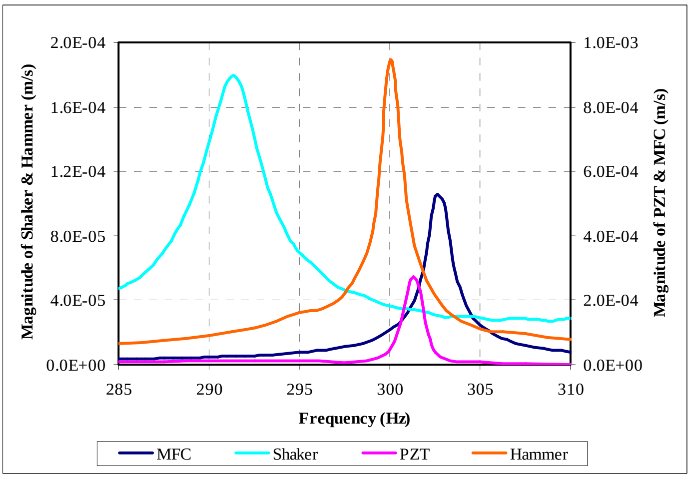


Fig. 6. Excitation devices influence over the frequency response function

Conclusions

Macro Fiber Composite actuator has been investigated in the present study as an actuator for experimental modal analysis of a composite plate. The tests illustrate the effectiveness and usefulness of the MFC device as an exciter. The results obtained from experimental modal analysis using MFC show good agreement with the results obtained from the experiments with classical exciters such as PZT, impact hammer as well as with finite element simulations.

Good accuracy of the results obtained from the experiment with application of MFC, PZT and impact hammer in comparison with the corresponding results obtained from numerical simulations has the origin in the application of the non-contact method for the vibration registration by means of laser Doppler scanning vibrometer.

Acknowledgement

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