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Composite Panel Dynamics using Experimental Modal Analysis

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***Abstract*—Finite element models for both the linear and nonlinear active composite panel flutter were derived by Lotfy and Elnomrossy**Error! Reference source not found.**],** Error! Reference source not found.**] with all characteristic matrices of the elements. An integrated computer program was designed and developed, based on the derived finite element model of the active composite panel, for static, dynamic, and flutter boundaries analyses.**

This paper is intended to test the derived finite element model in Error! Reference source not found.**] and** Error! Reference source not found.**]. A laboratorymodal testing was conducted to extract the dynamic characteristics of the composite panel. Ten Random and ten Burst Random testswere applied on the panels. The tests were performed using nine Kistler accelerometers and a Kistler Force Sensor connected toElectro-dynamic exciter. The data acquisitions were performed using LMS DIFA III system and analyzed using LMS CADA-X software to extract natural frequencies and corresponding mode shapes of the tested composite panel. A Carbon/Epoxy Composite panel model results was selectedamong sixteen autoclave-manufactured composite panels from prepregs.**

The results wereanalyzed with the analysis of variance ANOVA to verify the effect of the way of testing on the extracted dynamic characteristics. The experimental results were compared with the finite element results of Error! Reference source not found.**] and** Error! Reference source not found.**] and gave satisfactory results to ensure the validity of the developed finite element model of panel flutter.**

Keywords—composite panels; modal testing; ANOVA

INTRODUCTION

The experimental study of structural dynamics has always provided a major contribution to the efforts to understand and to control the many vibration phenomena encountered in practice**Error! Reference source not found.**]. Experience has shown that resonant vibration tests to determine panel natural frequencies and modes have proven excellent indicators of the quality of model construction for flutter testing. Determination of the sensitivity of the flutter model to environmental factors can be held early in the experimental program by resonant vibration tests. The sensitivity can also be estimated by theoretical means by vibration tests are generally more informative**Error! Reference source not found.**].

The most commonly used application of modal testing is the measurement of a structure's vibration properties in order to compare these with corresponding data produced by a finite element model or other theoretical model. This application is often borne out of a need to validate the finite element or theoretical model prior to its use in more complex analysis, such as panel flutter.

In the current study, Carbon/Epoxy laminate are tested and its natural frequencies are compared with that ones obtained from the finite element model. Moreover, two different types of tests namely, Random and Burst Random tests are applied. Each of which has its own advantages and disadvantages. Then, the results are analyzed with the analysis of variance ANOVA to verify the effect of the way of testing on the extracted dynamic characteristics.

The test is done by measuring the response levels at several points on the panel. The response points are chosen carefully to ensure adequate coverage of all mode shapes so as to permit clear identification and discrimination of those in the test range. Moreover, the excitation point is so chosen that all modes in question are excited.

Development of the FE and its Solution

In order to handleboth the in-plane and the out-of-plane deflections, two elements will be considered, namely, rectangular plate bending element and linear rectangular plate membrane element.

The plate bending element employed in the present study is a C_1 continuous rectangular element with sixteen nodal degrees of freedom at the four vertices:

$$\{w_b\}^T = \{w_1 \quad w_{,x_1} \quad w_{,y_1} \quad w_{,xy_1} \quad w_2 \quad w_{,x_2} \quad w_{,y_2} \quad w_{,xy_2} \cdots \\ \cdots w_3 \quad w_{,x_3} \quad w_{,y_3} \quad w_{,xy_3} \quad w_4 \quad w_{,x_4} \quad w_{,y_4} \quad w_{,xy_4}\} \quad (1)$$

The shape functions can be written, based on the sixteen-term cubic polynomial, in the form:

$$f_{bi}^{(w)} = \frac{1}{16}(\xi+\xi_i)^2(\xi\xi_i-2)(\eta+\eta_i)^2(\eta\eta_i-2)$$
$$f_{bi}^{(w_\xi)} = -\frac{1}{16}\xi_i(\xi+\xi_i)^2(\xi\xi_i-1)(\eta+\eta_i)^2(\eta\eta_i-2)$$
$$f_{bi}^{(w_\eta)} = -\frac{1}{16}(\xi+\xi_i)^2(\xi\xi_i-2)\eta_i(\eta+\eta_i)^2(\eta\eta_i-1)$$
$$f_{bi}^{(w_{\xi\eta})} = \frac{1}{16}\xi_i(\xi+\xi_i)^2(\xi\xi_i-1)\eta_i(\eta+\eta_i)^2(\eta\eta_i-1) \quad (2)$$

where i = 1, 2, 3, 4and $\xi = \frac{x}{a_e}$; $\eta = \frac{y}{b_e}$

where a_e , and b_e are the half width and half height of the rectangular element, respectively.The linear rectangular membrane element with eight membrane nodal displacements at the four vertices:

$$\{w_m\}^T = \{u_1 \quad v_1 \quad u_2 \quad v_2 \quad u_3 \quad v_3 \quad u_4 \quad v_4\} \quad (3)$$

The in-plane shape functions can be written in the form:

$$f_{u1} = f_{v1} = \frac{1}{4}(-1+\eta)(-1+\xi)$$
$$f_{u2} = f_{v2} = -\frac{1}{4}(-1+\eta)(1+\xi) \quad (4)$$
$$f_{u3} = f_{v3} = \frac{1}{4}(1+\eta)(1+\xi)$$
$$f_{u4} = f_{v4} = \frac{1}{4}(1+\eta)(-1+\xi)$$

The finite linear element equation of motion for active panel flutter with the effect of temperature change is derived as:

$$\frac{1}{\omega_o^2}\left[m_b^*\right]\left\{\frac{\partial^2 w_b}{\partial t^2}\right\} + \frac{g_a}{\omega_o}\left[g\right]\left\{\frac{\partial w_b}{\partial t}\right\} + \left(\lambda\left[a_a\right]+\left[k_b\right]\right)\left\{w_b\right\} = \left\{p_{b\Delta T}\right\}+\left\{p_{be}\right\}+\left\{p\right\} \quad (5)$$

For the definitions of the enclosed matrices and detailed derivation, refer to **Error! Reference source not found.**].The nonlinear finite element equation of motion for active panel flutter with the effect of temperature change is also derived as:

$$\frac{1}{\omega_o^2}\begin{bmatrix}[m_b^*] & 0\\ 0 & [m_m^*]\end{bmatrix}\begin{Bmatrix}\frac{\partial^2 w_b}{\partial t^2}\\ \frac{\partial^2 w_m}{\partial t^2}\end{Bmatrix} + \frac{g_a}{\omega_o}\begin{bmatrix}[g] & 0\\ 0 & 0\end{bmatrix}\begin{Bmatrix}\frac{\partial w_b}{\partial t}\\ \frac{\partial w_m}{\partial t}\end{Bmatrix}$$
$$+\left(\lambda\begin{bmatrix}[a_a] & 0\\ 0 & 0\end{bmatrix} + \begin{bmatrix}[k_b] & [k_B]_{bm}\\ [k_B]_{mb} & [k_m]\end{bmatrix} - \begin{bmatrix}[k_{N\Delta T}] & 0\\ 0 & 0\end{bmatrix} - \begin{bmatrix}[k_{Ne}] & 0\\ 0 & 0\end{bmatrix} + \begin{bmatrix}[k1_{Nm}]_b+[k1_{NB}]_b & [k1]_{bm}\\ [k1]_{mb} & 0\end{bmatrix} + \begin{bmatrix}[k2] & 0\\ 0 & 0\end{bmatrix}\right)\begin{Bmatrix}w_b\\ w_m\end{Bmatrix}$$
$$= \begin{Bmatrix}\{p_{b\Delta T}\}\\ \{p_{m\Delta T}\}\end{Bmatrix} + \begin{Bmatrix}\{p_{be}\}\\ \{p_{me}\}\end{Bmatrix} + \{p\} \quad (6)$$

For the definitions of the enclosed matrices and detailed derivation, refer to**Error! Reference source not found.**].

Panel Preparation

A composite laminated Carbon/Epoxy fabric[0]$_4$ panel was manufactured to perform the tests. The panel material was imported from HEXCEL COMPOSITES-France. The materials are prepregs. These prepregs ensure homogeneous distribution of resin into the fibers more than that of wet laying up. The material designation is 913/46%/G814NT/1250, i.e., resin type is 913, resin content is 49%, fiber type is G814NT, the width of the roll is 1250 mm. The material was kept at (-18 °C). Before manufacturing, the material was left 48 hours in room temperature (25 °C) to have the capability of being cut, formatted, and stacked in different shapes.

Four layers, Fig.1, were cut and stacked together in the zero direction to form a 600 x 600 mm panel. The panel was cured in autoclave according to the shown pressure-temperature cycle in Figure 2a andFigure 2b as recommended from the manufacturer.

The process of curing was conducted in the Aircraft Factory-AOI, Composite Workshop, Cairo, Egypt, using SHOLTZ GMBH & CO. autoclave, Fig.4.

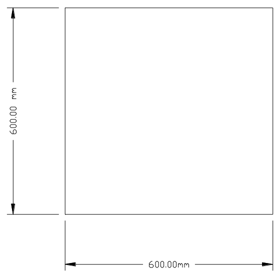


Fig.1: 600 x 600 mm Carbon/Epoxy fabric[0]4 panel

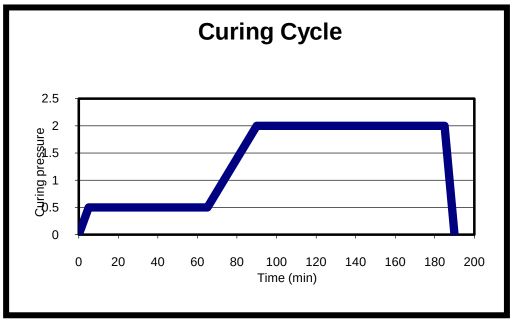


Figure 2a: Pressure vs. Time for laminate curing

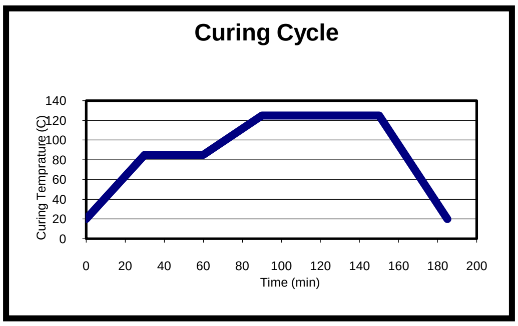


Figure 3b: Temperature vs. Time for laminate curing

Fig.4: Autoclave SHOLTZ GMBH & CO.

Panel modal Testing

While simulating the fixed boundary conditions in the finite element model by deleting the appropriate degrees of freedom is a simple task, it is much more difficult to implement in the practical case. The reason for this is that it is very difficult to provide a base or foundation on which to attach the test structure which is sufficiently rigid to provide the necessary grounding. All structures have a finite impedance (rigidity) and thus cannot be regarded as truly rigid but whereas it is possible to approximate the free condition by a soft suspension, it is less easy to approximate the grounded condition without taking extraordinary precautions when designing the support structure.

From the above comments, it might be concluded that structures should be tested in a freely supported condition. Ideally, this is so but there are numerous practical situations where this approach is simply not feasible because of the environment in which the structure is to operate. Theoretically, it is possible to test and to analyse a free structures and the structure can be modelled using its free properties and expect this to be equally applicable when some points are fixed. But in the real world, where we are dealing with approximations and less than perfect data, there is additional comfort to be gained from comparison made using modes which are close to those of the functioning structure, i.e. with the grounded one.

In the current study, a steel fixture was designed to simulate the built in boundary conditions for the four edges of the panel. It consists of two main frames. Each one consists of four steel angles welded together to form the net dimensions of the tested panels (500 x 500 mm). The two frames grip the panel and bonded with bolts and nuts cirumferencely. Figure 5shows a photograph of the two parts of the fixture bonded together with bolts and nuts. The fixture was designed and manufactured in Aerospace Research Center-AOI workshop, Cairo, Egypt.

The composite plate was clamped with its fixture with four clamps to four columns supported to concrete ground with steel columns. Levers were used so as to hang the exciter and preserve the rigidity of the test rigs as shown in Figure 6.

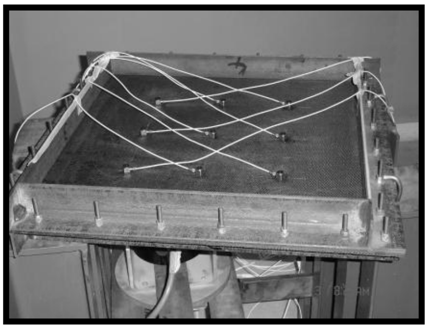


Figure 5: Steel fixture to simulate the case of built-in boundary conditions

Figure 6: Test rig

In order to measure FRF's, the source or command signal was first generated digitally within the generator and then outputted as an analogue signal to the power amplifier and then to the shaker via D/A converter. Within the same device, the two input signals from the force and response transducers went through signal conditioner then anti-aliasing filter then digitized via an A/D converter and then, one at a time, correlated numerically with the outgoing signal in such a way that all the components of each incoming signal other than that at exactly the frequency of the command signal were eliminated. This is a digital filtering process and, when completed, permitted the accurate measurement of the component of the transducer signals at the current frequency of interest.

At that time, the software modules could calculate FRF's and proceeded to extract the modal parameters. The overall schematic diagram of modal testing is shown in

Figure 7.

This scenario was done using measuring, acquiescing, and analyzingequipments listed in Table 1.

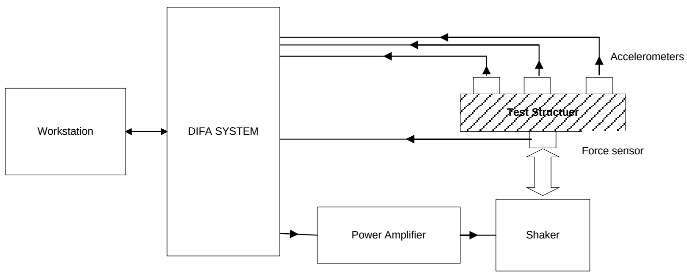
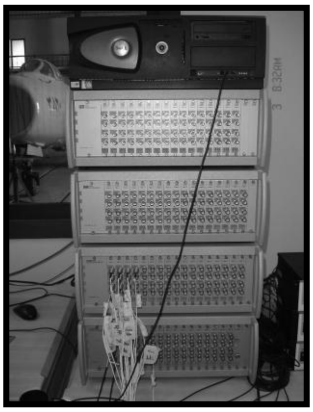
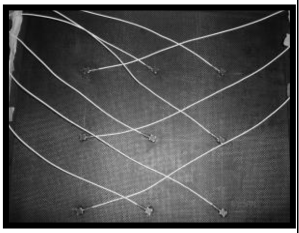


Figure 7: Overall schematic diagram of Modal Testing

TABLE 1: MEASURING, ACQUIESCING, AND ANALYZINGEQUIPMENTS USED IN MODAL TESTING

 LMS DIFA III system	 Nine Kistler accelerometers 8776M03 Ten 15meter signal cables 1761BSP15M
 One Electro-dynamic exciter ET-139 One Kistler Force Sensors 9712B500	 One power amplifier PA-138-1
 Wave Form Generator 33120A	 Accelerometer calibrator 28959Fv

The LMS software modules namely, LMS CADA-X Geometry Module, LMS CADA-X General Acquisition Monitor, LMS CADA-X MIMO test Monitor, and LMS CADA-X Modal Analysis, were used in the laboratory experiments so as to model the panel, setup the channels, performing the tests, and performing modal analysis.

The type of the test was studied to investigate its effect on the extracted modal parameters. Twenty tests, ten random and ten burst random, were performed on the panel. Time Domain MDOF Method was used to extract the dynamic characteristics of the panels, namely, natural frequencies and mode shapes. A one way ANOVA was done on the results.

Since the finite element model resulted in the solution that flutter frequencies lie between the first ten natural frequencies, see Figure 8, for the panels in question. It was decided to perform our modal testing to extract these modes. Referring to the mode shape of those modes obtained from the finite element program presented in. **Error! Reference source not found.**].

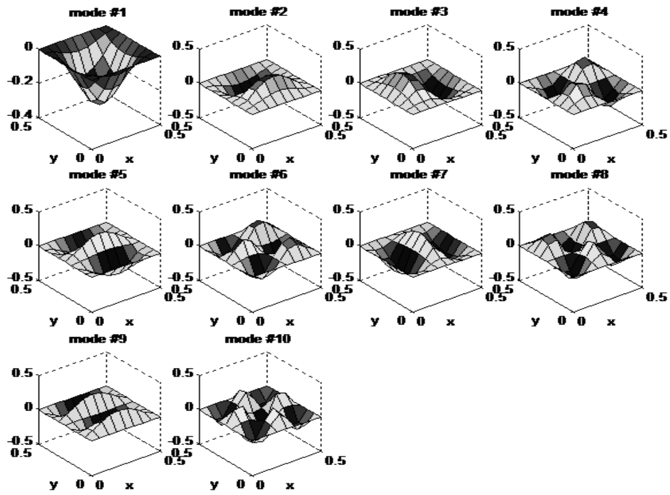


Figure 8: First ten mode shapes obtained from finite element program

Although it was very hard to obtain one configuration that suits ten modes simultaneously, it had been chosen to divide the effective area of the plate (500*500 mm) into 16 coincident squares as shown in Fig.9. It is obvious that the ninth mode couldn't be extracted by these locations of accelerometers since the lines of accelerometers are coincident with the node lines of that mode.

The plate was assembled to the fixture as shown in Figure 5. The whole assembly was held above the four columns and clamped with four clamps to them. Then, the columns were mounted to each other and to the concrete ground with levers and rods shown inFigure 6.

The ten random tests were conducted with 0.1 Hz minimum frequency and 256 Hz maximum frequency. This range was chosen after referring to the finite element results. The tests were conducted with 0.25 Hz resolution.

For the conducted ten burst random tests, the same parameters for minimum, maximum, and resolution frequency of the random testswere used. Seventy percent burst signal was used to conduct the tests. Since no leakage was expected from burst random tests, no windows were used; i.e., uniform window.

Ten random tests were performed to the Carbon/Epoxy fabric$[0]_4$ panel with the parameters mentioned in the previous sections at 23 ◦C temperature and 38% humidity. The frequency response function of point number three (excitation point) is shown in Fig.10. Ten burst random tests were conducted to the Carbon/Epoxy fabric$[0]_4$ panel with the parameters mentioned in the previous sections at 23 ◦C temperature and 38% humidity. The frequency response function of point number three (excitation point) is shown in Figure 11.The first ten natural frequencies obtained from ten random tests, are listed in Table 2. The first ten natural frequencies obtained from ten burst random tests, are listed in Table 3. The second mode from the experimental results will be discarded since it corresponds to bad coherence as shown in Fig.10 and Figure 11and its stability in the analysis software was weak.

TABLE 2: FIRST TEN NATURAL FREQUENCIES (HZ) OBTAINED FROM TEN RANDOM TESTS

mode #	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
1	38.30	38.34	38.22	38.23	38.18	38.24	38.18	38.27	38.35	38.38
2	56.26	55.94	55.69	55.79	55.71	55.93	55.87	56.23	56.64	56.73
3	60.22	60.11	59.92	60.19	59.98	59.99	60.05	60.51	60.53	60.79
4	93.00	92.83	92.67	92.75	92.59	92.64	92.61	92.99	93.16	93.23
5	98.03	98.00	97.83	97.91	97.76	97.74	97.78	97.94	-	98.25
6	124.67	124.43	124.20	124.32	124.20	124.32	124.26	124.86	125.08	125.08
7	144.98	144.84	144.80	144.80	144.56	145.03	144.53	145.02	144.83	144.92
8	150.78	-	-	150.41	150.18	150.09	150.05	150.17	150.19	150.29
9	169.68	169.43	169.18	169.31	169.13	169.22	169.13	169.75	169.93	170.05
10	203.56	203.51	203.28	203.37	203.33	203.51	203.38	203.61	203.90	204.37

TABLE 3: FIRST TEN NATURAL FREQUENCIES (HZ) OBTAINED FROM TEN BURST RANDOM TESTS

mode #	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
1	38.54	38.47	38.42	38.39	38.37	38.32	38.34	38.36	38.35	38.33
2	56.68	56.28	56.33	56.26	56.36	56.19	56.32	56.19	56.32	56.26
3	60.27	60.12	60.01	60.21	60.27	60.17	60.33	60.41	60.53	60.32
4	92.94	92.80	92.78	92.80	92.76	92.74	92.94	92.94	93.00	92.93
5	98.30	98.09	97.99	97.96	97.92	97.70	97.93	97.97	97.92	97.84
6	124.67	124.45	124.44	124.50	124.51	124.44	124.67	124.69	124.78	124.67
7	144.99	144.88	144.79	144.91	144.76	144.62	144.95	144.96	145.12	144.95
8	-	-	149.80	-	-	-	-	150.30	150.20	150.52
9	169.52	169.34	169.33	169.35	169.36	169.30	169.60	169.63	169.75	169.67
10	204.58	203.74	203.67	203.66	204.22	203.47	204.18	204.13	203.52	204.16

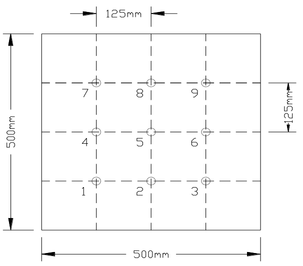


Fig.9: Locations of accelerometers on the panel

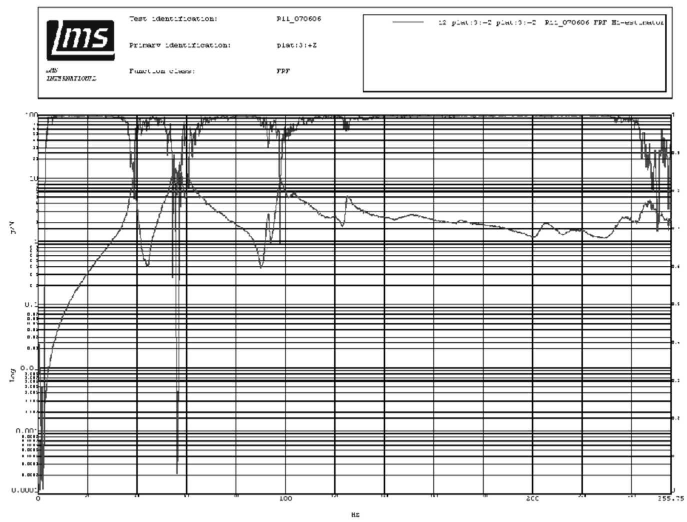


Fig.10: Frequency response function and coherence of point number three of a random test

Analysis of results

One way ANOVA (analysis of variance) was performed to each extracted mode from both types of tests which were repeated ten times. The analysis provides a test of the null hypothesis, H_0, that each sample is drawn from the same underlying probability distribution against the alternative hypothesis, H_1, that underlying probability distributions are not the same for all samples. Those hypotheses can be restated in the physical terminologies of the current study to be,

H_0: Different treatments don't affect the calculated values of the natural modes.

H_1: Different treatments affect the calculated values of the natural modes.

The ANOVA uses an F-Test to determine if "Between Groups" information provides sufficient additional information to improve the ability of the data to explain the variance in the "dependent" series. The ANOVA is asking "Does the Between Groups Sum of Squares Explained per Degree of Freedom" divided by the "Within Groups Sum of Squares" provide an ***F*** that is large enough to justify the statement "The use of Between Groups information explains a statistically significant amount of the Sum of Squares of the dependent series."

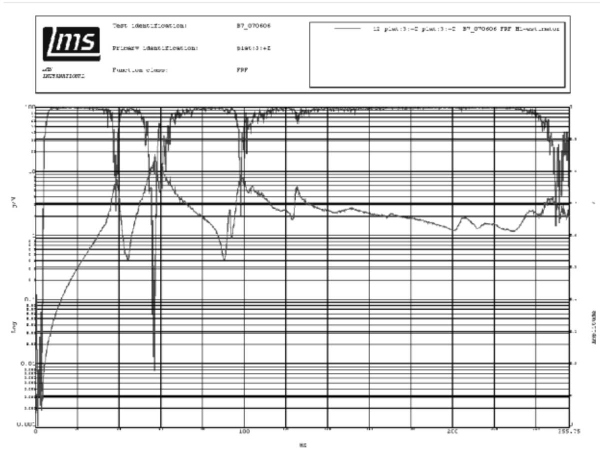


Figure 11: Frequency response function and coherence of point number three of a burst random test

The analysis was performed, for ***alpha*** = 0.05, and gave the results listed in Table 4. The following statistical quantities are used in the statistical analysis:

P-value: is the smallest level of significance that would lead to the rejection of the null hypothesis H_0 with the given data

alpha: is the level at which we want to evaluate critical values for $F\_Statistic$.

alpha level: is a significance level related to the probability of having a type I error (rejecting a true hypothesis)

$$F\_Statistic = \frac{MS_{Treatment}}{MS_E}$$

where,

MS : Mean Square, and the subscripts

E : represents the statistical quantity within the group

$Treatment$: represents the statistical quantity between groups

The composite panel used in laboratory experiments was modelled according to classical lamination theory. So the fabric four layers were represented as eight orthotropic unidirectional layers [0/90/0/90]s . The properties of the actual material are obtained from Hexcel Composites to be:E_1= 1.06E+11N/m^2; E_2= 6.58E+09N/m^2; G_{12} = 2.84E+09N/m$^{2;}$ v_{12}= 0.35; and density = 1469.18kg/m^3

TABLE 4: RESULTS OF ANOVA FOR THE FIRST EXTRACTED TEN MODES

mode #	MS_E	$MS_{Treatment}$	*F*	*P-value*	*F crit*
1	0.0049	0.07176	14.559	0.0013	4.4139
3	0.0528	0.0067	0.1261	0.7267	4.4139
4	0.032	0.0010	0.0319	0.8602	4.4139
5	0.0255	0.0106	0.414	0.5284	4.4513
6	0.0701	0.008	0.1142	0.7393	4.4139
7	0.0246	0.019344	0.7859	0.3870	4.4139
8	0.0660	0.012376	0.1874	0.6743	4.9646
9	0.0737	3.64E-05	0.0005	0.9825	4.4139
10	0.1225	0.609354	4.9724	0.0387	4.4139

As shown in Table 4, for all the modes except modes number one and ten, since ***F<F crit***, H_0 can't be rejected and it is concluded that different treatments don't affect the calculated values of natural modes. Since ***P-value*** is considerably greater than ***alpha*** = 0.05, there is a strong evidence to conclude that H_0 is not false.

These values were used in the finite element program represented in**Error! Reference source not found.**]. The mode shapes of the finite element model were presented early in Figure 8. The first four mode shapes of the experimental model are presented in Fig.12.

Conclusions

Experimental work was performed on Carbon/Epoxy panel to determine its natural frequencies and corresponding mode shapes in order to validate the numerical computations based on finite element model.

There is no effect of the type of the test on the extracted dynamic characteristics of the tested panel, i.e., the testsetup was adequate enough to represent the problem with its boundary conditions.

Moreover, when comparing the experimental results with those obtained from the developed finite element model, it gives satisfactory results.

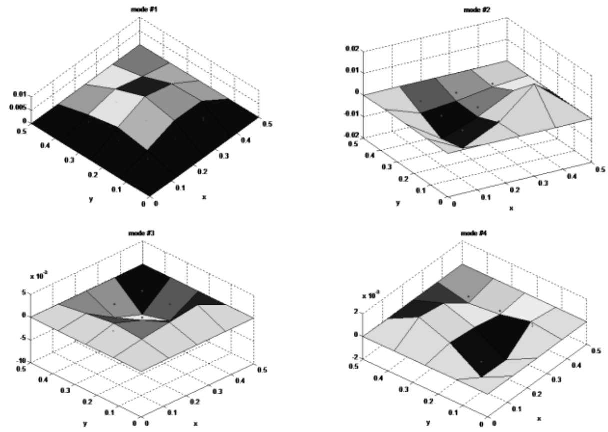


Fig.12: First four experimental mode shapes

Table 5 exhibits the comparison between the calculated modes with finite element program and the measured modes from modal testing. It is obvious that these results are satisfactory to ensure the validity of the presented finite element model in representing the composite panel.

Conclusions

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There is no effect of the type of the test on the extracted dynamic characteristics of the tested panel, i.e., the testsetup was adequate enough to represent the problem with its boundary conditions.

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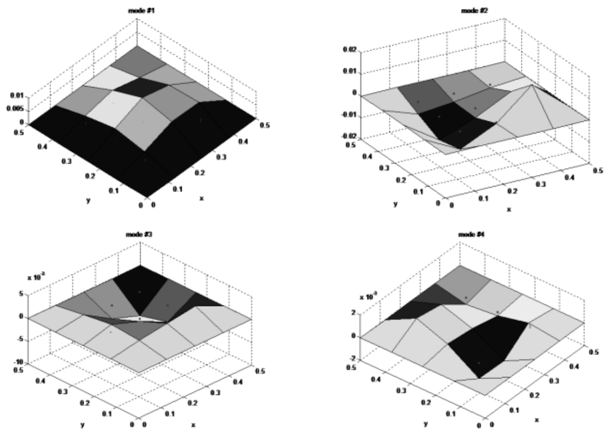

Fig.12: First four experimental mode shapes

TABLE 5: COMPARISON BETWEEN THE CALCULATED AND MEASURED MODES

Mode	Calculated(Hz)	Measured (Hz)
1	36.75	38.39
2	65.85	60.26
3	84.59	92.86
4	101.55	97.96
5	117.42	124.58
6	141.18	144.89
7	160.27	150.2
8	169.49	169.48

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REFERENCES

[1] Lotfy M., Elnomrossy M., "Active composite Panel flutter using finite element method," AEROSPACE SCIENCES & AVIATION TECHNOLOGY, ASAT- 13, May 26 – 28, 2009, ASAT-13-ST-25, Military Technical College, KobryElkobbah, Cairo, Egypt.

[2] Ewins D.J., "Modal testing: theory, practice and application," Second Edition, Research Studies Press LTD., Baldock, Hertfordshire, England, 2000.

[3] Dowell E.H.,"Aeroelasticity of plates and shells,"Noordhoff International Publishing Leyden, The Netherlands, 1975.

[4] Lotfy M., "A finite element approach for flutter control of laminated composite panel using piezoelectric actuators," Master dissertation, Aerospace Engineering, Cairo University, Egypt, September 2006.