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Operational Modal Analysis Implementation on a Hybrid Composite Plate

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***Abstract*—**In aerospace applications, interactions of airflow with aircraft structures can result in undesirable structural deformations. This structural deformation in turn, can be predicted if the natural modes of the structure are known. This can be achieved through conventional modal testing that requires a known excitation force in order to extract these dynamic properties. This technique can be experimentally complex because of the need for artificial excitation and it is also does not represent actual operational condition. The current work presents part of research work that address the practical implementation of operational modal analysis (OMA) applied to a cantilevered hybrid composite plate employing single contactless sensing system via laser vibrometer. OMA technique extracts the modal parameters based only on the measurements of the dynamic response. The OMA results were verified with impact hammer modal testing and good agreement was obtained.

***Keywords*—**Hybrid Kevlar composite, Laser Vibrometer, modal parameters, Operational Modal Analysis.

I. Introduction

AEROSPACE structures especially on lifting surfaces are continually exposed to fluctuating airloads and these aero-structural interactions lead to structural deformations that can be destructive in nature or compromise its structural stability. The science that studies these interactions is known as aeroelasticity and aeroelastic instabilities can be static or dynamic in nature. The airworthiness regulation requires that the full-scale aircraft is demonstrated free from flutter by a flight flutter test. Flutter is a dynamic, aeroelastic instability predominant on aircraft's lifting surfaces.

In aeroelastic analysis, knowledge of the natural modes of a structural system is necessary for flutter prediction. Technique that looks into the assessment of these modes is known as modal analysis. Modal analysis is a process whereby a structure can be described in terms of its natural dynamic characteristics which are the natural frequency, modal damping and mode shapes. These characteristics are also known as dynamic properties. If the material properties or boundary conditions of a structure change, the natural modes will also change. These modal properties can be obtained by artificially exciting the structure, measures its operating deflection shapes (motion at two or more DOFs) and post-processing the vibration data.

Conventional or experimental modal analysis (EMA) relies on the determination of the excitation input force and dynamic response where the frequency response functions (FRF) are simply the ratio of input over output response. The artificial excitation can be transient (impact hammer testing) as well as random, random burst or sinusoidal (shaker testing). Presently, impact testing, developed during the late 1970's is the most popular, fast and economical modal testing technique.

On-site modal testing can be complicated if the structure is difficult to access and excite as well as to mount the numerous wired sensors that are placed at strategic points on the structure that within the sensing system. Response sensing system usually is composed of accelerometers that introduce mass-loading effects into the dynamics of the structure. The effect of the mass-loading can be reduced if laser scanning vibrometer is used.

The current work presents preliminary work on developing an operational modal analysis (OMA) system employing a contactless sensor. Operational modal analysis is a technique that measures the vibration response of a structure due to operational excitations. However, it usually employs numerous wired sensors placed on strategic points on the structure to measure the vibrational modes. A single contact-less sensing system via optical sensor which is laser scanning vibrometer is therefore used to eliminate the mass loading effects.

Since 1990's, the significance of OMA has grown tremendously in the aerospace and civil engineering applications [1]. It uses only response measurements to identify the modal parameters which are eigenfrequencies, damping ratios and mode shapes from data measured on a structure during operational conditions. Zhang et al. [1] employed OMA for control surface with airflow excitation in a wind tunnel and had observed that the modal damping and frequencies changed when switched from wind-on to wind-off cases.

There are several modal extraction techniques employed in OMA which include Stochastic Subspace Identification (SSI), Frequency Domain Decomposition (FDD) [2] and Enhanced Frequency Domain Decomposition (EFDD). FDD employed a peak picking technique whereas EFDD techniques allow the resonance frequency and damping of a particular mode to be extracted by computing the auto- and cross-correlation functions. Both techniques were compared in a study and strong correlation was observed [3]. Meller et al. [4] compared FDD and SSI techniques to the traditional modal analysis for

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mechanical rotating machines. OMA algorithms are stochastic in nature; however mechanical applications such as rotating machineries are subject to deterministic harmonic excitations from parts of the machinery. Jacobsen et al. [5] studied the elimination of these harmonic noises from the response measured using OMA. The OMA technique provides operating deformation patterns and not scaled mode shapes (no identification of modal masses) which can be obtained from EMA [5].

Siringoringo & Fujino evaluated the accuracy and sensitivity of the modal parameters under different measurement conditions employing OMA technique with laser scanning vibrometer [6]. Experiments using laboratory-scale specimens and field measurement with different configurations showed that the system can accurately and consistently identify modal parameters. Apart from eliminating mass loading effects, laser scanning also reduces the measurement time as well as the need of roving response measurement can be made automatically without contacting.

In this present paper, OMA techniques are demonstrated on a cantilevered hybrid Kevlar/carbon composite plate subject to hand tapping excitation. The output response is measured via single point laser scanning vibrometer in conjunction with a single accelerometer reference point. It was compared with two other different setups using the EMA technique. The first is employing accelerometer and the second is employing laser scanning vibrometer to measure the output response.

II. Measurement Procedures

A. Composite Fabrication

The composite samples are composed of 3-layers laminated woven Kevlar/carbon fiber composite plates with epoxy resin fabricated via vacuum bagging technique. The dimension for the plate is 15cm width by 60cm height. Kevlar/carbon cloth used in this study is shown in Fig. 1. The kevlar is aligned in the 0° direction and carbon in the 90° or transverse direction.

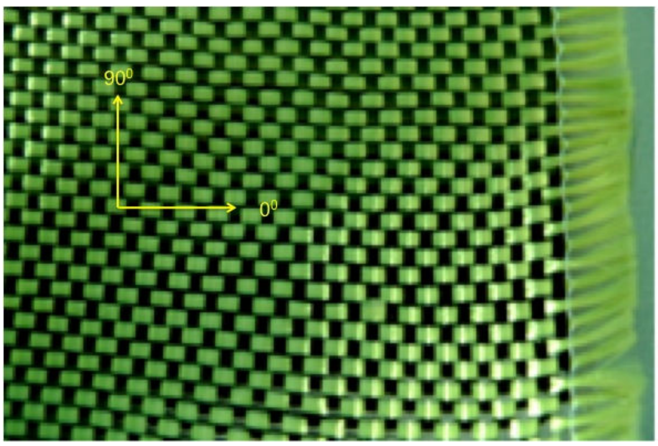

Fig. 1 Laminated Kevlar/carbon epoxy composite

B. Data Acquistion System and Hardware

In this study, measurements were made with a Brüel & Kjær PULSE Fast Fourier Transform (FFT) analyzer type 3560c. The geometry of the structure is assigned measurement points. Via natural excitation, the response is measured and modal extraction procedures were performed.

As for traditional modal testing, the same instruments were used to do the measurements. But only that Endevco Impact Hammer was used to excite the force for each point that has been assigned on the plate. Fig. 2 described the equipments used for the measurement setup for impact hammer testing. The accelerometer that measures the output response can be replaced with laser scanning vibrometer.

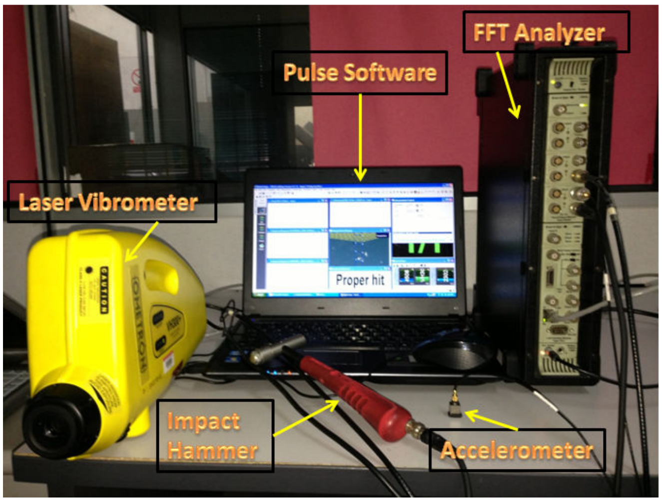

Fig. 2 Equipment for EMA testing

For OMA testing with non-contact laser vibrometer, the measurement setup is as shown in Fig. 3. The laser scanning device is OMITRON model VH300+ with wave length of 633nm. It can measure in the range of 16 inches up to 82 feet. The measurement frequency range is 0.1 to 25 kHz and resolution is 0.4µm/s. No known excitation is required and the excitation is provided via hand tapping.

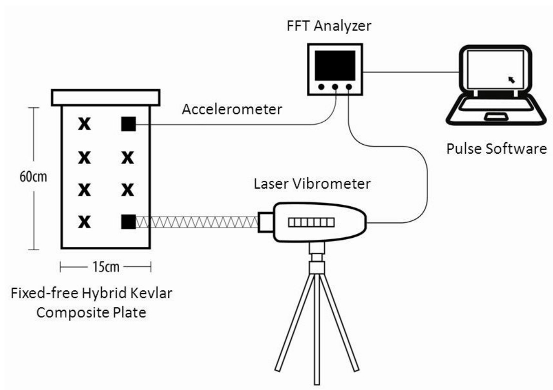

Fig. 3 OMA system setup with laser vibrometer

C. On-site Calibration Testing

Prior to modal testing, the laser vibrometer is calibrated according to the distance from the cantilevered composite sample. The laser is targeted to a point on a portable calibrator that produces 1g or $10.0ms^{-2}$ of acceleration. The calibration setup is shown in fig. 4. On-site calibration involved adjusting the gain or the calibration constant to get 10.0ms^{-2} at frequency of 159.3 Hz as depicted in Fig. 5.

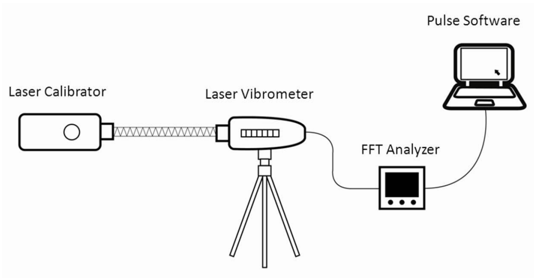

Fig. 4 Laser vibrometer calibration setup

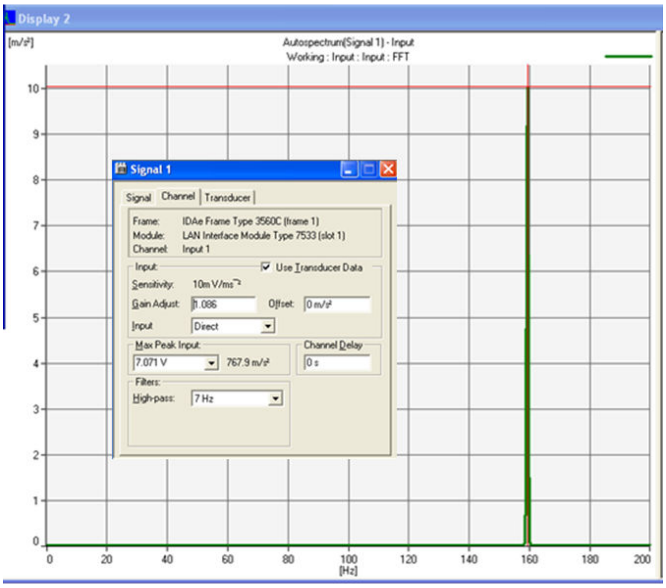

Fig. 5 Laser calibration data

D.Impact Testing Using Hammer

In this present paper, the modal analysis was performed on a cantilevered hybrid kevlar/carbon composite plate. At the clamped location, quarter inch thick rubber mat was attached to reduce the effect of the jig's interference to the FRF measurements. Then, rubber mat also placed under the platform to reduce vibration effects from the floor to the platform. The platform was stable therefore it will remain rigid during the excitation process.

Endevco Impact hammer is used to artificially excite the plate and the output responses are measured by two different setups, i.e. accelerometer and laser vibrometer. Plastic tip was used at the hammer because it can excite the structure to desired frequency range without causing overload. The plate geometry is divided into 8 measurement points. Roving hammer technique was employed whereby the sensor location was fixed at a single reference point while impact hammer was used to excite all 8 points of measurement. Direction vector for excitation force and response are in transverse direction to the plate at Z-direction.

The frequency band is set at 100 Hz to allow the measurement of lower order modes only as the number of measurement points are small and can only capture lower order mode shapes. Each measurement is averaged 3 times and coherence is measured to ensure quality of the data measured. It identified how much output signal was correlated to measure input signal [7]. Threshold of the coherence is set at 0.9 as the mode acceptance criteria. All measurements are collected by an FFT analyzer connected to the notebook equipped with Pulse Labshop software. In this software, the FRF measured was basically the ratio of the Fourier transform of the output (response as in the acceleration measured by the accelerometer) over the Fourier transform of the system input (excitation force induced by the impact hammer). Resonant occurred when the magnitude of the output was significantly higher than the input which is indicated by a sudden peak in the FRF plot. The modal identification was obtained via curve fitting (ME'scope VES software) and direct parameter estimation techniques from which natural frequencies, mode shapes and damping ratios are determined. The plate with 8 measurement points is modeled in Pulse Labshop software as shown Fig. 6.

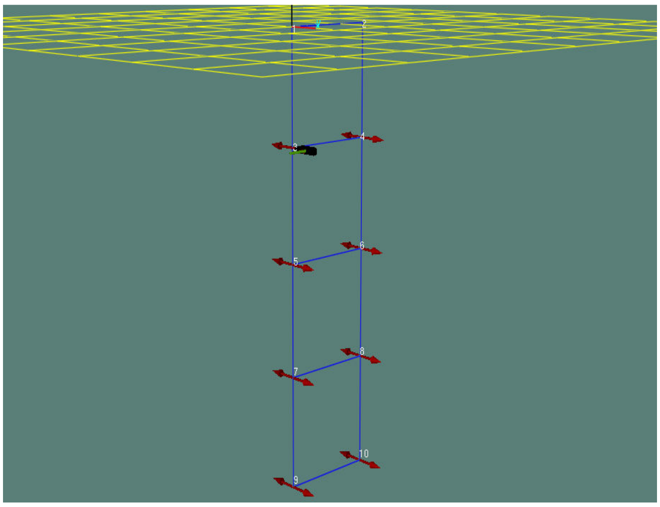

Fig. 6 Modal testing with impact hammer excitation

E. Operational Modal Analysis

1. Frequency Domain Decomposition (FDD)

The OMA measurement setup is similar to EMA except that the known excitation is not required and replaced with an unknown excitation that can be operational or instigated through other sources such as simple hand tapping technique or using acoustic sources.

The extraction method employed here is based on FDD is or commonly known as Peak-Picking method. The technique estimates the modal parameters directly from signal processing data calculations. It utilizes the property that the mode shapes can be estimated from the calculated spectral density for the condition of random noise input or stochastic input applied to lightly damped structure where the modes are well separated [4]. This technique is an extension of the Basic Frequency Domain technique.

In the classical technique, the power spectral density (PSD) matrix is directly and easily estimated via Fast Fourier Transformation (FFT) whereas in the FDD, it is not directly processed, but decomposed using the singular value decomposition (SVD) at each spectral line where the PSD matrix is decomposed into auto spectral density functions consist of single degree of freedom systems. The modes are simply picked by locating the peaks in the SVD plots. The accuracy of the estimated natural frequency depends on the FFT resolution with no modal damping is calculated [2].

III. Results and Analysis

A. Experimental Modal Analysis (EMA)

Typical curve fitted FRFs obtained from accelerometer and laser scanning testing with impact hammer excitation is shown in Figs. 7 and 8, respectively. Given the flexibility of the geometry of the composite hybrid, numerous lower order modes are identified below 100 Hz. Comparing the FRFs measured using accelerometer and laser indicated strong correlation between the two results. Both estimated similar plot at the same measurement points. This indicated that the effect of mass for a single accelerometer is negligible in this instance. The mass of the accelerometer used in this study is 5g.

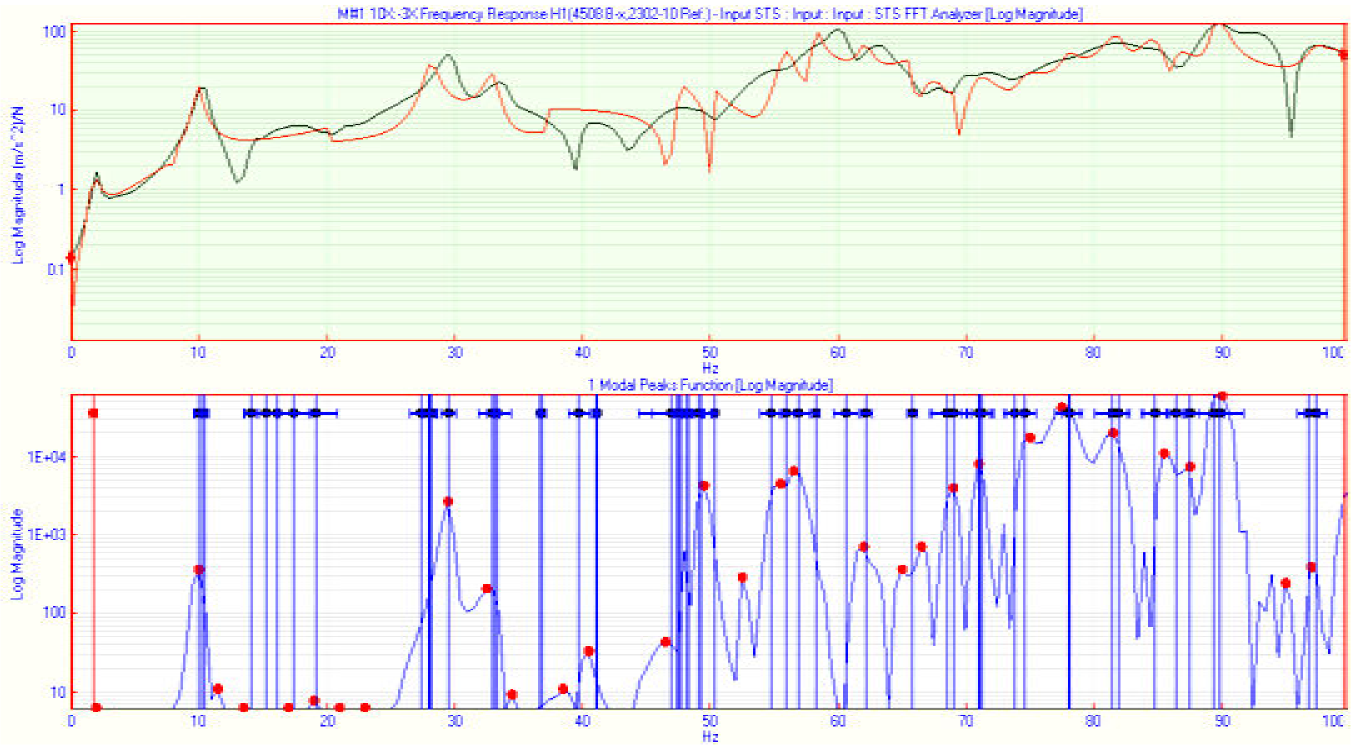

Fig. 7 FRF magnitude plots with output response measured with accelerometer

B. Operational Modal Identification

For the OMA testing, an example of the FDD plot is shown in Fig. 9. The plot shown that the resonant peak estimated is similar to the FRF peaks described in the previous section. This indicated that OMA is as reliable as EMA in predicting the modal properties. A comparison of the first six natural frequencies (below 50 Hz) is given in Table I. Modes that do not fulfill the minimum coherence requirement is not considered in the comparison. Good agreement is obtained from all three sets of data.

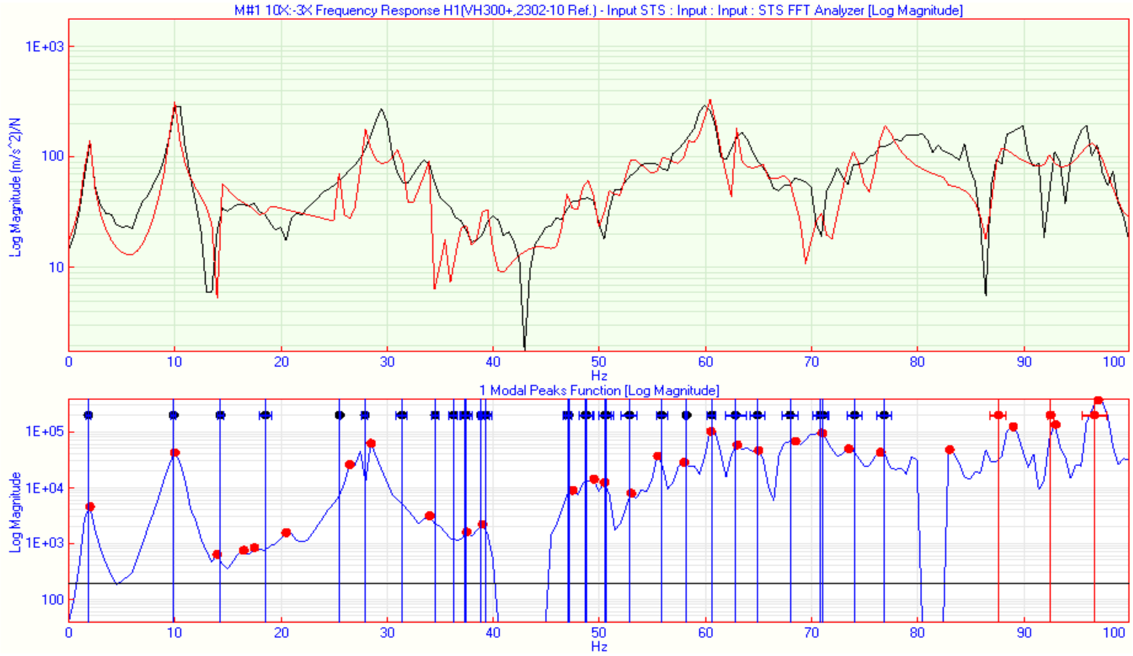

Fig. 8 FRF magnitude plots with output response measured with laser vibrometer

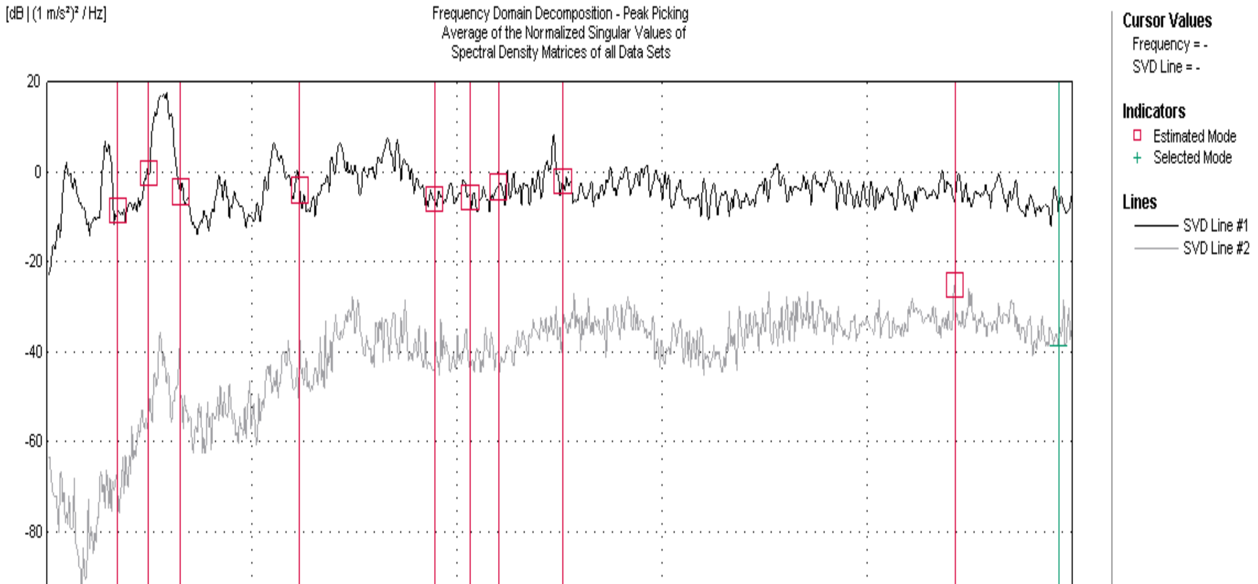

Fig. 9 FRF plots with FDD method

The following Table II described the mode shapes of the lower order modes that are plotted using ME'scope VES software. The mode shapes are further categorized as bending or torsional modes depending on the deflection shapes. A better representation of the mode shapes can be obtained if more points are measured.

TABLE I
MODAL PARAMETERS OF VIBRATION MEASUREMENTS

Mode	EMA		OMA (FDD Peak-Picking Method)
	Mode Frequency (Hz)Accelerometer	Mode Frequency (Hz) Laser	Mode Frequency (Hz) (% error with Laser EMA)
1	9.93	9.9	9.88 (0.25%)
2	14.1	14.3	13.00 (9.09%)
3	28.0	25.5	24.53 (3.80%)
4	36.8	37.5	37.75 (0.67%)
5	41.1	41.4	41.25 (0.36%)
6	48.1	48.8	50.25 (2.97%)

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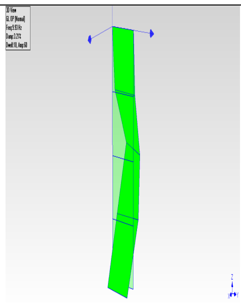
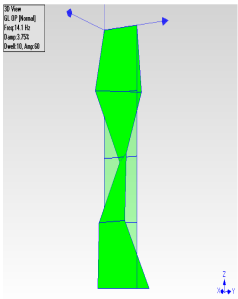
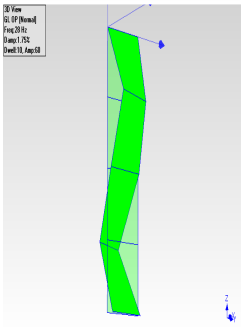
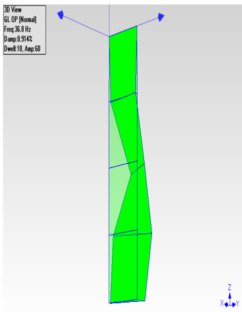
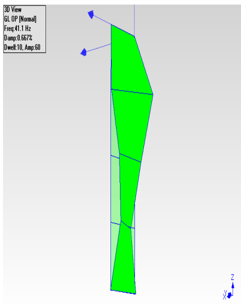
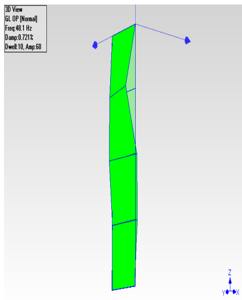
TABLE II
MODAL SHAPES OF VIBRATION MEASUREMENTS

Mode	Plate Deformation Patterns	
1		Bending
2		Torsional
3		Bending
4		Torsional
5		Torsional
6		Bending

IV. CONCLUSION

The result of this study showed that OMA using laser vibrometer technique is comparable to EMA techniques in extracting modal parameters of a composite plate with a fixed-free end condition. The technique is not only able to test the accuracy of the laser vibrometer as the response measurement, it is also able to find the bending and torsional modes of vibration and correlate very well using both accelerometer and laser vibrometer with the data acquisition system. The results presented here are preliminary results for a composite plate and the following work will look into using airflow excitation and the structure is a scaled-down aircraft wing fabricated from the same hybrid Kevlar/carbon composite material.

ACKNOWLEDGMENT

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