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**ACTIVE TAGGING NON-DESTRUCTIVE EVALUATION TECHNIQUES
FOR FULL-SCALE STRUCTURAL COMPOSITE ELEMENTS**

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ABSTRACT

A health monitoring technique is presented for on-site particle tagging non-destructive evaluation (NDE) of a full-scale structural element of advanced composites. Conventional non-destructive evaluation methods are not very effective in monitoring the material conditions of advanced composite and adhesive joints. A technology that has been proposed to enhance the inspectability of advanced composites is the particle tagging technique (Rogers, *et al.*, 1995), (Zhou, *et al.*, 1995). This technique which has been previously demonstrated on small scale, laboratory samples (Rogers, *et al.*, 1996(a)), (Rogers, *et al.*, 1996(b)), (Giurgiutiu, *et al.*, 1996) is now developed to scaled up on full-scale structural elements. The concepts for large scale tagged composite inspection build on the previously developed small scale concepts. The technique relies on comparing changes in local-area mechanical properties of the structure to identify damage. Unlike conventional passive tagging NDE inspection, the technique uses an electromagnet exciter to interrogate tagged composites. A laser Doppler vibrometer is used for high-speed and non-contact surface vibration detection. An accept-reject criteria based on the signature pattern difference of a healthy and a damaged structure is then applied to extract an index of the health of the structural elements. The experimental results of the active particle tagging inspection shows a variation in the dynamic response of the specimens when defects and/or damage are presents. The variation could be used to diagnose and to monitor the integrity of materials.

INTRODUCTION

Advanced reinforced composite materials are becoming increasingly important for high volume civil engineering constructions and industrial applications (Zhou, *et al.*, 1995). The use of these specialized materials can provide elegant solutions to difficult engineering problems. Unfortunately, the physical attributes of the composite materials present problems for the accurate detection and evaluation of internal flaws. This is especially true for the glass-fiber reinforced polymer (GFRP) composites, which are electrical insulators and, hence, non-conductive. These difficulties have created a need for new non-destructive evaluation (NDE) techniques optimized specifically for GFRP composite materials. However, conventional non-destructive evaluation (NDE) methods are not very effective in monitoring the material conditions of such non-conductive and non-magnetic GFRP composite. A technology proposed to enhance the inspectability of the composites is the particle tagging technique (Rogers, *et al.*, 1995 and Zhou, *et al.*, 1995). The ferromagnetic active tagging method is based on magnetic excitation of the tagging particles embedded in the composite. When the ferromagnetic tagging particles are exposed to an alternating magnetic field, the particles, driven by the magnetic force (mf), apply a distributed alternating force to the composite specimen. The specimen undergoes mechanical vibrations. Its vibration characteristics (natural frequency, damping, etc.) are expected to reflect its structural and material condition, and to indicate the presence of defects such as cracks and delaminations. The new NDE technique, dynamic characteristics evaluation using magnetic interrogation (DCEUMI), has been shown to be non-intrusive, capable of fast data acquisition, and sensitive to a wide range of common composite flaws. These performance characteristics make DCEUMI an excellent candidate for in-process and in-field inspection in an industrial environment. Authors (Giurgiutiu, *et*

al., 1996) found that , with glass-fiber reinforced composite, a presence of damage could be detected by signature-pattern identification of the frequency response and natural frequency peaks, whether this damage was localized on a saw-cut crack, or delamination of the specimen. As it has been known, changes of stiffness caused by flaws lead to changes in the natural frequencies of the structure and in the signature-pattern of the frequency response. The measured changes in the frequency response of the specimens carry meaningful information about the material condition and about possible defects. The sensor used in the previous work (Giurgiutiu, *et al.*, 1996) was a piezoelectric force gage fixed to the tagged composite specimen. This solution, though very sensitive to small amplitude vibration signals, is not practical for in-process and in-field inspection in an industrial environment because it requires that the sensor is physically connected to the specimen at the location being interrogated. In this paper, new vibration pick-up sensing methods have to be explored. The use of DCEUMI testing to detect the effects of internal damage on signature pattern of frequency response has been studied. Shifts in natural frequencies have been used to identify damage generated by mechanical damage such as saw cuts and delaminations. The following two aspects of the DCEUMI method have been developed to enhance its effectiveness to localized internal damage in real-life applications: (1) utilization of laser Doppler vibrometer for non-contact sensing; (2) developing electromagnetic exciter for full-scale composite elements inspection.

THEORETICAL BACKGROUND

The magnetic excitation method offers a promising opportunity for in-process and in-field full-scale implementation, since it uses non-intrusive examination of GFRP composites. Active tagging techniques with magnetic interrogation involve dynamic excitation using an electromagnet and vibration measurements using a vibrations sensor. This approach requires the creation of a strong magnetic field, and the search for the anomalies in the frequency response curves that would indicate a “defect” in accordance with established accept-reject criteria. The theoretical models previously developed for the mechanics of active tagging with ferromagnetic sensors (Rogers, *et al.*, 1995) were based on the assumption that the motion of the tagging particle near a resonant frequency, can be equivalent to a single-degree-of-freedom (SDOF) mass-complex spring system. The governing equation was:

$$m_i \ddot{z} = F_{mi} - Q_i \quad (1)$$

where m_i is the mass of the particle, F_{mi} is mf, Q_i is viscoelastic constraint force on the particle. Then the governing equation of the polymer material is expressed following:

$$D(z) + \rho \ddot{z} = \sum_i Q_i \delta(z - z_i) \quad (2)$$

where D denotes differential operator, ρ is the mass density of the polymer material and δ is Dirac's δ -function. Assuming that all the particles move in phase, the overall mf applied to the composite could be obtained by summation over all the particles:

$$F_m(t) = \mu_0 \alpha V \Delta w \frac{\rho}{\rho_p} \left[\frac{1}{(L - \bar{Z})^5} - \frac{1}{\bar{Z}^5} \right] \quad (3)$$

$$(C_m^2 + 2C_s^2 + 4C_m C_s \sin \omega t - C_m^2 \cos 2\omega t)$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability in free space; α is a coefficient that depends on the shape of the particle (e.g., for the sphere $\alpha = 3$); L is the distance between the poles; \bar{Z} is the average distance from the particle to the N-pole of the magnetic yoke; ω is the excitation frequency; C_m and C_s are coefficients; V is the volume of the tagged polymer; Δw is the weight ratio of particles; and ρ_p are the mass density of the particle material. Then, the governing equation of the equivalent system can be rewritten in the frequency domain:

$$-\omega^2 mX + KX = F(\omega) \quad (4)$$

where m is the generalized modal mass of the tagging particles; $K = K'(1 + j\eta)$ is the generalized modal stiffness of the system, η is the modal damping of the system; and $F(\omega)$ is the generalized force.

The principle of the method is that the defects of material such as cracks and delaminations exhibit a reduced stiffness. The proposed technique described in this paper utilizes electromagnetic exciter and laser Doppler vibrometer to provide high-frequency excitation, typically in the kHz range, to the composite elements being monitored. At such high frequencies, the response is dominated by local modes and small damage like cracks and delaminations which produce measurable changes in the vibration signature. Delaminations or disbonds may be regarded as a plate fully restrained around delamination edges. This plate can resonate. If the structure is excited over a band of frequencies which contains the resonance frequencies of all the defect sizes of interest, there will be modal response over each delamination. Furthermore, if the first few modes of each delamination, which have relatively larger modal response than high-order-modes, are excited simultaneously, the modal response over the delamination will be overwhelmingly larger than over an area of solid bonding. The delamination will then be highlighted and visualized by the vibration image. This is especially true for a flexible composite patch bonded to a rigid concrete block as the vibration response over the solid bond is essentially trivial, which has been investigated in Ref.7 (Sun, *et al.*, 1996).

EXPERIMENTAL TECHNIQUES

The principle improvement on the previously reported technique (Giurgiutiu, *et al.*, 1996) are the replacement of the piezoelectric force gage fixed to the tagged composite specimen with a laser Doppler vibrometer for the non-contact sensing and the development of an electromagnetic exciter to complement the inspection test apparatus.

The advantages of the new system are as follow:

1. The external impact on the tested specimens in successive evaluation is minimized. Since the laser detection operates on non-contacting, no extra mass is attached to composites being inspected.

2. Because the scanning laser head is remote from the composite elements being inspected, the new inspection implement allows the process of quality control to be on-site and in-field, so that the inspection can be operating while the composites is in fabricating process.

3. Since exciting the structure and monitoring the

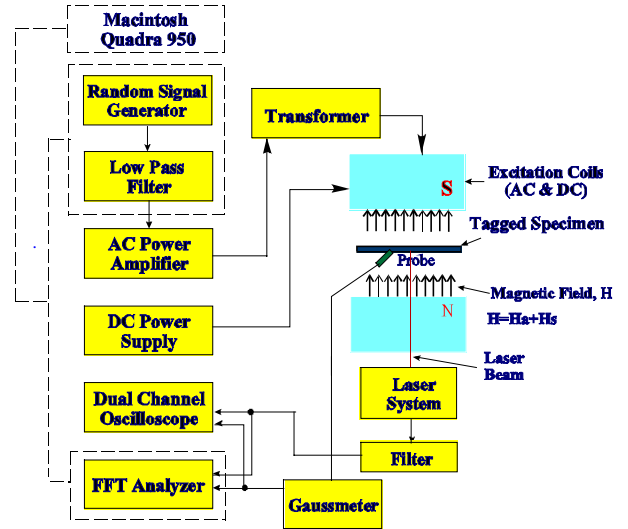


Figure 1. Diagram of the experiment set-up used to test dynamic response of the specimen using laser test system.

response are at the same position, the method can be used to detect the presence of defects at that point and to determine the location, and size of the defects. In addition, effects of boundary conditions on the evaluation are minimized on the measurements of modal parameter on high-order-modes.

The technique consists of the excitation of the vibration modes with an electromagnetic exciter manufactured by modification of the electromagnetic exciter used in the previously experiments. The response is sensed by the laser Doppler vibrometer. Input and response signals are fed into the FFT analyzer, and the desired frequency response function on the desired frequency span is displayed on the oscilloscope in real time. Processing of these signals yields frequency response curves. From the frequency response curves, the inherent characteristics of the specimen, the natural frequencies and damping ratios, will be ascertained.

Specimen and instrumentation

The initial experimental investigation of the technique was carried out on specimens cut from the Creative Pultrusions, Inc. long specimens, and then from the Reichhold's sample tagged with NiZn ferrite at 4.27% by weight of composite. The measurement were carried out by using the system shown schematically in Fig. 1. The latter specimen of dimensions 0.04 in x 1.37 in x 5.51 in, was found easier to excite. A defect was simulated by saw-cut of 0.422 in x 0.093 in. This form of "defect" was chosen because it is simple to produce. A small vise was used to hold the

specimen. Two pieces of soft foam were used at the holding one of ends to isolate vibration caused by environment.

The instruments consist of three main components, exciting instruments, measuring instruments, and signal processing instruments.

- The exciting instruments include a generator, filters, power amplifiers and an electromagnetic exciter. The electromagnetic exciter was manufactured by modification of the electromagnetic exciter used in the 1995 experiments (Giurgiutiu *et al.* 1996). One modification consisted in reducing the air gap to minimum possible in order to increase the magnetic field density. The second modification consisted in a 5 mm diameter hole made into one of the yoke end, normal to the air gap cross section. Through this hole, a laser beam could be pointed to sense directly the specimen region being magnetically excited. The excitation magnetic field was generated by an alternating current (AC) and a direct current (DC) in the different solenoidal coils of the electromagnet. The DC coils created a static bias flux density to magnetize the particles and maximize the excitation to improve signal-to-noise ratio and suppress the non-linear frequency component, while the AC coils created an alternating magnetic flux density to produce vibrations of the particles. The alternating component was frequency-dependent, as it was proportional to the energizing current. The effective impedance of the coil increased with frequency. Our experiments were conducted under constant voltage excitation, and hence the excitation current decreased with frequency.
- The measuring instruments consist of the laser Doppler vibrometer and a gaussmeter. The measuring instruments are termed “measuring transducers”, and accomplish the conversion of the physical quantity into an electrical quantity. After conversion and conditioning of the physical data, the test data could be either displayed, using oscilloscopes, or recorded, and eventually stored on floppy disks for signal post-processing. In the experiments, the specimens were interrogated with the electromagnetic field and their mechanical responses of velocity as an output were measured by the laser Doppler vibrometer. The input signal of the system were measured with a Hall probe of a gaussmeter.
- The signal processing instruments consist of a Fast-Fourier-Transform (FFT) analyzer and a computer. In our experiments, the signal generator, the filter, and the Fast-Fourier-Transform (FFT) analyzer were united into one instrumentation system constructed around a Macintosh Quadra 950 computer. Both input and output signals were passed to the frequency analyzer. The input data of the experiment was the magnetic field excitation. This was measured with the Hall probe of the gaussmeter, which was placed in proximity of the specimen. The output data was the velocity signal which was captured through a controller. Processing of these signals yielded frequency response curves. Search for the anomalies in the frequency response curves and comparison of natural frequencies of the evaluation specimens with an established accept-reject criteria would assess integrity of composite elements.

Testing procedure

Because NDE by DCEUMI is based on the fact that internal defects will generally result in changes in structural

stiffness which leads changes in natural frequency and frequency response signature pattern, magnetic excitation is used to cause the tagged specimens to vibrate in order to measure the changes of vibration characteristics. The responses induced by this vibration are measured with the laser Doppler vibrometer. The velocity and flux density signals from the laser Doppler vibrometer and from the magnetic field probe are input to the frequency response analyzer. In the processing the time record of the structural response to the magnetic excitation is converted to the corresponding frequency spectrum. The resulting frequency spectrum indicates the natural frequency peaks and frequency response signature pattern. This data is processed to extract the natural frequencies. The frequencies of the test specimen are readily identified from the peaks of the spectrum. In our experiments, we used the real component of the frequency response of the velocity signal. The general theory of experimental vibrations analysis (Ewins,1984) shows that, at resonance, the real part of the velocity signal goes through a peak, while the imaginary part crosses the zero axis. In general, neighboring frequencies of a structure contribute a noticeable amount to the total response at the resonance of the frequency being analyzed, which effects the peak value of the FRF greatly and makes the points at which the imaginary part crosses the zero axis move up. The analysis of the frequency response excited by magnetic force for NDE is very important. The detection of defects caused by saw-cut can be done by comparison of the changes in the frequency responses of specimens. This is one of dynamic properties of the structure and does not depend on the excitation of input and sensing manner of output. In this study, we concentrated our attention on the examination of the mechanical natural frequency of the excited specimen as a possible way to identify defects using the NDE technique.

RESULTS AND DISCUSSIONS

Preliminary experiments have been performed using a sample from Reichhold Chemicals tagged with NiZn ferrite at 4.27% by weight of composite for proof-of-the-concept of full-scale composite elements inspection. The experiments have been carried out with sinusoidal signal sweeper. As for the excitation, though broad-band random excitation forces are routinely used, harmonic force is most often used to determine the frequencies contributing to the frequency range of interest, and to identify natural frequencies over the frequency range. The laser signal obtained during excitation of the specimen over a frequency sweeping range of 65 - 160 Hz was found to correspond to two frequency modes. Frequency response functions of the specimen have been determined. Figures 2 presents the frequency response functions of the specimens. The frequency response function of the original specimen was compared with this of specimen having simulated defects in the form of saw cut. It can be noted that the defect can create significant changes in the shape of the frequency response function and in the location of its peaks.

Note that natural frequencies not only depend on the geometry of specimens but also on material stiffness. For specimens with the same geometry made from the same material, differences in frequency may occur due to the defects. For example, consider the original specimen without defects, the first two natural frequencies of the sample were 83.75 Hz and 142 Hz, respectively. A similar sample with a saw cut had the first two natural frequencies of 68 Hz and 128.5 Hz, respectively. We assumed that each specimen was tested under the same

experimental conditions; thus, these changes could be directly correlated with the presence of the defects in the specimen. Comparison of the values of the frequencies, it is found that the differences in frequency were 18.5% and 9.5%, respectively. The natural frequencies of the saw-cut specimen were significantly shifted. It is also clear that the changes in lower frequency mode were greater than those in higher frequency mode. In that sense, a higher-order-mode was less favorable for implementation of the technique as there were less sensitivities. Furthermore, the alternating component of the excitation was frequency-dependent. Under constant voltage excitation, since the excitation current decreased with frequency, the strength of the

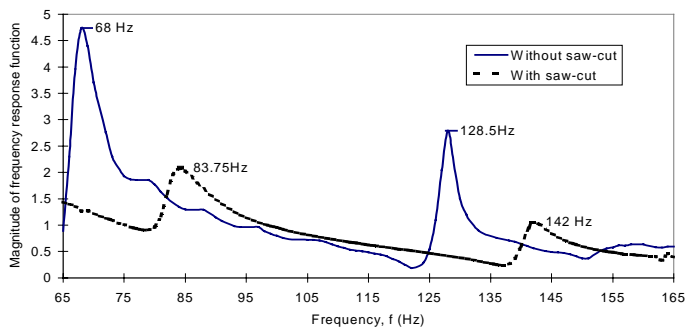


Figure 2. Comparison of frequency response functions of the testing specimen: (a) without saw-cut; (b) with saw-cut.

magnetic field of the excitation reduced too much to drive a specimen.

When driven by the magnetic field, the embedded particle sensors interacted with their host matrix and generated measurable signatures of the structural response which could be interpreted as structural information about damage. The sensory signature of the frequency response from the tagged specimen could be extracted as a result of the interaction between embedded particles and their host matrix. Relationships between the responses of tags and important physical and structural parameters have been experimentally studied previously to understand the fundamental physics and mechanisms involved in using the active tagging method (Rogers, *et al.* 1995). The active tagging technique of dynamic characteristic evaluation using magnetic interrogation (DCEUMI) has been found to be effective and sensitive enough to detect the simulated saw-cut defects. For full-scale composite element inspection in a real-life examination, further refinement of the technique and of the experimental equipment is required. Carefully conducted calibration and training experiments will also be necessary to achieve confidence in the experimental method.

PROPOSED CONCEPT AND METHOD FOR FULL-SCALE NDE INSPECTION EQUIPMENT

The proposed concept is presented schematically in Fig. 3. The 3 in × 1 in × 0.1 in C-channel composite section is passed through the narrow air gap of an electromagnetic exciter. Under the influence of the electromagnetic field, the tagged composite material is locally excited at high frequency. The resulting

vibrations response is picked up by a laser beam. The processing of the vibration response in correlation with the high frequency magnetic excitation yields meaningful information regarding the integrity of the composite material, possible delamination, cracks, and other defects.

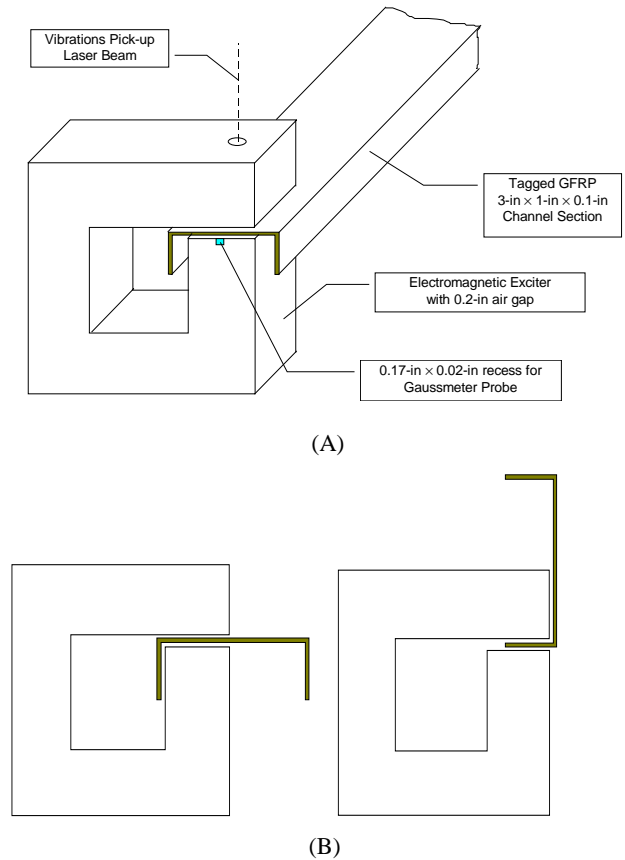


Figure 3. Layout of the active tagging interrogation of c-channel section using an 1.5 in × 1.5 in working section electromagnetic exciter and a laser beam for vibrations pick-up

System Description

The method of performing NDE on the full-scale GFRP Composite C-Channels is straight forward and consists of passing the channels through the interrogation window of the equipment. Since the method is non-contact, several passes may be applied without affecting the part being inspected. A number of specific issues must be addressed to obtain the full benefit of this NDE method:

The full-scale equipment for ferro-magnetic active tagging NDE of GFRP composite C-channels consists of three major components: excitation equipment, measuring equipment, and signal processing equipment which have been mentioned above.

Table 1 presents the list of equipment proposed in the inspection system. Most of the additional instruments are commercially available, but the electromagnetic exciter and the transformer will be custom built

Electromagnetic exciter

The electromagnetic exciter is a major component of the excitation system. It is required to create a strong magnetic field to drive the tested material. The electromagnetic exciter must be custom built and designed. The design of the electromagnetic exciter was performed using the theory presented in Ref. (9). This theory was developed from the standard theory of transformer design developed by McLyman (1978). The main difference between our theory and that of McLyman (1978) consists in the way the problem is posed. For transformers, McLyman (1978) theory designs the optimal transformer configuration to obtain the conversion of a certain power value from an input voltage value into an output voltage value. For inductors, McLyman (1978) theory designs the optimal inductor configuration to obtain a given inductance specification. In our case, we have to design an electromagnet that gives the maximum possible magnetic field density for a given cross-sectional area of excitation, and within some reasonable input voltage, current and power assumptions. Though our methodology and McLyman (1978) methodologies share the same basic principles, they are clearly different in the way they proceed to obtain the final design configuration.

To simplify the first design iteration, the following assumptions were made:

- The core losses are equal to the copper losses.
- The high frequency skin effect is ignored.
- Temperature rise is 50°C.
- The window area of the core is fully filled by the windings.
- The flux leakage and fringing are neglected.
- DC bias is ignored.

Hence, a 58,000 Maxwell magnetic field is obtained for the electromagnetic exciter. The actual flux may be less due to the fringing in the air gap and other losses.

The construction of the core will be made from Silicon-Steel-I-shape shims which is used in laminations to reduce losses and provide better permeability at high flux densities in kHz range of frequencies.

The electromagnetic exciter has a hole made into one end of the core, normal to the air gap cross section (Fig. 3). This hole is used to point a laser beam onto the specimen directly in the region being excited.

Power amplifier

The power amplifier for the electromagnetic exciter is of conventional design and will be acquired on the commercial market with the following characteristics. Output characteristics:

- Maximum output power = 2862 Watts into a 2 Ohms impedance.
- Maximum output voltage = 74.9 Volts.
- Maximum output current = 37.4 Amps.

Two power amplifiers will be used in series, hence the maximum output power would be approx. 5400 Watts into a 4 Ohms impedance. When using two power amplifiers in series the maximum output voltage and current are 150 Volts and 36.8 Amps, respectively.

Step-up transformer

Based on the design of the magnetic exciter, the required voltage is higher than that the power amplifiers can provide. Hence a step-up transformer of two turn ratio will be in use between the power amplifiers and the magnetic exciter in order to match input voltage to the magnetic exciter.

Table 1. List of proposed equipment

Name	Brand	Model	Application notes
Analyzer	ZONIC+A ND	4000	used for signal processing
Function generator	Hewlett-Packard	HP3314A	used for exciting signal generating
Power amplifier (2 count)	Techron	7780	allowed 2 or 3 amplifiers in series
Dc power supply	Hewlett-Packard	HP6268B	used for increasing signal-noise-ratio
Gaussmeter	Walker	MG-5D	used for picking-up magnetic signal
Laser Doppler sensor	Polytec	OFV353/OFD-06	used for picking-up vibration velocity
Vibrometer	Polytec	OFV3001	used for conditioning signal
Filter	Frequency devices	9002	used for conditioning signal
Oscilloscope	Tektronix	TAS220	used for monitoring
Magnetic exciter	N/A	N/A	used for magnetic interrogation
Transformer	N/A	N/A	used for step-up voltage supplied to the magnetic exciter

METHOD FOR PERFORMING FERRO-MAGNETIC ACTIVE TAGGING FULL-SCALE NDE OF GFRP COMPOSITE C-CHANNELS

Calibration

The system needs to be calibrated using control specimens regarding of accept-reject criteria. The frequency response signature pattern of the control specimens will be stored in PC memory as reference. Meanwhile a meaningful definition of what is a “conforming” and a “non-conforming” material condition needs to be achieved.

Tagging Sensitivity Threshold

Since the GFRP composite are inherently inert to magnetic excitation, the weight fraction of the tagging material plays a major role. The weight fraction of tagging particles are limited by both detectability of defects and requirements of strength of composite elements. Optimum of the weight fraction of tagging particles should be carried out in separated program.

Specimen Support

Since the method utilizes high-frequency excitation, only the small-wavelength vibration modes are excited. Hence, the

method is relatively insensitive to boundary conditions, as long as they satisfy the StVenant principle. The specimen can be supported either as a cantilever beam, or on end supports. To satisfy the StVenant principle for a typical defect length of 1-in, a distance of approximately 1-ft (i.e. > 1-in) between the interrogation window of the equipment and the nearest specimen support is recommended.

Number of Inspection Passes

To cover the complete area of the specimen, several inspection passes may be required. Each pass will interrogate a different side of the specimen (Fig. 3).

Since the method is non-contact, performing several inspection passes will not affect the specimen integrity in any conceivable way. (Future industrial implementation of the method may contemplate the used of multiple interrogation sites to perform the complete inspection in just one pass).

CONCLUSION

The ferromagnetic active tagging NDE technique based on the use of an electromagnetic excitation in conjunction with laser Doppler vibrometer and a computer-aid FFT analyzer has been demonstrated for full-scale GFRP composite elements, and the experimental results indicate that the technique of dynamic characteristic evaluation is effective and sensitive enough to detect the simulated saw-cut defect.

Because membrane resonance frequencies are much greater than structural resonance frequencies, detectable defects related to delaminations and debonds are greatly dependent of the power of the excitation system. The fact is that the alternating component of the excitation is frequency-dependent. Under constant voltage excitation, since the excitation current decreases with frequency, the strength of the magnetic field of the excitation reduces much over kHz frequency range. It is hoping that the proposed electromagnetic excitation system would supply sufficient magnetic force for local delaminations and disbonds detection.

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