Ultrasonic Verification of Composite Structures

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ABSTRACT

Ultrasonic Verification is a new method for the monitoring large surface areas of CFRP by ultrasound with few sensors. The echo response of a transmitted pulse through the structure is compared with the response of an earlier obtained reference signal to calculate a fidelity parameter. A change in fidelity over time is indicative for a new defect in the structure. This paper presents an experimental assessment of the effectiveness and reproducibility of the method.

KEYWORDS : *CFPR material, ultrasonics, complex echo, structural health monitoring aviation*

INTRODUCTION

Inspection and monitoring of carbon fiber reinforced polymer (CFRP) structures is an important part of modern aircraft construction and maintenance. In composite materials damages and imperfections are difficult to detect and may not be visible on the surface of the material. Non-Destructive Testing (NDT) techniques have been proven to be able to enhance safety, integrity and durability of aircraft structures over the last decades. NDT combined in Structural Health Monitoring (SHM) systems minimizes the ground time for inspections, increases the availability, and allows a reduction of maintenance costs by more than 30% for an aircraft fleet [1]. The present study concerns a new method for the monitoring of structural health of CFRP by ultrasound, called Ultrasonic Verification (USV). USV is a new non-destructive testing method that allows the monitoring of large CPFR surface areas with a small number of permanently fixed sensors. The feasibility of the USV method on a laboratory scale has been demonstrated in a variety of experiments [2], however leading practicalities require further research. This paper presents an experimental assessment of the effectiveness and reproducibility of the method.

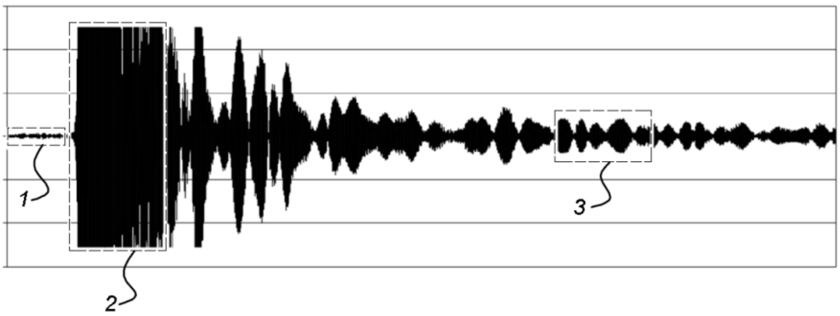

Figure 1: Complex echo of Gaussian pulse with time windows. Signal during time window 1 is the time lag of the sound travelling form transmitter to sensor; time window 2 shows the initial response at overshoot amplitude; time window 3 shows the complex response used in the analysis [3]

1 THEORY

1.1 Comparison of acoustic responses

The technique relies on the reproducibility of acoustic responses in a system if nothing changes. Due to the complexity of composites multiple reflections of a pulsed source will lead to a reverberation response that can be detected elsewhere in the plate (see Figure 1 for a typical recording). These reverberation responses, also called echoes, contain information of all locations where the sound has been before reaching the detector. An emerged defect such as a crack or delamination of the composite will change this response. The change of the signal is quantified using a fidelity parameter.

1.2 Fidelity calculation

Fidelity is a parameter which is used to compare two signals. This parameter is based on the presumption that the sound waves travel through material by the same route each time the signal is transmitted if conditions are unchanged.

$$\boldsymbol{\eta} = \frac{\langle V_1(t) \cdot V_2(t+\tau)\rangle}{\sqrt{\langle V_1(t) \cdot V_1(t+\tau)\rangle\langle V_2(t) \cdot V_2(t+\tau)\rangle}} \tag{1}$$

In equation (1) V_1 is a previously recorded signal from an undamaged material, which is known as the reference signal and V_2 is the control signal which is compared to the reference signal. t is time and η the fidelity. If $\eta = 1$ both signals are identical.

The expression $\langle V_1(t) \cdot V_2(t+\tau)\rangle$ is defined as

$$\langle V_1(t) \cdot V_2(t+\tau)\rangle = \int_{t_1}^{t_2} V_1(t) \cdot V_2(t+\tau)dt \tag{2}$$

With τ as a very small time shift needed to align both output signals in time with respect to the input signal and t_1 and t_2 as the start and end of the correlation time window. The time shift τ is calculated by maximizing the value of equation (1).

The USV method should be used to detect those damages that are barely visible to the naked eye. Barely Visible Impact Damage (BVID) are often described as damages which may not be found during heavy maintenance general visual inspections using typical lighting conditions from a distance of 1,5 meter. The typical dent depth for a BVID is between 0,25 and 0,5 mm.

In earlier tests the viability of this approach to observe small defects has been demonstrated in carbon-fiber composites in simple geometries such as plates and bars [4] [5]. A patent has been filed covering this integral monitoring technique [3].

2 EXPERIMENTAL PROCEDURE

2.1 CFRP plate, fitting and application of BVID

Experiments in a laboratory setting are used to determine the relationship between the fidelity and the detection of barely visible impact damage by ultrasonic verification. A transducer introduces a high frequency Gaussian sound pulse into a CPFR plate and a sensor captures the echo. For this experiment, rectangular carbon fiber composite plates will be used. Typical dimensions of the tested carbon plates are 350mm x 150mm x 3mm. The plate is clamped on the left and right side between wood, and mounted to a table. The piezoelectric sensor and actuator are attached to the plate, by using glue to ensure good transmission of the ultrasonic signal between the plate and the transducer. The transducers are positioned 70 mm from the short side of the plate and 75 mm from the long side. The distance between the transducers is 210 mm.

During the experiment, an initial measurement will be performed in undamaged state (the baseline measurement). In a second measurement the plate will be damaged with a small carve. The damage is applied by the researcher, using a handheld tool. The damage is located in de center of the plate and in the middle between the two transducers. The defect is approximately 10 mm long, 0,5 mm deep and 1 mm wide. In the double damage run the defect is approximately 2 times deeper and slightly longer. Whilst applying the damage the test plate remains suspended and transducers remain attached.

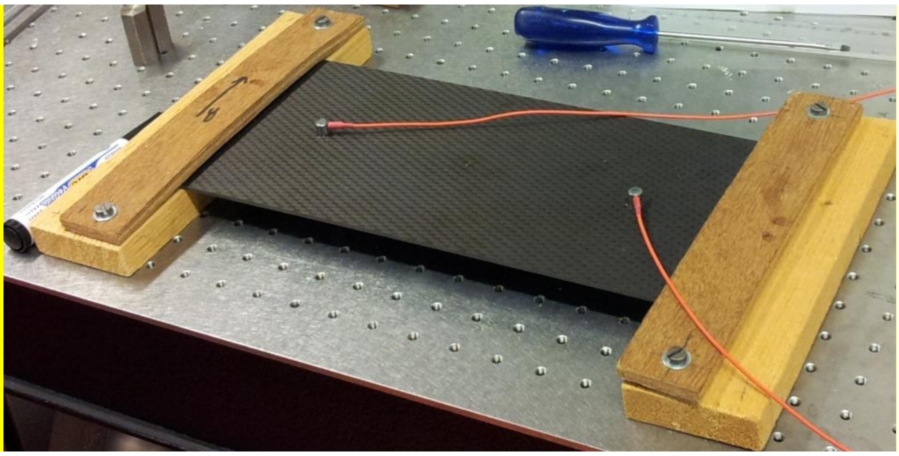

Figure 2: Carbon fiber test plate with sensor and actuator

2.2 Hardware and software

The setup consists of several connected components. The computer defines the required signal that is created by the HP 33120A function generator. This signal is then sent to the Falco Systems WMA-300 preamplifier to strengthen it before being sent into the CFRP coupon. The amplified pulse is launched into the plate using simple piëzo-electric Murata actuators, type 7BB-20-6L0 or 7BB-12-9. On the opposite end of the coupon, the signal is received using an identical transducer. The signal is sent through a Stanford Research Systems SR560 preamplifier and digitized and stored in the Tektronix DPO 2014 oscilloscope. From here the signal is transported back to the computer. Labview software is used as the controlling and receiving interface for the pulse generator and oscilloscope. A specially written script in Matlab software calculates the fidelity of the recorded data (equation 1), compared to the reference data that has been recorded previously.

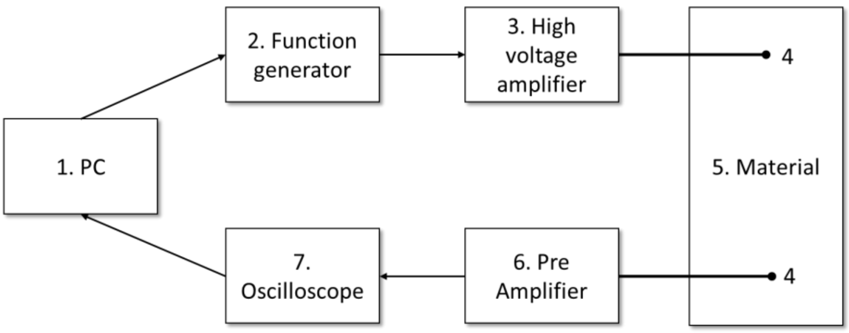

Figure 3: Test Equipment

2.3 Parameter settings

The variable of primary interest is the correlation coefficient (fidelity) as a measure of possible damage in the composite test object. To create an echo, a Gauss pulse is generated by a function generator, which is transmitted to the test object with a certain amount of gain and frequency which influence the echo. Increasing the gain will increase the energy send into the test object, which will result in stronger and longer echoes. Increasing the frequency will result in a smaller wavelength, making it more sensitive for damage detection.

The fidelity value depends on the time window used for the calculation. To ensure that the signal has covered a large area the start time of the correlation time window should be chosen such that the first arrival is excluded from the correlation [2]. Four correlation time windows are defined. The data points of start and end of the time window are: TW1: 4000-15.000, TW2: 15.000-27.000, TW3: 55.000-67.000 and TW4: 4.000-67.000.

As shown in previous research [5] [2] the settings of frequency, gain and time window have large influence on defect detection rate. The settings of other parameters are kept constant. The sample rate in the digitizer is set on 62,5 MHz, which is much higher than the ultrasound frequency. Every echo is recorded with 125.000 data points, which is equivalent to 2,0 milliseconds in time. To reduce the effect of noise the recorded echo is 320 times averaged i.e. 20 times in the oscilloscope and 16 times in the computer.

3 PERFORMANCE OF USV DEFECT DETECTION

3.1 Test program

In test program 1 the probability of detection of barely visible impact damages is determined for various plates and parameter settings.

- 6 CFRP plates of the same size from one production batch
- Plates are measured in 3 states: undamaged, single damaged, double damaged
- Measurements are taken with combinations of 6 frequencies: 105, 190, 210, 230, 440 and 660 kHz, and 3 gains: 1, 2 and 3 V
- Measurements with unchanged parameters settings are repeated 2 times in rapid succession

This results in 3888 fidelity values which comprise the input for statistical analysis.

3.2 Introduction to the performance analysis

First analyses are straightforward calculations of average and standard deviation of grouped fidelity data. With these calculations, we explore the relationship between the independent variables and the variable of primary interest, the fidelity (drop). After these initial calculations, the data will be studied in more detail. Noise in the echo impacts the accuracy of the fidelity value. In a baseline calculation the fidelity is calculated of two subsequent measurements of an undamaged plate. If the baseline already shows a relatively large fidelity drop, it could indicate a poor signal-to-noise ratio. The reliability of the USV method depends on the decision threshold of the method, a too high or too low decision threshold results in wrong decisions thus in a low reliability (false positive and false negative decisions). In this experiment the fidelity threshold is defined as 5 times the average standard deviation of the baseline measurements and fixed on a fidelity of 0,99. This equals a 0,01 or 1% fidelity drop.

3.3 Results & Analysis

For all echoes of damaged plates the fidelity drop is calculated, see Table 2.

TW3 has the largest fidelity drop. This is consistent with the theory of USV, stating that the tail of the echo contains most information about the presence of a damage.

Table 1: Fidelity drop varies with time window and defect size

	Average fidelity drop				**Standard deviation**			
	TW1	TW2	TW3	TW4	TW1	TW2	TW3	TW4
Single damage	4,0%	4,1%	7,8%	5,7%	5,2%	4,9%	8,2%	5,4%
Double damage	6,9%	7,4%	10,2%	9,3%	8,8%	8,5%	10,0%	9,5%

From here we present only the results of calculations with time window 3. Next the relationship between the strength frequency of the pulse signal and the fidelity drop is calculated for time window 3.

Table 2: Fidelity drop of damaged plate in time window 3

Rows: **Frequency [kHz]**	**Average fidelity drop in TW3**			**Standard deviation**		
Columns: **Gain [V]**	**1**	**2**	**3**	**1**	**2**	**3**
105	11,2%	13,7%	14,2%	13,1%	10,9%	11,9%
190	9,6%	10,4%	8,8%	7,3%	8,9%	7,4%
210	4,1%	3,9%	3,9%	3,2%	3,2%	3,7%
230	4,2%	5,9%	5,7%	4,6%	5,2%	4,7%
410	7,8%	8,9%	11,8%	8,6%	8,1%	12,0%
660	12,1%	12,2%	13,2%	9,4%	10,5%	11,0%

High gain shows slightly better response in fidelity drop. The effect of frequency change is stronger. Fidelity drops are high in frequencies 105, 180, 410 and 660 kHz.

In spite of these results the frequencies 440 and 660 kHz do not provide reliable defect detection. These frequencies give in undamaged plates too many false defect warnings. This is proven with baseline measurements in undamaged plates:

Table 3: Fidelity drop in undamaged plates (baseline)

Frequency [kHz]:	**105**	**190**	**210**	**230**	**410**	**660**
Average fidelity drop in TW3 in **undamaged** plate (baseline)	0,4%	0,2%	0,2%	0,3%	3,8%	4,6%

Another way to characterize the quality of the USV method is the ratio between the fidelity drops of the plate in damaged and undamaged state. For example the ratio of the fidelity drop is 50 if the undamaged plate has 0,1% fidelity drop and 5,0% after applying the damage. High ratios are a sign of a reliable method. The ratios of 410 and 660 kHz show an unacceptable ratio of 3, compared to ratios between 46 and 89 for the lower frequencies.

From here on the best performing parameter settings for time window 3 are used: The 8 combinations of 2, 3 V, and 105, 190, 210 and 230 kHz. With these settings 288 echoes were measured, resulting in 432 fidelity values in time window 3.

Applying the threshold value of 1% to distinct undamaged and damaged states results Table 4:

Table 4: Result of 432 fidelity values of the top 8 performing parameter settings

Setting: 105, 190, 210 and 230 kHz, 2 and 3V, TW3	**Method detects no defect**	**Method detects defect**
Plate is undamaged	47 of 48 fidelity values	1 of 48 fidelity values
Plate has damage	32 of 384 fidelity values	352 of 384 fidelity values

With these parameter settings the detection rate of defects is 91,7%. Double damages are easier to detect: 96,8%. For single damages is the rate: 87,5%. The average fidelity drop of undamaged plates (baseline) is 0,24% and the drop of damaged plates is on average 8,30%.

4 USV SENSITIVITY TO CHANGES IN CONFIGURATION AND ENVIRONMENT

4.1 Test program 2

Test program 1 and earlier experiments gave some evidence that the USV method is sensitive to changes in configuration and environment. In the test program 2 a selection is made of significant or obvious changes that could take place in the practical application of the USV method. If not reported otherwise, all experiments in this section are conducted with standard CFRP plates with straight cut edges and dimensions 350mm x 150mm x 3mm. Ultrasonic test frequencies were set 190, 210 and 280 kHz and gains 1, 2 and 3 V

4.2 Fixture of the CFRP plate

The possible effects of plate fittings and suspension on the fidelity calculation are investigated. See Figure 2 for an example of the wooden suspension. In the first experiment a cross correlation was done between the echoes of undamaged plates fitted in wood, construction foam or CFRP. Fidelity dropped between 2% and 15%. It can be concluded that echoes of various fittings are not comparable and a baseline measurement is required after every assembling of material [5]. In the second experiment the fidelity is measured in a wooden frame and metal frame before and after damaging the plate. Fidelity drops of both frames gave similar results [6].

4.3 Attachment of transducers

The first experiment is to determine if there is a significant difference in fidelity if the transducers are removed from the CFRP plate and reattached on the same CFRP plate, on the same location, in a similar manner and with unchanged test set up. The test set up did not reproduce the same signal when the transducers were removed and reattached. Fidelity drops up to 10% were measured. Therefore a baseline measurement is required after every attaching of transducers [6]. In the second experiment three glues are tested to attach the transducer to the plate. The goal is to determine which glue gives the best signal transmission, has the highest stability and is easiest to apply and remove. The selected glues are Hotmelt, Silicone Sealant and Hair gel extra strong. Hotmelt glue turns out to be the best couplant, resulting in 3 times stronger echoes [6].

4.4 Finishing of composite plate edges

The echoes of two types of CFRP plate are compared to determine the relationship between plate finishing and length of the echo. The first plate is a semi-finished product with raw edges. The second plate has finished straight-cut edges. Both plates have approximately the same dimensions.

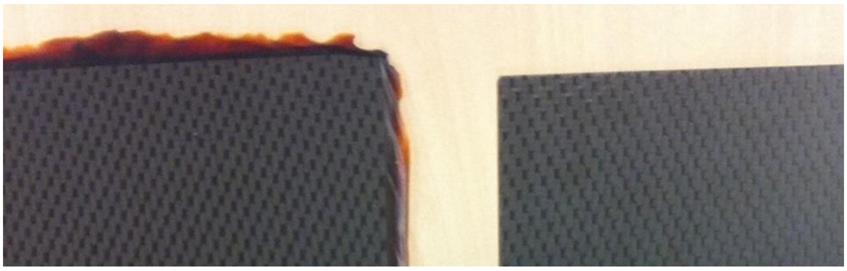

Figure 4: CFRP plates with unfinished resin edges (left) and straight edges (right)

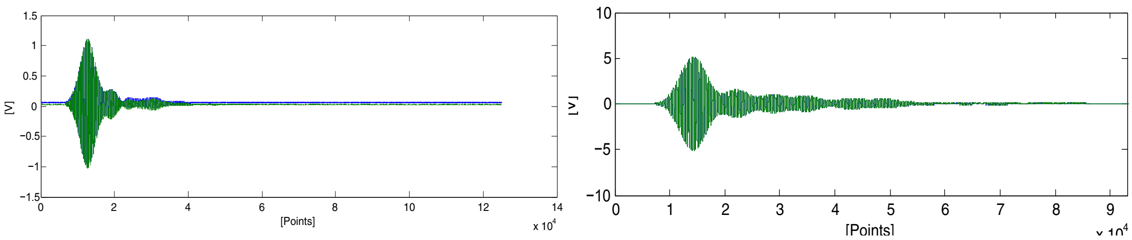

Figure 5: Echoes of plate with unfinished resin edges (left) and straight edges (right)

Measurements are taken with identical parameters settings: a frequency of 210 kHz, with gain setting 2 V. The visual differences in the echoes, as shown in Figure 5, are remarkable. The echo of the plate with raw edges is much shorter than the echo of the plate with the finished straight-cut edges. The maximum signal amplitude of the plate with raw edges is 5 times lower. This experiment shows that the USV method is sensitive to the edge finishing of material [7]. The observations are consistent with the theories of transmission and reflection and of sound waves.

4.5 Distance between transducers in regular and larger plates

Previous tests indicated that the location of the transducers has a large influence on the success rate of defect detection. This experiment is carried out with a CFRP plate of standard dimensions and a double sized plate. For the large CFRP plate the response behavior to propagation was different to the regular composite plate. The measured pulse was significantly weaker and attenuated much quicker than the regular plate. Once the transducers are placed further apart the signal begins to take form as an echo within the tail. This is expected as increasing the distances between the transducers will allow the signal to reverberate through the entire plate. [6].

4.6 Temperature changes

The speed of sound is susceptible for changes in temperature. This will also affect the trace of the Gaussian pulse. In the USV method temperature changes are expected to give unintended fidelity drops, even if the plate is not damaged. In this experiment the behavior of fidelity in relation to temperature is investigated. Cooling of the CPFR plate is done with frozen blocks and heating by using a hair dryer. The temperatures of the CFRP plate are verified with an infrared-camera. The average room temperature is estimated at 20ºC. The results when cooling and heating the CFRP plate showed in all parameter settings that there is a significant difference between the fidelity values [6].

See Figure 6 for a typical result. Without a proper compensation solution the USV method will produce false defect warnings when temperature changes from the temperature during the baseline measurement.

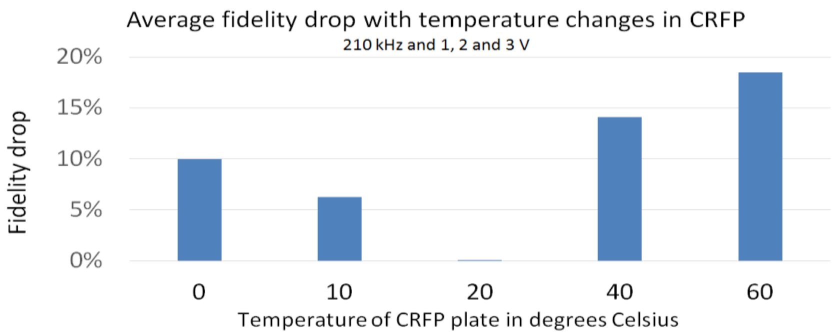

Figure 6: Relationship between fidelity drop and temperature change

CONCLUSIONS

The results of the Ultrasonic Verification experiments are promising and consistent with the theory. Under controlled conditions small defects can be detected in a rectangular CPFR plate with a high degree of certainty. Proper adjustment of ultrasound frequency, pulse gain and correlation time window is required to obtain high probability of defect detection. On the other hand there is a relative broad range of parameter setting that deliver good detection results. The experiments confirm the theory that correlation of the tail of the echoes delivers the best defect detection. The probability of false warnings is small if the threshold value is chosen correctly. Higher frequency settings suffer from noise and signal attenuation. With these results it is recommended to test the USV method in larger and more complex objects. It is important to further develop wave models to calculate the optimal settings and transducer locations.

The second series of experiments shows that there are still challenges in the practical application of the USV method in aviation. A new baseline measurement must be made after every mounting of plates or attachment of transducers. In aviation practices fortunately mounting and attaching happens not frequently. However in our experiments this is a factor to keep in mind. Finishing of the plate edges has a major impact on the results of USV method. This observation has important implications for plates with non-straight edges and plates that have been repaired. The method also works well on larger plates and larger distances, but requires a stronger pulse. The USV method shows false warnings if the temperature changes. Investigation in compensation techniques is very important.

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