

Bootstrap Method for Detecting Damage in Carbon Fiber Reinforced Plastic Using a Macro Fiber Composite Sensor

By Alradix DJANSENA*, Hiroaki TANAKA**, Akira KUDO***

(Received: September 30, 2014 ; Accepted for publication: June 5, 2015)

Abstract

CFRP has been used in aircraft structures for decades. Although CFRP is light, its lamination is its main weakness. We have developed a new method to increase the probability of detecting delamination in carbon fiber reinforced plastic (CFRP) by narrowing the confidence interval of the changes in natural frequency. The changes in the natural frequency in delaminated CFRP are tiny compared with measurement errors. We use the bootstrap method, a statistical technique that increases the estimation accuracy from small samples, for detecting damage in CFRP. The natural frequency was measured using a macro fiber composite sensor to investigate the efficiency of the method. The results show that the confidence intervals of the natural frequency are improved by using the bootstrap method.

Keywords: Composite Material, CFRP, MFC, Health Monitoring, Bootstrap Method

1. Introduction

Lightweight composite materials are now used in aircraft structures. However, internal damage caused by delamination is a problem. Even a small amount of delamination could have a large effect on weight-saving advanced structures and lead to a major failure. Therefore, using nondestructive techniques to detect damage is important to keep structures

healthy and safe. However, conventional nondestructive techniques, such as eddy current inspection, magnetic particle inspection, and X-ray imaging techniques, are expensive for aircraft maintenance, and the aircraft must be taken out of operation during the inspection. Therefore, an inexpensive, convenient nondestructive technique is required.

Techniques that measure dynamic changes in the characteristics of composite materials with piezoelectric material have been developed. For example, damage can be detected by applying a Lamb wave in real time¹⁻⁴. There are three advantages of a Lamb wave on a flat material. Firstly, propagation of the diffusion attenuation of

*Graduate Student (52nd term); National Defense Academy

**Associate Professor; Department of Aerospace Engineering, National Defense Academy

***Lecturer; Department of Aerospace Engineering, National Defense Academy

a Lamb wave is small. Secondly, Lamb waves can propagate over long distances. Thirdly, damage can be detected over a wide area. However, this technique requires a high-voltage amplifier to produce the Lamb wave. Another detection technique is to identify damage in carbon fiber reinforced plastic (CFRP) by measuring the change in the natural frequency⁵. This technique only requires a piezoelectric sensor to measure the natural frequency; the technique is convenient and does not require an amplifier. However, for micro-sized delamination, the change in the natural frequency is small and measurement error makes detecting damage difficult.

In this work, we develop a method to detect damage by narrowing the confidence interval of measurements by using the bootstrap method. This method is used for statistical approximation of measurement results. We measure the change in natural frequency with the hammer test by using a macro fiber composite (MFC) sensor for the unidirectional CFRP plates. The method is tested by evaluating the relationship between the confidence interval of the natural frequency and the number of hammer tests.

2. Problems in Damage Detection Using Natural Frequency Evaluation

2.1 Finite Element Analysis

To demonstrate the difficulties in damage detection using natural frequency evaluation, changes in the natural frequency of CFRP plates were

investigated through numerical simulation. As a reference, finite element analysis (FEM) was performed to obtain the natural frequency change due to delamination. The analysis is performed with commercial FEM code Abaqus 6.3. Analysis models corresponded to the following experimental specimen. Element: 3D solid, $170 \times 103 \times 1.9$ mm (length $\times$ width $\times$ thickness). Material: CFRP; density, 1.59 g/cm^3 ; Young's modulus, 135 GPa; Poisson ratio, 0.32. Boundary condition: both ends fully fixed. The analysis model is shown in Fig. 1. The simulation results of undamaged CFRP (1st mode, bending mode) are shown in Fig. 2. The delaminated CFRP plates are modeled by inserting strip delaminations with lengths of 2–8 mm into the middle of the models. There are four models with different delamination sizes and positions. Figure 3 shows a representative simulation result from the CFRP model with a 5-mm-wide delamination. Table 1 shows the results of the 1st mode natural frequency. The simulation results show that small changes in natural frequency of around 1 Hz occur. These fully fixed conditions are not the same as experimental conditions, because they do not consider the rigidity of the jigs that hold both ends of the CFRP plate and the clamping conditions. Therefore, the calculated natural frequencies are intended as only reference values that do not match the experimental results.

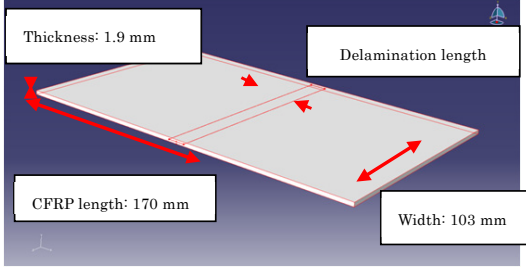


Fig. 1 FEA Model

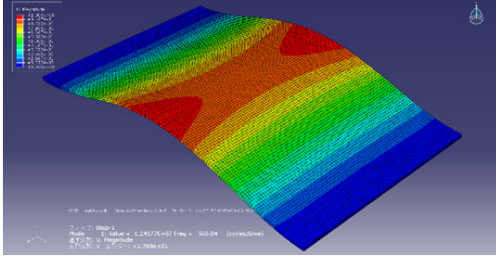


Fig. 2 1st mode of the undamaged CFRP plate (560.84 Hz)

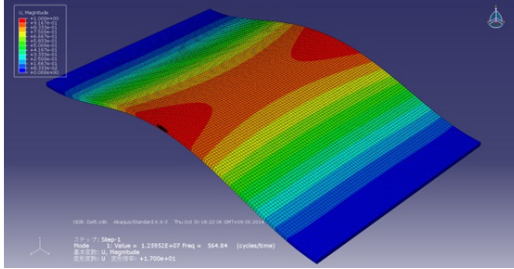


Fig. 3 1st mode of the delaminated CFRP plate (5 mm) (564.84 Hz)

Table 1 Results of FEA (1st mode: Hz)

	Undam aged	2 mm	5 mm	8 mm	5 mm#3
FEM	560.84	562.35	564.84	567.44	564.10

2.2 Differences in Natural Frequency

The differences in natural frequency between undamaged CFRP and damaged CFRP are used to detect damage. The size of the difference may be a problem when

the standard deviation and width of confidence interval of the measurement errors are larger than the change in the natural frequency.

The problem can be overcome by increasing the number of tests. However, in practice, it is desirable to collect a small amount of data to reduce cost and time. In this work, we use the bootstrap method to resample the data repeatedly to estimate the parameters. This method does not create new 100 data from existing data, although it does narrow the confidence interval by resampling the data. The bootstrap method also does not require us to know the data distribution.

3. Conventional Confidence Interval Estimation

For n samples in a data set, $(x_1, x_2, \dots, x_n)$, the equation for obtaining the average, $\bar{x}$, can be expressed as

$$\bar{x} = \frac{1}{n}(x_1 + x_2 + \dots + x_n) \quad (1)$$

Then, standard deviation s is expressed by

$$s = \sqrt{\frac{1}{n-1} \left\{ (x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + \dots + (x_n - \bar{x})^2 \right\}} \quad (2)$$

This $\bar{x}$ value is also called the point estimation. If these n samples are obtained from other data sets randomly, they may have different point estimations. Therefore, it would be difficult to determine which point estimation is the real value. There is an interval estimation formula to overcome this problem. When estimating parameter θ a confidence coefficient is set. This formula can be used to judge whether θ is inside the interval $[\theta_1, \theta_2]$ with the probability of the confidence coefficient.

The interval, $[\theta_1, \theta_2]$, is a confidence interval of θ^6 . A confidence coefficient of 0.95 (95%) is used in this work. Furthermore, based on the estimation method, there are two ways to estimate the confidence interval depending on whether the variance is known. For known variance, a normal distribution is assumed and is expressed by

$$[\theta_1, \theta_2] = \bar{x} \pm 1.96 \times \frac{s}{\sqrt{n}} \quad (3)$$

For unknown variance, the t-distribution is considered and a distribution table is required to calculate the coefficient of the confidence interval⁹. The equation for the confidence interval, which corresponds to a confidence coefficient of 95%, is

$$[\theta_1, \theta_2] = \bar{x} \pm t(n-1)(0.025) \times \frac{s}{\sqrt{n}} \quad (4)$$

4. Bootstrap Estimation

4.1 General

In the conventional method, if the data are taken randomly for a normal distribution, the confidence interval is directly estimated from the data. However, knowledge of the data distribution is not required in the bootstrap method. Data are resampled from the obtained data frequently, and many groups of data are obtained. The resampling is performed with the same data. Then, estimated distribution value is calculated from these groups of data, and finally parameter information is calculated by this method⁶.

4.2 Procedure of Bootstrap Method

The bootstrap method procedure is as follows.

- 1) The estimated value of parameter θ is determined from the original data.
- 2) By using the original data, $(x_1, x_2, \dots, x_n)$ of the same n samples are resampled randomly. Then, similar to step 1, the estimated value is calculated.
- 3) Step 2 is repeated N times.
- 4) The average and standard deviation are determined from the estimated values, $(\theta_{n,1}, \theta_{n,2}, \dots, \theta_{n,N})$, of the data resampled N times.
- 5) The confidence interval, $[\theta_1, \theta_2]^6$, is calculated.

5. Experimental Evaluation of Natural Frequency

5.1 Test Plates

The composite material used in this research is CFRP. The test plates were laminated 17 ply unidirectional prepreg CFRP. Five CFRP plates were made ($200 \times 103 \times 1.9$ mm, length $\times$ width $\times$ thickness). The first CFRP plate was the undamaged CFRP plate. The other four CFRP plates contained delaminations. Three delaminated CFRP plates had a Teflon film inserted (thickness: 0.05 mm; width: 100 mm; lengths: 2, 5, or 8 mm) in the middle of the CFRP (prepreg layer no. 9 from the surface) to create delamination during their fabrication (Fig. 4). The other delaminated CFRP plate contained Teflon film (width: 100 mm; length: 5 mm) in

prepreg layer no. 3 from the surface (5 mm#3).

Two MFC sensors (M-2814-P1, Smart Materials; thickness: 0.3 mm; width: 20 mm; length: 38 mm) were attached with adhesive to each CFRP plate 40 mm to the left and right of the center line. The CFRP plates were fixed in a jig (Fig. 5).

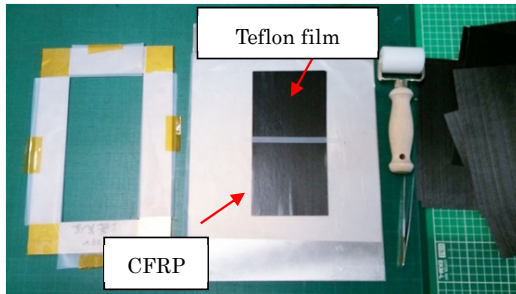


Fig. 4 Fabrication of 8 mm delaminated CFRP plate

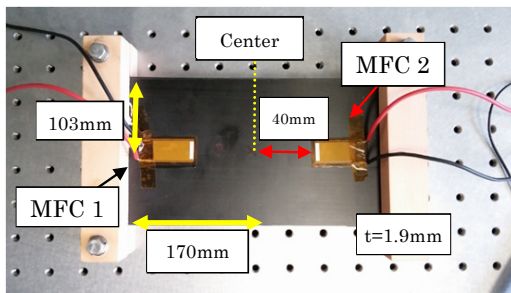


Fig. 5 Fixed CFRP plate with MFC attached

5.2 Experimental Equipment

The natural frequency was measured with the experimental setup shown in Fig. 6. The vibrations in the test plate originating from the hammer impulse were converted into electrical signals by the MFC sensors. These electrical signals were measured by

a digital oscilloscope (DS-5524, Iwatsu). Only the natural frequencies were evaluated; thus, a charge amplifier for producing an appropriate amplitude was not required.

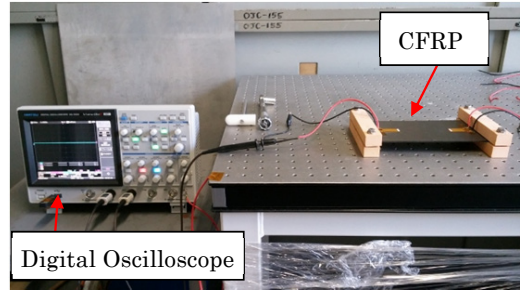


Fig. 6 Experimental equipment

5.3 Experimental Method

The natural frequency was measured by a hammer test (Fig. 7). A sampling rate of 100 kHz and sampling time of 100 ms (data number: 10,000 points) were used. Undamaged and delaminated plates were tested in the test jig. Measurement results were analyzed by using fast Fourier transform (FFT), which assessed the difference in the natural frequency between undamaged and delaminated plates.

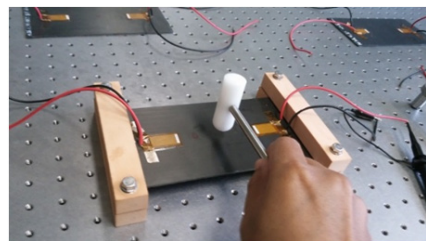


Fig. 7 Hammer test

5.4 Experimental Results

To obtain the natural frequencies, 100 hammer tests were performed on each CFRP plate (undamaged, delamination of 2 mm, 5 mm, 8 mm, 5 mm#3). Vibrations were measured by sensors MFC 1 and MFC 2 and were analyzed by FFT.

The first 10 results for the undamaged CFRP plate around the 1st mode are plotted in Fig. 8. The experimental results of the delaminated CFRP plates (1st mode) are shown in Figs. 9–12. The legends denote the test number and the 1st mode natural frequencies. The results in these figures are from MFC 2.

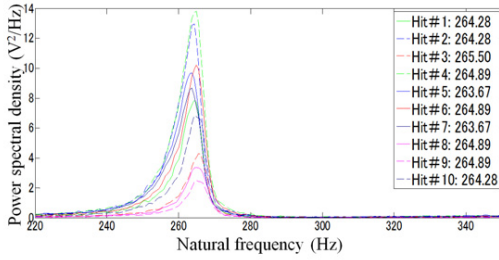


Fig. 8 Undamaged CFRP (1st mode)

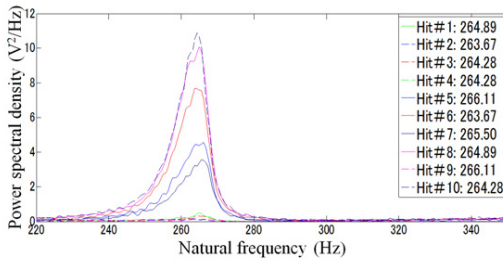


Fig. 9 Delaminated (2 mm) CFRP (1st mode)

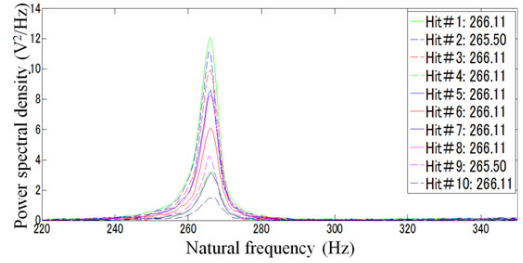


Fig. 10 Delaminated (5 mm) CFRP (1st mode)

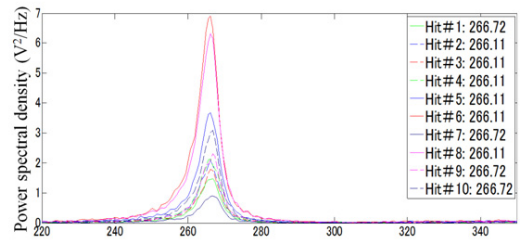


Fig. 11 Delaminated (8 mm) CFRP (1st mode)

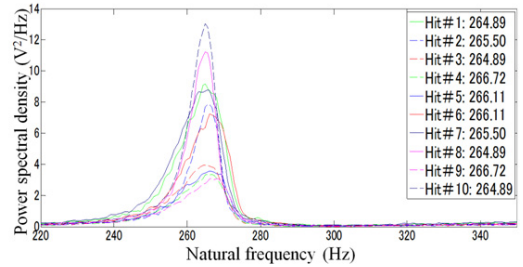


Fig. 12 Delaminated (5 mm#3) CFRP (1st mode)

Figures 9–12 show that the changes in the natural frequency caused by delamination follow the same trend as the FEA results, in which the natural frequency of delaminated CFRP is higher than the undamaged material. The average natural frequency and standard deviation were calculated and then the confidence interval was obtained from equation (4). The experimental results of the average,

standard deviation, and confidence interval are shown in Tables 2 and 3. The averages and confidence intervals of 100 experiments are plotted in Figs. 13 and 14. The results show that the difference in the confidence interval can be identified when 100 experiments are conducted.

Table 2 Results of 100 measurements by MFC 1 (Hz)

	Undamaged	2 mm	5 mm	8 mm	5 mm#3
Mean	264.10	265.33	265.74	267.04	265.46
Std. Dev.	0.91	0.64	0.82	0.73	0.75
Conf. Interval	263.92-264.28	265.20-265.46	265.58-265.90	266.90-267.18	265.31-265.61
Conf. Int. Diff	0.36	0.26	0.32	0.28	0.30

Table 3 Results of 100 measurements by MFC 2 (Hz)

	Undamaged	2 mm	5 mm	8 mm	5 mm#3
Mean	264.18	265.35	265.71	267.08	265.42
Std. Dev.	0.85	0.90	0.76	0.70	0.72
Conf. Interval	264.01-264.35	265.17-265.53	265.56-265.86	266.94-267.22	265.28-265.56
Conf. Int. Diff	0.34	0.36	0.3	0.28	0.28

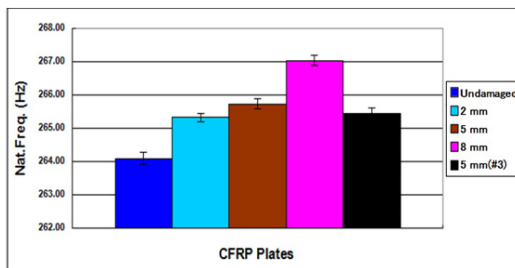


Fig. 13 Confidence interval of natural frequency (MFC 1)

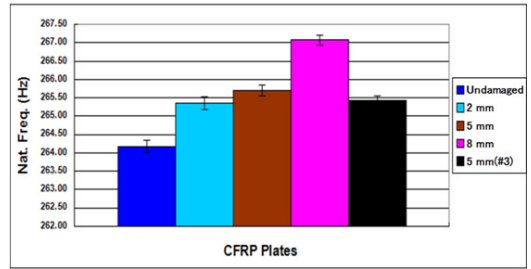


Fig. 14 Confidence interval of natural frequency (MFC 2)

6. Bootstrap Method

We confirmed the probability of detecting delamination based on the changes in natural frequencies by using 100 experimental results. However, during the operation of airplanes, cost and time limitations make it impractical to conduct 100 experiments. We used the bootstrap method to obtain the natural frequency from a small number of tests with high accuracy.

The confidence intervals calculated from three, five, and ten experimental samplings were compared. To determine the confidence interval, 120 samples were randomly resampled from the experimental sampling. One hundred groups of experimental data from the base data were constructed to evaluate the effectiveness of the bootstrap method statistically. The discrepancies between the test results of MFC 1 and MFC 2 were small; therefore, only data from MFC 2 were used.

6.1 Results of Three Experimental Samplings

The accuracy evaluation of the bootstrap

method using three experimental samplings was conducted. From 100 base data, any three pieces of data were taken randomly and the confidence interval was evaluated by using the conventional and bootstrap method. This evaluation was performed 100 times. The results of the conventional method are shown in Fig. 15 (vertical axis denotes frequency of occurrence and each plot shows the lower or upper confidence interval of each CFRP model). The bootstrap method results are plotted in Fig. 16. The averages of the confidence intervals are summarized in Table 4.

The results in Figs. 15 and 16 vary widely because there were a small number of original experimental samplings. Comparing undamaged CFRP with the 8 mm delaminated CFRP shows a clear difference in the confidence interval. However, the confidence intervals are similar for the 2 mm, 5 mm, and 5 mm#3 delaminated samples.

From these results, the confidence interval is achieved by using the bootstrap method. However, the evaluated confidence intervals of the natural frequency for each CFRP piece overlap, which makes it difficult to identify the extent of delamination. Therefore, the effectiveness of the bootstrap method using three experimental samplings is low.

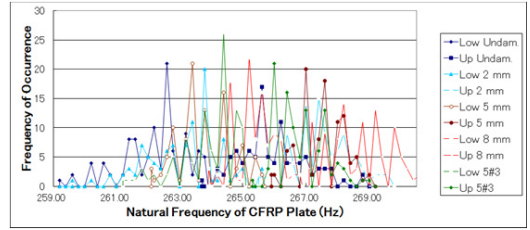


Fig. 15 Confidence intervals of conventional method (three experimental samplings)

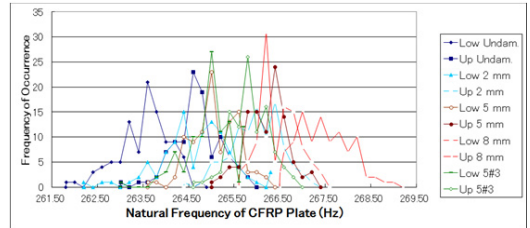


Fig. 16 Confidence intervals of bootstrap method (three experimental samplings)

Table 4 Comparison of confidence intervals (three experimental samplings)

	Undamaged	2mm	5mm	8mm	5mm#3
Orig.	262.31	263.24	263.87	265.44	264.00
Data	266.06	267.59	267.55	268.72	266.94
Conf. Int.					
Diff.	3.75	4.35	3.68	3.28	2.94
Bootstrap	263.61	264.74	265.17	266.58	265.04
Conf. Int.	264.78	266.10	266.31	267.57	265.95
Diff.	1.17	1.36	1.14	0.99	0.91

6.2 Results of Five Experimental Samplings

The results using five experimental samplings are shown in Figs. 17 and 18 and Table 5. Compared with the results from three samplings, the variation in the confidence interval is smaller and the

delamination of 5 mm or more can be distinguished, although the other delaminations cannot be distinguished.

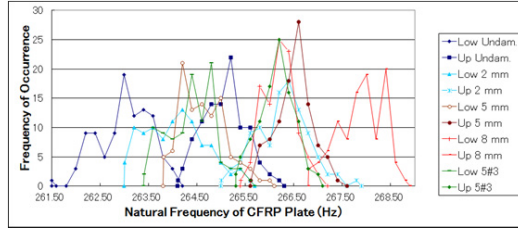


Fig. 17 Confidence intervals for the conventional method (five experimental samplings)

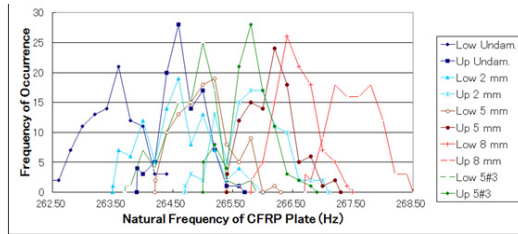


Fig. 18 Confidence intervals of the bootstrap method (five experimental samplings)

Table 5 Comparison of confidence intervals (five experimental samplings)

	Undamaged	2mm	5mm	8mm	5mm#3
Ori.Data	263.11-	264.18-	264.73-	266.29-	264.52-
Conf.Int	265.15	266.35	266.57	267.96	266.19
Diff.	2.04	2.17	1.84	1.67	1.67
Bootstrap	263.55-	264.64-	265.12-	266.65-	264.88-
Conf.Int	264.75	265.92	266.24	267.62	265.88
Diff.	1.2	1.28	1.12	0.97	1.00

6.3 Results of 10 Experimental Samplings

The results using 10 experimental

samplings are shown in Figs. 19 and 20 and Table 6. In 10 experimental samplings, the improvement of the confidence interval is clear, and the undamaged CFRP and each delaminated sample can be distinguished. Variations are still detected; however, they are smaller compared with the results from five samplings, making the confidence interval easy to differentiate. Comparing undamaged CFRP with CFRP with 5 mm, 8 mm, and 5 mm#3 delaminations shows clear differences in the natural frequencies. The 2 mm delamination was nearly distinguishable.

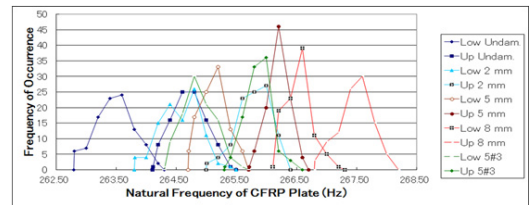


Fig. 19 Confidence intervals of the conventional method (10 experimental samplings)

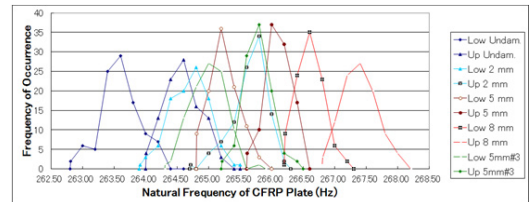


Fig. 20 Confidence intervals of the bootstrap method (10 experimental samplings)

Table 6 Comparison of confidence intervals
(10 samplings)

	Undamaged	2 mm	5 mm	8 mm	5 mm#3
Orig.	263.57	264.65	265.19	266.61	264.96
Data	264.81	265.87	266.29	267.57	265.96
Conf. Int.					
Diff.	1.24	1.22	1.1	0.96	1.00
Bootstrap	263.70	264.79	265.33	266.71	265.08
Conf. Int.	264.68	265.74	266.19	267.48	265.88
Diff.	0.98	0.95	0.86	0.77	0.80

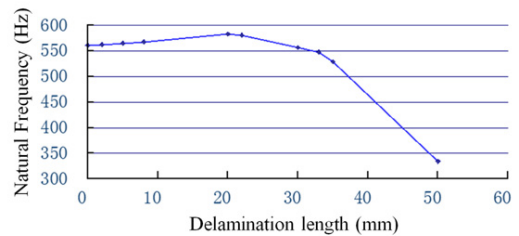
7. Summary

In CFRP plates, it is important to detect small changes in the natural frequency to detect delamination. The bootstrap method was used to improve the estimation accuracy of the natural frequency. Its effectiveness was demonstrated experimentally. To reveal the relationship between the estimated confidence interval and the experimental sampling number, three, five, and ten experimental samplings were studied. The experimental results showed that despite the small number of samplings, the confidence interval was clearly decreased by using bootstrap method. The distinction of the confidence interval was difficult for three experimental samplings. For five samplings, some delamination samples were detected. For 10 samplings, the distinction between undamaged CFRP and delaminated CFRP was clear for delaminations of 5 mm, 8 mm, and 5 mm#3. The delamination of 2 mm was nearly distinguishable. Finally, although these results were not the same as those for 100

hammer experiments, we demonstrated that delamination could be detected from a small amount of data (at least 10 experimental samplings) by using the bootstrap method. However, we only evaluated three, five, and ten samplings by using a 95% confidence coefficient to differentiate the undamaged and delaminated CFRP. Other confidence coefficient numbers will be considered in future research.

Appendix

The results of our study showed the same trend in the FEA and experiment results; the natural frequency of delaminated CFRP is higher than undamaged CFRP. The relationship between the delamination size and natural frequency were investigated through numerical simulations. The results are plotted in Fig. A1. The graph indicates that the natural frequency increases up to a delamination length of 20 mm. After that, the natural frequency decreases as the delamination length increases. The mechanism causing this behavior will be studied in future work.

**Fig. A1** Natural frequency of delaminated CFRP (both ends fixed)

References

- 1) K. Diamanti, C. Soutis, "Structural Health Monitoring Techniques for Aircraft Composites Structures", *Progress in Aerospace Sciences*, (2010), pp. 342-352.
- 2) B. S. Ben, B. A. Ben, K. A. Vikram, S. H. Yang, "Damage Identification in Composite Materials Using Ultrasonic Based Lamb Wave Method", *Measurement*, (2012), pp. 904-912.
- 3) S. S. Kessler, S. M. Spearing, C. Soutis, "Structural Health Monitoring in Composite Materials Using Lamb Wave Method", *American Society for Composites, ASC-2001#43*, (2001).
- 4) N. Hu, K. Sakai, H. Fukunaga, "Damage Detection of Beam Structures Using Lamb Wave, 48th Structural Strength Meeting", (2006), pp. 249-251.
- 5) T. Inada, Y. Shimamura, A. Todoroki, H. Kobayashi, H. Nakamura, "Damage Identification of CFRP Laminated Beam by The Natural Frequency Change Using Response Surface Methodology", *Journal of Japan Society of Mechanical Engineers (Book A)*, (1999), pp. 776-782.
- 6) K. Yoshihara, *Butosutorappu Ho wo Mochiita Deta Kaiseki (Analysis Data of Bootstrap Method Using Excel)*, Baifukan, (2009)(In Japanese).
- 7) W. Yanqing, W. Zhongyu, S. Jianyong, Z. Jianjun, Z. Mourelatos, "Gray Bootstrap Method for Estimating Frequency Varying Random Vibration Signals with Small Samples", *Chinese Journal of Aeronautics*, (2014), pp. 383-389.
- 8) A. E. Dudek, S. Maiz, M. Elbadaoui, "Generalized Seasonal Block Bootstrap in Frequency Analysis of Cyclostationary Signals", *Signal Processing*, (2014), pp. 358-368.
- 9) <https://staff.aist.go.jp/t.ihara/tinv.html>, National Institute of Advanced Industrial Science and Technology.