[Original Paper]
Journal of the Korean Society for Nondestructive Testing
Vol. 31, No. 2 (2011. 4)

Performance of Different Sensors for Monitoring of the Vibration Generated during Thermosonic Non-destructive Testing

Bubyoung Kang

Abstract Vibration monitoring is required for reliable thermosonic testing to decide whether sufficient vibration is achieved in each test for the detection of cracks. From a practical point of view, a cheaper and convenient monitoring method is better for the application to real tests. Therefore, the performance of different sensors for vibration monitoring was investigated and compared in this study to find a convenient and acceptable measurement method for thermosonics. Velocity measured by a laser vibrometer and strain provide an equivalent HI when measured at the same position. The microphone can provide a cheaper vibration monitoring device than the laser and the heating index calculated by a microphone signal shows similar characteristics to that calculated from velocity measured by the laser vibrometer. The microphone frequency response shows that it underestimates high frequency components but it is applicable to practical tests because it gives a conservative value of HI.

Keywords: Thermosonic, Ultrasonic Excitation, Vibration Monitoring, Laser Vibrometer, Microphone

1. Introduction

One typical characteristic of a thermosonic test is the lack of repeatability in the amplitude and the frequency characteristic of the vibration. This means vibration monitoring is necessary to decide whether sufficient vibration is achieved in tested structures during each test and the vibration level should be compared with the required vibration level for reliable crack detection which can be obtained in calibration tests. Therefore, a calibration test procedure is required to find the required vibration level for the reliable detection of the target defects.

Thermosonics uses vibrational energy to detect defects in structures and this vibrational energy is converted into heat at the defect. The surface temperature rise is detected by a thermal imaging camera. There are several parameters that influence the temperature rise at the defect, the most well known of which are the cyclic strain, frequency of vibration, damping characteristic, crack morphology and thermal properties of the structure[1-3]. If other parameters remain constant, the temperature rise $\triangle T$ can be expressed approximately as [4-6]:

$$\triangle T \propto \eta_r \epsilon^2 f \quad (1)$$

where ϵ is the amplitude of cyclic strain, f is the frequency of vibration, and η_r is the damping loss factor.

One of the advantages of the formulation shown in eqn. (1) is that the damping loss factor includes the effect of complicated parameters such as crack morphology on the temperature rise. Therefore, this formulation provides a relatively simple method for predicting the temperature rise by separating the

[Received: February 25, 2011, Revised: March 25, 2011, Accepted: April 7, 2011] *Super-Speed Train Research Department, Korea Railroad Research Institute, #360-1, Woram-Dong, Uiwang-Si, Gyeonggi-Do, 437-757, Korea (bbkang@krri.re.kr)

complicated effects into the loss factor[5,7]. As shown in eqn. (1), the strain amplitude excited in the structure and the frequency of the vibration are dominant variables for the temperature rise. Therefore, a parameter which considers the effect of vibration amplitude and frequency of the vibration on temperature rise can be used to decide quantitatively whether sufficient vibration is achieved or not. Morbidini et al.[4,5] proposed new parameters called energy index(EI) and heating index(HI) which consider the effect of the amplitude of the excited strain and the frequency components of the strain on the surface temperature rise and showed that the proposed heating index can be used successfully as a parameter to represent the surface temperature rise through the extensive experiments. They also showed that there is a threshold value of the HI depending on the crack size for generating heat around a crack and presented a calibration procedure considering this threshold value[4]. The calibration procedure involves controlling the test configuration, finding information on the target defect which has to be detected, gathering information of the response of the system to defective samples and non-defective reference samples. In this practical perspective, a number of thermosonic tests will be carried out on defective and non-defective samples to find the vibration threshold value for a given defect at a given position for the reliable detection of cracks in tested structures, using the excitation system and the IR camera available, before starting real inspections. The measured HI in each test should be compared to the threshold value in order to decide whether an crack with a target size will be detected in each test. A tightly closed crack may require a threshold strain to start opening the crack for heat generation and the threshold value can also be affected by the sensitivity of the infrared camera[8].

2. Experiments

Vibration monitoring is required for reliable thermosonic testing. The HI calculated from vibration amplitude and the frequency content of the vibration should be calculated for the comparison with a threshold value. Generally, the heating index has been calculated from the strain record in the work of Morbidini et al.[4, 5]. However, it may be possible to use other sensors such as a laser vibrometer, a microphone to provide a vibration record which can be used to calculate the HI. Vibration monitoring has been used successfully for health monitoring of parts and civil structures for the detection of the defects in structures but it is usually related to low frequency vibration below 1 kHz[9]. Sensors for ultrasonic measurements have been developed and used widely for conventional ultrasonic measurements and noble techniques such as Non-linear ultrasonics[10]. but it is usually applied to high frequency measurements above 1 MHz. This leads to this study to find an appropriate vibration sensors for thermosonics. The vibration signal should reflect the vibration of the tested structure up to the highest frequency that contributes significantly to the heat generation. From a practical point of view, a cheaper and convenient monitoring method is better for the application to real tests. Therefore, the performance of different sensors for vibration monitoring was investigated and compared in this study. The vibration in different tests was categorized qualitatively in order to see the performance of the sensors under different vibration conditions such as single frequency dominant or chaotic where the vibration consists of rich spectrum including many harmonics, side bands around the harmonics and sub harmonics.

Fig. 1 shows a schematic of the test setup used in this study to investigate the performance of different sensors. The test specimen is a new engine blade (the Stage-1 High Pressure Turbine blade) used in a turbine engine for air plane. This specimen was selected because the vibration in a complicated real structure can be investigated. The blade is made of single crystal nickel-base superalloy (CMSX4) and the clamp is steel.

Fig. 2 shows a schematic of the test instruments and signal flow for the experiment and Table 1 shows specifications of the equipment and sensors for vibration monitoring. The vibration was measured on the blade center by different sensors during the thermosonic excitation. The vibration with different frequency characteristics can be produced by varying the input signal from a function generator (Agilent 33220A) to the power amplifier, which can adjust the input power level from a general purpose power amplifier (AG1012) to an acoustic horn. A controllable general purpose power amplifier (AG 1012) supplied by T&C Power Conversion was used for supplying power to the acoustic horn (Sonotronic) which has a resonance frequency of 40 kHz. A laser vibrometer (Polytech OFV 552) and microphone (A 4138 B&K) were used to measure the vibration and the measured vibration signals were saved in the oscilloscope (Lecroy Wave Runner) for post processing. The acoustic horn was pressed against the clamp by spring force during the test as shown in Fig. 1. Higher spring force helped chaotic vibration to occur more easily and the impedance matching also helped to produce chaotic vibration. Different cases including fundamental frequency dominant and chaotic were investigated through many tests and example cases are presented in this paper.

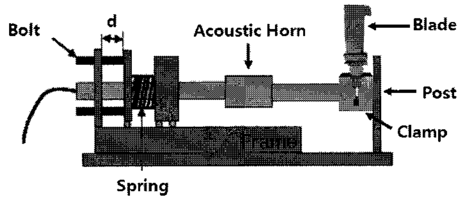

Fig. 1 Schematic of test setup used for the tests to investigate the performance of different sensors

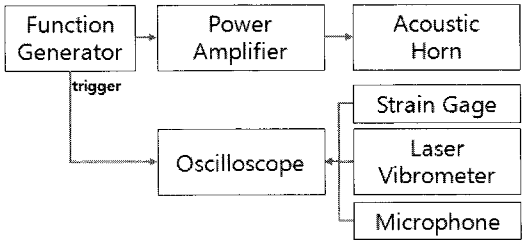

Fig. 2 Schematic of test setup and signal flow

Table 1 Specifications of the equipment and sensors for vibration monitoring

Instruments	Specifications	Model
Function Generator	Frequency and Amplitude Control, Trigger Signal	Agilent 33220A
Power Amp.	20 kHz-6 MHz Max Power:1000 W	T&C Power AG1012
Acoustic Horn	40 kHz Max Power: 400 W	Sonotronics DN 40M
Strain Amp.	High Frequency Compensation	Fylde FE-537-SGA
Laser Vibrometer	Optic Fiber Portable Type	Polytech OFV 552
Microphone	-2 dB@140 kHz Dia. 1/8 in	B&K A 4138
Oscilloscope	4 Ch up to 10 GS/s	Lecroy Wave Runner

3. Results and Discussions

3.1 The Comparison of the Heating Indexes Obtained by Velocity and Strain

A laser vibrometer can monitor structural vibration up to high frequencies. This method has been used by many authors for thermosonic research[11-13]. However, the heating index has been calculated from the strain record in the work of Morbidini et al.[4,5]. Therefore, it is required to compare the heating index calculated from vibration signals measured by a laser vibrometer and a strain gauge to see whether they are comparable. The strain gauge amplifier

(Fylde FE-537-SGA) used in this study has a frequency response characteristic which gives an attenuated strain output at high frequencies above 50 kHz. Therefore the measured strain was compensated.

Two different cases including fundamental frequency dominant and chaotic were investigated and examples are presented in Fig. 3 and Fig. 4. The excitation frequency was 42.8 kHz in these three cases which was one of the system resonance frequencies found before the tests. Fig. 3 shows the comparison of STFTs (short time Frier transform) and heating indexes of the signals obtained from laser vibrometer and strain gauge on the blade in the fundamental frequency dominant case. The measurement positions of the laser vibrometer and strain gauge were the same and shown in Fig. 3(d). The strain gauge on the blade measured a strain component in direction 1 at the position shown in Fig. 3(d). The measurement positions of the laser vibrometer and strain gauge and the direction of the strain gauge were the same in the results shown in Fig. 4. Fig. 3(a) and (b) show that the excited vibration contains the fundamental frequency component with a small amplitude of the first harmonic. Fig. 3(c) shows the comparison of the normalized heating index calculated from the vibration records measured by two different sensors. As shown in Fig. 3(c), the calculated heating indexes are very similar in shape between different sensors though the absolute magnitude of the measured signal is different. The absolute magnitude is not required to be the same in different sensors as it will be calibrated and the same measurement transducer and position will be used in both calibration test and real test. The results presented above show that velocity and strain can give the equivalent HI in the fundamental frequency dominant case when measured at the same position.

Fig. 4 shows the comparison of STFTs,

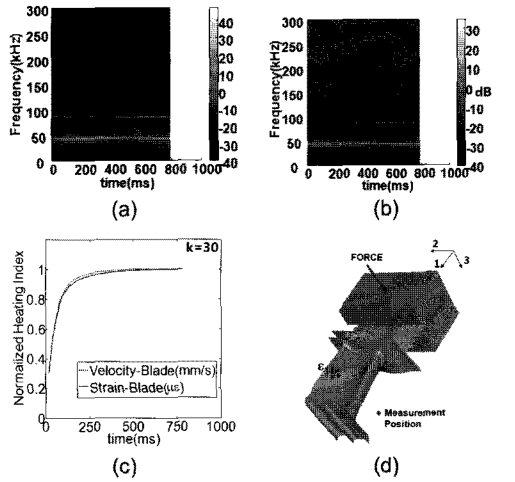

Fig. 3 The comparison of STFTs and heating indexes of the signals obtained from laser vibrometer and strain gauge in the fundamental frequency dominant case. (a) STFT of Velocity measured on blade (b) STFT of strain measured on blade (c) Calculated heating index (d) Measurement position

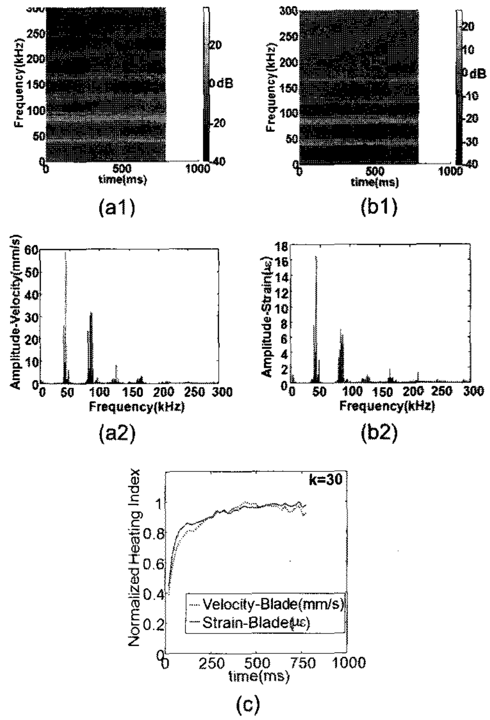

Fig. 4 The comparison of STFTs and heating indexes of the signals obtained from laser vibrometer and strain gauge in the chaotic case. (a1) STFT of velocity measured on blade; (b1) STFT of strain measured on blade (a2) FFT of velocity measured on blade (b2) FFT of strain measured on blade (c) Calculated heating index

FFTs and heating indexes of the signals obtained from laser vibrometer and strain gauge in a chaotic vibration case. Fig. 4(a2) and (b2) show that the excited vibration shows the characteristics of chaotic vibration with harmonics and multiple frequency components around the harmonic frequencies including sidebands and small sub harmonics. As shown in Fig. 4(c), the calculated heating indexes are similar in shape between different sensors though the agreement is poor than the case shown in Fig. 3(c). The frequency components in Fig. 4(a2) and (b2) do not have exactly the same spectra but the overall summation of the different frequency components in a case where the excited vibration has a very rich spectrum give a similar shape of heating index. This result shows that velocity and strain can give an equivalent HI in a chaotic vibration case when measured at the same position.

3.2 The Performance of Microphone for Vibration Monitoring

A microphone can be used as a velocity sensor and it can also provide a cheaper monitoring method than a laser vibrometer. Another advantage of a microphone is that it can provide a non-contacting measurement method which can increase the practicality of thermosonic testing. A 4138 microphone with a diameter of 1/8 inch (3.175 mm) supplied by B&K was used for this study. The microphone has a gain of -2 dB at 140 kHz and then rolls off sharply to -14 dB at 200 kHz[14]. Consequently it could underestimate amplitude of very high frequency components. However, it gives a conservative value of HI and it can be successfully applied in cases where low frequency vibration is dominant. It is required to investigate the sensitivity of the microphone to the position relative to the surface of the test structure. The effect of the distance between the surface of the tip of the acoustic horn and the microphone on the output of the microphone was investigated by using the test setup shown in Fig. 5. The excitation frequency was 40 kHz which is the resonance frequency of the acoustic horn. Fig. 5 shows the microphone output voltage as a function of the distance from the surface of the tip of the acoustic horn to the microphone. The results show that the peak value is seen at the distance of 7.5 mm and then decreases monotonically with little oscillation. This characteristic is similar to the near field effect which can be observed in the amplitude of the axial pressure distribution in the near field of a piston source. These results show that the microphone must be placed at a consistent distance from the test structure in the calibration tests where the threshold value is obtained and real tests because the magnitude of HI calculated in each test is compared with the threshold HI obtained during the calibration test. According to the test results, a distance around 40 mm marked with a circle in Fig. 5 seems to be appropriate because the sensitivity of the microphone to the distance is relatively small. If the microphone is placed too far from the surface of the test structure, the microphone output could be too small to measure the vibration. However, in the case of a large structure, the microphone should be placed further away from the structure because of the

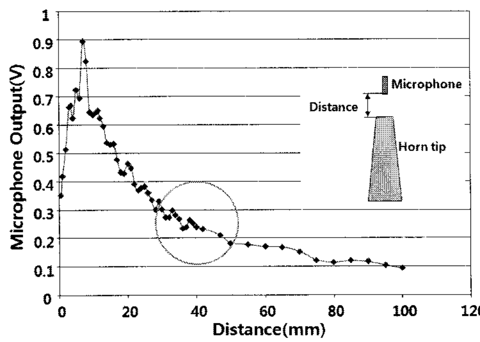

Fig. 5 The characteristic of the microphone; Microphone output voltage vs. distance from the surface of the tip of the acoustic horn

longer near field distance. Fig. 6 shows the comparison of STFTs and heating indexes of the signals obtained from laser vibrometer, strain gauge and microphone in the fundamental frequency dominant case.

The strain gauge on the blade measured a strain component in one direction at the position shown in Fig. 3(d). Fig. 6(a) and(b) show that the excited vibration is dominated by the fundamental frequency component. As shown in Fig. 6(c), the calculated heating indexes are very similar in shape between different sensors. This result shows that the microphone can be used to monitor the vibration achieved in the blade in the fundamental frequency dominant case.

Fig. 7(a), (b), and (c) show a case where the excited vibration is chaotic containing the very rich spectrum of vibration. The measurement positions of the laser vibrometer and strain gauges and the direction of the strain gauges were the same as shown in Fig. 3(d). As shown in Fig. 7(c), the calculated heating indexes are similar in shape between the different sensors. This result shows that velocity, strain and microphone can give equivalent HI when measured at the same position and the microphone can be used to monitor the vibration achieved in the blade in the chaotic vibration dominant case.

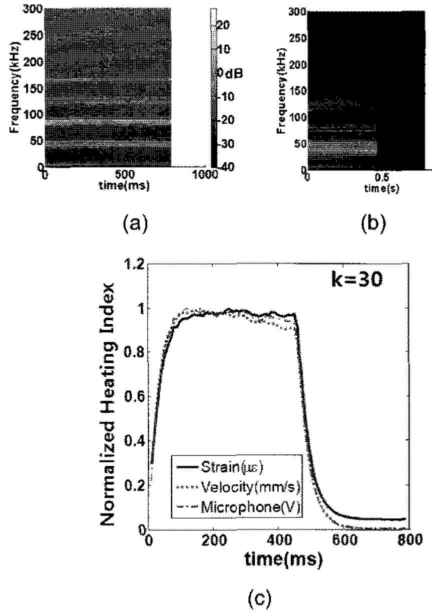

Fig. 7 Schematic diagram of a typical pig used for gas pipeline inspection The comparison of STFTs and heating indexes of the signals obtained from laser vibrometer, strain gauge and microphone in the chaotic case. (a) STFT of Velocity measured on blade (b) STFT of microphone output voltage measured on blade (c) Calculated heating index

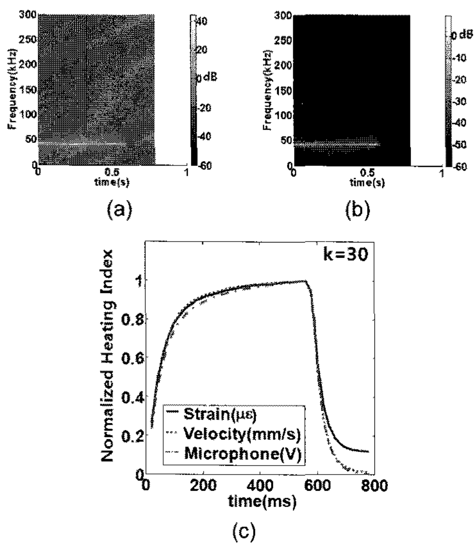

Fig. 6 The comparison of STFTs and heating indexes of the signals obtained from laser vibrometer, strain gauge and microphone in the fundamental frequency dominant case. (a) STFT of Velocity measured on blade (b) STFT of microphone output voltage measured on blade (c) Calculated heating index

4. Conclusions

Vibration monitoring is required for reliable thermosonic testing and a heating index (HI) has been proposed as a criterion indicating whether sufficient vibration is achieved in a tested structure or not. The HI was calculated from different vibration records measured by different sensors and these results were compared in this paper.

Velocity measured by a laser vibrometer and strain provide an equivalent HI when measured at the same position. The microphone can provide a cheaper vibration monitoring device than the laser and the heating index calculated by a microphone signal shows similar characteristics to that calculated from velocity measured by a laser vibrometer. The microphone frequency response shows that it underestimates high frequency components but it is applicable to practical tests because it gives a conservative value of HI.

References

[1] M. Imregun and K. Y. Sanliturk, "Natural frequency and damping changes produced by fatigue cracks," in *Proceedings of the 15th Seminar on Modal Analysis*, Leuven, Belgium, pp. 791-805 (1990)

[2] C. F. Beards, "Structural vibration: analysis and damping," Arnold, London, (1996)

[3] A. P. Bovsunovsky and C. Surace, "Considerations regarding superharmonic vibrations of a cracked beam and the variation in damping caused by the presence of the crack," *Journal of Sound and Vibration*, 288(4-5), pp. 865-886 (2005)

[4] M. Morbidini, "A comparison of the vibration-modulation and thermosonic ndt techniques," Ph. D. thesis, Imperial College, University of London (2007)

[5] M. Morbidini, P. Cawley, T. Barden and D. Almond, "Prediction of the thermosonic signal from fatigue cracks in metals using vibration damping measurements," *Journal of Applied Physics*, 100(10), pp. 1-13 (2006)

[6] C. J. Pye and R. D. Adams, "Heat emission from damaged composite materials and its use in nondestructive testing," *Journal of Physics D-Applied Physics*, 14(5), pp. 927-941 (1981)

[7] P. Duour, M. Morbidini and P. Cawley, "Comparison between a type of vibro-acoustic modulation and damping measurement as NDT techniques," *NDT&E International* 39, pp. 123-131 (2006)

[8] P. Duour, M. Morbidini and P. Cawley, "A study of the vibro-acoustic modulation technique for the detection of cracks in metals," *Journal of the Acoustical Society of America*, 119(3), pp. 1463-1975 (2006)

[9] D. D. Ho, D. S. Hong and J. T. Kim, "Nondestructive evaluation of railway bridge by system identification using field vibration measurement," *Journal of the Korean Society for Nondestructive Testing*, Vol. 30, No. 6, pp. 527-538 (2010)

[10] H. Jeong and D. Barnard, "Measurement of sub-and super harmonic waves at the interfaces of fatigue-cracked CT specimen," *Journal of the Korean Society for Nondestructive Testing*, Vol. 31, No. 1, pp. 527-538 (2011)

[11] X. Y. Han, Z. Zeng, W. Li, M. S. Islam, J. P. Lu, V. Loggins, E. Yitamben, L. D. Favro, G. Newaz and R. L. Thomas, "Acoustic chaos for enhanced detectability of cracks by sonic infrared imaging," *Journal of Applied Physics*, 95(7), pp. 3792-3797 (2004).

[12] M. Rothenfusser and C. Homma, "Acoustic thermography: vibrational modes of cracks and the mechanism of heat generation," *in Review of Progress in Quantitative Nondestructive Evaluation* 24, Vol. 760 of AIP Conference Proceedings, Edited by D. O. Thompson and D. E. Chimenti, American Institute of Physics, Melville, NY, pp. 624-631 (2004)

[13] X. Y. Han, "Frequency dependence of the thermosonic effect," *Review of Scientic Instruments*, 74(1), pp. 414-416 (2003)

[14] Technical Report, B&K, DK-2850 Nrum, Denmark