Session 2C (I) – Thermography

Chairman ***– Dr S Pickering***

14.00 **A comparison of methods used to predict the vibrational energy required for a reliable Thermosonic inspection**

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The vibration excited in a component during a Thermosonic test is non-reproducible and may lead to defects being undetected if sufficient energy is not applied at the defect location. The energy dissipated as heat by a defect is directly related to the frequency and amplitude of the vibration, and this energy can be represented by a single parameter computed from the vibration records obtained in a calibration test. This computed parameter has been shown to correlate linearly with the measured temperature rise from a defect, thus allowing prediction of the minimum vibration level required to detect a defect of a given size. The aim of this work is to compare different measurement methods that may be used to obtain the vibration records required to predict the minimum vibration level for an inspection. In this study, several metallic specimens with a range of crack lengths are inspected using a practical Thermosonic setup, after which the vibration records acquired from the different measurement methods are processed to obtain the single parameter used to represent the vibrational energy excited in the specimens. Results from this work will highlight the relative merits and limitations of the different methods that may be used to predict the vibration levels required for a reliable Thermosonic inspection.

A comparison of methods used to predict the vibrational energy required for a reliable thermosonic inspection

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Abstract

Thermosonics is capable of detecting cracks in several types of components. The component is excited with high-power ultrasonic vibrations, causing cracks to generate heat, which can be detected by an infrared (IR) camera. However, the excitation in a typical thermosonic test is non-reproducible and can lead to cracks being undetected if sufficient vibrational energy is not applied at the crack location. The vibrational energy dissipated as heat at the defect is directly related to the frequency and amplitude of the vibration, and this energy can be represented by a single parameter (Heating Index) computed from the vibration waveform. The Heating Index parameter is useful as it can be used to predict the vibration level required for a reliable thermosonic inspection. The aim of this work is to compare different vibration measuring devices that may be used to capture the vibration waveform required to compute the Heating Index. In this study, an aero engine turbine blade is inspected using a practical thermosonic setup, after which the vibration waveforms acquired from a laser vibrometer, microphone and strain gauge are processed. Results from this work will highlight the relative merits and limitations of these different vibration measuring devices for computing the Heating Index.

1 Introduction

Thermosonics is a non-destructive testing technique (NDT) capable of detecting defects in metallic and non-metallic components (1). In a typical thermosonics test, the component is excited at a single point with ultrasound for less than a second and observed with an infrared camera (1).The excited vibration causes crack faces to rub or clap and generate heat, which is detected by the observing infrared (IR) camera (1). One potential application of thermosonics is for rapid screening of cracks in aero engine components such as turbine blades (2). This application can potentially reduce cleaning and inspection costs associated with the traditional Fluorescent Penetrant Inspection (FPI) (2).

Although thermosonics is capable of detecting defects in several types of components [2,3,4], its reliability remains uncertain [5,6]. The reliability issue mainly concerns the non-reproducibility of the vibration in the component under test, which can lead to cracks being undetected if sufficient vibrational energy is not excited at the defect location. This non-reproducibility of the excitation has been attributed to the non-linearity in the coupling between the exciter (i.e. ultrasonic horn) and the component [7]. If the reliability of the excitation process is fully addressed, this would be a major step in thermosonics becoming an industrial NDT technique for various applications.

Rothenfusser et al. [8] and Morbidini et al. [9] investigated different calibration methods to address this reliability issue. Rothenfusser et al's method involves measuring the thermal response of a material attached to the component during a test, while Morbidini et al's method involves computing a single parameter from the measured vibrational waveform. Nevertheless, for both calibration methods, a threshold is set, and for subsequent tests the response (vibration or thermal) is monitored to determine whether the threshold is exceeded.

This paper is particularly concerned with monitoring the vibrational energy excited in a component, as proposed by Morbidini et al. [9]. Morbidini et al's method involves computing a single parameter called the Heating Index (HI), which can be used to represent vibration level in a test. The HI is useful because of the relationship between the vibration and the heat generated by the crack. However, there are various measuring devices that can used to capture the vibration waveform required to compute the HI. The aim of this work is to compare three vibration measuring devices: laser vibrometer, microphone and strain gauge. In this study, several thermosonics tests were carried out on a cracked aero engine turbine blade, during which the vibration was captured by the three different measuring devices. Finally, the vibration data were processed to obtain the HI for each test. Results from this work will highlight some of the advantages and limitations of the three different methods for computing the HI in turbine blades.

2 Monitoring the vibration

Monitoring the vibration in a component during a thermosonic test can ensure the test has been carried out satisfactorily [9]. This is possible because of the relationship between the vibration at a crack and the resulting crack temperature rise [10]. The basis for this relationship is the structural damping that all materials exhibit when subjected to vibratory load, whereby the vibrational energy is dissipated as heat [11]. This heat causes a temperature rise within the material; however, the highest temperature rise occurs at locations where the heat dissipation is greatest, such as defect locations [12]. This is because of the extra-damping introduced by the presence of the defect. The temperature rise generated by a crack is proportional to the power dissipated by the crack. This power can be described in terms of the vibration loss factor (damping), as shown in Equation 1 [9]:

$$P = 2\pi\eta_{crack} fV \qquad (1)$$

where η_{crack} is the crack loss factor, f is mode vibration frequency and V is the mode strain energy. Morbidini et al. [9] proposed a simpler parameter, called the Heating Index (HI), which can be used to represent the power released by a crack:

$$HI(\tau) = \int_0^{\tau} e^{k(t-\tau)} EI(t)\,dt \qquad \text{where } EI = \sum_i f_i u_i^2 \quad \text{..(2)}$$

where EI represents the instantaneous power released at the crack, f_i is the ith frequency component and u_i the amplitude of the ith frequency component. The typical vibration measured in a thermosonic test is composed of harmonics and fractions of the exciter resonant frequency. Therefore, computation of EI requires summation of all the frequency components present in the vibration. The exponential function in Equation 2 accounts for the crack depth and thermal response of the material [9]. This weighting function is important because the measured temperature rise at the surface is a sum of the contributions of the heat released over the crack depth [9]. The HI is useful because it requires no knowledge of the crack damping, which can be difficult to obtain or measure and also importantly, the HI correlates linearly with the measured temperature rise from a crack [9]. This linear relationship enables prediction of the vibration level (i.e. threshold) required to generate the minimum detectable temperature rise from a crack. This threshold can then be used in subsequent tests to ensure a test has been carried out satisfactorily.

Fundamentally, the temperature rise generated by a crack is directly related to the frequency and amplitude square of the vibration (see Equation 2). The frequency determines the heating rate, while the amplitude determines the amount of energy available for dissipation as heat [9]. Therefore, the method used to capture the vibration required to compute the HI is of paramount importance. The use of a strain gauge and microphone have been reported in different studies [9,13], while a laser vibrometer has been mentioned as a viable alternative [9]. The aim of this work is to compare these three vibration measurement methods for computing the HI for aero engine turbine blades in an industrial setting. The next section describes the experimental work carried out to facilitate this comparison study.

3 Methodology

3.1 Experimental setup

The experimental setup used in this study is shown in Figure 1. This study involved the use of a single turbine blade, which was clamped at its base with a steel holder. The ultrasonic exciter was a Sonotronic welding system, comprising a 400W, 40 kHz ultrasonic generator, UST600-40 piezoelectric transducer and a titanium horn. The horn tip was spring-loaded to the base of the blade holder via a piece of electrical insulating tape. The electrical tape was used to prevent surface damage to the blade holder and also avoid the horn tip from slipping across the surface of the blade holder. In this study, the horn load in all tests was varied between 42 N and 163 N (maximum) to ensure different amounts of heat was generated by the crack. This was to ensure a wide range of HI and temperature rise values in different tests. The IR camera shown in Figure 1 was a Cedip Silver 660M (cooled), with a detector array of 640 x 512 pixels, temperature sensitivity of 20 mK and a frame rate of up to 100 Hz.

Also shown in Figure 1 are the vibration measuring devices i.e. laser vibrometer, microphone and strain gauge. The strain gauge (KYOWA KFG 120) used was 5 mm in length, 120.4 ohm resistance and had a gage factor of 2.09. For practical reasons, the strain gauge was permanently bonded to the blade holder as opposed to the blade. This was primarily because of the complexity of the geometry around crack location. The strain gauge was connected to a calibrated FYLDE FE-537-SGA strain gauge amplifier with a 3dB frequency response of up to 100 kHz and gain of up to × 3000. The microphone employed in this study was a G.R.A.S Type 40DP pressure microphone (omni-directional) with a 3.175 mm diameter and a frequency response of up to 140 kHz at 2dB. The microphone is a non-contact vibration measuring device, which measures the acoustic pressure over the surface of a vibrating object. In this study, the microphone was placed at a distance of no more than 20 mm from the crack location.

The laser vibrometer (LV) is also a non-contact vibration measuring device. A laser beam is pointed at the surface of the vibrating component, and the amplitude and frequency of the vibration are extracted from the interference of the reflected laser and a reference laser beam [14]. The LV system used in this study comprised a Polytec OFV-3001 controller (velocity decoder, 1 MHz bandwidth) and OFV-3003 sensor head. This LV system was a single-point, out-of-plane vibrometer, which only measures the axial velocity component (i.e. in the direction of the laser beam). All three vibration measuring devices were connected to a 4-channel Lecroy WaveRunner oscilloscope, programmed to capture vibration for one second. The highest frequency component typically seen in the vibration waveform obtained in a thermosonic test is approximately 300 kHz. Therefore, the sampling rate for the oscilloscope was set to 1 MHz, which was over three times the highest frequency of interest. The oscilloscope was controlled via National Instrument software (LABVIEW) for simultaneous operation with the ultrasonic horn generator and IR camera.

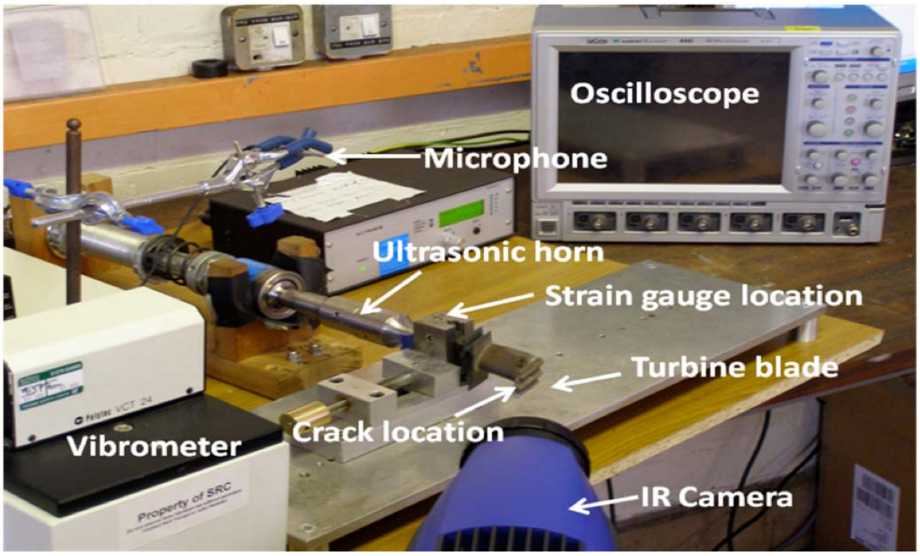


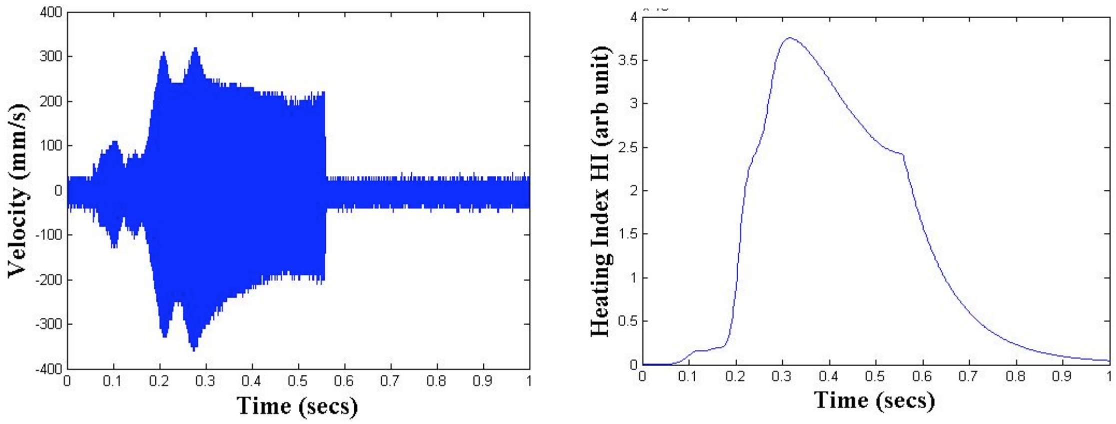
Figure 1 Experimental setup

3.2 *Thermosonic tests*

A thermosonic test involved three operations: blade excitation, data capture (thermal images and vibration) and data processing. Prior to the start of a test, at least 20 background images of the blade were captured and then averaged. Next, the excitation was turned on for 0.5 seconds while the IR camera and oscilloscope simultaneously captured images and vibration for 1 second respectively. The images were processed in MATLAB using background subtraction (subtraction of averaged background image from excitation images) to obtain the crack temperature rise profiles over the 1 second test duration. The vibration data were also processed in MATLAB to compute the HI profile. First, the EI (see Equation 2) was computed as a function of time. This involved using the Short Time Fourier Transform (STFT) algorithm to decompose the transient vibration waveforms into its different frequency components in 2 ms segments and then multiplying the frequency components by the square of their respective amplitudes. The 'k' parameter in the exponential weighting function (see Equation 2) was estimated using the measured temperature rise profiles of several tests [9]. An average value of 10 was obtained for 'k', which represented the decay rate for the crack, and hence, used in the computation of the HI for all tests. Figure 2 (a) and (b) show an example of a vibration waveform obtained in a test and the computed HI profile for the vibration. The maximum HI represents the time when the crack is most likely to be detected (i.e. achieve maximum temperature rise). Therefore, for the HI to be valid, the maximum HI should be proportional to the maximum measured temperature rise [9].

Two sets of tests (Set A and Set B) comprising of 24 and 23 tests were completed on the blade respectively. The difference between the two sets of tests was the position of the microphone relative to the crack. For Set A, the crack generated a detectable thermosonic signal (i.e. temperature rise) in all 24 tests, while for Set B, the crack generated a thermosonic signal in all but one test. In this study, the LV was classed as the benchmark measuring method because of its advantage in measuring the vibration at the defect location, as opposed to the acoustic pressure measured by the microphone or the strain gauge measurement at a different location. Therefore, a strong linear correlation between the HI and measured temperature rise was expected for the LV data.

Initially, the HI was computed using frequency components up to the upper frequency response limit of the devices i.e. LV (up to 300 kHz), microphone (up to 140 kHz) and strain gauge (up to 100 kHz). However, the HI was recomputed, but now using only frequency components up to the 100 kHz (maximum for strain gauge). This was necessary in order to determine the effect of the higher frequency components (i.e. between 100 kHz and 300 kHz) on the results (i.e. correlation of HI and measured temperature rise). The results for both sets of HI computations are presented in the results section (Section 4).



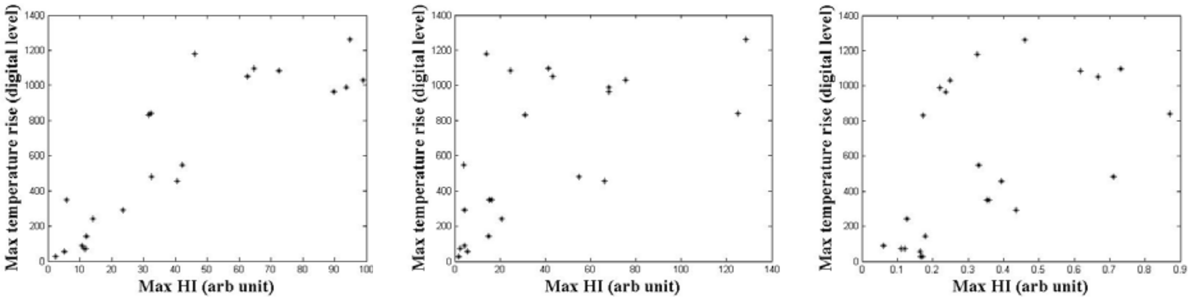
(a) (b)

Figure 2 Example of (a) vibration waveform (laser vibrometer) (b) computed Heating Index (HI) profile

4 Results

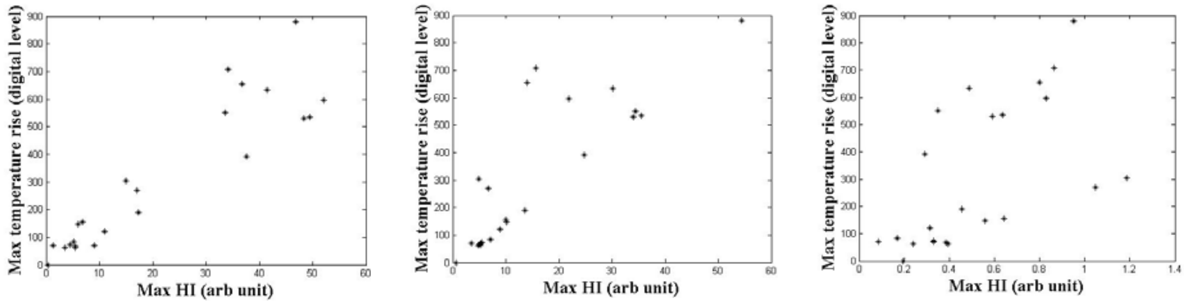
Figure 3 and Figure 4 respectively show the plot of the maximum temperature rise against the maximum HI for the two sets of thermosonic tests (i.e. Set A and Set B). The HI in these figures was computed using the maximum measurable frequency components of the respective devices. The LV data in Figure 3 (a) and Figure 4 (a) both show a linear trend with little scatter in the data, whereas for the strain gauge data in Figure 3 (c) and Figure 4 (c), more scatter can be observed in the data with no apparent linear trend. The result for the microphone data is mixed, where no linear relationship can be observed for Set A in Figure 3 (b), whilst for Set B in Figure 4 (b), a linear trend is evident.

The strength of linear correlation between the temperature rise and HI was quantified using the square of the normalised correlation coefficient r_{xy}^2 [15]. This statistical quantity is useful as it gives the proportion of variance of the temperature rise that can be predicted from the HI. Table 1 shows the calculated correlation coefficient for Set A and Set B. The correlation coefficients in Set B were higher than that of Set A for all three methods, although the biggest change was seen for the microphone, confirming the mixed result observed earlier. For both Set A and Set B, the LV had the highest correlation coefficient at 0.77 and 0.85 respectively, whilst the strain gauge had the lowest correlation coefficients. At present, there are relatively few studies similar to the study carried out in this work, limiting any extensive comparison of the correlation achieved. However, one study that can be used for comparison is Morbidini et al's HI study on similar-sized turbine blades [13]. The degree of linear correlation seen in Morbidini et al's work compares favourably with the results obtained in this study.



(a) Laser vibrometer (b) Microphone (c) Strain gauge

Figure 3 Plot of maximum temperature rise vs. maximum HI for Set A (24 tests) (a) Laser vibrometer (up to 300kHz) (b) Microphone (up to 140 kHz) (c) Strain gauge (up to 100 kHz)

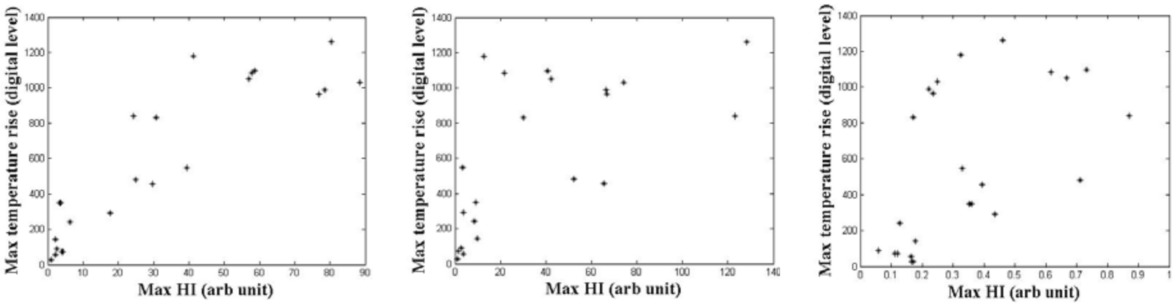


(a) Laser vibrometer (b) Microphone (c) Strain gauge

Figure 4 Plot of maximum temperature rise vs. maximum HI for Set B (23 tests) (a) Laser vibrometer (up to 300 kHz) (b) Microphone (up to 140 kHz) (c) Strain gauge (up to 100 kHz)

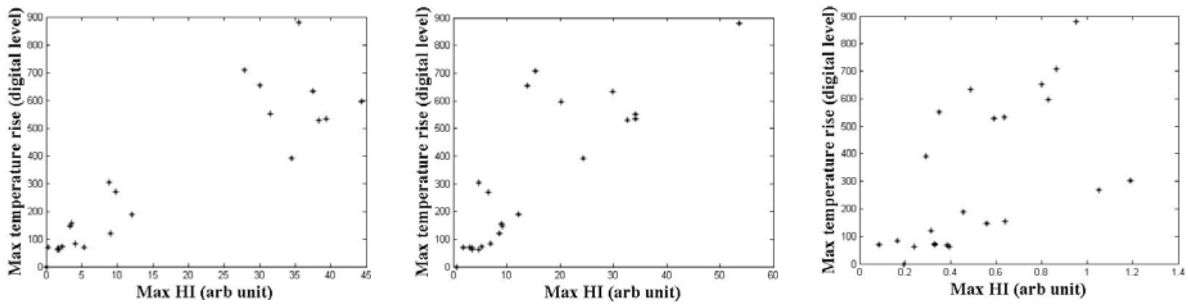
Table 1. Normalised correlation coefficient for Set A (24 tests) and Set B (23 tests), using the maximum measurable frequency components of the respective vibration measuring methods. Laser vibrometer (up to 300 kHz), microphone (up to 140 kHz) and strain gauge (up to 100 kHz)

Correlation coefficient r_{xy}^2	Laser vibrometer	Microphone	Strain gauge
Set A (24 tests)	0.77	0.43	0.30
Set B (23 tests)	0.84	0.70	0.36



(a) Laser vibrometer (b) Microphone (c) Strain gauge

Figure 5 Plot of maximum temperature rise vs. maximum HI for Set A, using frequency components up to only 100 kHz (a) Laser vibrometer (b) Microphone (c) Strain gauge



(a) Laser vibrometer (b) Microphone (c) Strain gauge

Figure 6 Plot of maximum temperature rise vs. maximum HI for Set B, using frequency components up to only 100 kHz a) Laser vibrometer (b) Microphone (c) Strain gauge

Figure 5 and Figure 6 show the results of Set A and Set B for the three methods when using only frequency components up to 100 kHz. Comparing these results with the results in Figure 3 & Figure 4, there appears to be no obvious difference in the degree of linear correlation. This was confirmed with the new normalised correlation coefficients (see Table 2), which showed only a marginal change from the coefficients in Table 1. This suggests that frequency components above 100 kHz did not contribute significantly to the computed HI or perhaps to the heat generated by the crack. Nevertheless, for cracks where higher frequency components contribute to the heat generated, a higher bandwidth device such as a LV has an advantage over the microphone and strain gauge.

Table 2. Normalised correlation coefficient (squared) for Set A (24 tests) and Set B (23 tests), using frequency components up to only 100 kHz to compute the HI

Correlation coefficient r_{xy}^2 (up to 100 kHz only)	Laser vibrometer	Microphone	Strain gauge
Set A (24 tests)	0.80	0.45	0.30
Set B (23 tests)	0.83	0.71	0.36

5 Discussion

The linear correlation between the HI and temperature rise for the LV was shown to be higher than that of the microphone and strain gauge. This was expected at the start of this study, primarily because of the LV's capability of measuring the local vibration at crack. The poor correlation for the strain gauge can be mainly attributed to the strain gauge location. Fundamentally, the measured temperature rise is proportional to the vibration at the defect. This is because the vibration is very complex, and the vibration characteristics (i.e. frequency and amplitude) excited at one point on a component may differ from the characteristics at a different point. This was the case with strain gauge attached to the blade holder rather than at the crack location, although this was mainly because of the complex geometry around the crack location. In addition, it was important to also understand the effect of placing the strain gauge in a different location from the crack. This is because, in a real industrial environment, bonding and removal of strain gauges from individual turbine blades might be considered not only inappropriate, but also cumbersome. Nevertheless, a strain gauge is still a useful method if can be placed around the defect location, as demonstrated in Morbidini et al's HI study on rectangular metal bars [(9)].

Although the non-contact characteristic of the microphone can be considered an advantage, the measured vibration closely resembles an average of the vibration of the whole component rather than the desired vibration at the defect location. In addition, the microphone is susceptible to noise generated either by the equipment (during a test) around the microphone or to background noise, which for an industrial environment must be considered as likely. This bulk vibration is not surprising given the omni-directional response of the microphone. One of the consequences of the bulk vibration measurement is that frequency components that do not directly contribute to the heating may be used in the computation of the HI. This may be the one of the reasons for the mixed and at best, modest linear correlation achieved by the microphone in this work. Another possible reason for the mixed microphone result (i.e. between Set A and B) was the change in microphone position, which was the difference between the two sets of tests. Further work is planned to study the effect of microphone position and also on the use of directional microphones for measuring the vibration at locations of interest.

Given that the LV was used to measure the vibration at the crack location, it would have been reasonable to expect a higher correlation than that achieved in this work, perhaps between 0.9 and 1. This degree of correlation will enable a more accurate prediction of the temperature rise from the HI. Two possible reasons why a higher degree of correlation was not achieved by the LV could be: assumption made in the formulation of the HI and the limitation of the LV in measuring only out-of-plane vibrations. Firstly, the assumption made in formulation of the HI is that damping is constant at all frequencies and amplitude for small cracks [(9)]. However, this is not strictly the case, as highlighted by Morbidini et al. [(9)]. This means that the correlation achieved may be lower than ideal (i.e. < 0.9) even when the vibration is measured at the defect location. Secondly, the limitation of only out-of-plane vibration measurements by the LV means that any other vibration modes (e.g. in-plane or torsional) that contribute to the crack heating would not be used in the computation of the HI. This again may have contributed to the less than ideal correlation coefficient achieved by the LV in this work.

The LV has some disadvantages, which are not pertinent to the microphone or strain gauge. These disadvantages include non-suitability to dark surfaces (i.e. surfaces with poor reflectivity), bulkiness of the system and its high cost. In order to get good measurements using a LV (i.e. high signal-to-noise ratio), the reflectivity of the component is crucial. Dark or black surfaces, which absorb the laser light, can lead to poor measurements (i.e. low signal-to-noise ratio); therefore, the potential effect of the surface condition of turbine blades must be considered. This is because the harsh environment (i.e. high temperatures) these components operate in can lead to an unsuitable surface for laser vibrometry measurements. The cost of a LV system can be a disadvantage, particularly if several LV systems are required for different inspections are to be carried out simultaneously. Hence, the possibility of using a strain gauge or better still a non-contacting device such as a microphone becomes a more attractive option.

6 Conclusions

This study has outlined some of the advantages and disadvantages of using a laser vibrometer, microphone and strain gauge to capture the vibration required to compute the HI in turbine blades. This is important as the method used to capture the vibration will determine the accuracy of the computed HI and hence the reliability of the calibration procedure. The LV was shown to produce the best results because of its capability of measuring the vibration at the defect location. From this study, two important conclusions can be drawn: first, it is important that the vibration captured closely represents the vibration characteristics at the defect location and second, the vibration method used must be robust to account for factors inherent to an industrial setting as opposed to a controlled laboratory environment (e.g. component geometry, surface condition of component and background noise).

This study mainly focused on the calibration aspect of the HI, where the minimum HI (i.e. vibration level) required to reliably detect a defect is determined (9). However, post-calibration (i.e. real inspection scenario), issues such as multiple and unknown crack positions on the blades, and the industrial conditions (i.e. environmental) become important considerations. These various considerations will be investigated to determine the most reliable and practical vibration measuring method for computing the HI, during calibration and also during the real inspection. The outcome of the investigation will be reported at future NDT conferences.

Acknowledgements

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