Temperature and Load Effects on Acoustic Emission Signals for Structural Health Monitoring Applications

Maurits J.G.N. Boon, Dimitrios Zarouchas, Marcias Martinez, Daniel Gagar, Benediicus Rinze, Peter Foote

TEMPERATURE AND LOAD EFFECTS ON ACOUSTIC EMISSION SIGNALS FOR STRUCTURAL HEALTH MONITORING APPLICATIONS

Maurits J.G.N. Boon[1], Dimitrios Zarouchas[1,], Marcias Martinez[1], Daniel Gagar[2], Rinze Benedictus[1], Peter Foote[2]*

[1]*Structural Integrity & Composites Group, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, the Netherlands*
[2]*Enhanced Composites and Structures Group, School of Applied Sciences, Cranfield University, Bedfordshire, UK MK430AL*

[*]Corresponding author: d.zarouchas@tudelft.nl

ABSTRACT

The present study focuses on understanding the effect of load and temperature on Acoustic Emission (AE) signal propagation in an Aluminium 2024-T3 panel. In addition, the ability of an AE system to locate damage under these operational and environmental conditions was evaluated. The work was performed in two stages. In stage one, the wave group velocities of guided Lamb waves were measured for a range of temperatures from -40 ˚C to +70 ˚C. At each temperature level, six different static loads were applied that ranged from 0 MPa to 250 MPa in increments of 50 MPa. It was observed that the variation of temperature and load altered the wave group velocities, which were verified with analytical solutions found in the literature. In stage two, a representative AE signal, simulating a fracture phenomenon was emitted from a randomly selected point. Using values of wave velocity measured in stage one, the location of the representative AE signal under these conditions was calculated and errors were determined. It was found that the location algorithm was not sensitive to wave group velocities changes due to temperature and loads, thus providing an accurate location of the source within 1cm for 93% of the cases studied.

KEYWORDS : *Structural Health Monitoring, Acoustic Emission, Environmental and Operational Conditions.*

INTRODUCTION

Aircraft structures operate under variable Environmental and Operational Conditions (EOC), sustaining fatigue loads and extreme temperature variations. In order to ensure structural integrity, aircraft structures are subjected to regular maintenance programs. However, these programs involve complicated time-consuming operations impacting the maintenance costs [1]. Therefore, the aerospace industry addresses an increasing demand for lower operational and maintenance costs by pointing to Structural Health Monitoring (SHM) strategies that can assess the structural integrity during service. SHM is defined as "the process of acquiring and analyzing data from on-board sensors to evaluate the health of a structure" [2, page 4]. Modern SHM systems consist of network of sensors incorporating active and passive techniques, which can be used on, and offline. i.e. Guided Lamb Waves (GLW) and Acoustic Emission (AE) [3].

GLW are commonly used as an active technique for online damage detection. Several studies have been performed to evaluate and verify the effectiveness of the GLW under realistic conditions and it was found that the EOC, i.e. temperature and load variations affect the GLW response [4]. The main reason is that the elastic properties of the structures, the piezoelectric properties of the sensors and the connections between the sensors and the structure change under different environmental and operational conditions [5]. Dodson and Inman developed an analytical model that calculates

dispersion curves for different temperatures, and it was shown, that wave speed changes due to temperature alteration and is frequency dependent [6].
In addition, Gandhi et al. [7] studied the effect of bi-axially stressed plates and their effects on GLW. In [7], the effects of loads were only considered in a uniaxial test specimen. However, it was stated that the directional effects of multi-axial loads could be superimposed on each other. A main conclusion of this study was that the phase velocity increases linearly with increasing stress levels and has a sinusoidal dependence with the angle in between the wave propagation and the applied load.

AE is one of the most known techniques for online passive monitoring of structures. The AE system has been successfully used for damage location in complex structures [8] and its capability for damage identification has been proven in coupons and realistic structural specimens [8]. However, advanced signal processing of the recorded AE signals is required, which is one of the main obstacles to widespread implementation of AE in the aerospace and wind energy industry [9]. Nevertheless, the combination of these two techniques in a hybrid (active-passive) SHM system can potentially provide reliable results.

Similar to GLW, it is expected that the EOC will affect the AE signals and therefore change the signal characteristics. Thus, it is crucial to investigate the effect and the dependency of the AE signals on these EOC, so as to be able to revise all the needed parameters for improving the damage location and identification process. Therefore, this paper focuses on understanding the effect of load and temperature on the AE signal propagation and the ability of the AE system to locate damage. The work was performed in two stages. In stage one, an active approach was employed where the wave speeds of lamb waves were measured for different temperatures and loads. In the second stage, the measured wave speeds were used as AE system input parameters in order to evaluate the accuracy of its localization algorithm, which is based on triangulation, using time difference of arrival measurements obtained with a fixed detection threshold criterion. In most AE studies a constant wave velocity is used throughout the experiment for localization regardless of changes in wave velocities due to EOC. Typical values of 5400 m/s are standard in the literature for aluminium structures. In more complex structures in situ pencil lead break tests, which also assume constant wave velocities are used to calibrate the system for localization of AE sources. However, few studies have been conducted on the impact of EOC on these wave speeds.

The paper is structured as following: the second section presents the structural material, the instrumentation, the set-up and the experimental campaign. The third section describes the experimental results in two different subsections. The first subsection highlights the wave speeds for the different EOC while the second subsection emphasizes the impact of the EOC on the damage localization process. Finally, the fourth section presents the conclusions and recommendations for future work.

1 MATERIALS, INSTRUMENTATION, SET-UP AND EXPERIMENTAL CAMPAIGN

The specimen was a 650 mm by 600 mm Aluminium 2024-T3 plate with a thickness of 2.1 mm. An AMSY-6, 8 channel AE system provided by Vallen Systems Inc. [10] was employed with eight non-permanently attached VS150-M sensors. These sensors have been evaluated by the manufacturer for sensitivity (-70dB re 1V/microbar to -80dB re 1V/microbar) for a frequency range from 100-450 kHz and allowable operational temperature range from -50 to 100˚C. An MTS 500 kN fatigue testing machine was used to apply the load and a temperature chamber was built around the hydraulic actuation system. Figure 1 illustrates the experimental set-up and the position of the sensors.

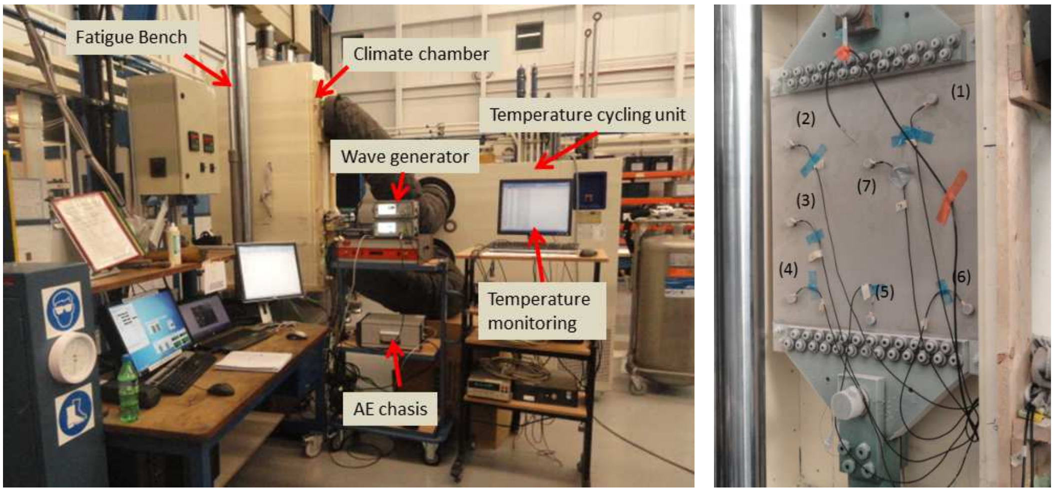

Figure 1 : The experimental set-up and the layout of the sensors on the test panel.

In stage one of our study, the wave speeds of GLW were measured for a range of temperatures from -40 ˚C to +70 ˚C in nine steps. At each temperature level, six different loads were applied ranging from 0 MPa to 250 MPa in increments of 50 MPa. For this task, six sensors (sensor one to six depicted in Figure 1) were attached to the surface of the plate using a silicon-based glue. Lead pencil breaks were performed to check the mounting of the sensors as specified in ASTM E976-10 standard [11]. Sensor 1, in the upper right location as depicted in Figure 1, was used to emit the lamb waves while Sensors 2 to 6 recorded the transmitted signal. This active sensor was connected to a signal-generator (Agilent 33522B) and an amplifier, which was configured to generate Lamb waves using a Hanning window with central frequencies of 150 KHz and 300 KHz. Furthermore, a threshold for AE signal was set to 41dB for this stage of the tests. In order to ensure repeatability of the measurements five signals at each frequency were emitted for each 'temperature-load' combination. This resulted in a database of 2700 signals with their corresponding wave speeds.

In stage two of our study, several lead pencil breaks (second type of lamb wave signal) were performed in a randomly selected point on the aluminium plate to simulate an AE source (e.g. crack growth). The six sensors were used to record the corresponding pencil break signals. In order to obtain a representative AE signal of the pencil break and thus avoid lack of consistency from one pencil break test to another, ten lead pencil breaks were recorded for which an average representative AE signal was obtained. The waveform and the corresponding FFT of the signal are shown in Figure 2. Sensor 7, shown in Figure 1, was used to actuate the representative AE signal at the same location where the lead pencil breaks were performed using a signal-generator. The representative AE signal was emitted in a similar way as in stage one and also for the same 'temperature-load' combinations. In this stage of the test campaign the AE threshold was reduced to approximately 31dB in order to be able to measure the AE signals that have decreased amplitude. However, this decrease in AE threshold comes at the cost of introducing more noise into the captured signals. The AE system's localization module was used to locate the source. For the localization analysis and for each load-temperature combination, two wave speeds were used as inputs to the AE localization module (one at 25˚C while the second one at the temperature under study, in both cases with the same load condition). In our study all load-temperature combinations are compared to a baseline lamb wave velocity obtained at '25 ˚C, 0 MPa'.

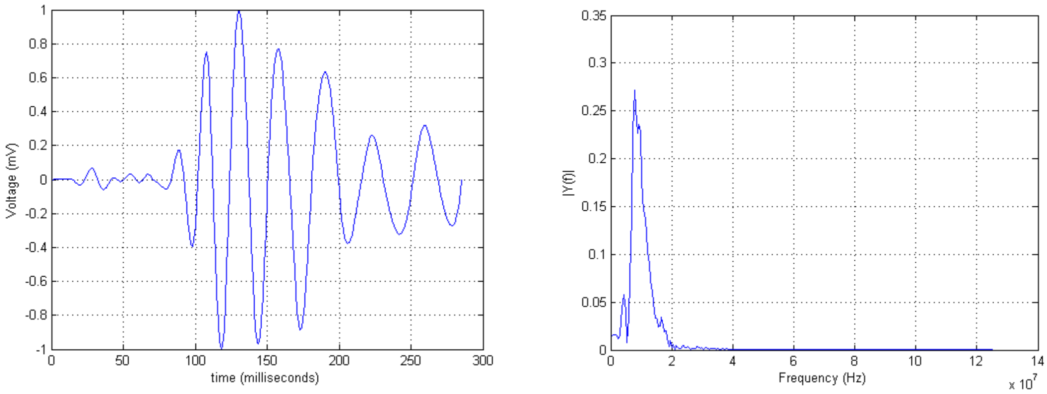

Figure 2 : The representative AE signal waveform and its corresponding FFT.

2 RESULTS

This section discusses the results of the experimental campaign as it was outlined in the previous section. In the first stage, the wave group velocities of a Hanning window signal at 150 and 300kHz were emitted from sensor 1 and recorded at sensors 2 through 6 (see Figure 1) at different temperatures and load combinations.

Figure 3a depicts the influence of temperature on the wave group velocities as measured in the range of -40 ^{0}C to 70 ^{0}C. Accordingly, Figure 3b depicts the influence of the temperature on the change of the wave group velocity with reference to the wave velocity measured at 70 ^{0}C. The analytical curves are derived from the methodology presented by Dodson and Inman [6]. Our results match the analytical results. It is important to note in Figure 3a, that the measured values at 150 and 300 kHz follow the same slope as the analytical dispersion curves. In addition, the absolute group velocity difference of approximately 300 m/s is only within an error of 6% from the analytical solution. This 6% difference can be attributed to the appropriate selection of an AE threshold. A low AE threshold translates into too much noise in the acquired signals at different location, while a high AE threshold translates into incorrect group velocity measurements. Dodson and Inman also observed that the wave speed change due to temperature is frequency dependent. However, in the case of AE where the emitted signals are in the range of 0.1-0.45 MHz this effect is negligible. This is shown in Figure 3b where the results of the two Hanning window signals overlap and match with the analytical change in the group velocity (analytical dispersion curves in Figure 3b).

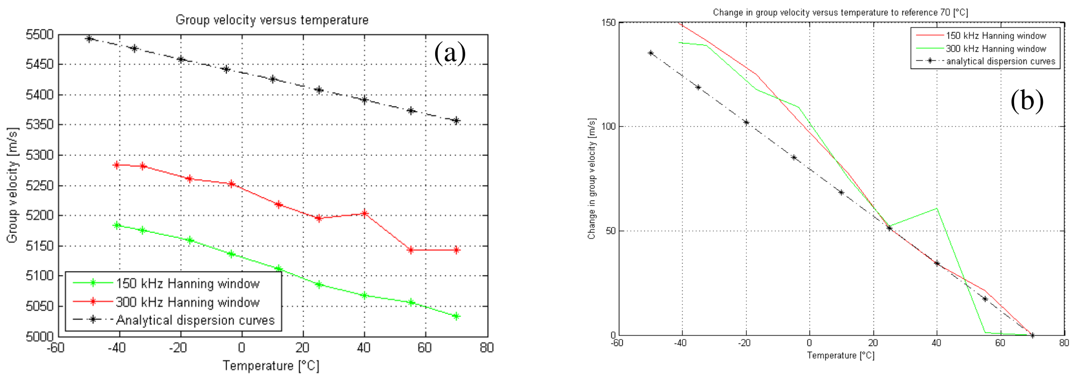

Figure 3 : The influence of temperature on wave group velocities. a) Absolute group velocity; b) change in group velocity relative to values at 70^{0}C.

Figure 4a illustrates the influence of the load on the wave group velocities taking into account the different sensor paths at a specific applied load cases (0 through 250 MPa). The five different paths considered are sensors 1-2, 1-3, 1-4, 1-5 and 1-6 as shown in Figure 4b. Each point in Figure 4a, consist of the change in group velocity, due to a 150kHz Hanning window emitted from sensor one at different loads. In order to exclude the effect of temperature and only show the effect of loads, a reference to a zero load case condition at each temperature was taken. All the changes in group velocities were obtained at 9 different temperatures values (from -40 to 70^{0}C). The depicted points in Figure 4a, represent the average change in group velocity for all the 9 different temperatures.

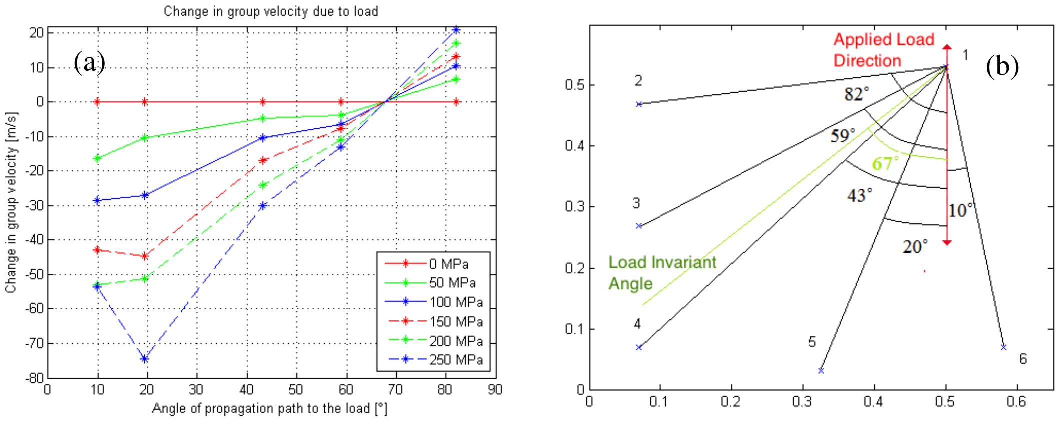

Figure 4 : The influence of load on wave group velocities. a) results of change in group velocity due to load; b) schematic indicating angles of each pair with respect to applied load.

A load invariant point shown Figure 4a at 67 degrees, represents a 67-degree angle with respect to the applied load as shown in Figure 4b. At this invariant point the wave velocity is independent of load. This observation is in a good agreement with the analytical solution presented in [7] were a 63-degree load invariant point is analytically obtained for Al-6061-T6, which is different from our 2024-T3 panel.

The second stage of our study was to determine the effects of the correct input velocity for temperature and loads on the ability of the AE system to localize the representative AE signal (an averaged lead pencil break signal). Tables 1-3 highlight the representative results of the wave group velocities for three temperatures and three applied load levels for a Hanning window signal at 150 kHz. These velocities shown in Table 1-3, were used as inputs to the AE localization module.

Table 1 : Wave group velocities at -40 ^{0}C.

Stress (MPa) @ -40 ^{0}C	Wave Group Velocity (m/s)		
	Minimum	Average	Maximum
0	-	5115,416	-
150	5072,906	5100,454	5128,001
250	5063,480	5099,298	5135,116

Table 2 : Wave group velocities at 25 ^{0}C.

Stress (MPa) @ 25 ^{0}C	Wave Group Velocity (m/s)		
	Minimum	Average	Maximum
0	-	5018,865	-
150	4976,355	5003,903	5031,450
250	4966,929	5002,747	5038,565

Table 3 : Wave group velocities at 70 ^{0}C.

Stress (MPa) @ 70 ^{0}C	Wave Group Velocity (m/s)		
	Minimum	Average	Maximum
0	-	4952,022	-
150	4909,512	4937,06	4964,607
250	4900,086	4965,904	4971,722

The selection of a random point as an emitting source, serves to understand the effect of the load path on the localization process when the angles with respect to the load direction between the source and the sensors are unknown. In order to facilitate this, three different velocities are used per pair; minimum, average and maximum as presented in Tables 1-3. These three velocities were derived from the results presented in Figure 4a.

Within this paper only the results of the 'temperature-load' of Tables 1-3 will be shown due to the enormous amount of data generated during the study. Figure 5 illustrates the sensors' and source's location as well as the position of the AE signal and the Hanning window as calculated from the localization module of the AE system. The calculated locations were within 1 cm to the actual location of the AE source for 39 out of 42 signals, regardless of the velocity used from Tables 1-3 as input parameter. The localization module of the AE requires a known velocity in order to locate the source of damage as previously stated. The primary challenge in this study is that the wave speed is no longer a constant due to the effect that temperature has on the material and thus on the wave speed. In addition, it is also known that loads create an anisotropic behaviour on the material, which has a consequence on the wave velocity. As such the wave speed due to the effects of loads also varies per sensor path. However, despite these many effects of temperature and loads on wave speed as seen in tables 1-3, the results seem to indicate that these effects have little influence on the ability of an AE system to localize the source of the damage as shown in Figure 5. This figure depicts all of the calculated locations as function of the Hanning window and representative AE input signals at the different input wave velocities (Max, Avg. and Min) found in Tables 1-3. It is important to note that 93% of all results lie on top of each other and are within an error of 1 cm from the true location.

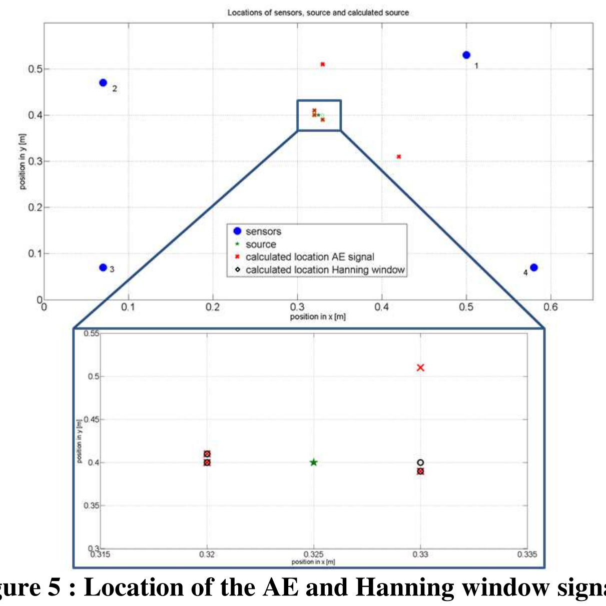

Figure 5 : Location of the AE and Hanning window signals.

CONCLUSIONS

In this study the effects of combined load and temperature effects on AE signals have been considered. The experimental verification on the EOCs match those already found in the literature. The frequency dependence effect of temperature on the group velocity for AE signals has been shown to be negligible. In addition, this study demonstrated that even though changes in group velocity due to EOC can be in the order of 160 m/s these effects have very little consequence on the ability of an AE system to localize the damage. Future studies are required for more complex AE signals and structures. Furthermore, it is recommended to consider the development of a new trigger criterion in order to minimize the effect of AE threshold on group velocity measurements, since a new trigger algorithm could lead to an optimal accuracy in localization.

REFERENCES

[1] W.J. Staszewski, C. Boller, G.R. Tomlinson. Health monitoring of aerospace structures. Wiley, 2004, ISBN: 0470843403.

[2] SAE –Aerospace Recommended Practices – Guidelines for Implementation of Structural Health Monitoring of Fixed Wing Aircraft ARP6461

[3] W.M. Ostachowicz. Guided waves in structures for SHM. Wiley, 2014, ISBN: 978047097839.

[4] A. J. Croxford, P. D. Wilcox, G. Konstantinidis and B. W. Drinkwater. Strategies for overcoming the effect of temperature on guided wave structural health monitoring. *Health Monitoring of Structural and Biological Systems,* 2007.

[5] G. Konstantinidis, B. Drinkwater and P. Wilcox. The temperature stability of guided wave structural health monitoring systems. *Smart Materials and Structures,* pp. 15: 967-976, 2006.

[6] J. Dodson and D. Inman. Thermal sensitivity of Lamb waves for structural health monitoring applications. *Ultrasonics,* pp. 677-685, 2013.

[7] N. Gandhi, J. E. Michaels and S. J. Lee. Acoustoelastic Lamb wave propagation in biaxially stressed plate. *Journal Acoustical Society America,* pp. 1284-1293, 2012.

[8] D. Gagar, M. Martinez, M. Yanishevski, B. Rocha, J. McFeat, P. Foote and P. Irving. Detecting and locating fatigue cracks in a complex wing-box structures using the acoustic emission technique: a verification study, Stanford, CA: DEStech Publication, Inc., 2013.

[9] D. Zarouchas and D. van Hemelrijck. Monitoring the integrity of wind turbine blades subcompoments using advanced signal processing techniques, Stanford, CA: DEStech Publication, Inc., 2013.

[10] Vallen, AMSY 6, The Acoustic Emission System," 2010. [Online]. Available: http://www.vallen.de/sites/default/files/pdf/amsy6-brochure.pdf. [retrieved 10-04-2014].

[11] ASTM E 976-10. Standard guide for determining the reproducibility of acoustic emission sensor response.