IMPROVED SOURCE LOCATION METHODS FOR PRESSURE VESSELS

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ABSTRACT

In this work, results of an acoustic emission source location study using both linear and planar location strategies are presented. The study was performed on a submarine steel gas flask with pencil-lead breaks used as artificial acoustic emission sources. Plate wave propagation theory is used to analyze the effects of dispersive Lamb wave modes on source location accuracy. Narrow-band filtering techniques are used in conjunction with different sensor arrays of 2, 4, 6, and 8 sensors to improve source location accuracy. By combining these two factors, location accuracy of 1% of the length of the flask and 3% of its circumference can be achieved. The results are presented in the form of 2-D accuracy color maps. The total average error in source location for each one of the sensor configurations is calculated. Finally, a summary of the results is presented in the form of a table indicating the advantages and disadvantages of every sensor configuration studied.

INTRODUCTION

Acoustic emission (AE) source location in an extended structure, such as a pressure vessel, is subject to inaccuracies caused by two factors: the location method, i.e. linear or planar, and by the ratio of the acoustic signal frequency to the thickness of the structure under study. When AE signals received by two sensors are used to locate an AE source, i.e. linear location methods, the arrival times of the signal produced by an AE source will define a hyperbola with its foci located on the position of the sensors. Thus, the position of the AE source could be at any point along this hyperbola [1]. To avoid this problem, planar location methods must be used; that is, signals from a minimum of three sensors have to be used to calculate the position of the AE source [2].

The ratio of the AE signal wavelength (\(\lambda\)) to the vessel wall thickness (T) determines the nature of the wave propagation phenomena in the structure. In the case of a wavelength much smaller than the wall thickness, \(\lambda/T \ll 1\), the stress waves produced by the AE source will propagate in the form of bulk longitudinal, bulk shear, and surface waves, with constant velocities. When the wavelength is comparable to the wall thickness, \(\lambda/T \approx 1\), the situation becomes more complex. In this case, the stress waves produced by the AE source will propagate as multiple Lamb (plate) wave modes, each with a particular velocity and attenuation depending on its frequency; that is, the modes will be dispersive [3]. The immediate effect in the location method is, depending on the position of the AE source in relation to each of the sensors, that different wave modes, traveling with different speeds, may trigger different sensors.

In the case of very large structures, such as large storage tanks or civil structures, the problem of multiple wave mode propagation does not have an effect on AE source location due to the long paths that the wave modes have to travel to reach the sensors. However, in the case of AE inspection of relatively smaller pressure vessels, such as compressed gas cylinders, it is important to precisely locate AE sources. The solution of the problem becomes even more critical when these compressed gas cylinders are located inside large structures such as submarines and other ships. In submarines, for
instance, the cylinders are located behind bulkheads and the inspector must be certain of the location of any AE indications, as removal of the bulkheads is very time consuming and expensive. Therefore, it is important to study the effect of multiple wave mode propagation in these pressure vessels in order to improve the accuracy of source location techniques.

EXPERIMENTAL SETUP

In order to study the effect of Lamb wave mode propagation in AE source location, a steel gas flask was removed from a Trident nuclear submarine. The cylindrical shell is 4.57 m (180") long, with an external diameter of 509 mm (20"), and spherical end caps. The flask was instrumented with eight PAC AE R15I sensors (with a peak resonance frequency at 150 kHz) as shown in Fig. 1. Figure 1(a) presents an unwrapped view of the flask with the approximate positions of the sensors on its surface and Fig. 1(b) shows the approximate position of the sensors around the circumference of the flask.

The wall thickness of the cylindrical shell of the flask was measured using an ultrasonic thickness gauge and was found to be 31 mm (1.2"). The sensors were connected to a PAC DiSP 52 channel AE system. According to the US Navy requirements, the maximum permissible error in AE source location is 127 mm (5") in the circumferential and axial directions. Accordingly, the entire surface of the flask was divided into a rectangular grid of 127 x 127 mm (5" x 5").

A series of five pencil-lead breaks (PLB) using a 2H/0.3 mm mechanical pencil with a Neilsen shoe, were performed at the center of every square on the grid. Files containing the amplitudes, arrival times, and waveforms of each PLB were stored on the DiSP AE system. Later, the data were processed using PAC’s source location software in order to calculate the position of every PLB. The five readouts obtained for each PLB position were averaged and the result was assigned to the PLB location. The difference between the real and the measured locations of the PLB was calculated and then plotted on 2D-color maps of the extended surface of the flask.

LINEAR LOCATION

The first case analyzed is that of linear location, in which the sensors are located along the axis of the flask. In this case, sensors 2 and 6 were used to calculate the positions of the PLB. In order to demonstrate the effect of the different wave modes propagating on the flask as a result of a simulated source, the averaged differences in arrival times (ΔT) from the five PLB on each square of the grid were used to calculate the position of the simulated sources. For this purpose, a set of two values of the wave velocity was selected: 3.10 mm/μs (122 x 10^3 in/s) and 4.88 mm/μs (192 x 10^3 in/sec), which correspond to the a₀ and s₁ Lamb wave modes. These values were selected based on the group velocity dispersion curve for Lamb waves propagating along a steel plate with a thickness of 31 mm in the frequency range of the sensors used or 150 kHz. This group velocity dispersion curve is shown in Fig. 2.

Figure 3 presents accuracy maps of PLB location obtained using linear location. These maps present the error point by point on the surface of the flask. The x-axis represents the flask coordinates along the axial direction and the y-axis represents the flask coordinates along the circumferential direction. Each square on the error map, corresponding to a 13 cm square on the real flask, has been colored according to the difference between the real and calculated PLB for that particular point. Red and yellow tones indicate higher differences while blue tones represent small differences. The color bars situated by the maps indicate the numerical equivalence of the error in source location.
Figures 3(a) and 3(b) clearly show the influence of wave-mode velocity choice on linear location and confirm the hypothesis of higher velocity modes arriving at nearby sensors, while the lower velocity modes are the ones that trigger the sensors furthest away. When the $a_0$ wave mode group velocity (3.10 mm/µs) is used to calculate the positions of the sources, the areas close to sensors, located at the edges of the cylindrical shell, present an error in location as high as 76 cm (30”). The points located towards the center of the flask present errors below 25 cm (10”). When the $s_1$ (4.88 mm/µs) wave mode velocity is used in the calculation, the large errors in location shift towards points in the center of the cylindrical shell, while the areas close to the sensors present errors below 13 cm.

Fig. 1. Position of the AE emission sensors on the Trident submarine steel gas flask. (a) Extended surface of the flask. (b) Position of the sensors around the circumference of the flask.

Fig. 2. Lamb group velocity dispersion curves for a 31 mm (1.2”) thick steel plate.
In order to reduce the inaccuracy of source location due to the effect of Lamb waves, we have investigated the technique of narrow-band filtering. Previous studies at PAC have shown that by applying narrow-band digital filters to signals from simulated AE sources in a gas flask, accuracy in source location can be improved [4,5]. The dispersion curve shown in Fig. 2 indicates that in the frequency band of interest, the $a_0$, $a_1$, $s_0$ and $s_2$ modes have very similar group velocities, around 3.10 mm/µs, and the $s_1$ mode has a maximum group velocity of 4.88 mm/µs. However, the $s_1$ mode propagates with low amplitude when compared to that of the $a_0$ mode. Therefore, if the signals from the AE source are narrow-band filtered in the frequency range of interest (before being processed by the AE system), the amplitude of the $s_1$ mode will not be large enough to trigger the sensors while the $a_0$ mode will. An accuracy map generated using narrow-band filtered signals and a group velocity of 3.10 mm/µs is presented in Fig. 4. In this case, the errors observed along the flask are below 13 cm for all the points.

Although linear location combined with narrow-band filtering can achieve good location accuracy, its main drawback is the fact that it only provides the source position along the longitudinal axis between two sensors. In order to obtain the axial and circumferential position of an AE source on the flask, planar location methods must be used.
In this work, three different configurations for planar location were studied. The first configuration was a “F-placement” using sensors 1, 2, 4, and 5 positioned at coordinates (0,5), (31.5,5), (15.75, 175), and (47.25,175), respectively, according to Fig. 1(a) coordinates (unit in inches). As in the case of linear location, the signals were narrow-band filtered. The results obtained with the F-placement configuration are shown in Figs. 5(a) and 5(b).

![Accuracy map for planar source location on a cylindrical gas flask using an array of four sensors. (a) Along the circumference of the flask. (b) Along the axis of the flask.](image)

Figure 5(a) presents the accuracy map for source location in the circumferential direction of the flask. It is clear that two bands of high inaccuracy, where the error can be as high as 76 cm, appear on the surface of the flask. These bands are located symmetrically on opposite sides of a band of very low inaccuracy, where the error is lower than 13 cm, and which runs from the (0,5) to the (47.25, 175) position on the extended flask surface. The accuracy map of source location along the axial direction is shown in Fig. 5(b). In this case, the accuracy is very good and the error is below 13 cm in nearly all the positions of the simulated AE sources. A practical way of estimating the overall accuracy of the sensor configuration is to calculate the total average error (TAE) in both directions, circumferential and axial. In the case of the F-placement with 4 sensors, the TAE is 15.5 cm (6.11") and 4.30 cm (1.69") in the circumferential and axial directions, respectively. It is important to mention that the F-placement is an ideal configuration for a length-to-circumference ratio approximately equal to 1. In the present case, the length to circumference ratio is 2.77.

The second configuration studied was an array of six (6) sensors, with sensors 1 to 6 located according to Fig. 1. In this case, the PLB positions were calculated using PAC’s arbitrary sensor configuration software. This software selects the three first arrival times, regardless of the sensor position, and calculates the intersection point of the three hyperbolae defined by the three sets of two-sensor combination. Figure 6(a) presents the accuracy map for source location along the circumference of the flask and Fig. 6(b) the corresponding one for the source location along the axis of the flask. The circumferential error decreases substantially when compared to the previous case. Except for a section on the center of the flask, the location error is less than 13 cm in the circumferential direction. For the axial direction, the map indicates errors below 13 cm in almost every point of the flask. The TAE in this case is 5.23 cm (2.06") for the circumferential direction and 4.55 cm (1.79") for the axial direction.
The last configuration analyzed is the array of eight sensors positioned as indicated in Fig. 1. Arbitrary location software was used for source location and Figs. 7(a) and 7(b) show the resulting accuracy maps for the axial and the longitudinal directions, respectively. Figure 7(a) shows no spots with errors above 13 cm, the same is observed in Fig. 7(b). The TAE is 4.04 cm (1.59”) and 4.50 cm (1.77”) for the circumferential and longitudinal direction, respectively.
CONCLUSIONS

The results obtained in this study clearly demonstrate that the propagation of Lamb wave modes in plate-like structures has a serious impact on the accuracy of AE source location. The use of narrow-band filtering eliminates this problem by filtering out low amplitude higher velocity Lamb wave modes. In addition, if very accurate source location is required, such as in the case of the Trident nuclear submarine compressed gas cylinders, planar source location methods have to be implemented during inspection. Also, other factors have to be taken into account when a source location strategy is implemented, such as cost, availability of AE channels, number of cylinders to inspect, and access to the whole surface of the cylinders. Finally, Table 1 summarizes the practical advantages and disadvantages of using different source location strategies.

Table 1. Comparison between advantages and disadvantages of linear and planar source location strategies

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<th>Sensor number</th>
<th>Total Average Error (TAE) [in]</th>
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<th>Disadvantages</th>
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*These percentages were calculated assuming PAC DiSP 52 channel system.

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REFERENCES