AE MONITORING OF CRYOGENIC PROPELLANT TANK

YOSHIHIRO MIZUTANI\(^1\), TAKAYUKI SHIMODA\(^1\), JIANMEI HE\(^1\),
YOSHIKI MORINO\(^1\) and SOUICHI MIZUTANI\(^2\)

\(^1\) National Space Development Agency of Japan, Sengen, Tsukuba, Ibaraki 305-8505, Japan
\(^2\) Advanced Engineering Services Co., Ltd., Takezono, Tsukuba, Ibaraki 305-0032, Japan

Abstract

In order to study the cryogenic properties of CFRP tank, we conducted pressurization test of a small filament-wound (FW) tank at cryogenic temperatures. We first investigated the orientation dependence of acoustic emission (AE) signals at both room temperature and LN\(_2\) temperature by using artificial source. Lamb-mode dispersive AE signals were monitored in the CFRP tank. In tests at room temperature, we used A\(_0\)-mode Lamb waves for source location. However A\(_0\)-mode Lamb waves at several angles were hardly observed at LN\(_2\) temperature. In this study S\(_0\)-mode were used for source location. 60% of tank wall was damaged before this test, and many AE signals are generated from this damaged zone. We developed a new method to separate AE signals generated at damaged zone utilizing signal duration. When the AEs from monitoring (or non-damaged) zone are evaluated, detail source location is possible using arrival time differences of AEs. Next we conducted pressurization test of the CFRP tank at LN\(_2\) temperature. About 660 AE events were visually extracted from detected 2800 AE hits. We then investigated the duration of AE events and 100 AE events are evaluated as AE generated at non-damaged zone. Source locations of 7 AE events are obtained from the area where leakage was identified by snoop test conducted after the pressurization test.

Keywords: CFRP tank, Lamb wave, cryogenic pressure test, source location

Introduction

It is essential to develop a cryogenic CFRP tank in order to realize the drastic weight reduction needed for reusable launch vehicle (RLV) [1]. In order to study the cryogenic properties of such CFRP tanks, we conducted pressurization test of a small filament-wound (FW) tank [2] and monitored micro-cracks, which possibly grow to provide leak path of the propellant. We used acoustic emission technique for micro-crack monitoring. Several studies regarding AE monitoring of FRP tank were reported [3 - 6], but the study under cryogenic temperature is limited. We conducted 4-channel AE monitoring during cryogenic pressurization test of a CFRP tank. We first compared characteristics of AE signals detected at room temperature and LN\(_2\) temperature by using artificial AE source. After that, we constructed source location method, which utilizes the signal duration and arrival time difference of AE signals. The proposed source location method is applied to the AEs detected during a cryogenic pressurization test of the CFRP tank. Estimated source location is compared to the leak point, which was found by snoop test conducted after the pressurization test.

CFRP Tank and Experimental Setup

A 300-mm-diameter CFRP tank was fabricated using filament-winding method. The prepreg tape was BESFIGHT IM600#133 with 3.5-mm width. The tank shape was 320-mm long cylin-
der with isotensoid dome at both sides (see Fig. 2). The tape was wound on a plaster mandrel and cured in autoclave at 180°C for 2 hours. The layer construction of the cylindrical part is \([\pm 30^\circ, 90^\circ_2, \pm 30^\circ, 90^\circ_2, \pm 30^\circ]\). The thickness of the cylinder is 1.2 mm.

We conducted water-proof testing and cryogenic low-level pressurization tests on this tank in the past two years. After these tests, some areas were damaged and we patched additional prepreg sheets on these areas from the inner side of the tank wall. Epoxy resin adhesive (HYSOL EA9394) was also pasted on the serious damage zone on the outside surface to prevent leakages. The photo images of damaged and non-damaged zones are shown in Fig. 2. In this study, we investigated cryogenic characteristics of the non-damaged zone. We call non-damaged zone as “monitoring zone” in this paper.

Figure 3 shows the schematic illustration of the CFRP tank used and experimental setup for cryogenic pressurization. Nickel-steel flanges are attached to both sides of the tank. Five pipes are connected to the top flange. Three of the five pipes are connected to pressure gauge, liquid level meter and safety valve. The other two pipes are used for filling and exhausting liquid nitrogen. These two pipes are also utilized for controlling the internal pressure during pressurization tests.

Liquid level meter output was connected to the monitor. The meter roughly indicates the liquid nitrogen level. The pressure gauge was connected to a digitizer and the data was digitized at 1-Hz sampling rate. Digitized data was fed to the computer. Strain and temperature of the outer surface were also measured, but we will not discuss these data here.

We used four 150-kHz resonant-type AE sensors (PAC, R15) in the test. These sensors were mounted on the corners of a 200-mm square on CFRP tank as shown in Fig. 3. Outputs of the sensors were amplified 40 dB and digitized at an interval of 250 ns with 4096 points at 16-bit amplitude resolution, and fed to a PC for analysis. We set the threshold level at 65 dB (1.78 mV at sensor output) during the pressurization test.
Fig. 2. Appearances of the non-damaged and damaged zones. Epoxy resin was pasted on the damaged zone. In this study, we evaluated non-damaged (monitoring) zone only.

Fig. 3. Schematic illustration of the CFRP tank and experimental setup. 4-channel AE monitoring used 40-dB preamplifiers and Mistras system (PAC).
Procedure for AE Monitoring

We first measured the orientation dependence of AE signals propagating in CFRP tank at both room temperature and LN₂ temperature. We filled water or LN₂ into the tank at atmospheric pressure. As shown in Fig. 4, pulses were generated by a compression-type piezoelectric transducer (PAC, PICO, 4-mm diameter, nominal resonant frequency 0.45 MHz) and detected by an R15 AE sensor mounted on circles of 100-mm radius at angle \( \theta \). Examples of detected AEs are shown in Fig. 5. Left figure represents AEs at room temperature and right at LN₂ temperature. Small amplitude S₀-mode Lamb waves followed by large amplitude A₀-mode are observed at room temperature, but A₀-mode Lamb waves are hardly observed for several direction (\( \theta = 150°, 180° \) in Fig.5) at LN₂ temperature. In a previous paper, Mizutani et al. [4] used wavelet coefficients of a specific frequency of A₀-Lamb waves for source location in room temperature tests, but this method cannot be applied to the cryogenic tests. Though some difficulties were expected (large source location error due to fast velocity of AEs, arrival time reading error due to small S/N ratio, etc.), we decided to use the arrival times of initial S₀-mode Lamb AEs in this study. The orientation dependence of the S₀-mode velocity was determined by dividing the inter-transducer distance (100 mm) by the first-peak arrival time. Measured orientation dependence is shown in Fig. 6. We fitted data by a quadratic equation, \( V(\theta) = 7.97 \times 10^{-2} \theta^2 - 1.49 \times 10 \theta + 6.40 \times 10^3 \) (m/s), shown by a solid line in Fig. 6 and used this function for the source location.

Next, we examined the accuracy of the source location method by using two types of artificial sources. Figure 7 shows top view and development of the tank. Monitoring area surrounded by 4 sensors is shown in tan color. About 60 % of the tank wall was patched by additional CFRP prepreg sheets from inside. The area which epoxy resin adhesive (HYSOL EA9394) was pasted from the outer surface is also indicated in the figure (shown in green color). We artificially generated AEs by pencil-lead breaks and a PICO sensor in the monitoring zone and damaged zone. Source location is shown by the symbol “X” in the figure.
Fig. 5 Examples of Lamb wave AEs detected at room temperature (left) and LN₂ temperature (right) as a function of the propagation direction $\theta$. $A_0$-mode Lamb waves are hardly observed in some directions at LN₂ temperature.
Fig. 6  Orientation dependence of $S_0$-Lamb velocities in the tank. Solid line indicates fitted curve used for the source location.

Fig. 7  Top view and development of the tank with AE sensor locations. The monitoring zone is shown in the figure by tan color. Source locations are indicated by symbol “X”. Two types of artificial sources are shown in top right.

Figure 8 shows detected AE signals induced at $(x,y) = (50,50)$ and $(620,100)$ by a sensor (left) and pencil-lead breaks (right). It is noted that arrival-time differences of AEs induced at damaged zone $(620,100)$ is at the same level as AEs induced at the monitoring zone $(50, 50)$. 
Fig. 8 Detected AEs induced at the monitoring zone (x,y)=(50,50) and damaged zone (620, 100) due to artificial source. Two types of artificial sources were used.

Therefore, we have to separate AEs generated at the damaged zone before the source location is conducted. Duration of the largest amplitude AEs for all events are investigated. The result is shown in Tables 1 and 2. Definition of duration is shown in Fig. 9. We defined the threshold as
50% of the maximum value. Duration of AEs generated far from the monitoring zone is much longer than those for AEs from the monitoring zone. It is also noted that the duration of AEs generated by the PICO sensor (possibly generated high frequency AEs) and by pencil-lead breaks (generated low frequency AEs) is similar. This is due to the narrow-band AE sensor working as a band-pass filter. We set the threshold duration as 200 µs and try to separate AEs from the damaged zone. The result is shown in Table 1 and 2. Colored areas in the tables indicate the long duration AE. This clearly shows that AEs generated far from the monitoring area can be separated by utilizing duration.

<table>
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<tr>
<th>Table 1</th>
<th>Duration of AEs produced by transducer</th>
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Fig. 9. Procedure for determining AE signal duration.

When detected AE is determined as AE from the monitoring zone, detail source location is conducted by the following steps; 1) Monitoring area is divided into 4 areas as shown in Fig. 10. 2) The channel that detected the largest AE is searched. The area that involves the maximum channel is selected. 3) One size larger area is defined as a scanning area of virtual source. (shown by dark rectangular in Fig. 9.) 4) Determine the arrival times of detected AEs (S₀-mode arrival time). 5) Determine the source location by minimizing the differences of the measured arrival times and the arrival time differences computed by moving a virtual source position in the scanning area in 1.0-mm step. Orientation dependence of the S₀-mode velocities (Fig. 6) is incorporated.
Detailed results of source location are shown in Fig. 11 for transducer (left) and pencil-lead break (right). A square indicates an original position and a circle the located source position. The source locations agree well with the input positions. The maximum error of 12.1 mm and average error of 6.2 mm were obtained for the transducer sources. For the pencil-lead break sources, the maximum error of 18.0 mm and average error of 9.2 mm were obtained.

Fig. 10. Algorithm for source location. Virtual source is moved in 1-mm step. Arrival time is theoretically calculated by using the fitted curve shown in Fig. 6.

Fig. 11. Comparison of input location (■) and source location (●) of transducer (left) and pencil lead break (right) on the tank wall.
Fig. 12. The time history of an inner pressure and the cumulative AE counts. The timing of AE occurrence in area 1 is indicated by the blue arrow symbol.

Fig. 13. Overlapping of source location result (indicated by symbol “●”) and leak point (“×”) at area 1.

**Cryogenic Pressurization Test**

The tank was filled with liquid nitrogen under atmospheric pressure. After the filling, we closed the valve and kept it for 5 minutes. The tank was chilled down to LN2 temperature and boiling of LN2 stopped. After that, we started AE monitoring and the tank was pressurized by gaseous N2 to 2.0 MPa. Figure 12 shows the pressure history and AE counts. When the inner pressure reached 1.0 MPa, the pressure was held for 60 seconds. Pressurization was stopped at 2.0 MPa when a serious leakage from the damaged zone occurred. After the cryogenic pressurization test, we conducted snoop test by using soapsuds for identifying the leak points. Several leak points were observed in the damaged zone (x = 300 to 850 mm) and doom parts. Only one leak point was found near the monitoring area at (x,y) = (-20,90) on a wrinkle. (shown by symbol “×” in Fig. 13).
Fig. 14. Detected AEs located at area 1. Arrival time differences were used for detailed source location.

Each AE sensor detected about 2800 AEs. After the test, we visually extracted 663 AEs due to fracture (event), separating them from noise AEs and continuous AEs due to leakage. 123 AE are estimated to be the AEs generated within the monitoring zone by the zone location method explained previously. The time history of AE event and AEs in the monitoring zone are also shown in Fig. 12. An example of detected AEs from the monitoring zone is shown in Fig. 14. Detail source location is estimated for 9 AEs that were found to be in area 1. Source location results are shown in Fig. 13. Seven of the 9 AEs are located near the leak point. The timing of these 9 AEs are shown in Fig. 12 by arrows. It is noted that most AEs were generated at low pressure levels (<1.0 MPa) and this result shows that micro-cracks were produced at low stress levels under cryogenic condition at wrinkled parts.

Conclusion

AE monitoring was conducted during cryogenic pressurization test of a CFRP tank. Before the test, we investigated characteristics of AEs in the CFRP tank using artificial source and develop source location method. The results are summarized below.

1) \( A_0 \)-mode Lamb waves were hardly observed at several directions at LN\(_2\) temperature and could not be used for source location.
2) Duration of AE signals produced at sources far from monitoring zone became longer. AE signals from non-monitoring zone can be separated by using signal duration.
3) Virtual source scanning method is used for source location. The source locations of transducer inputs were determined with the average error of 6.2 mm. Pencil-lead break sources were located within 9.2 mm on average.
4) 7 AE events monitored at low inner pressure levels are located near the leak point on the wrinkle on the tank. Micro-cracks were possibly produced at low stress levels at cryogenic temperature.
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References

References