Leak Source Beam-forming Location of Spacecraft in Orbit Based on Dispersion Characteristics of Lamb Wave

Lei Qi1,2,*, Yaoqi Feng1, Lichen Sun1, Xi Li3, Tao Liao1, Yu Zhang2 and Xiaobo Rui2

1Beijing Institute of Spacecraft Environment Engineering, Beijing, China
2State Key Laboratory of Precision Measurement Technology and Instrument, Tianjin University, Tianjin, China
3China Academy of Launch Vehicle Technology, Beijing, China

*Corresponding author email: qilei@tju.edu.cn

Abstract. In recent years, the number of space debris is increasing rapidly, threatening the safety of spacecraft. More and more spacecraft are at risk of colliding with space debris, which may cause air leakages on the sealed container of spacecraft. This is a huge danger for spacecraft and astronauts. In this paper, a leak source location method based on beam-forming and dispersion characteristics of Lamb wave is proposed. The ‘L’ shaped sensor array with 8 acoustic emission sensors is used to collect the Lamb waves. Due to the dispersion characteristics, a 10 kHz narrow band pass filter is used firstly to process the signals. And then with a priori knowledge of guided-mode frequency dispersion curves of Lamb waves, the corresponding propagation speeds of waves are determined to obtain the time delay matrixes. By the delay-and-sum beam-forming algorithm, the leak source can be directed. The experiment result shows that the accuracy rate of the leak location is more than 90% evaluated by location error less than 5°.

Keywords: Leak location; Beam forming; Spacecraft; Lamb wave.

1. Introduction

With the increasing of human space activities, the amount of space debris is increasing rapidly. More and more spacecraft are at risk of colliding with space debris [1-4]. Once the debris collides with the spacecraft, it may break through the spacecraft and cause gas leak, threatening the life safety of astronauts. Thus a new method is need to solve the problem of leak location in the complex stiffened plate structure of spacecraft. From 2004, Holland [5] of Iowa University has carried out researches on acoustic array sensing technology to determine gas leak on the container of the Space Station. In the research, two 64-element sensor arrays were utilized to position the leak source. Because of large number of data samples, this method is a time and financial consuming task. Due to this reason, this approach is less than ideal for real time processing on the ISS. As a consequence, it is not practical [6]. G.C. McLaskey [7] firstly applied the beam forming techniques to the method of acoustic emission for damage detections. The method is performed on a steel concrete bridge in the study and is based on Rayleigh wave theory instead of Lamb wave theory. And the wave velocity shows no dispersion in mediums of their experiments. Tian He [8] researches near-field beam forming method based on Lamb wave theory and tests this method in a thin plate. Lead break acoustic emission signals are applied in the experiments and the time difference of arrival (TDOA) techniques is used. But the variable phase speeds of the continuous signals lead the TDOA method lack reliability and the dispersion characteristic of Lamb waves are not taken into consideration.
The method proposed in this paper concentrated on the study of dispersion curves of Lamb waves. Signals, of which the frequency components were 190-200 KHz and its corresponding phase speed 1732 m/s, were chosen to acquire the time delay matrixes. Once the time delay matrixes were given, beam-power-versus-azimuth curves can be drawn, from which the best estimate of the direction of the source was determined. When two or more sensor arrays are combined, the source can be located by triangulation.

2. Related Terminologies

2.1. Delay-and-sum Beam Former

Beamforming is a signal processing technique for orientation that requires the use of sensor arrays\[^{[9]}\] As shown in Figure 1, a set of sensor arrays located at positions \( p_n \). Sensors spatially sample the signal field at locations \( p_n \): \( n = 0, 1, 2, \ldots, N \), where \( p_0 \) represents the position of the reference element. This yields a set of signals that denote by the vector \( F(t, p_n) \), which is shown in Eq. (1).

![Figure 1. Demonstration of beam forming](image)

$$F(t, p_n) = \begin{bmatrix} f(t, p_0) \\ f(t, p_1) \\ f(t, p_2) \\ \vdots \\ f(t, p_N) \end{bmatrix}$$ (1)

When the distance between signal source and sensor array is far bigger than the size of the array, the model conforms to the far-field assumption. The signal waves are considered to propagate along parallel paths and the time delay between each array element signal and the reference array element signal is determined by the array geometry parameters and wave velocity. The geometrical parameters of the array are known, so the signal delay is only related to the direction of arrival of the signal, which is assumed to be \( \theta \). And the dotted lines in Figure 1 illustrate the relative distance \( d_n \), \( \theta \) under assumed azimuthal direction of arrival \( \theta \). In this case, if inputs from each sensor are shifted rightly in time, the signals will be aligned\[^{[10]}\]. As shown in Eq. (2), inputs from the sensor elements are shifted in time and summed under assumed azimuthal direction of arrival \( \theta \), and \( g(t, \theta) \) will be gotten.

$$g(t, \theta) = \sum_{n=0}^{N} f(t + \tau_{n, \theta}, p_n) + f(t, p_0)$$ (2)

Where \( \tau_{n, \theta} \) denotes the time delays of array element \( n \) under the assumed azimuthal direction of arrival. Upon the geometry of the sensor array being confirmed, the time delays of array elements depend on the propagation speed of signals and the assumed azimuthal direction of arrival in Eq. (3), where \( v \) is the propagation speed of the incoming wave.

$$\tau_{n, \theta} = \frac{d_{n, \theta}}{v}$$ (3)
By steering azimuths over the range from 0° to 90° with 1° spacing, beam-power \( B(\theta) \) defined by Eq. (4) gets its maximum value ideally if the assumed azimuthal direction of arrival corresponds to the actual direction of arrival. And it is illustrated in Eq. (5), where \( \theta_s \) represents the estimated direction of arrival.

\[
B(\theta) = \int g^2(t, \theta) \, dt
\]  

(4)

\[
B(\theta_s) = \max(B(\theta))
\]  

(5)

2.2. Dispersion Curves of Lamb Wave

In the experiment of this paper, the thin plate was used as the research object. Ultrasonic guided waves will propagate through them. Compared with bulk waves, they introduce boundary conditions. Lamb wave is a kind of guided wave in a uniform isotropic free boundary plate. There is no limit stress in the up and down direction of the plate. Using the potential function analysis method, the frequency equation of the Lamb wave can be obtained \[^{[11]}\] :

- Symmetric mode:
  \[
  \frac{\tan(qh)}{q} + \frac{4k^2 p \tan(ph)}{(q^2 - k^2)^2} = 0
  \]  

(6)

- Anti-symmetric mode:
  \[
  q \tan(qh) + \frac{(q^2 - k^2)^2 \tan(ph)}{4k^2 p} = 0
  \]  

(7)

Where three variables \( p^2 = \frac{c_t^2 - k^2}{c_t} \), \( q^2 = \frac{c_s^2 - k^2}{c_s} \) and \( h = \frac{d}{2} \) are defined; \( c_t \) and \( c_s \) denote the propagation speeds of longitudinal and transverse waves, respectively; \( k \) is the wave number and \( \omega \) is the wave frequency; \( d \) means the plate thickness.

By solving the above Rayleigh–Lamb equations, the relationship between Lamb wave phase velocity, frequency and plate thickness can be obtained. Due to the multi-mode characteristics of Lamb waves, there are multiple modes for the received signal, including symmetric (S\( \text{h} \), S\( \text{i} \),..., S\( \text{n} \)) and antisymmetric (A\( \text{h} \), A\( \text{i} \),..., A\( \text{n} \)) modes. Combined with the dispersion curve, the wave speed at any frequency and thickness can be obtained, which is critical for the positioning of the signal.

3. Experiment and Discussion

3.1. Experimental Platform Setup

The experiment system, as shown in Figure2, consists of three parts—the aluminium alloy test plate, the leak simulation system and the leak signals acquisition system.

The aluminium alloy plate, which is the same as the hulk of the spacecraft, is 1 m×1 m in diameter, and 2 mm thick. A hole, 1mm in diameter, is drilled at the center of the plate. Equipped with the vacuum simulation system, the hole simulates the air leakage on the ISS. Several lines were drawn on the plate to indicate the array position.

The leak simulation system acted as evacuation device consists of the vacuum-to-plate adapter, exhaust pipe, vacuum pump and the vacuum meter. After putting the adapter under the hole of the experimental plate, turn on the valve and wait until the adapter is attached tightly to the plate. Adjust the valve according to the indicated value of the vacuum meter.
Figure 2. The experimental setup
The leak signals acquisition system, is made up by AE sensor array, customized fixture for the sensor array, pre-amplifiers and AE instrument. The frequency response of the sensor is from 100 kHz to 400 kHz. The 8 sensors numbered from 0 to 7 and placed in ‘L’ as shown in Figure3. AE instrument samples the data at the rate of 3 MPS. Leak signals are acquired by array sensor first, and then amplified by 8 pre-amplifiers by 40 dB. At last, signals are transmitted to the AE instrument and restored in disc by PC for later processing.

3.2. Data Acquisition
A hole located at (0, 0), 1 mm in diameter, is drilled before on the plate marked as a red point in Figure3. An “L” array is placed at position A to position I successively. The corresponding angles of leak direction were 9°, 13°, 20°, 24°, 31°, 45°, 57°, 73° and 79°. The distance from the element #0 of sensor array to the leak source is 300 mm during the experiment. Open the leak signals acquisition system and synchronously collect 8 leak acoustic emission signals.

4. Results and Discussions
The background noises signals is always below 100 kHz and the leak signals are weak after 500 kHz. Thus, the signals between 100 kHz and 500 kHz are used to process later. The frequency spectrum of signals between 100 kHz and 500 kHz at position A are sampled. Figure4 shows the frequency spectrum of signals without leak, while Figure5 shows the frequency spectrum of signals with leak. By contrasting two figures, amplitudes of signals, of which the corresponding frequencies are between 150 kHz and 250 kHz, increase greatly while leak happens. Fourier transforms are done to the signals from the rest 8 positions, the same conclusion is derived. So, signals between 150 kHz and 250 kHz are chosen to direct the leak source in our experiment.

Figure 4. The frequency spectrum of signals without leak
Figure 5. The frequency spectrum of signals with leak.

From the beamforming theory, the identical amplitude, phase and frequency responses of array elements are critical to ideally eliminate the different location sensitivities of sensor array. If some array elements have higher power donations than others or sensor elements have different phase shifting to the inputs, when time-delayed and summed-up, the inputs from these sensors lead to an
undesired location result. Based on this phenomenon, data from array elements are normalized by energy firstly in experiments to relieve different amplitude responses, while phase shifting leaves to be resolved. Although the signals in different frequency have different phase speeds for Lamb waves, the phase speed is assumed to maintain the same within narrow frequency bands. Different from the TDOA methods proposed in other papers, distinguishing phase speeds according to narrow band frequencies in one mode is firstly applied to our experiments. Thus, the data are then processed by narrowband pass filtering into 10 frequency bands: 150-160kHz, 160-170kHz, ..., 240-250kHz. And the corresponding phase speeds of different frequency components are acquired by dispersion curves for test plate. In our experiment, the frequency-thickness parameter is between 0.3 MHz·mm and 0.5 MHz·mm and only A₀ mode and S₀ wave mode exist. Because the delay matrices calculated by the phase speeds of S₀ mode wave have poor agreements with the actual direction of arrival, only A₀ mode signals are discussed in the rest of the paper. The green dotted rectangular in Figure6 shows the range of frequency-thickness products and phase speeds in our experiments. Table.1 listed the value of the frequency and its corresponding phase speed \( c_p \) of A₀ mode. The phase speed is acquired by the central frequency \( f_c \), which is the mean value of the frequency bands. Within the frequency band, the phase speeds are assumed to be the same.

### Table 1. Phase speeds of A₀ mode signals with different frequency bands

| Frequency (kHz) | Phase speed \( c_p \) (m/s) | Frequency (kHz) | Phase speed \( c_p \) (m/s) |
|-----------------|-----------------------------|-----------------|-----------------------------|
| 150-160         | 1581                        | 200-210         | 1765                        |
| 160-170         | 1621                        | 210-220         | 1797                        |
| 170-180         | 1661                        | 220-230         | 1827                        |
| 180-190         | 1696                        | 230-240         | 1857                        |
| 190-200         | 1732                        | 240-250         | 1885                        |

The time delay matrix \( \tau_{n,\theta} \) can be obtained by Eq.(4) when the wave speeds and the sensor geometry are known. After the \( \tau_{n,\theta} \) are calculated, beam-power-versus-azimuth curves are accessed by Eq. (2) and Eq. (4). When the obtained value reaches the maximum, the corresponding angle is estimated as the source direction of the leak. Figure6 shows the beam-power-versus-azimuth curve. The actual azimuthal direction of arrival is 31° and the corresponding assumed azimuth is 28°, from the figure, when the power gets its maximum. So the location result of the leak source is 28°. Conclusions are also derived from the figure that lead by the interferences from reflected waves and inconformity of sensors, several grating lobes exist, and in some cases, it worsens the location accuracy rate when its value gets larger than the main lobe.

![Figure 6. Beam-power-versus-azimuth curves](image1)

![Figure 7. The scatter diagram of location errors at 9 positions](image2)

The absolute values of location errors are calculated under different frequency bands and the corresponding phase speeds at the above 9 positions. Apparently, signals between 190 kHz and 200 kHz perform best among the 15 frequency bands, of which the mean location error is 2.28°. Therefore, signals between 190 kHz and 200 kHz are chosen to process the total 180 data series, and the scatter
diagram of location errors are illustrated in Figure 7. Each position has been orientated for 20 times, so there are 20 dots at each position. The triangles show the absolute values of average location errors at each position, which is less than 5°. And the green dotted lines in the figure represent 90% confidence intervals, which is plus or minus 5°. So, conclusions can be derived that, evaluated by location errors less than plus or minus 5°, the accuracy rate of the approach is 90%.

5. Conclusions
This paper comes up a novel approach to determine the phase speeds of different frequency components of signals by solving Rayleigh-Lamb equations. Compared to applying a uniform propagation speed obtained by experiment regardless of signal frequency components, this method has higher reliability. In our experiments, the sensor array measures the leak-noise generated ultrasound propagating through the test plate. And then the data are processed by narrow band pass filtering into 10 frequency bands. With dispersion curves of Lamb wave, the corresponding phase speed for each frequency components is confirmed. By analysing the location results of beam-power-versus-azimuth curves under different phase speeds, and choose the signal components of 190-200 kHz to locate the leak. And the corresponding phase speed is 1732 m/s. The experiment result shows that, evaluated by location errors less than plus or minus 5°, the accuracy rate of the approach is 90%. This method can provide some helpful suggestions about leak detecting of spacecraft in orbit.

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