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# A Study of Structural Damage Detection for Spacecraft In-Orbit Based on Acoustic Sensor Array

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***Abstract*****—**With the increasing of human space activities, the number of space debris has increased dramatically, and the possibility that spacecrafts on orbit are impacted by space debris is growing. A method is of the vital significance to real-time detect and assess spacecraft damage, determine of gas leak accurately, guarantee the life safety of the astronaut effectively. In this paper, acoustic sensor array is used to detect the acoustic signal which emits from the damage of the spacecraft on orbit. Then, we apply the time difference of arrival and beam forming algorithm to locate the damage and leakage. Finally, the extent of the spacecraft damage is evaluated according to the nonlinear ultrasonic method. The result shows that this method can detect the debris impact and the structural damage, locate the damage position, and identify the damage degree effectively. This method can meet the needs of structural damage detection for the spacecraft in-orbit.

***Keywords*****—**Acoustic sensor array, spacecraft, damage assessment, leakage location.



## I. Introduction

WITH the progress of space science technology and the development of the manned space engineering, the quantity of spacecraft on orbit are growing [1]. The spacecraft is subjected to the test of space environment for a long time. It is important to strengthen the security protection in order to guarantee the normal operation of the spacecraft and the life safety of the astronauts. Spacecraft safety testing, system running state monitoring, and risk protection system establishment have become the problems that need to study and solve immediately.

Now, a large number of micro meteor and space debris have been present with the rapid development of the global aerospace industry [2]. These micro meteor and space debris have become the major threats that destruct the seal performance of manned spacecraft [3]. Space debris distributed in the altitude of 200 km to 800 km may impact frequently with space station and other spacecraft and causes the damage of the structure [4], even results in gas leakage which will threaten the safety of the astronauts, and may lead to the failure of the space mission [5], [6]. In 2004, the window's soft tubes of American fate capsule of International Space Station leaked. When the inner pressure descended abruptly, the astronauts utilize an apparatus to find the leakage point so that the air pressure turned back to normal level [7]. In 2007, the Endeavour was crashed by space debris in the task STS-118 [8]. The debris went through the radiator's panel and the shell of the heat control system, which led to severe leak of the space shuttle. The astronauts found and shot the structure damage by debris in 2008 during space walking of task STS-122&123 [9].

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## II. Methods Overview

This method uses two-staged acoustic sensor array. The primary sensor array is composed of 8 * 8 array element. A number of primary sensor arrays are pasted on tank wall in the spacecraft by a certain topological structure to make up the secondary sensor array, as shown in Fig. 1. Application of the secondary sensor array has the following two advantages: a) Combined with beam forming algorithm, it can realize the direction of the continuous acoustic emission signal of leakage source accurately, and then realize localization by superimposing two or more than two directional results of the secondary node in specific areas. b) It can realize the evaluation of damage degree by using ultrasonic phased array technology conveniently.

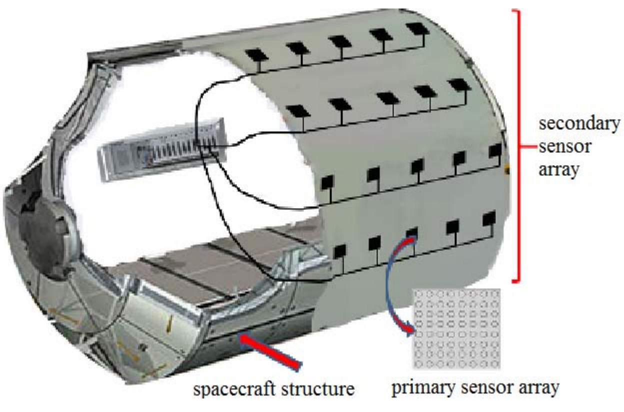


Fig. 1 The diagram of two-staged acoustic sensor array

Impact detection module is always working to determine whether impact occurs. If it occurs, the leak identification module will start and determine whether gas leak exists. When gas leak occurs, the leakage localization module will start and calculate the location of leakage precisely. If there is no leakage, damage assessment module will start and assess damage degree of structure near the point of impact according to the results of the impact position. Data processing module stores all calculation results in the database. The astronauts and ground operators can obtain test data by monitor display and communication interface.

## III. Impact Detection

Acoustic emission signals produced by impact are sudden signals. Signal source can be positioned by time difference of arrival (TDOA) [10], [11]. It uses multiple sensors to measure the differences of arrival time from the same signal source to each sensor. Then, the position of the signal source is determined. In the two-dimensional plane, the arrival time difference of the signal source determines a hyperbola with two sensors as focus. In general, using three sensors can form two unilateral hyperbolic to generate the intersection point that is the location of the signal source. The principle diagram is shown in Fig. 2, and three sensors marked as A, B, C synchronously receive the leak acoustic emission signal from the source. The time differences $t_{AB}$ and $t_{AC}$ are calculated through the correlation algorithm. Then, the distance difference can be obtained by time difference multiplied by the speed of sound. Two hyperbolas MN and RS can be drawn by the distance difference, and their intersection T is the point of impact.

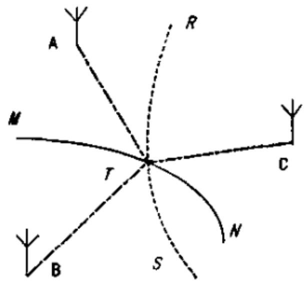


Fig. 2 Principle diagram of TDOA

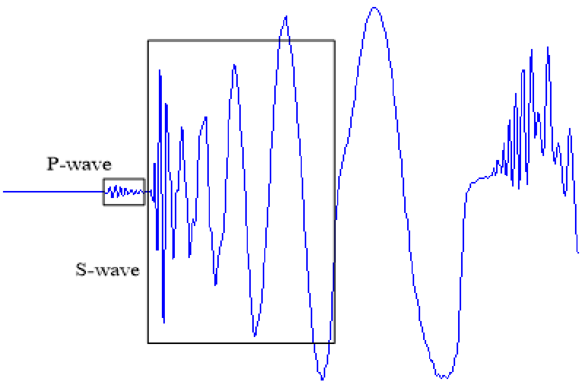


Fig. 3 The wave of impact signal

The precision of TDOA system mainly depends on the precision of time delay estimation. With the constant innovation of signal processing theory, time delay estimation technology is also developing constantly. At present, many classical methods of time delay estimation are developed such as threshold level method and correlation method. And Correlation method includes basic correlation method, the generalized correlation method, cyclic correlation method, spectral correlation method and adaptive correlation method. S-wave and P-wave have to be distinguished effectively in the time delay calculation. The wave of impact signal received by a sensor is shown in Fig. 3. From the figure, P-wave is received by the sensor earlier than S-wave, but the amplitude is smaller than the amplitude of S-wave. The arrival time can be obtained by setting threshold method reasonably. And then, the point of impact can be positioned by corresponding wave velocity.

## IV. Leakage Location

Leak acoustic emission signal belongs to continuous signal. The traditional time difference of arrival (TDOA) cannot position this kind of signals because arrival time cannot be obtained directly. But, beam forming method can position the leakage [12]. Orientation of the acoustic emission source can be realized by base on time delay beam forming technology of multi-sensor array. Its directional principle diagram is shown in Fig. 4.

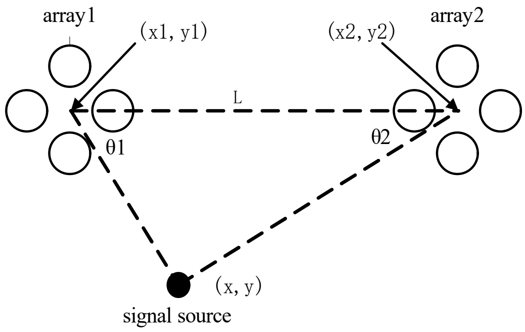


Fig. 4 Leak locating with Beam Forming method

We calculate the angles $\theta_1$and $\theta_2$ from the sound source incident using beam forming algorithm. According to direction angle and the distance between sensor arrays, the coordinates (x,y) of acoustic emission source can be calculated as shown in the following type

$$\begin{aligned} L_1 &= \sqrt{(x-x_1)^2+(y-y_1)^2}, \\ L_2 &= \sqrt{(x-x_2)^2+(y-y_2)^2}, \\ L &= L_1\cos(\theta_1)+L_2\cos(\theta_2) \end{aligned} \tag{1}$$

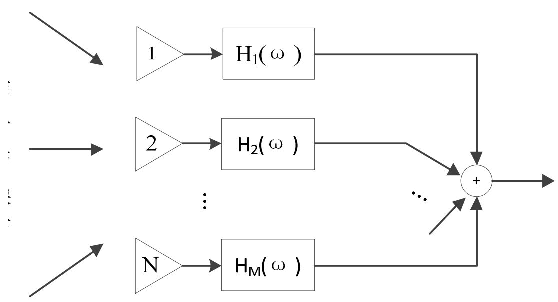


Fig. 5 The signal flow chart of beam forming

In beam forming process, the time delay of signal is calculated according to the element position in the array. Then the signal from each array element in the array is phase shifted and summed. The flow chart of beam forming processing is shown in Fig. 5.

To sensor array composed of n sensors, its response of signal can be described as

$$g(t,\mathbf{s}) = \sum_{i=1}^{n} u_i(t - d_i(\mathbf{s})) \tag{2}$$

In this expression, $u_i$ is the $i^{th}$ output signal in sensor array, $d_i$ is the time delay which leak signal arrives in each sensor of array. Its value depends on the distribution of the array and the vector **s** which contains the direction of the sound wave propagation and the directivity of propagation velocity of acoustic signal under this mode. Leak signal produced by the same leak is consistent, but the noise signal is random, so the SNR of the signal output of sensor array can be improved through the signal superposition technique. The noise power of acoustic beam can be further derived by this method through calculating the moving mean square value of sensor array output with time. Derivation formula is as:

$$P(t,\mathbf{s}) = \int_{t-T/2}^{t+T/2} g(t,\mathbf{s})^2 \, dt \tag{3}$$

The value of computing time window T is not only large enough to obtain most of the acoustic emission signal produced by leak, but also avoids the impact of edge reflection acoustic signal as far as possible. It depends on the parameters of the structure to be tested. Different time delay respectively corresponds to different pointing angles of array. According to the relation of the delays and the angles of antenna array, we can get the amplitude curve, which is shown in Fig. 6. The angle which corresponds to the largest amplitude in the curve is the incident angle from acoustic emission wave source to the sensor array.

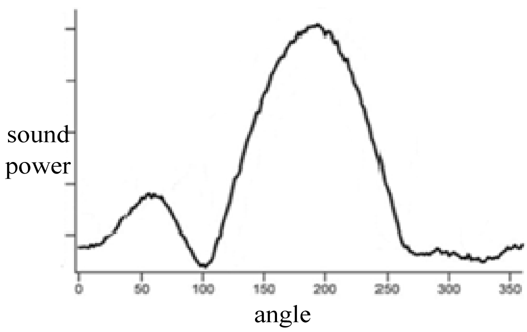


Fig. 6 The relationship curve between beam-forming angle and sound power

## V. Damage Assessment

The material performance degradation is always accompanied by some kind of nonlinear mechanical behavior. That is to say, nonlinear term appears in material constitutive equation. To intact material without any defects under ideal situation, when a sine wave with a single frequency transmits within material, it still keeps its original frequency and its waveform does not distort. When fatigue crack exists in sheet metal, if an ultrasonic signal with a single frequency is loaded, local elastic turbulence of particle will appear. Therefore, whether there are defects or not in material can be identified quickly and accurately from the nonlinear acoustic features to the sensitivity of defects [13].

The relationship of stress $\sigma$ and strain $\varepsilon$ is nonlinear by Hooke's law, the one dimensional equation is as follows

$$\sigma = E\varepsilon(1 + \beta\varepsilon + \cdots) \tag{4}$$

$E$ is the Young's modulus, $\beta$ is the second order nonlinear elasticity coefficient, which is called nonlinear coefficient for short.

In isotropic elastic solids, one-dimensional longitudinal wave equation is

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma}{\partial x} \tag{5}$$

$\rho$ is material density, $x$ is transmission distance, $\sigma$ is stress, $u$ is the displacement, and the relationship between u and strain $\varepsilon$ is $\varepsilon(x,t) = \frac{\partial u(x,t)}{\partial x}$. The nonlinear wave equation about can be obtained from (4) and (5):

$$\rho \frac{\partial^2 u}{\partial t^2} = E \frac{\partial^2 u}{\partial x^2} + 2E\beta \frac{\partial u}{\partial x} \frac{\partial^2 u}{\partial x^2} \tag{6}$$

The value of $\sigma$ depends on the second-order constant generally. We use the singular perturbation method to solve it. Assuming that $u$ is decided by the following formula

$$u = u_0 + u' \tag{7}$$

$u_0$ is the initial displacement of the excitation wave, $u'$ is a first-order perturbation solution. Suppose that $u_0$ is a sine wave with a single frequency:

$$u_0 = A_1 \cos(kx - \omega t) \tag{8}$$

where $k$ is the wave number. Then, the second order perturbation solution can be obtained as the following formula:

$$u = u_0 + u' = A_1 \cos(kx - \omega t) - A_2 \sin 2(kx - \omega t) \tag{9}$$

$$A_2 = \frac{\beta}{8} A_1^2 k^2 x \tag{10}$$

The second order constant in (9) is a part of the second harmonic, its amplitude depends on the value of $\beta$.

Equation (10) can be changed into (11)

$$\beta = 8\frac{A_2}{k^2 A_1^2 x} \tag{11}$$

It can be seen that the nonlinear coefficient $\beta$ has a linear relationship with $A_2/A_1^2$. Therefore, the damage rate of the dielectric materials can be evaluated by measuring the amplitude of harmonic wave when the fundamental wave propagates in the medium. Firstly, determine the location of leakage source, as shown in Fig. 7 (a). Secondly according to the arrangement of sensor array around the leakage source determine the works of each sensor, as shown in Fig. 7 (b). Then provide high enough pumping frequency for emission sensor to excite the ultrasonic which is depicted in Fig. 7 (c) and process data of signal received by receiving sensor. Evaluate the degree of spacecraft damage according to the nonlinear coefficient and the evaluation results are obtained as shown in Fig. 7 (d).

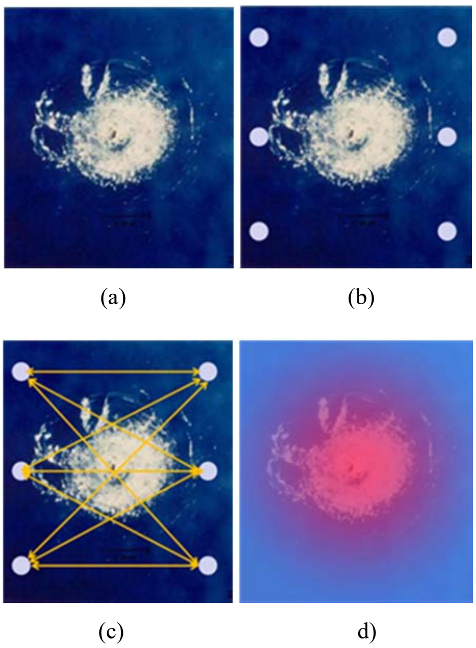

Fig. 7 Schematic diagram of Nonlinear Ultrasonic Method

## VI. Conclusion

The method of structural damage detection for spacecraft on orbit based on acoustic sensor has been successfully used abroad in the field of manned space flight [14], [15]. This paper introduces the latest research of Beijing Institute of Spacecraft Environment Engineering, hoping to provide some reference for China's manned spacecraft damage and leak detection.

Through the study of this article, we get the following conclusions:

i. With this method, the impact location accuracy is better than ±100 mm, and the leak location accuracy is better than ±200 mm when the leak rate is more than 1 Pa.m$^3$/s. It can also identify the damage such as a crack, a pit and a breakdown, etc.

ii. The equipment developed by this method is light weight, easy to operation, high reliability, and can meet the needs of structural damage detection for the spacecraft on orbit.

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