

Development of the Noise-Resistant and Sound Focusing Accessory of Ultrasonic Leak Detector for Spacecraft on Orbit

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Abstract: Ultrasonic signal produced by the gas leak is so weak that it is difficult to detect, and easily interfered. So developing the noise-resistant and sound focusing accessory for the ultrasonic leak detector is very important for improving ultrasonic leak detector sensitivity and noise-resistant capability. Based on the theory analysis of the leak ultrasonic signal reverberation and anacampsis, the 5A06 aluminium alloy and nylon were selected as the material of noise-resistant and sound focusing accessory by calculation and compare. Then the circular cone trumpet structure was design as the accessory main structure, and the nylon expansion port, nylon shrinking port and aluminium alloy expansion port structures were manufactured. The different structure characters were shown by the contrasting experiment. The results indicate that the nylon expansion circular cone trumpet structure has better sound focusing performance and it can improve the testing sound pressure amplitude 10 bigger than the detector without the accessory. And the aluminium alloy expansion circular cone trumpet structure has better noise-resistant ability than others. These conclusions are very important for the spacecraft leak detection and it can provide some references for the design of the noise-resistant and sound focusing structure.

Key Words: ultrasonic leak detection, noise-resistant, sound- focusing

1. Introduction

Sound environment in spacecraft cabin is utterly complex, and the inboard noise is very important space environment factor[1-3], and it seriously affects the ultrasonic leak testing sensitivity. So it is necessary to develop a noise-resistant and sound focusing accessory loading on the ultrasonic leak detector for improving the detector sensitivity and reducing noise environment influence. At the same time ,NASA have developed an ultrasonic leak detector for spacecraft on-orbit leak testing with a ABS plastics expansion port circular cone structure as the noise-resistant and Sound focusing accessory[4], and the UP9000 Ultrasonic leak detector made in USA has a similar throat structure accessory[5] and Jiang Yang developed an aluminum alloy parabola expansion port structure as the accessory[6].This article researched new noise-resistant and Sound focusing structure and testing these performances for providing some references.



2. Theory analysis of the leak ultrasonic signal reverberation and anacampsis

According on aeroacoustics theory, gas leak can lead to the ultrasonic signal production. And the leak ultrasonic propagates in air. When the sound reaches solid boundary, reverberation and anacampsis are happened as the Figure1 shown. In the Fig.1, incident wave P_i and reflected wave P_r both are the longitudinal wave, and their sound speed is c_1 , and the air acoustic impedance is $\rho_0 c_0$, incidence angle and reflected angle are the same ($\theta_i = \theta_r$). But in solid medium, there are refracted longitudinal wave P_{zz} and refracted transverse wave P_{zh} . At the same time, because the longitudinal wave speed c_{zz} is approximately the double of the c_{zh} transverse wave, longitudinal wave refracted angle θ_{zz} is more than the transverse wave refracted angle θ_{zh} . Hence, based on the wave reverberation and anacampsis rules, the Formula 1 can be gotten.

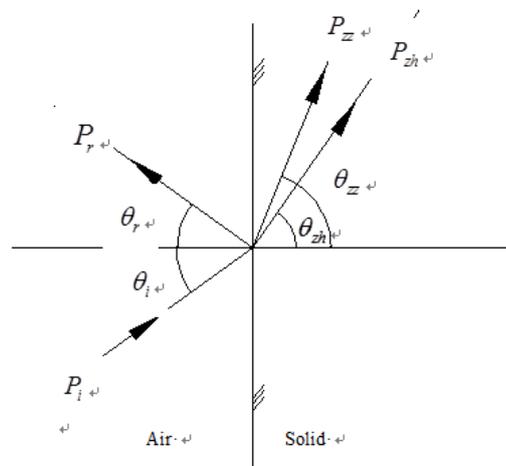


Figure 1. Leak ultrasonic signal reverberation and anacampsis between air and solid boundary

$$\theta_i = \theta_r; \frac{\sin \theta_r}{c_r} = \frac{\sin \theta_i}{c_i} = \frac{\sin \theta_{zz}}{c_{zz}} = \frac{\sin \theta_{zh}}{c_{zh}} \tag{1}$$

When the incidence angle θ_i is increasing to some value, θ_{zh} will be 90° and there is no refracted wave to achieve the all reverberation.

For reducing the noise environment influence and focusing the leak ultrasonic signal, Designing one structure can make the incident wave happen total reflection on the solid surface as the Figure 2 shown.

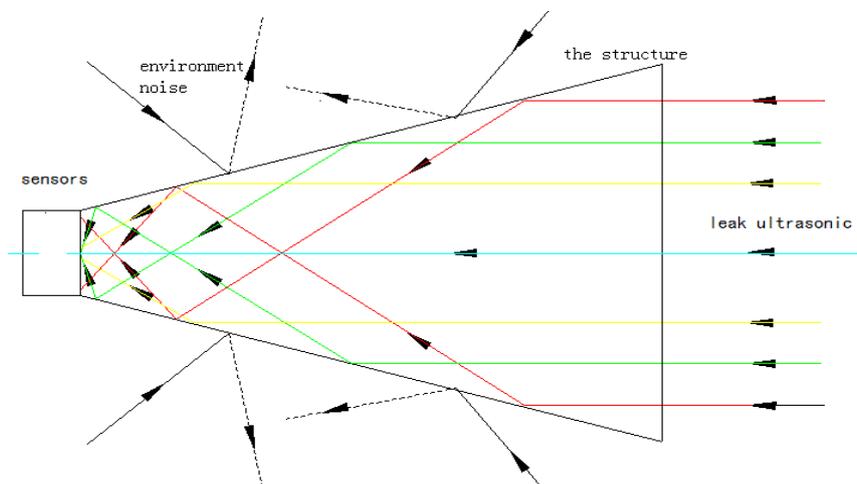


Figure 2. Total reflection on the structure solid surface

The horn structure is a variable cross-section acoustic tube, which can focus the leak ultrasonic and reflect the environment noise by the total reflection design.

Depending on Webster equation, the relationship between the sound pressure and variable cross-section can be described as the following:

$$\frac{1}{S} \frac{\partial}{\partial x} \left(S \frac{\partial p}{\partial x} \right) + k^2 p = 0 \quad (2)$$

Where S is as the sectional area, m^2 . P denotes the sound pressure, Pa. x denotes the axial distance, m. $k = w/c$, and w is angular frequency, c is sound speed, m/s.

The pyramid type structure area is described as the following:

$$S = S_0 \left(1 + \frac{x}{x_0} \right)^2 \quad (3)$$

Where S_0 denotes the throat sectional area, m^2 . x_0 is the distance from throat to the top of pyramid. And the sound pressure can be gained by formula (2) and formula(3).

$$p = \frac{P_0}{x + x_0} e^{j(wt - kx)} \quad (4)$$

The particle velocity can be described as the following equation:

$$u = \frac{1}{\rho_0 c_0} \left[1 + \frac{c_0 / (jw)}{x + x_0} \right] p \quad (5)$$

And the acoustic impedance Z_a can be gain as the equation (6) shown:

$$Z_a = \frac{p}{u} = \frac{\rho_0 c_0}{1 + c_0 / (jwx_0)} = \left[\frac{\rho_0 c_0}{1 + (c_0 / (wx_0))^2} + \frac{c_0}{wx_0} j \right] \quad (6)$$

Hence, for realizing the total reflection result, the noise-resistant and Sound focusing accessory need have the high reflection and the low refraction characteristics, and its acoustic impedance need be matching with environment air acoustic impedance $\rho_0 c_0$. When $f > f_0 = c_0 / 2\pi x_0$ the Acoustic impedance is level off to $\rho_0 c_0$.

3. The material selection

Depending on the equation (1), the Second critical incidence angle need be so little that the total reflection is happened. Hence, ultrasonic propagation velocity must be much bigger than propagation velocity in air.

In ultrasonic application, Metal often is used as the flared horn material. And then in the sound application, ABS plastic, nylon often is used as sound material. At same time ,according to process ability and mass, Aluminum alloy、ABS plastic and nylon are analyzed. The total reflection angle can be gained by comparing with ultrasonic speed in air as 343.38m/s, some data is shown as the table 1.

Table 1. Acoustic material character and total reflection critical angle

material	Density kg/m ³	velocity of longitudinal wave m/s	velocity of transverse waves m/s	Attenuation coefficient Np/m	total reflection critical angle	Transmission incidence range
5A06	2640	6420	3040	230	6.48°	12.96°
ABS plastic	1050	2130	950	1.7	21.19°	42.38°
Nylon 1010	1046	2300	990	1.0	20.29°	40.58°

Through comprehensive analysis, the 5A06 (aluminum alloy) and Nylon 1010 are selected as the structure material.

4. The noise-resistant and Sound focusing structure design

The conical horn type structure is used as the main structure of the noise-resistant and sound focusing accessory by integral forming.

According to the engineering design of the conical horn maximum directivity coefficient as the following equation, the Optimum length and caliber can be gained.

$$L = \frac{D^2}{2.4\lambda} - 0.15\lambda \quad (7)$$

Where L is the optimum length, mm. D denotes the conical horn diameter, mm. and the λ denotes the ultrasonic wave length, mm.

According to the experience, when $L=n\lambda/4$, sound power is higher.at the same time, the leak ultrasonic features frequency is 40kHz, and its wave speed is 343.38m/s in air, so its wave length is 8.58mm.the formula can be described as the following equation.

$$D = \sqrt{0.6n + 0.36} \times \lambda \quad (8)$$

At present, ultrasonic sensor diameter is 70mm, n is 110.5 by according to the formula (7) for 40 kHz ultrasonic wave. Hence, the structure diameter is more than sensor's diameter, n must be larger than 111.

And then ,the acoustic impedance characteristics of the conical horn noise-resistant and sound focusing structure is related to the distance x_0 the distance from the throat to the cone and the frequency, the leak ultrasonic wave frequency should be $f \gg f_0 = c_0 / 2\pi x_0$, so $x_0 \gg 14$ mm.

The focusing performance is related with the cone angle. The focusing distance and the diameter D have the $F/D < D/4\lambda$ relationship, the focusing ability is better. So the structure parameters are designed as the Figure 3 shown.

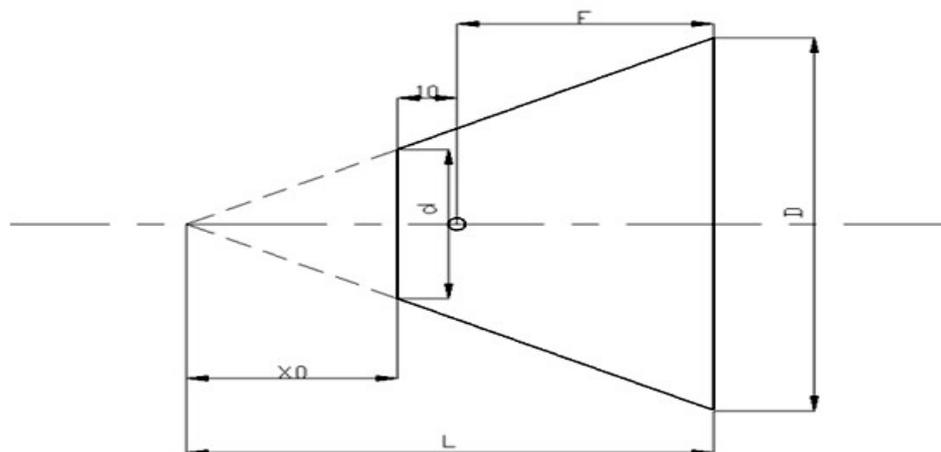


Figure 3. The structure design parameters

The structure throat diameter is 70mm, the whole length is $L - X_0 < 200$ mm because the structure mass cannot be too high. Selecting the $D=100$ mm, the λ is Calculated as 8.58mm, so $L=484.9$ mm; And the $X_0=339.43$ mm as the following formula.

$$\frac{d}{D} = \frac{X_0}{L} \quad (9)$$

Hence, the structure length is $l = L - X_0 = 145.47$ mm < 200 mm.

And the structure can focus the sound to the sensor, $F=1-10=135.47\text{mm}$. and $F/D=1.35 < D/4\lambda=2.91$, it can have better focusing performance. And then, for the total reflection, when $X_0=339.43\text{mm} \gg 14\text{mm}$ and $f=40\text{kHz} \gg f_0=c_0/2\pi x_0=161\text{Hz}$, the structure can have better impedance characteristic for the 40kHz leak ultrasonic wave.

Through the calculation, the design parameters can be gained as the Table 2 shown.

Table 2. The structure design parameters

Structure parameters	throat diameter d/mm	Diameter D/mm	Length l/mm	Cone length L/mm	Distance from throat to the cone top X_0 /mm	Focusing distance F/mm
data	70	100	146	484.9	340.67	136

The nylon expansion port, nylon shrinking port and aluminium alloy expansion port structures are manufactured.

5. Experimental analysis

For validating the designed structure performances, some experiments are developed as the Figure 4 and Figure 5 shown. The vacuum pump draws out air from the vacuum vessel to keep vacuum environment inside of the vessel for simulating the space environment, and the external air flows into the vacuum vessel from the leak and emits ultrasonic which is diffusing through air. The leak ultrasonic is tested by the leak ultrasonic detector which consists of sensor, amplifier, AD sample and processor, the leak ultrasonic sound pressure can be analyzed. In the Figure 4, the square part entitled 'noise' is the external noise signal generator which can produce the different frequency ultrasonic signals to simulate background environment noise or other disturbing leak detection noise for validating the noise-resistant performance.

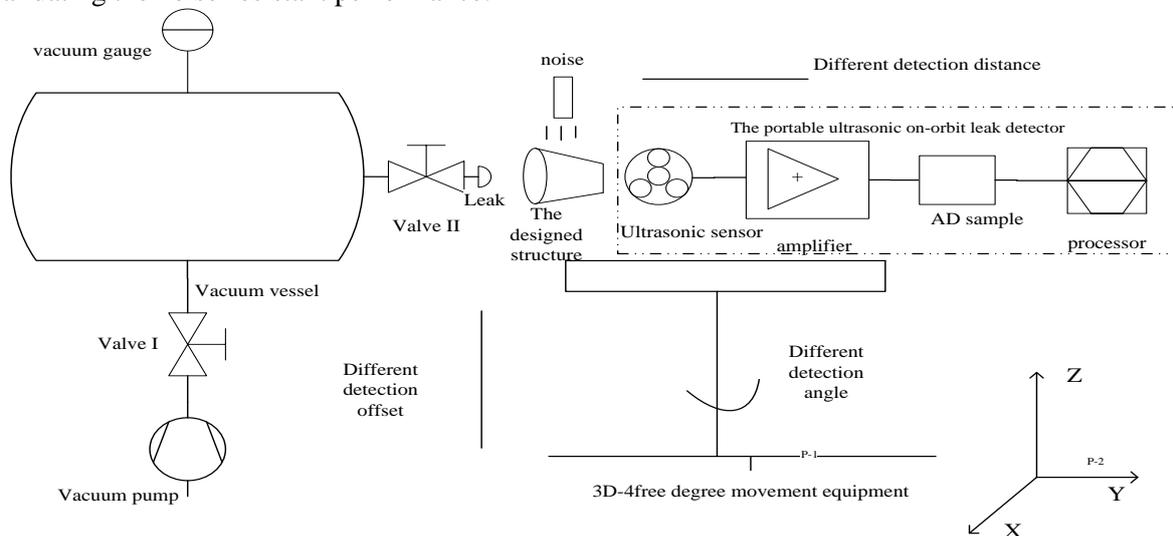


Figure 4. Experiment scheme

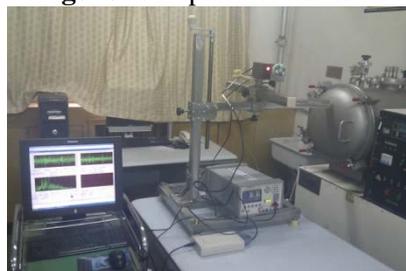


Figure 5. Experiment system photograph

With vacuum tank simulating the space environment, the air would leak from the atmosphere into the inside of the tank in which gas pressure can be $1 \times 10^{-1} \text{Pa}$ by the vacuum pump. And the leaks' geometry is an cylinder structure with $\varnothing 0.3 \text{mm}$ diameter and 3mm length.

The nylon expansion port, nylon shrinking port and aluminum alloy expansion port structures are tested by detecting different leaks. And the noise-resistant and sound focusing performances are compared between the leak detection with the noise-resistant and sound focusing structure and without.

The distance from the structure to the leak is set as 100mm, and the $\varnothing 0.3 \text{mm}$ leak is used as the leak ultrasonic source, and air is used as the leak gas medium. Changing the different noise-resistant and sound focusing structures, the ultrasonic signal is detected thirty times. And the signal can be gained and stored, by the FFT, Chebyshev band-pass filter, the 40 kHz signal is used as leak ultrasonic main characteristic. Through analyzing sound pressure in the frequency, these differences can be gained. And the maximum value, average value and minimum value are shown as the Figure.6.

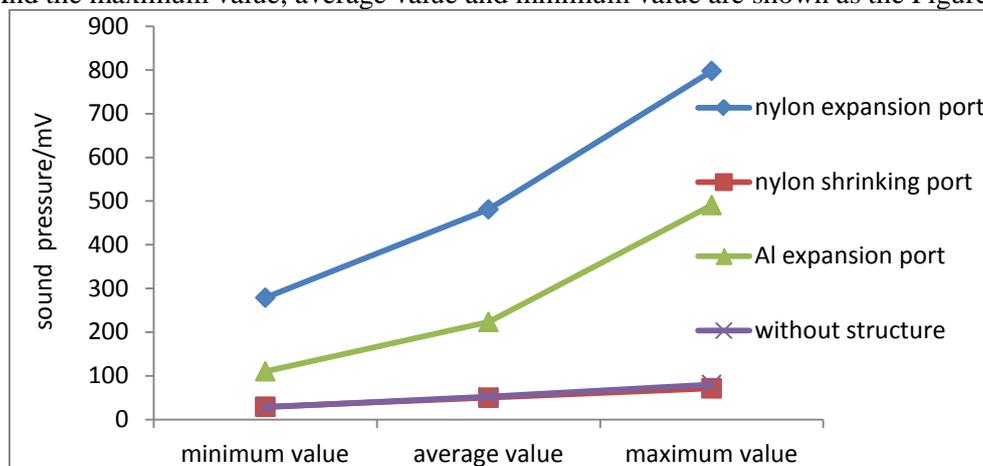


Figure 6. Focusing performance testing results

In the noise-resistant experiment, 40 kHz ultrasonic source is used as the noise interfere source is perpendicular to leak ultrasonic detecting direction. The leak ultrasonic with noise can be tested through analyzing sound pressure change in the frequency between leak with noise and without, the designed structures' noise-resistant character will be shown. The structure can reflect external noise. And the results for $\varnothing 0.3 \text{mm}$ leaks detection are shown as the Figure 7.

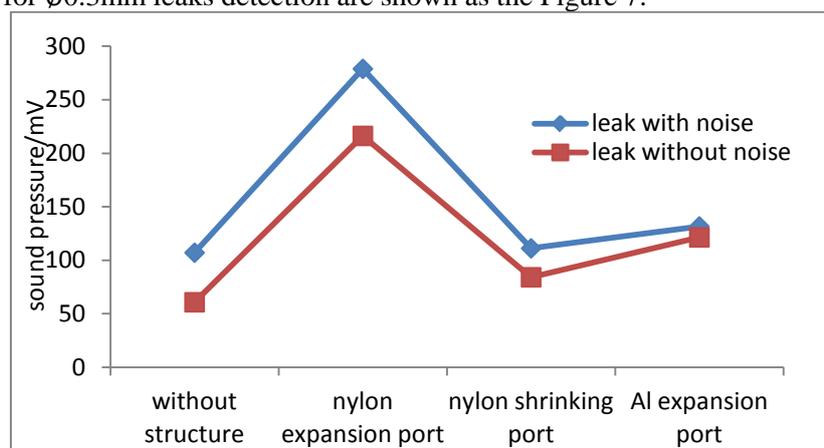


Figure 7. The noise-resistant experiment results

Through the noise-resistant and the sound focusing experiments, some results can be shown as the following:

1. Expansion port type structure has better focusing performance, and the shrinking port type structure has better noise-resistant performance.

2. Nylon structure has better sound focusing performance, but the noise-resistant is not better than others. And then, the aluminum alloy structure has better noise-resistant and focusing performances.

6. Conclusions

Because the ultrasonic leak detector is used on orbit, whose mass is more little the better. According to the study results, the nylon can be selected as the noise-resistant and sound focusing accessory, and the expansion port type and shrinking port type structures are manufactured. And then the expansion port type structure can be used when the environment noise is little. But the shrinking port type structure can be used when the environment noise is large. And the ultrasonic leak detector with the structure has higher sensitivity and lower noise influence than the without. This paper study conclusions are very important for the spacecraft leak detection and it can improve the ultrasonic leak detector sensitivity and reduce space noise environment influence for leak detection and provide some references for the design of the noise-resistant and sound focusing structure.

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