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LEAK DETECTION IN SPACECRAFT USING A 64-ELEMENT MULTIPLEXED PASSIVE ARRAY TO MONITOR STRUCTURE-BORNE NOISE

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**ABSTRACT.** We demonstrate an array sensor method intended to locate leaks in manned spacecraft using leak-generated, structure-borne ultrasonic noise. We have developed and tested a method for sensing and processing leak noise to reveal the leak location involving the use of a 64-element phased-array. Cross-correlations of ultrasonic noise waveforms from a leak into vacuum have been used with a phased-array analysis to find the direction from the sensor to the leak. This method measures the propagation of guided ultrasonic Lamb waves passing under the PZT array sensor in the spacecraft skin structure. This paper will describe the custom-designed array with integrated electronics, as well as the performance of the array in prototype applications. We show that this method can be used to successfully locate leaks to within a few millimeters on a 0.6-m square aluminum plate.

**Keywords:** Leak location, manned spacecraft, ultrasonic array, cross-correlation, spatial Fourier transform

**PACS:** 43.40Dx, 43.60.Fg

**INTRODUCTION**

Previously, we introduced \cite{1} and explored \cite{2} the problem of locating leaks in spacecraft using the random noise generated by turbulence at the exit of a small leak and coupled into the spacecraft structure. The fundamental problem is that manned spacecraft are at risk from air leaks caused by damage from micrometeorite and space debris hits\cite{3}, as well as air leaks caused by mechanical or seal failure. The problem of locating leaks is much more difficult in spacecraft than in terrestrial pressure vessels because in space the leak is into vacuum and therefore most of the leak noise generated in the gas occurs on the downstream side of the leak, that is, in the vacuum, and this airborne noise almost undetectable inside the spacecraft. Conventional industrial leak detectors currently deployed on the International Space Station \cite{4} are not particularly effective because they attempt to measure the tiny amount of leak noise that propagates up the near Mach 1 free jet of the leak into the interior of the space station. Moreover, the inner surface of the spacecraft pressure vessel is almost completely occluded from view or access by insulation, life-support systems, and spacecraft experimental equipment.

The focus of our work has been on developing leak location methods that use ultrasonic leak noise propagating in the spacecraft structure (the thin hull of the pressure vessel), and
Correlation operation transforms random noise waveforms into predictable functions of the leak spectrum, leak location, and detector geometry.

![Figure 1](image1.png)

**FIGURE 1.** Correlation operation transforms random noise waveforms into predictable functions of the leak spectrum, leak location, and detector geometry.

Experimentally measured cross-correlation waveform showing large correlation amplitude for zero differential time offset.

![Figure 2](image2.png)

**FIGURE 2.** Experimentally measured cross-correlation waveform showing large correlation amplitude for zero differential time offset.

out previous publications [5, 6] outline some of these methods. In this paper we discuss our latest development, which is a low-cost passive array that very effectively solves the leak location problem, even in the presence of integral stiffeners or other mechanical interruptions in the path of the elastic wave emanating from the leak.

**METHODS**

All of our leak location methods rely on the mathematical operation of cross correlation to compensate for the random nature of the leak noise signal. As illustrated in Fig. 1, a single-frequency leak noise signal $\hat{A} e^{j\omega t}$ propagating in a single plate-wave mode to sensors at distances $d_1$ and $d_2$ gives a cross-correlation that depends primarily on the difference in propagation lengths $d_1 - d_2$. In short, cross correlation transforms a pair of measured leak noise waveforms into a reproducible function of the leak noise spectrum, geometry, and elastic coupling. Even in the more complicated case of multimode propagation and dispersion (modal velocities that vary with frequency), the cross correlation remains a reproducible function of the leak noise and sensor parameters. Fig 2 shows an experimentally measured leak-noise cross correlation, where a large correlation amplitude at zero differential time
FIGURE 3. Diagram of incident wave (wavevector $\mathbf{k}$), wavefronts, and sensor array.

FIGURE 4. (a) Diagram of triangulation process; (b) experimentally measured spatial frequency image (integrated over temporal frequencies).

offset is seen. Most of the signal content visible in Fig. 2 is actually spurious, coming from low frequency resonances in either the plate or transducer element. The usable portion of the leak signal has a much higher frequency content, but lies about 20 dB below the amplitude of the largest low-frequency peak. Extraction of this useful signal requires high-pass filtering, which is done in the digital domain.

A single-frequency elastic wave incident at a particular direction on an array sensor on a thin plate, as illustrated in Fig. 3, will induce a characteristic pattern of signal phase delays on the array elements. One array element is selected as a “reference element”. If cross correlations are recorded between the reference element and all the other elements, the same pattern of phase delays will appear in the cross correlations. A three-dimensional spatial-temporal $(x, y, t)$ Fourier transform of the cross correlations then gives the amplitude of the incident elastic wave as a function of wavevector $(k_x, k_y)$ and frequency $f$. The Fourier transform is then integrated over a preselected temporal frequency range ($\sim 200–300$ kHz) to exclude large amplitude low-frequency resonances. An additional advantage of this operation is to reduce the dimensionality of the measured data to two spatial-frequency dimensions, permitting convenient plotting and visualization, as shown in Fig. 4b). The leak is located by using two or more sensor arrays, the spatial Fourier analysis described above to determine
the direction from each sensor array, and subsequent triangulation from the two directions. The triangulation process is illustrated in Fig. 4.

MULTIPLEXED ARRAY

To make the array measurement practical, we have developed a multiplexed passive array sensor specifically for this application. The array was designed to use analog multiplexers and a printed circuit board placed in direct contact with a monolithic (undiced) piezoelectric element as illustrated in Fig. 5. Pads on the printed circuit board function directly as the transducer electrodes. The $8 \times 8$ array consists of 63 multiplexed elements plus a reference element for cross correlation. The sensor is integrated with analog multiplexers and two dual stage ultra low-noise preamplifiers mounted on the opposite side of the circuit board, as shown in Fig. 6. The array multiplexers are controlled through optoisolators by a PC parallel port and are powered by a pair of 9 volt batteries.

RESULTS

We coupled the array elastically with mineral oil to a 3.2-mm thick aluminum plate. The plate included a crosshatch pattern of one-inch tall integral stiffeners. We pulled a vacuum on one side of a 1-mm diameter hole, to simulate the leak, and measured 63 cross correlations of the multiplexed elements with the reference element. These data were Fourier transformed in space and time and integrated over the frequency range 200–300 kHz to yield the spatial frequency image shown in Fig. 7. An estimated direction to the leak was determined from the direction having the maximum radial line integral from the center of the plot in Fig. 6, and this estimated direction is shown as a white line in the figure.

This procedure was repeated two more times at different locations and leak directions were found at the other locations. Figure 8 shows the three array locations, the estimated
FIGURE 6. Photograph of the component side of the printed circuit board showing the multiplexers (square integrated circuits) and preamplifiers.

FIGURE 7. Measured spatial frequency spectrum over 200–300 kHz and predicted leak direction.
FIGURE 8. Least-squares triangulation of the leak location from three points on a plate with integral stiffeners.

directions, the estimated (least squares) leak location illustrated with an asterisk, and the positions of the integral stiffeners. The actual leak location is at the origin \((0, 0)\). In contrast with some other methods we have previously developed [5, 6] these results show successful leak location despite the presence of integral stiffeners.

CONCLUSIONS

The 64-element passive multiplexed array sensor provides a simple and direct measurement of the vibration field propagating under the sensor. It is electrically and mechanically robust because of the simple integrated design. It is extremely low cost with a total parts cost for one array under $200. This array is an effective solution for the ultrasonic source location of leaks into a vacuum, such as in spacecraft. Our method uses cross correlation to transform the leak noise into a measurable and deterministic quantity. It uses simple but effective processing—the three-dimensional Fourier transform—to determine the dominant direction of propagation and therefore the direction to the leak. Triangulation from multiple array locations then finds the location of the leak. The large amount of data collected and the simplicity of the processing make this method extremely robust.

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REFERENCES


