Leak detection in spacecraft using structure-borne noise with distributed sensors

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We have developed and tested in the laboratory a method for in-orbit detection and location of air leaks in manned spacecraft that uses only a small number of sensors distributed arbitrarily on the inner surface of the spacecraft skin. Then, structure-borne ultrasound in the range of 300–600 kHz is monitored from each of the sensors. When cross correlations between measured sensor waveforms indicate the presence of a leak, these correlations are compared with a large dynamically generated database of simulated correlations to locate the the leak on the pressure vessel. A series of experimental tests were performed and at worst the method identified some false locations, but the true location of the leak always appeared. © 2005 American Institute of Physics. [DOI: 10.1063/1.1906324]

Leak detection and location in terrestrial pressure vessels is usually performed using directional microphones to detect the characteristic acoustic signature near 40 kHz generated by the downstream leak turbulence. Currently deployed leak detectors on the International Space Station¹ are of this type. Directional microphones work well for leaks into ambient, because few high-amplitude noise sources exist at 40 kHz. The noise generated in a spacecraft air leak, however, occurs on the space vacuum side of the vessel. Acoustic propagation of the turbulence-generated noise upstream back into the spacecraft is suppressed because the free jet velocity at the leak site is nearly Mach one. Therefore, this technique is ill-suited to the spacecraft environment. We propose, instead, a method based on detection of structure-borne noise generated by the leak in the spacecraft skin and carried to distant sensors by propagating plate waves.

Manned spacecraft are at risk from pressure vessel penetration by micrometeorites and low-Earth orbit space debris.² Because larger objects can be tracked and avoided,³ it is the smaller, more common, debris particles 0.5–50 mm that pose the greatest danger.² Despite shielding, a debris hit might cause a leak small enough to be survivable, but large enough to cause loss of air supply. A continuous leak detection and location system would allow the crew quickly to locate and plug such a leak, thereby salvaging the affected module.

In this letter, we present an algorithm using a limited number of sensors that automatically identifies possible leak source locations from recorded waveforms. This method represents a state-of-the-art exercise in the extraction of useful signals and information from noise. In our method we calculate cross correlations from measured waveforms for all possible pairs of sensors in a given vicinity. These cross correlations are then compared with simulated cross correlations calculated using the theory of guided Lamb waves and an arbitrary candidate source point and Lamb mode for the leak. We use vector inner products to compare simulated and measured cross correlations for all modes and all possible candidate source points to determine the calculated source intensity as a function of candidate leak location. A small fraction of the ultrasonic energy couples from the leak into the spacecraft skin. Measured leak noise is itself buried in noise from other sources, including the detection amplifiers. Cross correlation is the key to extracting a coherent signal from the measured leak noise, and this operation has a history of use in leak detectors, e.g., Kupperman⁴ and Rewerts *et al.*⁵ Consider a frequency domain representation of the leak noise $N(f) = e^{j\phi(f)}$, where $\phi(f)$ is the stochastic phase of the leak. The measured spectrum at a distance *d* from the leak (ignoring attenuation) will be

$$\sum_{m} A_m(f) e^{j\phi(f)} e^{-jk_m(f)d},\tag{1}$$

where $A_m(f)$ and $k_m(f)$ are the frequency spectrum and dispersion relation of the wave mode having index *m*. The spectrum of the cross correlation between measured waveforms at distances d_1 and d_2 is

$$\sum_{m,n} A_m(f) A_n(f) e^{jk_m(f)d_1 - jk_n(f)d_2},$$
(2)

or for a single mode with flat spectrum,

$$e^{jk_m(f)d_1-jk_n(f)d_2}.$$
 (3)

The random portion of the phase has canceled. That is, the process of cross correlation has transformed the noise of Eq. (1) into a predictable function of its modal amplitude spectra. By performing very long correlations or averaging, detector noise and other incoherent noise can be eliminated from the measurement, and a coherent signal from the leak noise, represented by Eq. (2) can be recorded.

Successful source location requires that the ultrasound in the spacecraft be localized near the leak and propagate away from the leak in the structure. Because the leak is continuous, some material damping is important to maintain localization by minimizing echoes and reverberations.

In our frequency range, 300–600 kHz, the 4.76-mmaluminum test plate has two detectable Lamb guided ultrasonic modes: the lowest order symmetric S_0 compressional mode, and the lowest order asymmetric A_0 flexural mode. These two modes, with dispersion relations $k_m(f)$ that are readily calculable from Lamb wave theory,⁶ give rise to a total of four terms in Eq. (2). Two of these terms correspond

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FIG. 1. Leak location maps from two individual experimental cross correlations utilizing transducer pairs at coordinates (a) (453 200) mm and (446 400) mm, and (b) (453 200) and (260 578) mm. "o" indicates the location of a transducer. The cross hair indicates the actual location of the leak.

to propagation in a single mode, the two others correspond to propagation from the leak to one sensor in one mode and to the other sensor in the second mode. In order to fully analyze the detected waveforms, the dispersion of all four terms must be considered.

Our algorithm for locating the leak involves first assuming a particular point for the location of the leak. This trial point is exhaustively scanned across all possible leak locations. For each point, a single term of a simulated frequencydomain cross-correlation spectrum for a single pair of sensors (whose locations are well known) is calculated from Eq. (3). Then, the vector inner product of the simulated correlation with the measured cross correlation is evaluated by integrating the product of the two spectra over the 300-600 kHz frequency range (df=312 Hz in this case). Figures 1(a) and 1(b) show this inner product of an experimentally measured cross correlation with the S_0 - S_0 term as a grayscale function of assumed trial leak location for two different pairs of sensors. The spatially varying inner product with synthetic correlations transforms dispersion-distorted correlation wavetrains into peaks, which appear as hyperbola-shaped striations in Fig. 1 with the transducers at the foci of the hyperbolas. The dark bands in Fig. 1 suggest but do not guarantee that the leak is located on the dark band. To locate the leak, inner product maps for all sensor pairs and all modes must be combined. This is achieved by multiplying the maps of the different sensor pairs of a given mode together, and adding the magnitude of the products for all the modes to give an overall mapping of perceived source strength. Figure 2 shows the product of Figs. 1(a) and 1(b), and four other such mappings from other sensor pairs, added to similar products corresponding to the A_0 mode and the

FIG. 2. Composite experimental source strength map (sum of leak location products for all terms) (a) in the vicinity of the leak and (b) zoomed out, showing the transducer locations.

cross terms of Eq. (2). This gives a single amplitude at each candidate source point, plotted as a grayscale, that indicates the overall perceived source strength at that point. The center of the cross hairs in Figs. 1 and 2 is the actual location of the leak. The estimated leak location is the position of the peak, just below and to the left of the center of the cross hairs in Fig. 2 and 8.6 mm from the actual leak.

Our algorithm is an imperfect compromise between efficiency and accuracy, and even under ideal circumstances, it may generate spurious peaks. Neither the different terms of Eq. (2), nor the simulated waveforms for different source points are mutually orthogonal, so there is the opportunity for interference between the terms in the inner product calculations. The possible consequence is an identification of a false leak location. To test the occurrence of false peaks at incorrect locations, we have used our algorithm on synthetic data calculated from Eq. (2) for the worst-case of equal magnitudes for the A_0 and S_0 modes. This maximizes the amplitude of the cross-terms relative to that of the largest singlemode term. After 32 simulation runs, each with four randomly located sensors, we found the average crossinterference level to be -5 dB, with the largest at +4 dBrelative to the peak at the leak location. We conclude that, under worst-case conditions using synthetic data, interterm interference can generate spurious peaks equal to, or larger than, the peak at the leak location. But, it is important to note that the actual leak location is *also* predicted.

Interference from echoes within the 610-mm-square plate we use for testing can also cause spurious peaks in the source strength mapping. To minimize the effects of wholeplate resonances, we filter out low frequency signals below 300 kHz and exploit the higher attenuation at higher frequencies to obtain improved localization. We expect that in an



FIG. 3. Measured source strength mappings for four different transducer configurations.

actual spacecraft, the larger panel size and fewer boundaries will reduce resonance and echo interference even further.

Our experimental apparatus consists of the 610-mmsquare, 4.76-mm-thick aluminum plate, containing a 1-mmdiameter leak and four arbitrarily distributed piezoelectric point sensors (PZT, diameter 2 mm). We applied the previously described algorithm illustrated in Figs. 1 and 2 to generate perceived source strength mappings for a variety of additional sensor configurations. These are shown in Figs. 3(a)-3(d). In all cases, a peak in the source strength is found in the vicinity of the leak. These are visible in Fig. 3 as small black dots within the areas circumscribed by the cross hairs. While the distance from the leak to the measured source strength peak varies, it is always within a few wavelengths. Measured deviation distances in Figs. 3(a)-3(d) are 13.3, 9.5, 8.6, and 9.5 mm, respectively, compared with an S_0 wavelength at 500 kHz of 8.2 mm. These deviations are likely due to a combination of transducer positioning errors, transducer coupling phase delays, and wave velocity errors. Unlike all the other results, the image shown in Fig. 3(b) displays an interference peak, visible as a dot on the left of the figure at x=180 and y=280 mm that exceeds the peak near the leak in strength. This likely comes from interference between the terms of Eq. (2) and between components of echoes from the plate edge. Based on our simulation results above, such spurious interference peaks must be anticipated.

We have found that in our experiments, the apparent peak of source strength comes from the S_0 - S_0 term as opposed to the A_0 - A_0 term or either of the cross terms. There are possible reasons for this. Our leak may couple more energy into S_0 in the frequency range involved. The S_0 mode has a longer wavelength and is therefore less sensitive to transducer positioning errors. Our transducers, as mounted, may couple S_0 better than A_0 . The leak location algorithm takes multimode propagation into account and would be expected to yield accurate predictions regardless of which mode dominates.

We have demonstrated an effective and efficient algorithm using a limited number of sensors for finding the location of a leak-into-vacuum through a plate by monitoring structure-borne noise. This algorithm transforms cross correlations of measured ultrasonic signals into a mapping of possible leak locations by exploiting the known material properties and known dispersion behavior of Lamb modes. The algorithm has been demonstrated experimentally on a 1 mm hole in 4.76 mm aluminum, over the frequency range 300– 600 kHz. We have found that the algorithm is able to identify in a repeatable fashion the leak location for a variety of sensor configurations. This method could be implemented for locating leaks in long-endurance spacecraft generated by space-debris or meteorite impact.

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