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Keywords

nondestructive testing, nondestructive evaluation

Disciplines

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Comments

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Two-sensor ultrasonic spacecraft leak detection using structure-borne noise

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Abstract: Micrometeorite hits can create air leaks in manned spacecraft. Leak-generated-guided ultrasonic waves can be monitored within the plate-like spacecraft skin to detect and locate leaks. Cross-correlation techniques allow measurement of the deterministic behavior of the leak-generated noise. Measured leak-into-vacuum cross-correlations of noise signals from two adjacent transducers are recorded as the transducer pair is rotated to determine the relative phase delay as a function of rotation angle. The direction to the leak is found from the variation of phase with angle or from synthetic aperture analysis. The leak is then located through triangulation from two or more sensor-pair locations.

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Introduction

Micrometeorite or space debris impacts pose a substantial danger to manned spacecraft.¹ Large space debris are tracked by radar and actively avoided.² Because closing speeds can be as large as 15 km/s, even very small objects can still cause catastrophic damage. The smallest particles will be stopped by the spacecraft shielding or pressure vessel. There is, however, an intermediate size of particle that can penetrate the skin and create a leak that is too small to be obvious, yet can still cause significant air loss over time. A leak (not caused by a meteorite) in an International Space Station vacuum hose took two weeks in January 2004 to identify and locate, during which time the space station was losing 2 Torr of pressure per day. Astronauts are currently provided with an ultrasonic leak detector, but this instrument has been shown to be only minimally effective for leaks into a vacuum.³

Most of the sound generated by air leaking from a pressure vessel comes from turbulence in the air at the downstream side of the jet. For a leak into a vacuum, this sound can propagate neither in the vacuum nor back up the Mach 1 free jet into the spacecraft, and therefore cannot be detected. As a result, conventional industrial leak detectors that monitor airborne ultrasound are appropriate only for leaks from a pressure vessel into an ambient atmosphere. To accommodate the unique situation of an air leak aboard a long-duration spacecraft into a vacuum, we propose an alternate approach that monitors the small amount of random vibration that couples from the leaking air into the skin of the pressure vessel itself.

Analysis

The structure-borne ultrasonic noise from a small 1 mm air leak is very faint. Not only is it an unknown unpredictable signal, but because of its low amplitude it tends to be buried in other noise. Cross correlation is an established method for extracting information from leak noise and is widely used industrially for locating leaks in water and steam pipes.^{5,6} By performing long cross correlations between ultrasonic leak noise signals measured at two sensors, the leak noise

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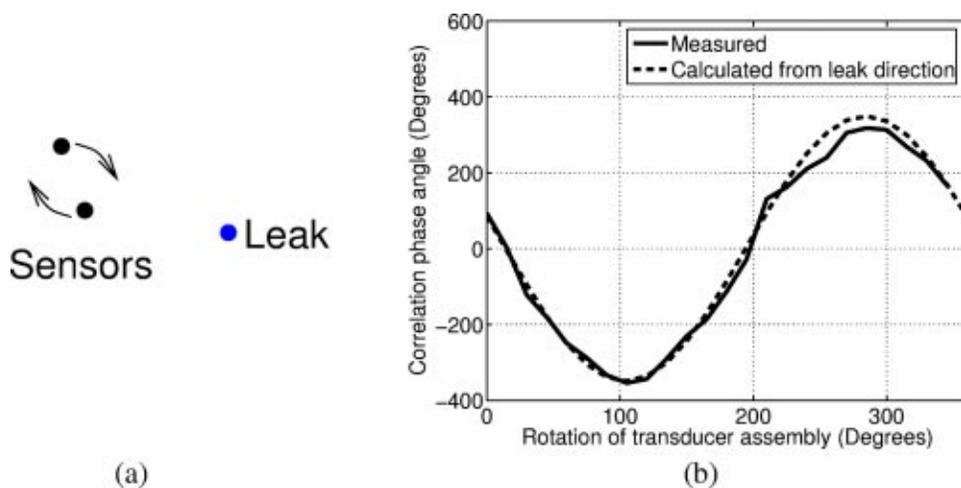


Fig. 1. (a) Transducers are rotated to find the leak direction. (b) Measured median variation of unwrapped correlation phase with rotation of transducer assembly.

is transformed into a repeatable signal with a large signal-to-noise ratio. Spectral whitening⁵ and dispersion compensation⁷ are often used as tools for interpretation of the cross-correlation waveform. Consider a single frequency ω of the sound generated by the leak that has coupled into a single mode i of propagation in the spacecraft skin. The waveform component at that frequency in the immediate vicinity ($r \ll \lambda$) of the leak can be described by the expression $\tilde{A}_i e^{j\omega t}$. The frequency-dependent complex factor \tilde{A}_i represents the amplitude and phase of the leak coupled into mode i , with repeatable amplitude but random phase. The measured waveform of that mode at that frequency at a distance d will be the same waveform, phase shifted and attenuated according to the distance: $\tilde{A}_i \exp(j\omega t - jk_i d - \kappa_i d)$. Since the Lamb modes propagating in the skin of the spacecraft are dispersive, their wave velocities and wave numbers k_i are functions of frequency. The complete single-frequency waveform at distance d will be the sum of the components in each mode,

$$\sum_i \tilde{A}_i \exp(j\omega t - jk_i d - \kappa_i d). \tag{1}$$

The cross correlation of two of these single-frequency waveforms at distances d_1 and d_2 is

$$\text{XCORR}(d_1, d_2) = \sum_i \sum_l \tilde{A}_i \tilde{A}_l^* \exp(j\omega t - jk_i d_1 + jk_l d_2 - \kappa_i d_1 - \kappa_l d_2). \tag{2}$$

If we ignore the cross terms ($i \neq l$), the cross correlation becomes

$$\text{XCORR}^{\text{reduced}}(d_1, d_2) = \sum_i |\tilde{A}_i|^2 \exp(j\omega t - jk_i(d_1 - d_2) - \kappa_i(d_1 + d_2)). \tag{3}$$

The most important result of this analysis is that the cross correlation is a function of the leak noise amplitude $|\tilde{A}_i|$ only, not its random phase. That is, cross correlation converts a pair of noise waveforms into a single predictable waveform. Moreover, the cross correlation is primarily a function of the path length difference $d_1 - d_2$. Unlike the leak noise itself, the correlation is a coherent signal that comes from the geometry of the leak and the sensors. The correlation is still not as easy to interpret as an impulse response. Arrivals with the same arrival time difference

appear superimposed in the correlation. Multiple dispersive modes and cross-term interference also appear in the correlations, necessitating relatively complicated analysis methods. A thin plate, such as the outer skin of a spacecraft, has at least two ultrasonic propagating Lamb modes: The lowest order symmetric (S_0 , compressional) mode and the lowest-order antisymmetric (A_0 , flexural) mode. For the frequency range and plate thickness of our measurement, only these two modes are present.

Method

In this article, we discuss the results of our minimalist approach to leak location. In our method, we use exactly two point sensors in a manually movable assembly; these sensors give a single cross correlation at each position. Figure 1(a) illustrates the experiment to be performed, although it is not to scale. The direction to the leak is found by measuring the cross correlation between the sensor pair as a function of angular rotation of the transducer assembly. Ignoring attenuation and cross terms allows a simple expression for the cross correlation as a function of transducer assembly angle

$$\text{XCORR}_{d,\theta}^{\text{reduced}} = \sum_i |\tilde{A}_i|^2 \exp(j\omega t - jk_i d \cos(\theta - \phi)), \quad (4)$$

where θ is the rotation angle of the transducer assembly and ϕ is the direction of propagation of the incident wave. These correlations can then be analyzed either by directly analyzing the phase variation as a function of direction and frequency to determine a single value of ϕ , or with a circular synthetic aperture analysis to determine the angular spectrum of incident energy. In either case, a linear wavefront, a single propagation direction at the transducer assembly location, and a homogeneous medium are assumed. Once source directions have determined from two locations on the spacecraft skin, simple triangulation determines the leak location.

Assuming that a single mode is dominant at a particular frequency, the phase of the cross correlation will vary sinusoidally as a function of the orientation of the transducer assembly according to the cosine in Eq. (4), and illustrated in Fig. 1(b). The zero crossings of the phase sinusoid correspond to both transducers equidistant from the source. The extrema of that sinusoid, at approximately 105° and 285° in Fig. 1(b), indicate when the sensors are in line with the leak. From the position of this sinusoid, the direction to the source can be determined.

An alternative method for analyzing the same data is to treat the set of cross correlations as an array and apply a circular synthetic aperture analysis. In this, we follow roughly the approach of Yen,⁸ modified to work with an array of correlations rather than raw waveforms. Given a discrete set of transducer assembly orientations θ_l and possible incident wave directions ϕ_m and amplitudes in each mode A_{mi} , we can write the expected correlations as

$$\text{XCORR}_l^{\text{reduced}} = \sum_m \sum_i |\tilde{A}_{mi}|^2 \exp(j\omega t - jk_i d \cos(\theta_l - \phi_m)). \quad (5)$$

Let $D_{ilm} \equiv \exp(-jk_i d \cos(\theta_l - \phi_m))$. At each frequency ω , we can construct a matrix $E_{lq} \equiv [D_{A_0lm} D_{S_0lm}]$ and a vector

$$C_q = \begin{bmatrix} |\tilde{A}_{mA_0}|^2 \\ |\tilde{A}_{mS_0}|^2 \end{bmatrix}$$

such that Eq. (5) reduces to

$$\text{XCORR}_l^{\text{reduced}} = E_{lq} C_q \exp(j\omega t). \quad (6)$$

Equation (6) represents the forward problem of predicting correlations from a known angular and modal distribution of single-frequency waves at incident angles as a matrix multiplication.

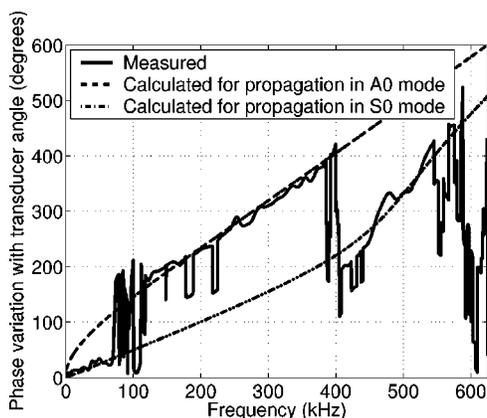


Fig. 2. Comparison of measured phase variation with calculated values for determining usable frequency range.

In a traditional synthetic aperture problem, multiplication by E_{lq} is a spatial Fourier transform. The essence of the synthetic aperture algorithm is the inversion of this operation to estimate the angular distribution C_q from the measured correlations. In a traditional synthetic aperture problem E_{lq} is unitary and its inverse is E_{lq}^H , the inverse spatial Fourier transform. In this case, E_{lq} is not square and may be ill conditioned. We use the Lanczos inverse,⁹ modified with exponential eigenvalue rolloff to limit variance, to create a linear operator E_{ql}^{inv} for estimating the angular distribution from measured correlations. The estimated angular and modal distribution is

$$\hat{C}_q = E_{ql}^{inv} XCORR_l \exp(-j\omega t). \tag{7}$$

Equation (7) gives the synthetic aperture calculation for estimating the incident angular and modal distribution from a single frequency component of a measured correlation.

Results

To evaluate the two methods described above we used a 60 cm square 4.76 mm thick aluminum plate (the approximate thickness of the skin on the International Space Station) as a model of the

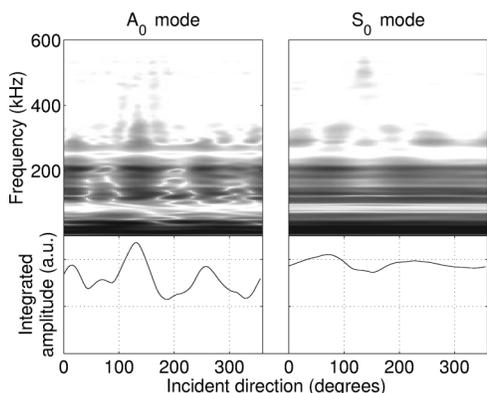


Fig. 3. Synthetic array analysis: Measured amplitude (\hat{C}) is shown as a grayscale function of frequency and incident angle for each mode. The frequency integral at each direction is plotted underneath.

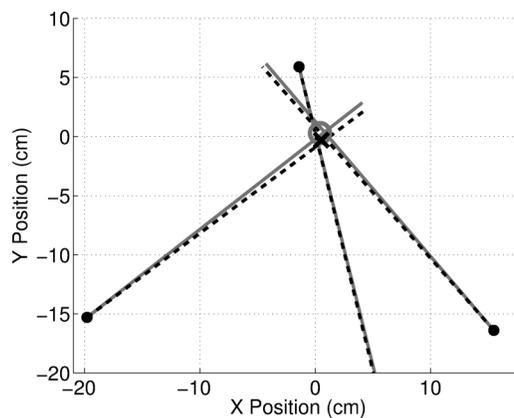


Fig. 4. Identification of leak location by triangulation from three measurement points. Results of the phase analysis method are in solid gray, and results of the synthetic aperture analysis are in dashed black.

spacecraft skin. A 1 mm (No. 59) hole was drilled through the plate and a vacuum pump was attached to pull air through the hole. A transducer assembly, consisting of two 1.35 mm diameter piezoelectric sensors operating well below resonance and spring loaded for repeatable coupling, was used to make measurements at 15° rotation increments and at frequencies between 80 and 600 kHz. The transducer spacing of 6 mm was selected to be on the order of the wavelengths involved. The measured leak noise signals from the transducers were fed into preamplifiers, sampled at 5 million samples per second (MSPS) for 1.6 s and immediately cross correlated. Cross correlations were recorded as the transducer assembly was rotated at each of three measurement locations on the plate, for redundant triangulation.

Both the phase variation and synthetic aperture methods can be used to analyze the measured cross correlations. In order to use the phase variation method, a frequency range in which one mode is dominant must be determined. This can be accomplished by comparing, as in Fig. 2, the measured amplitude of the phase variation with that calculated from Eq. (4) as a function of frequency for each of the two modes. In Fig. 2, we see dominance of the compressional mode up to around 80 kHz, flexural-mode dominance from 120–380 kHz, and compressional-mode dominance from 400–550 kHz. The more smoothly and closely the measured variation matches a calculated curve over a frequency range in Fig. 2, the better that frequency range is for direction finding. Experimentally, we are usually able to find an interference-free frequency range.

Estimated direction is calculated from the median phase over the frequency range of the variation of correlation phase with angle. With a selected a frequency range of 290–380 kHz the data from the experiment shown in Fig. 2 gives an estimated direction to the source of 133° compared with the actual direction of 131° . The same data analyzed with the synthetic aperture algorithm gives the angular distribution of each mode as a function of frequency, shown in Fig. 3, and an estimated (peak) direction of 132° . While the synthetic aperture analysis does not require a single-mode frequency range, selection of such a range may substantially improve contrast and hence robustness. For example, a 290–380 kHz frequency-limited synthetic aperture analysis more than quadruples the contrast (relative difference between the frequency peak and secondary frequency peaks) shown in Fig. 3.

The leak source location is determined through triangulation from measured directions from two or more measurement points. Figure 4 illustrates a complete leak location problem in our 4.76 mm thick aluminum plate with a 1 mm hole. Solid disks indicate the transducer assembly positions. Solid gray lines indicate directions measured with the phase method from the 290–380 kHz frequency range, while dashed black lines indicate directions measured with the synthetic aperture analysis of the same data set. The origin is the actual location of the leak,

while the gray “○” identifies the least-squares location estimate from the phase analysis method at (.4,.3) cm, and the black “×” indicates the least-squares location estimate from the synthetic aperture analysis at (.5,-.3) cm. Both methods provide approximately the same result from the same data.

Conclusions

Using a manually relocatable two-sensor array to make repeated measurements and triangulating allows estimation of the location of leaks-into-vacuum with a minimum of equipment and signal processing. The cross-correlation algorithm extracts the leak noise from incoherent electronic and ambient noise. The direction to the leak can be found either by measuring the phase variation over a 360° rotation, or with a synthetic aperture analysis. The Actual leak location is estimated by triangulating results from two or more sensor-pair locations. Our algorithm has been successfully tested experimentally on a 1 mm (No. 59) hole in 4.76 mm thick aluminum plate with signals measured from 80–600 kHz.

Acknowledgment

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