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An ultrasonic array sensor for spacecraft leak direction finding

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Abstract

We have developed an ultrasonic array sensor useable for locating air leaks in manned spacecraft and have found that this sensor locates leaks in a 1-m^2 plate to within 2 cm. The sensor consists of a 63-element multiplexed array plus a reference element, all constructed from a single PZT disc and a printed circuit board. Cross-correlations of signals from the array elements with signals from the single reference element provide a measurement of the leak noise passing through the spacecraft skin under the array. A spatial Fourier transform reveals the dominant direction of propagation. Triangulation from multiple sensor locations can be used to find the source of the leak.

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nondestructive testing, nondestructive evaluation

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Aerospace Engineering

Comments

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An ultrasonic array sensor for spacecraft leak direction finding.

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We have developed an ultrasonic array sensor useable for locating air leaks in manned spacecraft and have found that this sensor locates leaks in a 1-m^2 plate to within 2 cm. The sensor consists of a 63-element multiplexed array plus a reference element, all constructed from a single PZT disc and a printed circuit board. Cross-correlations of signals from the array elements with signals from the single reference element provide a measurement of the leak noise passing through the spacecraft skin under the array. A spatial Fourier transform reveals the dominant direction of propagation. Triangulation from multiple sensor locations can be used to find the source of the leak.

I. INTRODUCTION

Manned spacecraft are vulnerable to air leaks caused by micrometeorite and space debris impact [1, 2]. The ability to quickly detect, locate, and patch leaks is critical to the safety of any long duration spacecraft, such as the International Space Station or the proposed lunar base or mission to Mars. Current spacecraft use handheld ultrasonic directional microphones [3], similar to those widely deployed industrially [4], to detect the 40 kHz airborne ultrasonic hiss generated by the downstream leak turbulence. This method is less than ideal for the spacecraft environment because the downstream leak dissipates into the vacuum of space, leading almost no leak noise inside the spacecraft pressure vessel. The alternative approach that we propose is to monitor the spacecraft structure itself—the pressure vessel skin—for leak-generated ultrasound.

Our own previous work [5, 6] has demonstrated the applicability of structure-borne ultrasound in the spacecraft skin for locating leaks into vacuum. There is a substantial body of literature on using arrays for direction finding and source location. Sachse and Sancar [7] developed a small-array concept for locating the source of acoustic emission transients. A wide variety of algorithms have been developed in the signal processing community for array-based radio or sonar direction finding [8, 9]. Because the mathematical models underlying many of these algorithms are based on stochastic signal models, these same algorithms may be useful for situations such as the present case of locating a noise source in a environment dominated by other sources of noise. In this paper we discuss the development and characterization of an array sensor designed to provide robust measurements at low cost with minimal weight and size. Unlike most ultrasonic array sensors, our sensor does not require a large number of channels of complicated pulse-generation or data acquisition electronics, but instead uses an integrated multiplexer to minimize the required electronics. Because the sensor is passive—the ultrasonic source is the sound from the leak—no pulse generator is required. A spatio-temporal Fourier transform based f-k analysis of cross-correlations of detected signals is used to find the direction of the leak from the measured array data..

II. METHODS

The primary use of ultrasonic array sensors is in diagnostic medical ultrasound. For non-destructive testing applications, mechanical scanning has traditionally been used as a low cost alternative to large arrays. In recent years the use of arrays for non-destructive testing applications has increased dramatically, for example as a way to accelerate data collection, but these arrays remain very expensive.

Our ultrasonic array sensor is designed for the special purpose of locating leaks in the outer pressure vessels of manned spacecraft. Since a large number of arrays would be required in a practical application, the array must be simple, reliable, and of low cost. This array also has special capabilities, such as a reference element for cross-correlation of leak noise. The array is fabricated from a single printed circuit board using copper pads on one side of the board as array element electrodes, with associated electronics on the other side. While such construction details are not exactly new (e.g. [10]), this method of construction is not widely used, but is of broad utility because of the opportunity to integrate electronics and minimize interconnecting wiring.

Our sensor is constructed from a multilayer printed circuit board with multiplexers and preamplifiers on the front and 64 electrodes arranged in an 8×8 array on the reverse side. To mediate the sensing of ultrasonic vibrations, the electrode pattern on the reverse side of the circuit board is placed in direct mechanical contact with a disc of PZT (lead zirconate titanate). The 400-kHz resonant frequency piezoelectric disc is grounded on the side opposite the electrodes so that vibrations of the disc induce a voltage on the electrodes. Hence no sensitive solder connections to

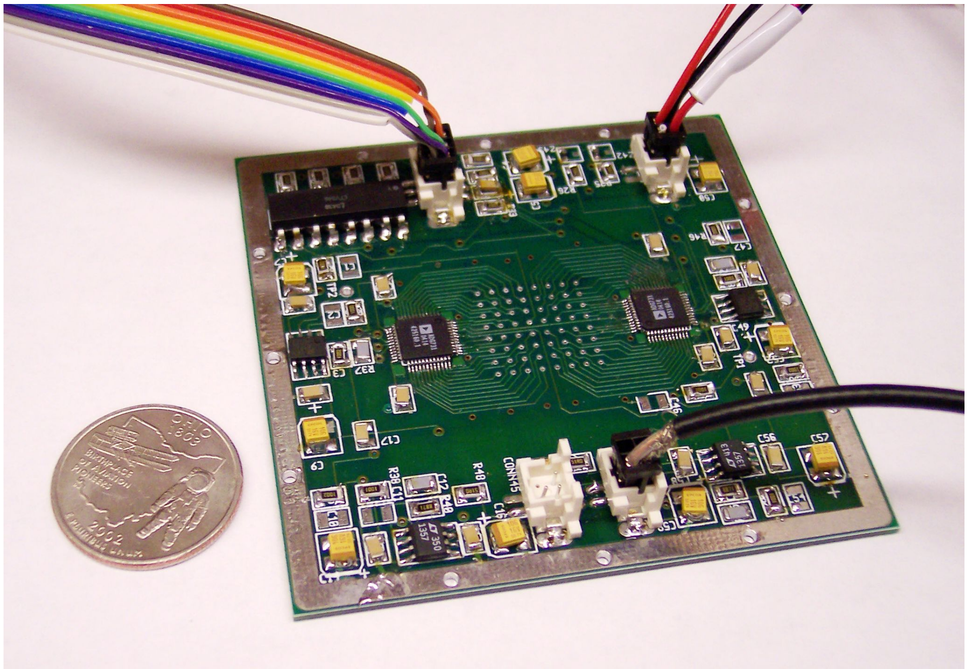

FIG. 1: Array sensor, showing electronics. A PZT disc element is placed under the grid at the center.

the PZT element are required, and neither is a large multiwire cable required to connect the transducer array to the electronics. Elimination of cabling also minimizes parasitic capacitance that acts to reduce the signal-to-noise ratio (SNR), and avoids the potential for noise-inducing ground loops.

Locating a leak from an internal pressurized volume into the vacuum of space with structure-borne noise is difficult because not only is the leak noise random, but also it tends to be buried under other noise sources, such as Johnson noise in the preamplifier. The mathematical operation of cross-correlation, as in [11], can be used to extract meaningful and repeatable statistics from the measured noise, but requires data from an extra reference sensor with which to cross-correlate.

Our model for the skin of the spacecraft is a 3.2-mm thick aluminum plate with integral stiffeners and a localized evacuation device on one side attached to a vacuum pump. Air leaks through a 1-mm drilled hole generating noise that couples into the plate itself. The leak noise is assumed to propagate radially outward through the plate as guided Lamb modes. The array sensor, shown in Fig. 1, is placed a short distance away. It consists of a 4.5-mm thick, 25-mm diameter PZT disc (400 kHz thickness resonance) underneath a printed circuit board with an 8×8 array of electrodes on 2-mm centers printed on the back. In the middle of each electrode is a "via", or conductor, through the circuit board that connects the electrode to a trace on the top layer of the circuit board and is visible as one of 64 tiny circles in the center of Fig. 1. All but one of these traces is connected through one or two ganged 32 channel analog multiplexer IC's (Analog Devices ADG731) into a two-stage preamplifier. The one remaining electrode is for the reference element and connects to its own dedicated two-stage preamplifier.

The preamplifiers are designed for near optimal noise performance. They are very high impedance (10 MΩ) to match the PZT source and use the high impedance Texas Instruments OPA637 amplifier as a front end. Both preamplifiers give 40 dB gain in the first stage followed by a capacitive-load capable second stage with 20 dB gain. The preamplifiers have useable bandwidth from 1.5 to 500 kHz. The preamplifier outputs are attached directly to a PC waveform capture card, and the multiplexer control inputs are attached through an optoisolator to the PC's parallel port. The PC is programmed to switch between the elements as it collects and cross-correlates waveforms from the two preamplifiers. Of note is the very small amount of interconnect wiring required. The sensor has only two analog outputs, a handful of digital control wires, and power input. Conceptually it could be mated with a dedicated processor to perform the waveform acquisition and cross-correlation, leading to a unit which requires only power and a single (possibly RF) communications medium.

III. THEORY

Passive leak location is fundamentally different from most ultrasonic inverse problems because it deals exclusively with random signals. Locating the leak is an exercise in extracting the leak-generated noise from other background noise sources such as Johnson (preamplifier) noise. This is achieved by extracting statistics of the noise using the mathematical operation of cross-correlation. By using the cross-correlation and spatial- and temporal- Fourier transforms (f-k analysis) we are able to examine only that noise which has the temporal and spatial coherence patterns expected for guided ultrasonic Lamb waves in the plate-like skin of the spacecraft and determine the direction to the leak. The continuous-wave nature of the leak noise makes the source-location problem quite different from that for locating transient events. For example, time windowing cannot be used to gate out distant reflections, as those reflections still correlate with themselves.

Let us begin by writing the frequency spectrum (Fourier transform) of the leak generated ultrasound at the location of the leak:

$$A_i(f)\exp(j\phi(f)), \tag{1}$$

where $A_i(f)$ is the amplitude spectrum of the leak noise coupled into guided mode i in the spacecraft structure and $\phi(f)$ is the phase spectrum. The amplitude $A_i(f)$ is a consistent quantity, whereas the phase $\phi(f)$ is random. Suppose the leak is at the origin $(x, y) = (0, 0)$ of a two dimensional surface, and suppose we measure waveforms at locations $\underline{r}_1$ and $\underline{r}_2$. The measured waveforms, ignoring irrelevant amplitude losses due to geometric diffraction and material attenuation, will be phase delayed according to the propagation distances,

$$\sum_i A_i \exp(j\phi + jk_i|\underline{r}_1|) \tag{2}$$

at $\underline{r}_1$ and

$$\sum_l A_l \exp(j\phi + jk_l|\underline{r}_2|) \tag{3}$$

at $\underline{r}_2$, where k_i and k_l, implicit functions of frequency, represent the dispersion relations of modes i and l respectively. The frequency dependence of ϕ and A_i will also be implicit from here on. The time-domain cross-correlation (frequency domain: complex conjugate product) of Eqs. 2 and 3 is

$$\sum_{i,l} A_i A_l \exp(-j\phi + j\phi - jk_i|\underline{r}_1| + jk_l|\underline{r}_2|). \tag{4}$$

What is important here is that given a sufficiently long cross-correlation the signal randomness cancels out of the equation. The random factor $\exp(-j\phi)\exp(j\phi)$ is unity (nonrandom). The resulting cross-correlation, represented in the frequency domain, is

$$\sum_{i,l} A_i A_l \exp(-jk_i|\underline{r}_1| + jk_l|\underline{r}_2|). \tag{5}$$

Suppose we fix $\underline{r}_1$ and replace $\underline{r}_2$ with a fixed $\underline{r}_2$ plus a variation vector $\underline{r}_3$. Figure 2 illustrates the newly defined geometry. The vector $\underline{r}_1$ points from the leak at the origin to the reference sensor, $\underline{r}_2$ points to the center of the array, and $\underline{r}_3$ points to a particular array element from the center of the array. The cross-correlation from Eq. 5 is now

$$\sum_{i,l} A_i A_l \exp(-jk_i|\underline{r}_1| + jk_l|\underline{r}_2 + \underline{r}_3|). \tag{6}$$

If $|\underline{r}_2| >> |\underline{r}_3|$ (the leak is much further from the array than the size of the array), then we can approximate $|\underline{r}_2 + \underline{r}_3|$ by $|\underline{r}_2| + \underline{r}_3 \cdot \hat{e}_2$, where $\hat{e}_2$ is the unit vector in the direction of $\underline{r}_2$, $\hat{e}_2 \equiv \underline{r}_2/|\underline{r}_2|$. The cross correlation therefore becomes

$$\sum_{i,l} A_i A_l \exp[-jk_i|\underline{r}_1| + jk_l|\underline{r}_2| + jk_l(\underline{r}_3 \cdot \hat{e}_2)]. \tag{7}$$

To simplify let

$$C_l = \sum_i A_i A_l \exp(-jk_i|\underline{r}_1| + jk_l|\underline{r}_2|). \tag{8}$$

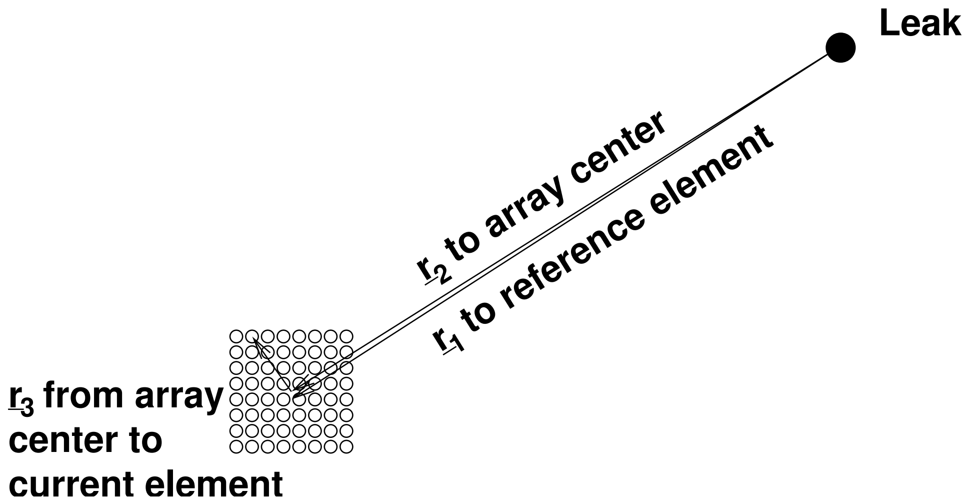

FIG. 2: Diagram showing $\underline{r}_1$, $\underline{r}_2$, and $\underline{r}_3$ relative to leak and sensor.

The new coefficient C_l depends on the fixed r_1 and r_2, but not on the varying r_3. C_l carries the implicit frequency dependence of the amplitudes and wavenumbers A_i and k_i. By factoring out C_l, the cross-correlation is simplified into

$$\sum_l C_l \exp[jk_l(\underline{r}_3 \cdot \hat{e}_2)]. \tag{9}$$

To represent the fact that we will only be varying $\underline{r}_3$ over a very limited range we add a spatial windowing factor $w(\underline{r}_3)$,

$$\sum_l C_l w(\underline{r}_3) \exp[jk_l(\underline{r}_3 \cdot \hat{e}_2)]. \tag{10}$$

This windowing factor will be unity over the array and zero elsewhere. A two-dimensional spatial Fourier transform of the cross-correlation, transforming $\underline{r}_3$ to $\underline{k}$ is

$$\int\int \sum_l C_l w(\underline{r}_3) \exp[jk_l(\underline{r}_3 \cdot \hat{e}_2) - j(\underline{k} \cdot \underline{r}_3)] d^2\underline{r}_3 \tag{11}$$

or

$$4\pi^2 \sum_l C_l \delta^2(\underline{k} - k_l\hat{e}_2) *_{\underline{k}} W(\underline{k}), \tag{12}$$

where δ^2 is the two-dimensional Dirac delta, $*_{\underline{k}}$ represents wavevector-space convolution, and $W(\underline{k})$ is the spatial Fourier transform of the windowing factor $w(\underline{r}_3)$. Recall that k_l is the scalar wavenumber of mode l at the frequency under consideration and that $\hat{e}_2$ is the direction from the leak to the sensor array. Equation 12 predicts that the spatial Fourier transform of the cross-correlations will consist of dots (from the two-dimensional Dirac delta) located at $\underline{k} = k_l\hat{e}_2$. All of the dots will be in the direction $\hat{e}_2$ from the leak to the array, and the radius from the origin to the dot is the magnitude of the wavenumber k_l of the corresponding propagating Lamb mode. These dots will also be spread and blurred according to the spectral response $W(\underline{k})$ of the windowing factor $w(\underline{r}_3)$, which is a simple rectangular window.

Our procedure for determining the direction of the leak, inspired by Eq. 12, will involve collecting cross-correlations of the array element waveforms with the reference element waveform for all array elements, then performing Fourier transforms in time, x, and y. These data will be integrated over frequency to maximize the signal-to-noise ratio, and then the dominant direction in $\underline{k}$ space is determined by radial integration. To simplify interpretation, we will reverse the data when plotted so that the peak in (k_x, k_y) space points towards the leak rather than away from it.

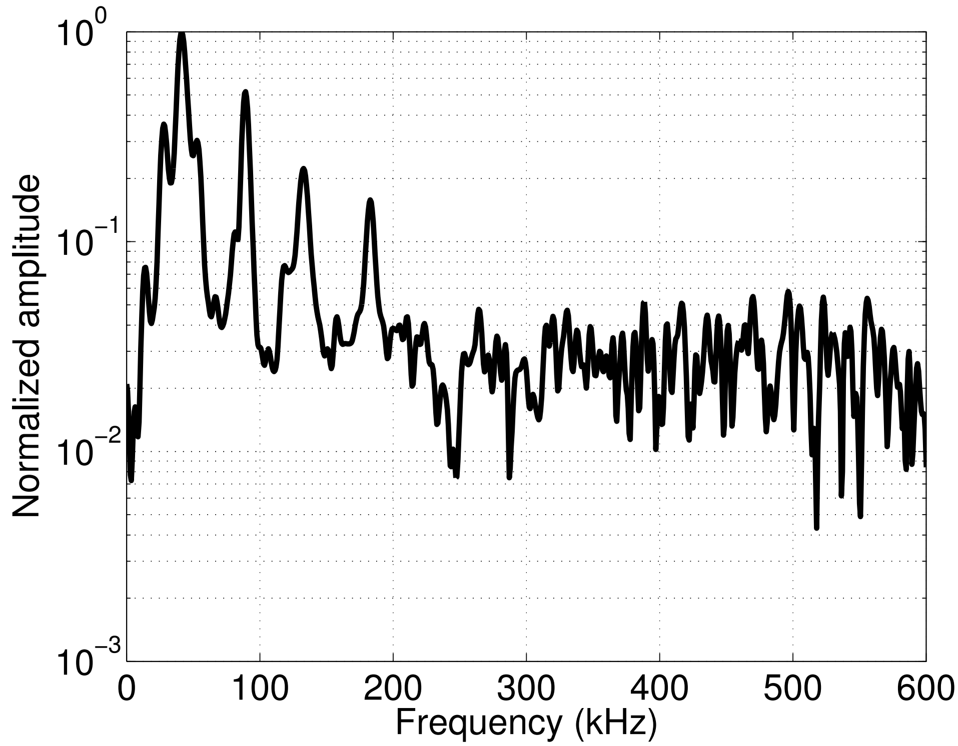

FIG. 3: Frequency spectrum of a leak noise cross-correlation. The peaks below 200 kHz are resonances within the PZT element.

IV. RESULTS

We performed a series of experiments with our prototype array at a variety of locations on our test plate to evaluate the performance of the array sensor in locating the leak. Figure 3 illustrates the frequency spectrum of a typical correlation. The data shown comes from 2M samples collected at 5 MSamples/s. It has been processed first by differentiation, then by 500-kHz low pass filtering, by division-by-four downsampling to 1.25 MSamples/s, and finally split into 2000 segments which were each cross-correlated and then averaged together. The segmentation process improves cross-correlation performance and discards correlations with large time deltas that are not useful for direction finding. Primarily visible in Fig. 3 is a series of peaks below 200 kHz. These peaks correspond to radial resonances of the PZT disc. Useful information for source location is contained in the spectrum above 200 kHz, and we therefore selected the frequency range 200–300 kHz for our processing.

We collected and recorded processed cross-correlations of waveforms from each of the 63 multiplexed elements with the corresponding waveforms from the reference element. Because data from the reference element could be used directly, the average of the correlations from the four nearest neighbors was used in its place as the 64'th element. Processing consisted of a series of steps:

1. The spectra were compensated in the frequency domain to correct for frequency- and element-dependent parasitic capacitance by multiplying by a calibration spectrum.

2. The spatial average voltage for each time-sample was subtracted from the data.

3. The data were fast Fourier transformed in time.

4. Temporal frequencies beyond the Nyquist limit (equivalently, negative frequencies) were zeroed.

5. The resulting spectra were spatially zero-padded from 8×8 to 32×32 and fast Fourier transformed in both spatial dimensions.

6. The complex magnitudes of the transformed data were integrated over the frequency range 200–300 kHz.

7. The resulting integral was plotted to show intensity as a function of horizontal and vertical wavenumber.

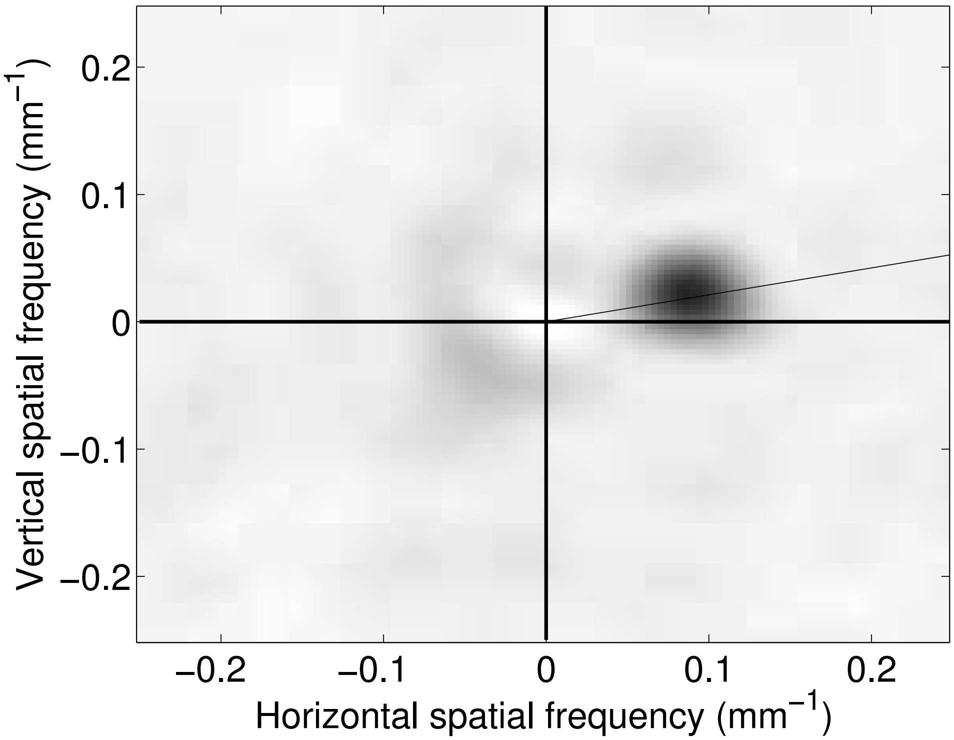

FIG. 4: Spatial Fourier transform of measured correlations, integrated from 200-300 kHz. The estimated direction of the leak is 12 deg from the horizontal.

Figure 4 shows the amplitude as a function of wavenumber, integrated over frequency from 200 to 300 kHz. The direction of the leak was found to be at an angle of 12 deg above the horizontal. Triangulation from two more array locations, illustrated in Fig. 5, gives a reliable estimate of the leak location. In this case the leak was located with an error of 10.6 mm on a 1 m^2 plate with integral stiffeners. These results are typical of many others we have obtained, and location error is generally less than 2 cm. While the experiment shown is not worst-case from a geometric perspective (the sensors are not maximally separated on the 1 m^2 plate), this experiment does illustrate the effect of integral stiffeners used in aerospace structures to enhance stiffness.

We therefore investigated in more detail the case in which there is an integral plate stiffener between the leak and the array. The integral stiffeners in this plate are 25mm-high ridges in the aluminum which increase bending stiffness while minimizing added weight, and are commonly used in aerospace applications. In contrast to other previously developed methods [6], which we have since shown to be ineffective across integral stiffener boundaries, the presence of an integral stiffener between the leak and the array does not inhibit direction finding. The lower right array position used for the above-described results in Fig. 5 was on the far side of an integral stiffener. The resulting $\underline{k}$ space map from the array at this location, shown in Fig. 6, is essentially similar to Fig. 4, but with a slightly higher noise floor. The wavenumber mapping from this array location, shown in Fig. 6, clearly shows the direction to the leak. It also indicates a reflection from another integral stiffener, barely visible as a darkened region in the lower left quadrant of Fig. 6. Phase interference from reflections within a stiffener does not inhibit direction finding by the array. Nevertheless, waves scattered or reflected by a stiffener can appear as smaller secondary peaks. In this experiment, in addition to the two stiffeners shown on fig 5, there were several more just off the edge of the plot. These generated additional reflections and interference, but not enough to prevent successful direction finding.

V. CONCLUSIONS

The array sensor directly measures the angular spectrum of the leak-noise-generated ultrasound propagating under the array. This is accomplished with an analysis based on the spatial Fourier-transform of phased array cross-correlations. The direction to the leak is determined from the dominant direction in wavenumber (k_x, k_y) space. Triangulation from multiple arrays or different positions of one movable array gives the location of the leak. The

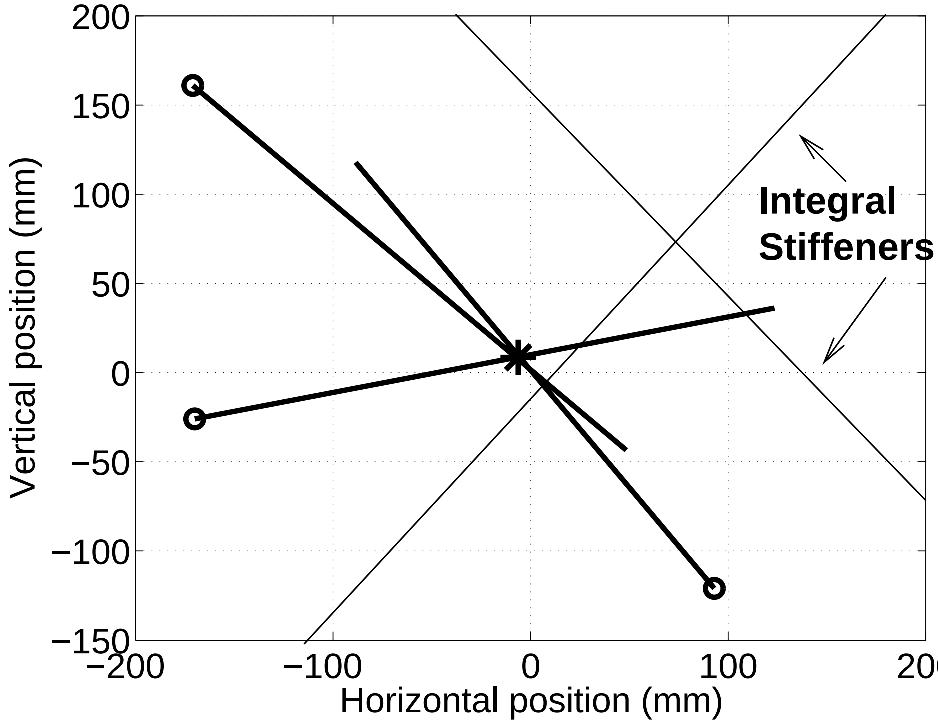

FIG. 5: Leak location and least-squares triangulation from three array locations ('o') to find the estimated leak location ('*') at coordinates (-6.3,8.5) mm. The actual location of the leak was the origin. Data from the sensors at coordinates (-175,-25) and (90,-120) are shown in Figs. 4 and 6 respectively.

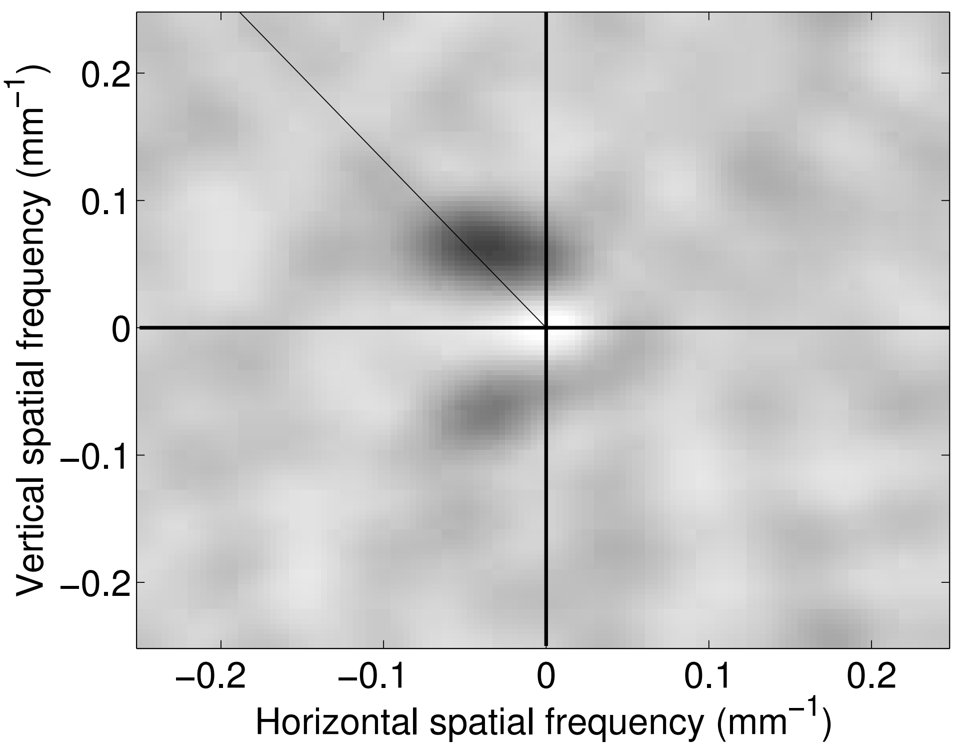

FIG. 6: Spatial Fourier transform of measured correlations, integrated from 200-300 kHz of the sensor shown in the lower right of Fig. 5.

method is inherently robust both because of the simple processing, and because of the small amount of information being extracted – direction to the leak – from the large amount of data collected – the 63 cross-correlations. The direction to the leak can be found simply and reliably, even in the presence of tall integral stiffeners.

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