THE ROLE OF PROPAGATION CHARACTERISTICS IN ACOUSTIC EMISSION PIPELINE LEAK LOCATION

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INTRODUCTION

The highly dispersive nature of fluid-filled pipeline systems makes the use of traditional time-of-flight source location techniques generally ineffective. Because such methods rely on the assumption of a non-dispersive signal, they do not compensate for the multimodal characteristics of a real acoustic signal. This paper describes on-going work at ISU to understand the underlying principles of multi-mode propagation in fluid-filled pipes and to develop leak location signal processing which accounts for these propagation characteristics. Results which examine some of the practical problems to be encountered in the application of the previously-reported method, which uses both spatial and temporal transforms to isolate modes and determine source location, are reported. Data are presented that show the effect of transmission line interruptions. It is shown that the characteristics of a pipeline vary as a function of distance along the pipe, and that these characteristics can be determined empirically. Results indicating the effect of system background noise are also presented.

BACKGROUND

The typical time-of-flight method for performing source location in liquid-filled pipes is cross-correlation. Use of this technique assumes that each of the received signals is a non-dispersed time-delayed replica of the source signal. A large peak in the cross-correlation function indicates the delay in arrival times of the signals, where the difference in arrival times is directly related to the distance between the two sensors and the source. However, in a dispersive system, energy propagates in multiple dispersive modes, each with a different velocity, and cross-correlation generally does not produce a well-defined peak. In fact, the more dispersed the signals become, the poorer the results of the method, so method performance degrades as source-to-sensor distance increases.

To account for these dispersion-related weaknesses, previous work at CNDE [1] has focused on two issues: gaining a better understanding of pipeline propagation, and accounting for dispersive effects in location algorithms. A symmetric pipeline model was developed to help better understand a pipeline system's dispersive nature. The model, developed around the simplest case of an axi-symmetrically located source in a long water-filled pipe surrounded by air, was verified and used to predict the dispersion characteristics of the pipeline.

Development was also begun on a robust, generalized cross-correlation algorithm. [1] The method requires that the individual modes within the leak signals be isolated. Mode isolation, discussed more fully in [1], is accomplished empirically by taking a spatial array of time-series waveforms along the length of the pipe and Fourier transforming the data in both the spatial and temporal directions. The transformed data can be used to produce an image of the pipeline dispersion characteristics. Figure 1 shows the results of such a transformation on both theoretical and experimental axi-symmetric signals captured at 81 spatial points with one centimeter intervals along a water-filled 2" steel pipe.

DISPERSION CHARACTERISTICS: STRAIGHT PIPE

To more thoroughly characterize the dispersion properties discussed above, extensive data were gathered along the length of a straight, water-filled pipe. Over 1300 waveforms were collected at one centimeter intervals, extending more than 44 ft. from the source, along the same 63' length of 2-inch, schedule 40 galvanized steel pipeline used to collect the experimental data in Figure 1. A 500 kHz center-frequency ultrasonic transducer, coupled directly to the water through a thin rubber membrane, was used as a repeatable axi-symmetric source. The waveforms were collected with a 10-100 kHz sensor in point-contact with the pipe wall and recorded with a digital oscilloscope. Each signal was bandpass filtered from 20 - 100 kHz and averaged twenty-five times to minimize background noise. Waveforms were sampled at 500 kHz with a total window of 20 ms.

Dispersion plots similar to the ones presented in Figure 1 were then produced at five pipe diameter (PD) intervals out to a distance of 250 PD along the characterized pipeline. Eighty-one consecutive waveforms were used to generate each image.

An examination of the dispersion plots from various locations show several interesting phenomena. First, non-symmetric as well as symmetric modes are being generated within the system. A comparison between the theoretically predicted dispersion curves in Figure 1 and the curves in Figure 2 illustrate the presence of the extra modes. The non-symmetric modes, however, appear to contain much less energy than do the symmetric modes, as indicated by the lighter, narrower curves. Energy traveling in the opposite direction as the original signal can also be seen as the "mirror image" effect along the top axis of the plots in Figure 2. This is energy which is believed to have been reflected either from the end of the pipe or some other pipeline feature (e.g. pipe coupling).

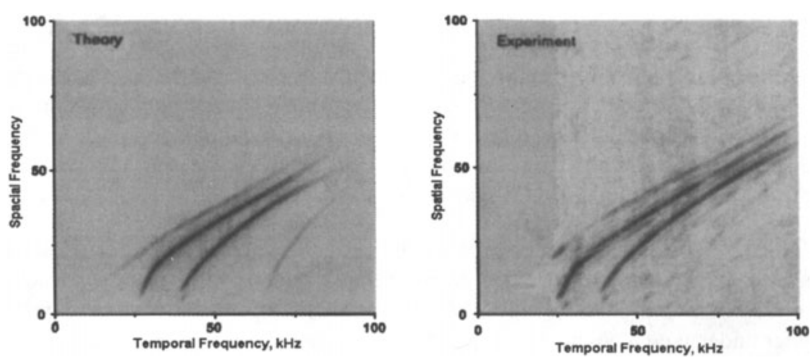

Figure 1. Theoretical and experimental dispersion characteristics of a 2" water-filled pipe.

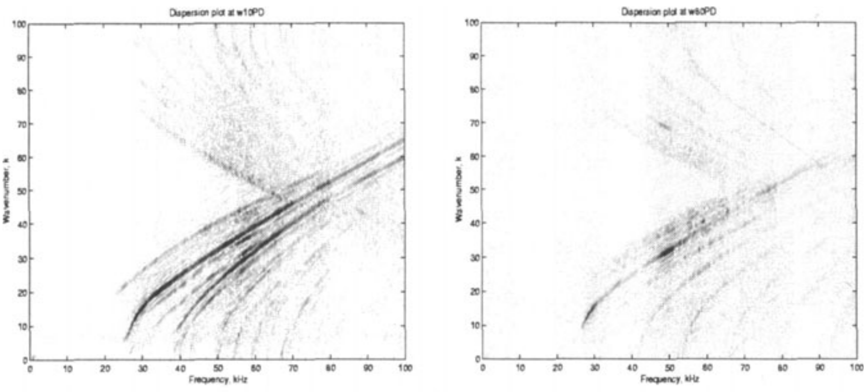

Figure 2. Dispersion properties at 10 and 80 pipe diameters from source.

A comparison of the dispersion curves at various axial locations shows that the dispersion properties are not constant. For example, certain modes appear at nearly every location along the pipe, while other modes appear only at particular, non-consecutive positions. Mode strength also appears to change as a function of location, as seen in Figure 2.

Further, and perhaps most interestingly, mode position within the frequency plane varies as a function of location along the pipe. Figure 3 shows a composite plot of the dispersion properties at 125 and 235 PD from the source. While the two prominent curves appear to represent different modes, an examination of plots of intermediate positions shows that they are in fact the same mode, shifted to different positions within the frequency plane. Possible reasons for this shift may include variations in pipe wall thickness, pipe diameter, and metal homogeneity. Precisely speaking, a rigorous source location would require an equally rigorous characterization of all such variations in propagation properties along the pipeline. However, for practical applications, a reasonable average estimate of the propagation characteristics of the detected modes should provide a sufficient location accuracy.

The aspect of the problem in which these fluctuations *are* critical to source location is in mode detection within the array measurement interval. Clearly, in Figure 3, if one assumed

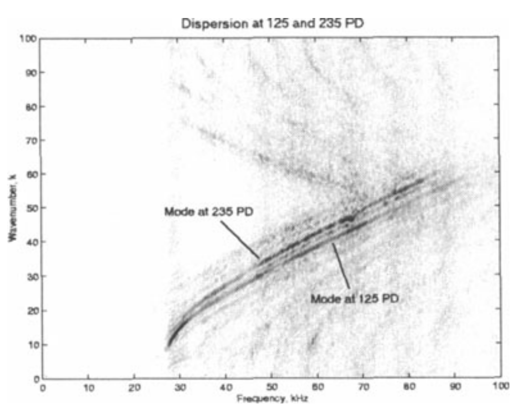

Figure 3. Composite of dispersion curves from 125 and 235 pipe diameters.

data collected at 235 PD lay in the same position as the dispersion curve measured at 125 PD, the mode's contribution would be completely missed! This observation underscores the importance of careful characterization of the propagation characteristics over each measurement access interval. It may in practice be possible to visually identify mode positions by viewing the data from a detected leak in the frequency plane, provided adequate signal-to-noise is available. As will be shown later in Figure 8, however, robust locations can be extracted from noisy data in which the mode structure is not visually detectable. For maximum sensitivity it therefore appears prudent to perform an explicit transmission line characterization at each measurement position using a locally-positioned source.

PIPELINE DISPERSION PROPERTIES: ELBOWED PIPE

The effect of transmission line interruptions was studied by collecting data on a pipeline configuration consisting of a straight 63' section and a shorter 21' section, connected by a single 90 degree elbow. Experiments similar to those described above were conducted to determine what effect a line complication, in this case an elbow, would have on both the dispersion characteristics of the line and on the ability to perform source location using the algorithm. As in the original experiments, an axi-symmetric source was used. Waveforms were collected at 0.5 cm intervals along nearly the full length of the 21' section of pipe, and along approximately 10' of pipe following the elbow. In all, nearly 1800 waveforms were collectedout to a distance of 190 PD from the source. In the data shown below, the spatial and temporal sampling frequencies from the previous experiments, 100 samples/m and 500 kHz, respectively, were used.

Figure 4 shows examples of the dispersion curves found at locations both before and following the elbow, 50 and 150 PD, respectively. Comparing these plots to those presented in Figures 2 and 3, the most obvious difference is the increased number of modes in the elbowed pipe configuration. It is evident that reflection/transmission at the pipeline elbow is coupling the axi-symmetric modes generated at the source into numerous non-symmetric modes. An indication of the complexity of mode structure introduced by inclusion of non-symmetric modes is provided by Figure 5, which superimposes the loci of all cusps (infinite and finite) in the denominators of mode terms for angular orders 0 through 3, corresponding to both free-propagating and spatially decaying modes of propagation. The increased density of contributing modes presents challenges for mode isolation. Resolution of closely-spaced

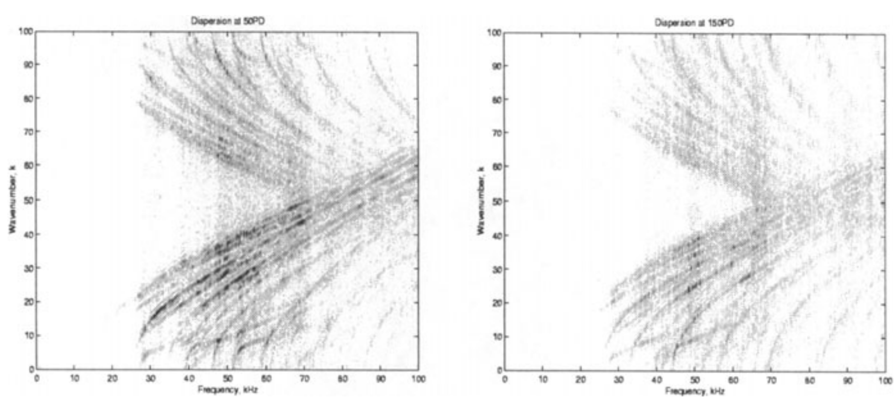

Figure 4. Non-symmetric dispersion properties of an infinitely long fluid-filled pipe.

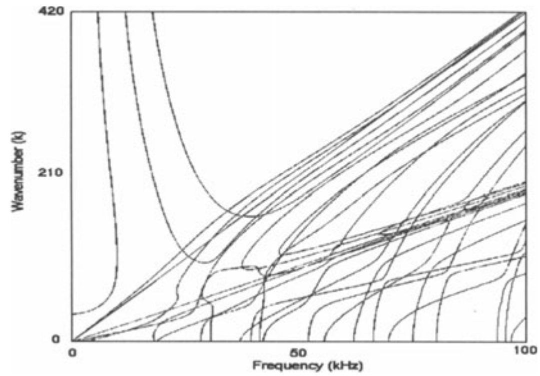

Figure 5. Dispersion characteristics of an elbowed pipe configuration at different locations.

modes requires a correspondingly large spatial sampling interval - a potential problem in practice. This result suggests a procedure which selects a well-isolated mode for source location, determined through an *a priori* pipeline characterization.

Data on the elbow configuration were also collected using a low frequency (100 Hz - 20 kHz) accelerometer. These data were used to check the low frequency dispersion properties of the system and, in conjuction with the data taken previously, generate a plot of the dispersion properties for the full frequency range between approximately 10 - 100 kHz. Figure 6 shows the low frequency response and the total dispersion map after combining with the earlier data.

The most notable information found from the low-frequency data is that the modes do not appear to shift with prosition, as demonstrated in Figure 3. Analysis of the mode response at all locations where low-frequency data was recorded shows that modes' positions within the frequency plane are constant, with no changes either over single intervals or longer distances.

SOURCE LOCATION

Source location using the generalized cross-correlation [1] can be accomplished in two ways: by isolating two separate modes in the data from one sensor location and determining the difference in their arrival times, or by isolating the modes in data from two different sensor locations and finding the difference in those arrival times. In the following discussion, the second method, using data from two different sensor locations, is described.

If the signal V from each of two sensor locations A and B is assumed to be the sum of n modes, with each mode consisting of an amplitude A_n and a phase $e^{ig_n(\omega)z}$, where g_n is the wave number and z is the distance to the source, then for any two modes i and j, the following expression [1] can be written

$$C(z) = \int \hat{A}_i^A(\omega)\hat{A}_j^{B*}(\omega)e^{i(g_i(\omega)z_A - g_j(\omega)z_B)}e^{if(\omega, z)}d\omega. \quad (1)$$

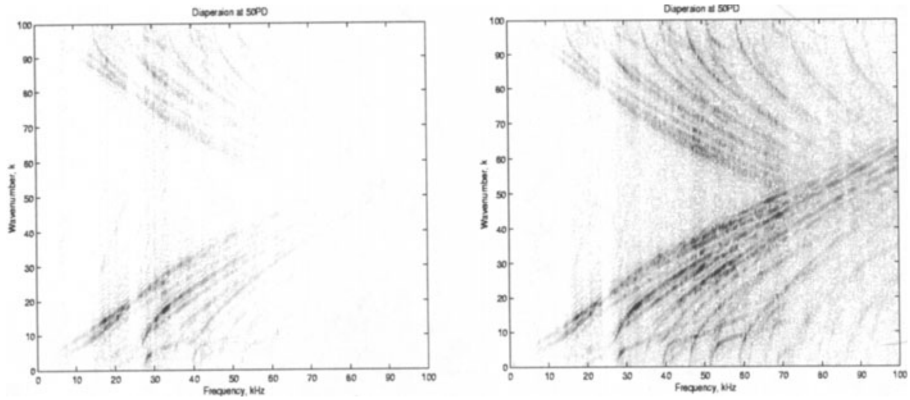

Figure 6. Low frequency mode response and full dispersion map at 50 PD

For this calculation, it is desired that the arbitrary function $f(\omega, z)$ in the second phase term have conjugate phase of $\hat{A}^{A}\hat{A}^{B*}$ when z corresponds to the location of the leak. Under these conditions, if $i=j$ (i.e. the modes are the same), then $f(\omega, z) = -ig_i(\omega)(z_A - z_B)$, the integrand becomes real-valued, and the function is maximized at the distance $z = z_A - z_B$. This produces a peak in the function similar to the peak found in a typical cross-correlation. In fact, if the wavenumber is linear with frequency, i.e. $g_n(\omega) = \omega/q$, where q is a constant, Equation 1 reduces to the cross-correlation function.

Location calculations were performed on both the straight and elbowed data, using both symmetric and non-symmetric modes. For the straight pipe data, calculations were done at sensor-to-source distances up to 250 PD (12.7 m), or a maximum sensor separation of more than 83 ft (25.4 m). For the elbowed data, location calculations were performed for sensor separations up to 63.2 ft, around either zero, one, or two elbows, depending on the data.

Figure 7 shows the results of a typical location calculation using straight pipe data from 20 and 135 PD, a sensor separation of approximately 26 ft (7.8 m). The figure includes a plot of the dispersion map produced by Fourier transformation in time and distance, as well as location estimates calculated by both a modal analysis and standard cross-correlation. The dispersion map is used to find a prominent mode segment over which to perform the line integration show in Equation 1. The line segment highlighted in Figure 7 was used to calculate the location shown in the modal analysis location estimate.

In this case, with a very large (> 60) signal-to-noise ratio (SNR), the modal analysis produces a nearly exact location, after accounting for measurement and rounding errors. The location estimate is also sharply peaked, corresponding to the length (bandwidth) of the mode segment used to calculate the location. Spatial resolution of the location is inversely proportional to the bandwidth of the signal, meaning the larger the bandwidth, the finer the resolution on the location estimate. This also means that, theoretically, location estimates can be produced using mode segments covering very small bandwidths. For this data, meaningful locations can be determined using this mode segment down to bandwidths of less than 2 kHz.

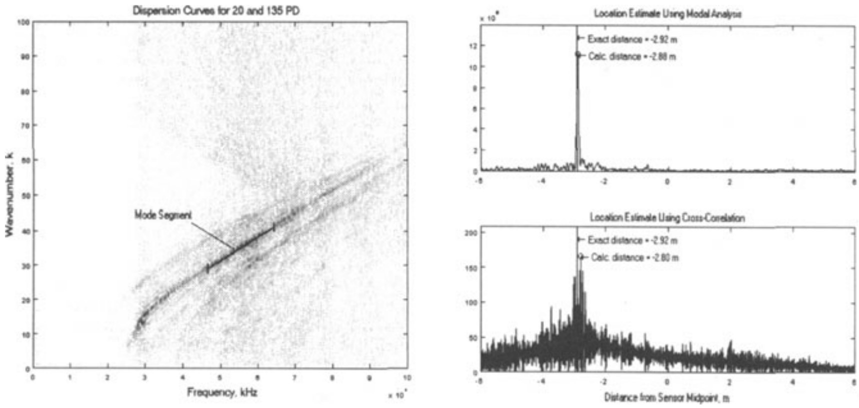

Figure 7. Location estimates for data from a straight pipe.

It has been found, however, that the method is sensitive to the ability to adequately isolate a strong mode. In any calculation where the mode can be located and isolated in the frequency plane, the method should produce exact results, assuming the dispersion properties are uniform everywhere between the array measurement interval and the source, since the method utilizes the phase information contained in the chosen mode segment. However, as the chosen segment moves from the actual mode location within the plane, errors appear in the location estimate. The presence of multiple, overlapping modes in a line segment can also give rise to errors, where the phase information contained in each mode contaminates the estimate calculated using the dominant mode. Given the large number of modes shown in Figures 4-6, it is obvious where this has the potential to be a problem.

Several experiments were conducted to determine the method's performance under more realistic noise conditions. A white noise signal was introduced into the pipeline via function generator and several 81-waveform data sets of background noise were recorded at different locations on the pipe. This guaranteed that the noise was random and uncorrelated. The background noise was then added to the original signals at different SNRs and the location calculations repeated with both the modal algorithm and standard cross-correlation.

The results of these experiments showed that the standard cross-correlation was more sensitive to the level of background noise, in some cases an order of magnitude more sensitive, than was the generalized method. Overall, the cross-correlation was unable to determine an accurate location below a SNR of approximately 0.60. The modal analysis, by comparison, was able to determine an accurate location estimate to a SNR of 0.10 or better. Figure 8 shows the results of the same location calculation presented in Figure 7 at a SNR of 0.20. While the cross-correlation has spread and the location peak been lost completely, the peak from the generalized method is still easily discernable, despite the fact that the additional noise has nearly hidden the modes within the dispersion map and the noise surrounding the peak has increased. As was noted earlier, however, in order to perform this calculation it was necessary to know *a priori* the location of the chosen mode within the frequency plane. In this case, that information was determined using the virtually noiseless data in Figure 7.

Similar experiments with data from the elbow configuration show similar results. Since, however, the energy in the system is spread among more of the non-symmetric modes,

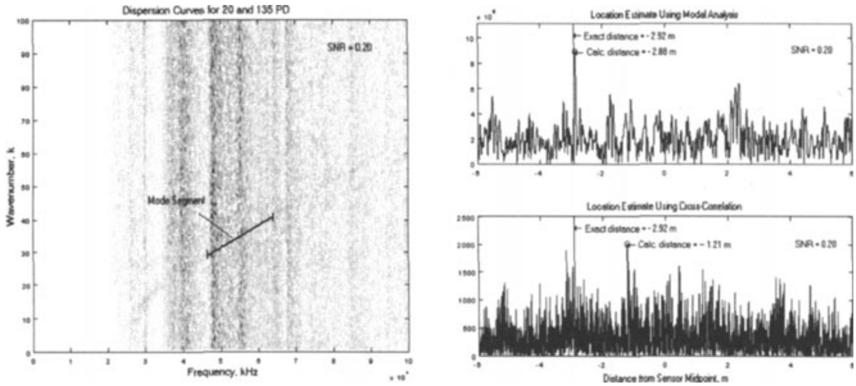

Figure 8. Straight pipe location in the presence of background noise.

the method is not as noise-intolerant as it is with the straight pipe data. Nonetheless, even with greater noise sensitivity, the modal analysis is still less sensitive to noise than is the standard cross-correlation. It was also found that greater care must be used when picking a mode along which to perform the integration, since a larger number of modes tend to appear in the more complicated pipeline system.

SUMMARY

A generalized cross-correlation method is under development at CNDE to help account for the effects of dispersion in acoustic emission leak location. Data were collected to examine several problems that would be expected in moving the method to field application. From the data, the following observations have been made. First, both symmetric and non-symmetric modes are generated. Second, mode dispersion characteristics vary over the length of the pipe, particularly at frequencies above 30 kHz. And third, energy distribution among the modes varies over the length of the pipe.

Finally, the method has also been found to be sensitive to the ability to properly isolate modes to use in the location algorithm. Future work is expected to focus on developing methods to better isolate chosen modes, and help pick appropriate modes in complicated multi-mode systems. Additional experiments will extent the study to longer, more complicated systems, and test different types (e.g. size, material) of pipe.

ACKNOWLEDGEMENTS

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