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Frequency Domain Analysis for Detecting Pipeline Leaks

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ABSTRACT

This paper introduces leak detection methods that involve the injection of a fluid transient into the pipeline, with the resultant transient trace analyzed in the frequency domain. Two methods of leak detection using the frequency response of the pipeline are proposed. The inverse resonance method involves matching the modeled frequency responses to those observed to determine the leak parameters. The peak-sequencing method determines the region in which the leak is located by comparing the relative sizes between peaks in the frequency response diagram. It was found that a unique pattern was induced on the peaks of the frequency response for each specific location of the leak within the pipeline. The leak location can be determined by matching the observed pattern to patterns generated numerically within a lookup table. The procedure for extracting the linear frequency response diagram, including the optimum measurement position, the effect of unsteady friction, and the way in which the technique can be extended into pipeline networks, are also discussed within the paper.

Keywords—
Leakage; Water pipelines; Frequency response; Resonance; Transient flow; Linear systems.

I. INTRODUCTION

Fluid transients in pipes—water hammer waves—are affected by pipeline features, including leaks and blockages, thus leaving clues that can be used for the identification and location of such features. Analysis of transients can reveal a substantial amount of information concerning the integrity of the system. Numerous methods utilize transient behavior for the purpose of leak detection. These include the inverse transient method ~Liggett and Chen 1994; Nash and Karney 1999; Vítkovský et al. 1999; 2001!, the transient damping method ~Wang et al. 2002!, and timedomain reflectometry techniques ~Jönsson and Larson 1992; Brunone 1999; Covas and Ramos 1999!. This paper proposes the use of a generated input signal for leak detection and signalprocessing techniques as a means of analyzing these signals in the frequency domain. The concepts of steady oscillatory flow and pipeline resonance are well established, and details can be found in Zielke et al. ~1969!, Zielke and Rösl ~1971!, Chaudhry ~1970, 1987! , and Wylie et al. ~1993!. While a pipeline reinforces and transmits input signals of a particular frequency ~for example, the fundamental frequency!, others are effectively absorbed within the system. Thus, pipeline systems are similar to frequency filters for weakly nonlinear unsteady systems, the characteristics of which are determined by system properties, such as boundary conditions, friction, and wave speed. The degree that each frequency component is absorbed or transmitted within the pipeline is defined by a frequency response diagram ~FRD!, also known as the transfer function for the system ~Lynn 1982!. This diagram relates both the magnitude and phase of the system output to the system input for different frequencies. A transfer function—describing the relationship between the frequency spectra of the input and the output—can be obtained using linear systems theory ~Lynn 1982; Liou 1998; De Salis and Oldham 1999, 2001!. A wide-band input signal fed into the system while measuring the output, generates the response at a wide range of frequencies simultaneously. When a pipeline system is excited by such a signal, the frequency response function is related to the Fourier spectrum of the input and output signals by

*H*svd = *Y*svd *X*svd s1d where *X*svd and *Y*svd5Fourier transforms of the input and output signal, respectively; *H*svd5frequency response function of the linear system; and v5angular frequency.

Eq. ~1! is known as the system identification equation. Wylie et al. ~1993! and Ferrante et al. ~2001! used the impedance equations to generate the transfer function for single pipeline systems. The input and output were defined as the complex discharge and complex head at a point in the pipeline, respectively. Ferrante et al. ~2001! indicated that the location of a leak.

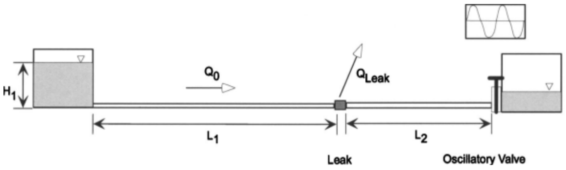

Fig. 1. Single pipeline used for proposed resonance leak detection method

the relative magnitude of the resonance peaks in the transfer function, but the impact of a leak on the location of resonance frequencies is minimal, except in the case of large leaks ~contrasting with the effect of nondiscrete blockages, which do influence the location of resonance frequencies!. This finding leads to a proposed method that uses the relative sizes of resonance peaks of different harmonic frequencies as a means of leak location in a single pipeline as explained below. The techniques of extended blockage detection—proposed in Antonopoulous-Domis ~1980!, Qunli and Fricke ~1989, 1991!, and De Salis and Oldham ~1999, 2001! that use resonant peak shifts—are not directly applicable to leak detection. This paper uses the perturbation of flow generated by an inline valve that fluctuates in a specified pattern. An upstream reservoir and the fluctuating downstream valve discharging into a constant head reservoir bound the pipeline. An illustration of the pipeline configuration is shown in Fig. 1. Two methods of leak detection are proposed in this paper. An inverse technique in the frequency-domain forms the basis one of the method. In addition, a method for locating the section of leaking pipe within the system using a resonance peak-sequencing method is also introduced. Both methods require the accurate determination of the FRD. A discussion of the generalizations of the techniques forms the final part of the paper.

II. Properties of the Frequency Response Diagram

Two important parameters that can affect the FRD are the measurement position and the presence of a leak within the pipeline. The system in Fig. 1 is used to illustrate the impact of these parameters on the FRD of a pipeline system. The system parameters are shown in Table 1. In the case of a linearized pipeline system with asymmetric boundary conditions, the FRD consists of a series of evenly spaced peaks and troughs with the peaks occurring at the odd multiples of vth and the troughs occurring at the even multiples of vth, where vth is the fundamental angular frequency of the pipeline, defined as vth = ap 2L s9d where L5length of the pipeline. While the location of the resonance ~peaks! and antiresonance ~troughs! points on the frequency axis is fixed by the fundamental frequency, vth, the response magnitudes at these frequencies are affected by the position of the measuring point ~Muto and Kanei 1980!. Fig. 3 shows the magnitude of various peaks in the FRD as a function of the measurement position along the pipe for the system shown in Fig. 1. Each series in Fig. 3 describes the magnitude of response from a particular harmonic frequency ~vr=v/vth=1.0, 3.0, 5.0¼!, and the response changes significantly with a change in the measuring position. They are also known as the “mode shapes” of the system. The shape of the FRD at any position in the pipeline can be derived from the relative magnitude of the harmonics at that position. The FRD at 742 and 2,000 m along the pipe are shown as insets in Fig. 3. The peaks of all harmonics converge at the extremities of the pipeline. The FRD produced from the downstream end of the pipeline ~at 2,000 m, at the excitation valve in Fig. 1! is particularly important as it displays equal magnitude peaks as a result of this convergence. From Fig. 3, the frequency responses for all harmonic peaks are also at a maximum at the downstream boundary, resulting in stronger signals and a subsequent higher signal to noise ratio ~Lee et al. 2002a!. The importance of this measurement position becomes apparent when the impact of a leak on the FRD is considered. The impact of a leak on the FRD measured at the end of the diagnosis.

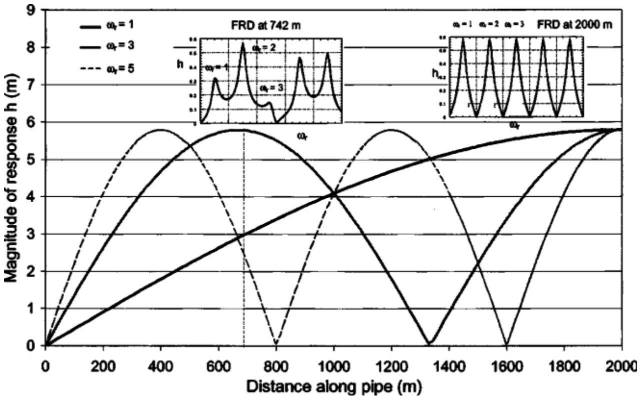

Fig. 3. Response of major harmonic frequencies as measurement position is changed along the nonleaking pipeline of Fig. 1, insets indicate the frequency response diagram obtained at two different measurement positions.

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III. Inverse Resonance Technique

As indicated in Fig. 4, a single leak in a pipeline can lead to a change in the shape of the FRD, caused by the frequencydependent damping of components in the transient signal. Inverse fitting minimizes the sum of the difference squared between measured and modeled frequency response functions by varying the value of the leak size sCdALd and leak position sxLd within the transfer matrix model. The leak size is changed within the transfer matrix of the leak @Eq. ~8!# and the leak position is changed by the length of the pipe sections between the leak and system boundaries @Eq. ~4!#. This method is similar to the inverse transient method of Liggett and Chen ~1994!. The objective function is given by the least-squares criterion E =o j=1 M fhj m − hjg2 s10d where E5objective function value; hj m and hj5measured and calculated frequency domain amplitude responses at the jth frequency, respectively; and M5number of measurement points. The minimization algorithm used for the results in this paper is the shuffled complex evolution ~SCE! algorithm ~Duan et al. 1993!. The SCE algorithm performs a global search based on the simplex method and does not require the use of local gradient information. The settings for the SCE algorithm are as follows: the number of complexes=number of fitted parameters=2, error tolerance=1310−12, the bounds for the leak size sCdALd are from 0.0 to 0.005, and the bounds for the leak position are from 0.0 to 2,000 m pipe is shown in Fig. 4. The figure indicates that a leak causes a nonuniform pattern in the resonance peaks in the FRD. This finding has also been observed in Ferrante et al. ~2001! and Lee et al. ~2002a, 2003!. When the response is measured at the excitation boundary of the pipeline, the FRD of an intact pipeline ~no leak! consists of a series of equally spaced peaks of equal magnitude. The presence of a leak results in a deviation of the FRD from this known pattern and clearly indicates the presence of a leak prior to the application of any leak analysis technique.

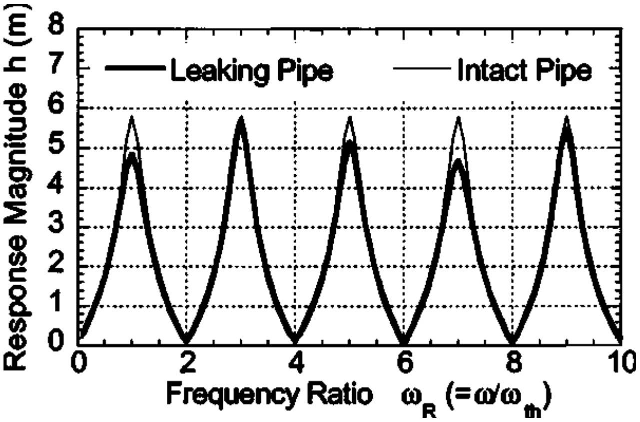

Fig. 4. Frequency response from the leaking and intact pipeline of Fig. 1 measured at the inline valve at downstream boundary.

IV. CONCLUSION

The presence of a leak within a single pipeline induces changes in the shape of the frequency response function ~FRD! and can be used as a means of identifying the position of the leak within the system. Two methods of leak detection in a pipeline system have been presented in this paper including the inverse resonance method and resonance peak-sequencing method. The former draws upon existing inverse transient techniques and carries out a parameter estimation process by fitting the FRD from a numerical model to a measured FRD. The resonance peak-sequencing method involves a comparison between the shape of the FRD and known shapes generated by leaks at various positions in the pipe. Summarizing the shape of the FRD in a sequence of harmonic peaks, ranked in order of magnitude, can provide the means through which this comparison is carried out. Both methods provide accurate information concerning the leak. The resonance peak-sequencing method is a fast and efficient method of locating a leak within a region of the pipeline and should be used in conjunction with the inverse resonance method to limit the size of the search space.

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