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SINGLE EXTENDED BLOCKAGE IDENTIFICATION USING A MODEL-BASED MATCHED-FIELD PROCESSING APPROACH

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ABSTRACT

A new transient-based approach for single blockage detection is proposed which requires two measurement stations at both ends of a single pipe system. The method uses the frequency response and gives satisfactory results using low frequency bandwidth. The first advantage of the proposed technique is to obtain the location and length of the blockage independently from the blockage's area. The second advantage is that the method uses information not only from the eigen-frequencies, but also from the whole frequency spectrum. This brings more accuracy especially when the identification of the resonant frequencies and their corresponding mode number are not accurate. Moreover, the method has the ability of tolerating noise as long as it is Gaussian of zero-mean and has a well-known structure. Comparison with other blockage detection methods is given and the benefits and drawbacks of the proposed method are discussed.

Keywords: blockage detection, transient flow, frequency response, matched-field processing, inverse problem.

1 INTRODUCTION

Extended blockages in water supply systems are ubiquitous and they cause many inefficiencies such as energy loss and increase in potential contamination and leaks. Unlike other defects in pipe, blockages are very difficult to detect as they do not have any external visible trace nor do they induce a detectable sound like leakages under steady state condition. However, researches showed that anomalies such as blockages can be detected if a transient response of a pipe system is measured (e.g. Duan et al. 2012, Meniconi et al., 2013, Louati, 2016, Ignarcio et al., 2016).

Similar inverse problems were addressed in different research fields, ranging from the identification of blockage in a sewage line (Tolstoy, 2010), and in the cooling system of nuclear reactors (Wu and Fricke, 1990) to the vocal tract shape reconstruction (Shroeder, 1967; Sondhi and Gopinath, 1970; Gopinath and Sondhi, 1970, DeSalis and Oldham, 2001) and the identification of conductivity in electrical lines (Bruckstein and Kailath, 1987).

In general, the methods for blockage detection or area reconstruction could be divided into two main categories: methods that model the blockage as a step function, and therefore the blockage is simply a pipe section with smaller diameter (see sketch in Fig. (1)). Other methods model the blockage with a smooth function of the longitudinal coordinate x . In both categories, the techniques/tools used for blockage detection are differentiated by whether the time domain or frequency domain signals are used. For example, in time domain wavelet analysis is applied by Meniconi et al. (2013) and reconstructive Method of Characteristics (or Layer peeling) by Gong et al. (2014). In frequency domain, Fourier decomposition and Ehrenfest theorem can be applied to write an explicit relation between the area of the pipe and its acoustic properties (e.g. Schroeder, 1967, Qunli and Fricke, 1990, DeSalis and Oldham, 2001); and recently, Duan et al. (2012) and Louati et al., (2017) combined the frequency response with the dispersion relation to determine the blockage location, length and size. So far, the frequency domain methods (Schroeder, 1967, Duan et al. (2012) and Louati et al., (2017)) rely on the accurate identification of several resonant frequencies and their corresponding mode number. In many practical situations, a limited number of resonant frequencies are available and their identification may be affected by the presence of noise.

In this work a new model-based matched-field processing approach (MFP) is proposed for the detection of a single blockage in pipes. It relies on measuring the frequency response at both ends of a pipe and makes use of the transfer matrix method. In contrast to other methods in the literature, the proposed technique does not require the identification of the resonant and the anti-resonant frequencies and also tolerates the presence of noise. This approach is recently applied for leak detection in pipes by Wang and Ghidaoui (2017).

2 PROPOSED NEW METHOD FOR BLOCKAGE DETECTION

2.1 Theoretical framework

In most water supply application the location, the length and the size of the blockage are the most critical information. Therefore an idealized single blockage in a reservoir-pipe-valve system is considered as shown in Fig. (1). The blockage has a length l_2 and an area $A_0 - \delta A$ and it is located at a distance l_1 from the reservoir. A_0 is the area of the intact pipe (before the formation of the blockage). Two measurement stations are setup at

both ends of the pipe at distance x_{m_1} and x_{m_2} from the reservoir. The pipe flow is assumed frictionless and the wave speed a is assumed constant.

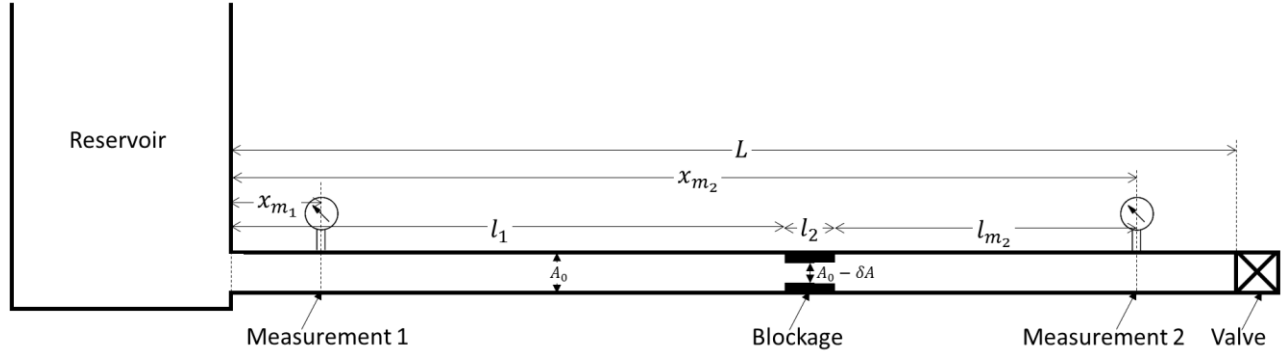


Figure 1. Pipe system layout and characteristic lengths.

In this case, for any l_1, l_2 and δA , the pressure head variations from the mean in the frequency domain at distance x_{m_1} and x_{m_2} from the reservoir ($h_{m_1}^c$ and $h_{m_2}^c$) are given from the Transfer Matrix method (Chaudhry, 2013)

$$h_{m_1}^c = - \frac{Z_0 \sin(kx_{m_1}) q_v(\omega)}{\cos(kL) + \frac{\delta A}{A_0} \cos(kl_1) \sin(kl_2) \sin(kl_3) + \frac{\delta A}{A_0 - \delta A} \sin(kl_1) \sin(kl_2) \cos(kl_3)} \quad [1]$$

$$h_{m_2}^c = \frac{h_{m_1}^c}{\sin(kx_{m_1})} \left(\sin(kx_{m_2}) + \frac{\delta A}{A_0} \sin(kl_1) \sin(kl_2) \sin(kl_{m_2}) + \frac{\delta A}{A_0 - \delta A} \cos(kl_1) \sin(kl_2) \cos(kl_{m_2}) \right) \quad [2]$$

where the superscript "c" in $h_{m_i}^c$ denotes computation; $Z_0 = i a / g A_0$ is the characteristic impedance of the intact conduit with g is the gravitational constant; $k = \omega / a$ is the wave number; $q_v(\omega)$ is a known discharge variation at the valve used to generate the transient. From Eq. (1) and (2) it can be shown that

$$-\frac{Z_0 q_v(\omega)}{h_{m_1}^c} \sin(kx_{m_1}) - \cos(kL) = \frac{\delta A}{A_0} \cos(kl_1) \sin(kl_2) \sin(kl_3) + \frac{\delta A}{A_0 - \delta A} \sin(kl_1) \sin(kl_2) \cos(kl_3) \quad [3]$$

$$\frac{h_{m_2}^c}{h_{m_1}^c} \sin(kx_{m_1}) - \sin(kx_{m_2}) = \frac{\delta A}{A_0} \sin(kl_1) \sin(kl_2) \sin(kl_{m_2}) + \frac{\delta A}{A_0 - \delta A} \cos(kl_1) \sin(kl_2) \cos(kl_{m_2}) \quad [4]$$

With regards to blockage detection, the quantities on the left hand side (LHS) of Eqs (3) and (4) are related to the known "measured" variables; whereas the quantities on the right hand side (RHS) are related to the unknown variables. Hence, the quantities on the LHS of Eqs (3) and (4) will be referred as the "measured" synthetic signals $S_{m_1}^c$ and $S_{m_2}^c$.

$$S_{m_1}^c(\omega) = -\frac{Z_0 q_v(\omega)}{h_{m_1}^c} \sin(kx_{m_1}) - \cos(kL) \quad ; \quad S_{m_2}^c(\omega) = \frac{h_{m_2}^c}{h_{m_1}^c} \sin(kx_{m_1}) - \sin(kx_{m_2}) \quad [5]$$

The main advantage of using these synthetic signals S_{m_1} and S_{m_2} rather than directly using the measured pressure head h_{m_1} and h_{m_2} is that these signals (S_{m_i}) can be written in a "quasi-linear" relation with respect to the change in area (i.e. when l_1 and l_2 are fixed). This will allow the length and the location of the blockage to be estimated independently from its size. That is the three dimensional problem reduces to a two dimensional one.

In practice, the measured pressure head h_{m_i} will not be exactly equal to the predicted pressure head from the model (Eqs. (1) and (2)), it will rather contain noise such as environmental noise, measurement noise and many other types of noise. Therefore, the "measured" synthetic signal are given by $S_{m_i}(\omega) = S_{m_i}^c(\omega) + \text{noise}$ $i \in \{1,2\}$.

2.2 Model-based matched-field processing approach (MFP)

Given the measurements $S_{m_1}(\omega)$ and $S_{m_2}(\omega)$, for a given set of frequencies $\omega_1, \omega_2, \dots, \omega_N$, Eqs (3) and (4) can be written in a compact form as

$$\mathbf{S}_{m_i} = \mathbf{G}_{m_i}(l_1, l_2) \boldsymbol{\alpha}(\delta A) + \mathbf{n} \quad i = 1,2 \quad [6]$$

where $\mathbf{S}_{m_i} = (S_{m_i}(\omega_1), S_{m_i}(\omega_2), \dots, S_{m_i}(\omega_N))^T$; $\boldsymbol{\alpha}(\delta A) = (\delta A / A_0, \delta A / (A_0 - \delta A))^T$; in which the superscript "T" denotes transpose operator; \mathbf{G}_{m_1} and \mathbf{G}_{m_2} are 2-by-N matrices where the elements of their j^{th} row are $(\mathbf{G}_{m_1})_{1,j} = \cos(k_j l_1) \sin(k_j l_2) \sin(k_j l_3)$; $(\mathbf{G}_{m_1})_{2,j} = \sin(k_j l_1) \sin(k_j l_2) \cos(k_j l_3)$; $(\mathbf{G}_{m_2})_{1,j} = \sin(k_l l_1) \sin(k_l l_2) \sin(k_l l_{m_2})$; $(\mathbf{G}_{m_2})_{2,j} = \cos(k_l l_1) \sin(k_l l_2) \cos(k_l l_{m_2})$; and \mathbf{n} is the added noise vector.

If the noise \mathbf{n} is zero-mean Gaussian white noise, then the blockage parameters can be found by minimizing the l_2 -norm of the difference between the “measured” signal \mathbf{S}_{m_i} and the model $\mathbf{G}_{m_i}(l_1, l_2)\alpha(\delta A)$

$$\{\hat{l}_1, \hat{l}_2, \hat{\delta A}\} = \arg \min_{l_1, l_2, \delta A} \left\| \mathbf{S}_{m_i} - \mathbf{G}_{m_i}(l_1, l_2)\alpha(\delta A) \right\|^2 \quad [7]$$

If the noise \mathbf{n} is non-white Gaussian of a well-known structure (known covariance matrix) then a filter can be applied to the signals \mathbf{S}_{m_i} and to the model $\mathbf{G}_{m_i}(l_1, l_2)\alpha(\delta A)$ to whiten the noise, and thereafter the same method can be used (Wang and Ghidaoui, 2017).

Because of the quasi-linearity between the area of the blockage and the “measured” signal, an estimate of $\alpha(\delta A)$ which has the minimum mean square error (least square solution) is given by (for any l_1 and l_2)

$$\hat{\alpha} = (\mathbf{G}_{m_i}^H \mathbf{G}_{m_i})^{-1} \mathbf{G}_{m_i}^H \mathbf{S}_{m_i} \quad [8]$$

where the superscript “H” denotes the conjugate transpose. Replacing $\hat{\alpha}$ into Eq. (7) leads to

$$\{\hat{l}_1, \hat{l}_2\} = \arg \max_{l_1, l_2} \mathbf{B}_{m_i}(l_1, l_2) \quad [9]$$

where $\mathbf{B}_{m_i} = \mathbf{S}_{m_i}^H \mathbf{G}_{m_i} (\mathbf{G}_{m_i}^H \mathbf{G}_{m_i})^{-1} \mathbf{G}_{m_i}^H \mathbf{S}_{m_i}$.

Using this approach, the number of variables in the optimization problem in Eq. (7) has reduced from three variables to two variables in Eq. (9). In this case the objective function \mathbf{B}_{m_i} can be evaluated and plotted for all possible l_1 and l_2 , and an estimate of the blockage length and location can be easily found by enumeration. This is one of the advantages of the proposed method comparing to other methods in the literature where the blockage identification involves an optimization problem with at least three variables (Duan et al., (2012) and Ignarcio et al., (2016)).

Once the blockage’s length and location are estimated, the blockage area can be easily found by substituting the values of the estimated l_1 and l_2 into Eq. (8).

Note that the objective function \mathbf{B}_{m_2} has a symmetry line related to the measurement location x_{m_2} given by $\mathbf{B}_{m_2}(l_1, l_2) = \mathbf{B}_{m_2}(x_{m_2} - l_2 - l_1, l_2)$. Whereas \mathbf{B}_{m_1} has a fixed symmetry line independent from the measurement location x_{m_1} given by $\mathbf{B}_{m_1}(l_1, l_2) = \mathbf{B}_{m_1}(L - l_2 - l_1, l_2)$. Therefore to avoid multiple solutions of l_1 and l_2 the measurement location from the valve side should not be at the valve (i.e. $x_{m_2} \neq L$). Also note that the objective functions \mathbf{B}_{m_1} and \mathbf{B}_{m_2} are not defined at the trivial solutions $l_1 = 0$, $l_2 = 0$, $l_1 + l_2 = x_{m_2}$ and $l_1 + l_2 = L$.

The procedure of the blockage identification using this approach can be summarized in the following algorithm

Algorithm 1: Blockage identification using MFP

- 1: Use \mathbf{h}_{m_1} and \mathbf{h}_{m_2} at known locations x_{m_1} and $x_{m_2} \neq L$ and \mathbf{q}_v to construct the signals \mathbf{S}_{m_1} and \mathbf{S}_{m_2} (Eq. (5))
- 2: Construct the matrices \mathbf{G}_{m_i} corresponding to each signal \mathbf{S}_{m_i} $i \in \{1, 2\}$
- 3: Compute the objective functions \mathbf{B}_{m_i} at every possible blockage location and length (l_1, l_2)
- 4: Find an estimate $(\hat{l}_1$ and $\hat{l}_2)$ which correspond to the maximum of the objective function $\mathbf{B}_{m_1} + \mathbf{B}_{m_2}$
- 5: Compute two estimates of $\hat{\alpha}$ by substituting $(\hat{l}_1$ and $\hat{l}_2)$ found into Eq. (8) using \mathbf{G}_{m_1} and \mathbf{G}_{m_2}
- 6: Compute the estimates of $\hat{\delta A}$ by $\hat{\delta A} = A_0 \hat{\alpha}_1$ and by $\hat{\delta A} = A_0 \hat{\alpha}_2 / (1 + \hat{\alpha}_2)$

3 RESULTS AND DISCUSSION

To validate the proposed method, and to illustrate its advantages and limitations, a numerical case study is considered. The numerical setup consists of a reservoir pipe valve system containing a single blockage as shown in Fig. (1). The lengths of different pipe sections are $L = 2000$ m, $l_1 = 700$ m, $l_2 = 200$ m, $x_{m_1} = 50$ m, $x_{m_2} = 1950$ m. The intact pipe area is $A_0 = 0.1963$ m² and the change of area due to the blockage is $\delta A = 0.1257$ m². The wave speed is assumed to be constant $a = 1000$ m/s and the pipe is assumed to be frictionless. The pressure head response $h_{m_1}(\omega)$ and $h_{m_2}(\omega)$ at the measurement locations (x_{m_1} and x_{m_2}) are computed using the transfer matrix method (i.e. using Eq. (1) and (2)), where the transient is generated by an impulse (i.e. $q_v(\omega) = 1$). The frequency domain is sampled from 0 to $\omega_N = 16\omega_0$ with a step size $\Delta\omega = \omega_0 / 100$, where ω_0 is the fundamental frequency of the intact system $\omega_0 = 2\pi a / 4L$.

Algorithm (1) is applied to compute the objective function $\mathbf{B}_{m_1} + \mathbf{B}_{m_2}$ at every point in the feasible domain discretized with $\Delta x = 2$ m. Fig. (2) shows a color plot of the objective function together with the location of the maximum. The results shows that the objective function $\mathbf{B}_{m_1} + \mathbf{B}_{m_2}$ has a single maximum which corresponds to the blockage’s location and length estimates $(\hat{l}_1 = 700$ m and $\hat{l}_2 = 200$ m). This is how the method provides the blockage length and location. Regarding, the blockage area, two estimates of the change in pipe area are obtained from Eq. (8) for each signal \mathbf{S}_{m_1} and \mathbf{S}_{m_2} . The estimates of δA are $\hat{\delta A} = \{0.1256, -0.0561, 0.1254, 0.1256\}$ m². Note that one of the estimated value is negative which may represent a pipe wall thinning. This negative value is ignored since it is assumed that there is only positive change in area (blockage). Hence the estimate of the area is $\hat{\delta A} = 0.1256$ m².

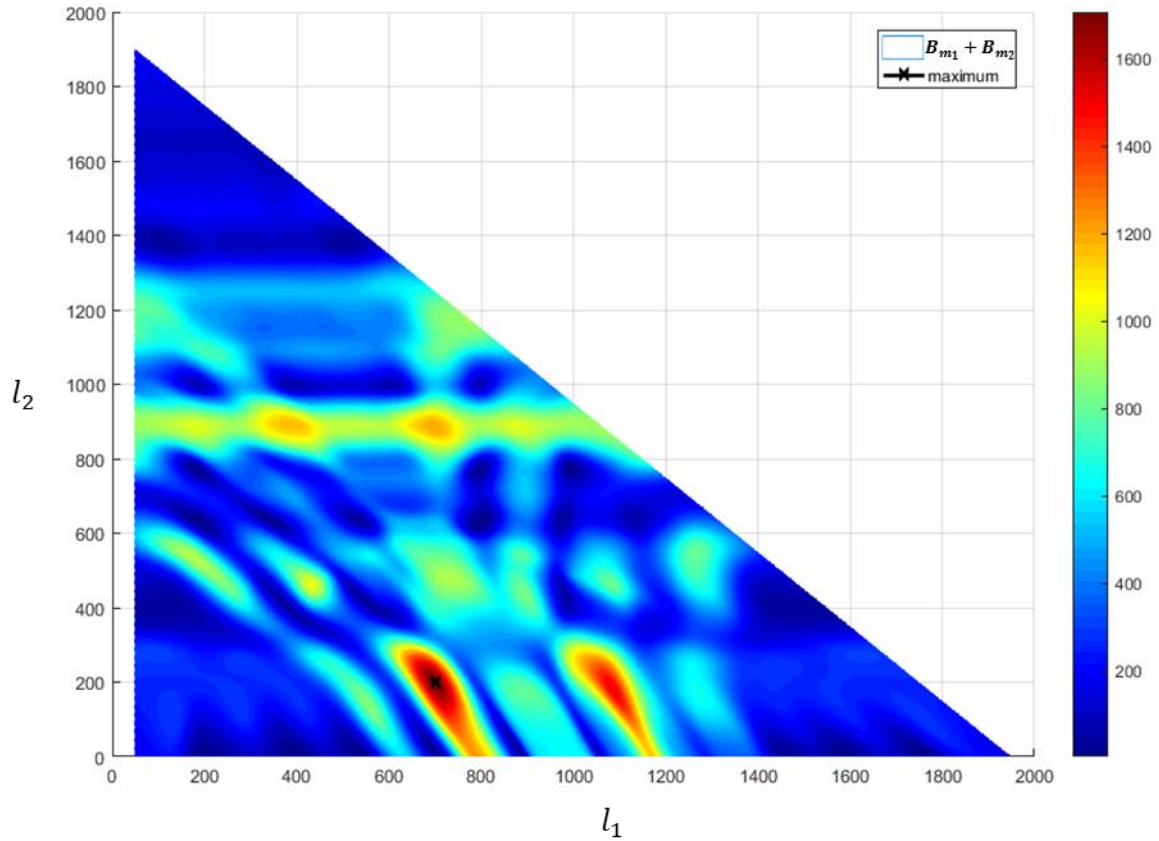


Figure 2. Objective function $B_{m_1} + B_{m_2}$ and location of the maximum.

The above numerical example illustrates how the method can be applied to identify a single blockage in a pipe. This proposed method differs from most of the frequency domain methods for blockage detection (DeSalis and Oldham 2001; Duan et al. 2012; Louati, 2016) by the fact that it uses the frequency response of any set of frequencies rather than using only the resonant and the anti-resonant frequencies locations. Using the frequency response at all frequencies gives more accuracy in the blockage identification especially in the cases (i) presence of noise (ii) inaccurate identification of the eigen-frequencies. These two advantages will be discussed in what follows.

(i) *Presence of noise*

To illustrate the advantage of using the response of frequencies other than the resonant and anti-resonant frequencies, the results for the blockage identification are compared in the presence of noise. A zero-mean Gaussian white noise (the noise power is the same at all frequencies) of different values of Signal-to-Noise Ratio (SNR) is added to the deterministic computed signals $S_{m_1}^c$ and $S_{m_2}^c$. The SNR is herein defined in decibel (dB) as the ratio between the power of the signals $S_{m_i}^c$ (i.e. $|S_{m_i}^c|^2$) to the power of the noise (i.e. the variance of the random variable noise σ^2). That is $\text{SNR} = 20 \log_{10} |S_{m_i}^c| / \sigma$, where $|S_{m_i}^c|$ is the average of the magnitude of the signal $S_{m_i}^c$ at different frequencies.

A set of numerical simulations are conducted in which two cases are considered, the first one is the case where “all frequencies” are used for blockage identification (i.e. frequency response for the frequencies in the range $[0.01 \omega_0, 16\omega_0]$ with a step size $0.01\omega_0$). Whereas the second one is the case where only the “resonant and anti-resonant frequencies” are used (i.e. 8 resonant and 8 anti-resonant frequencies contained in the interval $[0.01 \omega_0, 16\omega_0]$).

The simulation is repeated 30 times for different values of SNR from -10dB to 40dB and Algorithm (1) is again used for blockage identification. The ensemble average and the standard deviation of the estimation error in the two cases are summarized in Fig. (3). Here, the estimation error is defined by

$$\epsilon = \frac{1}{2} \left(\frac{|\hat{l}_1 - l_1| + |\hat{l}_2 - l_2|}{L} + \frac{\sum |\delta\hat{A} - \delta A|}{nA_0} \right) \quad [10]$$

in which n is the number of feasible estimates of the change in area $\delta\hat{A}$. The estimates \hat{l}_1 and \hat{l}_2 are found by enumeration of the entire feasible region with a discretization $\Delta x = 10$ m.

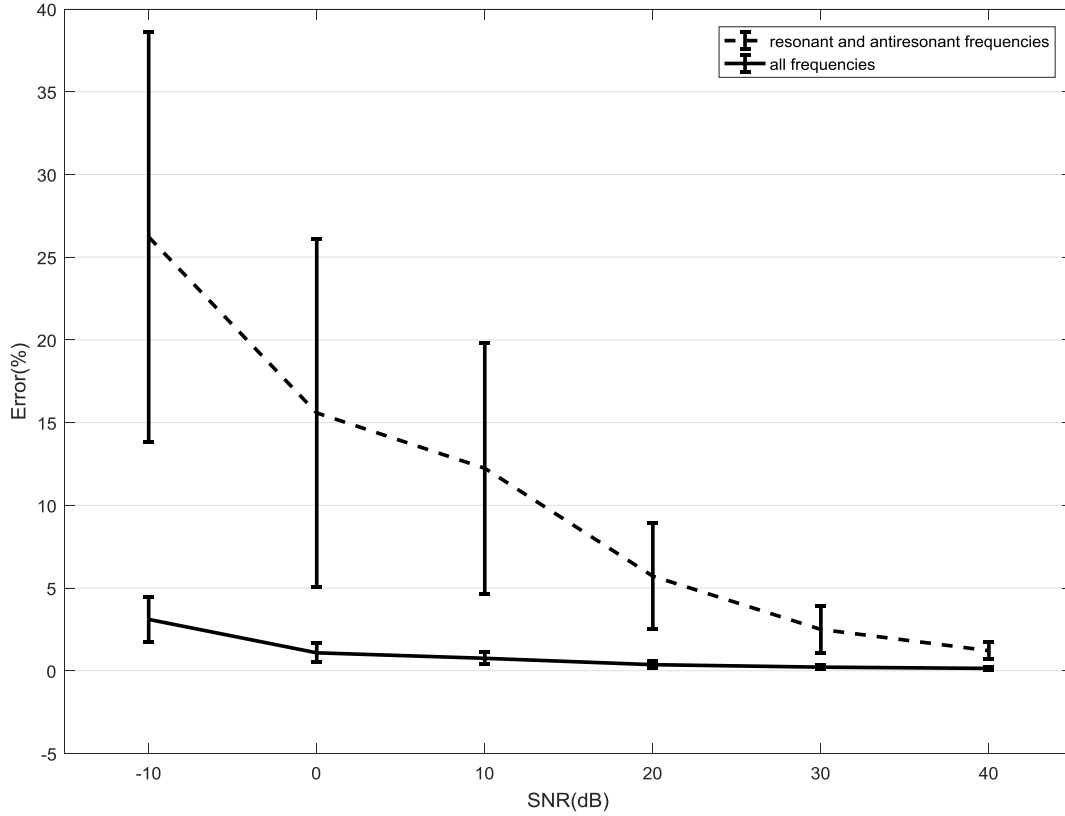


Figure 3. Error bar of the estimation error with increasing SNR.

Fig. (3) shows that the estimation error, is about 5 times lower when the whole frequency bandwidth is used than for the case where only the first 8 resonant and anti-resonant frequencies are used. This shows that using more frequencies increase the accuracy of the blockage detection results. This is because, for the case of zero-mean Gaussian white noise, the matched-field processing (MFP) approach has the ability of identifying the blockage parameters which maximize the SNR (Wang and Ghidaoui, 2017). In other words, the blockage parameters are estimated such that the corresponding signal generated from the model (i.e. $S_{m_i}^c$) fits the estimated mean value of the noisy measured response (i.e. S_{m_i}). However, the mean is only well estimated if a large enough sample size is used for its estimation. Therefore, in cases where only the resonant and anti-resonant frequencies are used for blockage identification, the mean value of the “measured” signal is not well estimated because of the lack of “measurement” data. However, for the case where more frequencies ($0.01\omega_0:0.01\omega_0:16\omega_0$) are used for the estimation of the blockage parameters, the mean value of the measured response can be better estimated and therefore a more accurate results of the blockage parameters are obtained.

Note that, in this case the noise is added to the amplitude of the frequency response. Therefore, blockage detection methods which do not use the amplitude of the frequency response, (e.g. (Duan et al., 2012) and (DeSalis et al., 2000)), are not directly affected by the presence of such type of noise. However, the presence of noise can make the identification of the eigen-frequencies inaccurate. In this case, MFP method has advantage comparing to the methods based on the eigen-frequencies.

(ii) Inaccurate identification of the eigen-frequencies

There are several reasons which can make the identification of the resonant and the anti-resonant frequencies inaccurate, for instance, the measurement of the frequency response with a large frequency step. In this case, methods based on the eigen-frequencies identification become less accurate. However, since the MFP method does not rely on the identification of the resonant and anti-resonant frequencies. It can give more accurate results. To illustrate this, consider the same numerical example given above, the pressure heads h_{m_1} and h_{m_2} are simulated using the transfer matrix method (i.e. using Eqs (1) and (2)) in the frequency range ($0:4\omega_0$) with a frequency step size $\Delta\omega = \omega_0/15$. The resonant frequencies ω_r and the anti-resonant frequencies ω_{ar} are estimated by a linear interpolation and are found to be $\omega_r = \{0.9181, 3.1401\}\omega_0$ and $\omega_{ar} = \{2.0825, 3.7208\}\omega_0$.

Under these conditions, the blockage is identified using the MFP method and results are compared with two other methods which only use the resonant and the anti-resonant frequencies. The first method used for comparison, estimates the blockage characteristics using a minimum error in the dispersion relation (MEDR) approach (Duan et al., 2012). The main advantage of this method is that it does not require the knowledge of the input signal (i.e. q_v) as it only uses the eigen-frequencies. However, this method relies on the accurate

identification of the eigen-frequencies and involves an optimization problem with at least three variables. The second method used for comparison, uses an explicit area function based on the perturbation method (AFPM) (DeSalis and Oldham, 2001). The main advantages of this method comes from the fact that it does not assume the number of blockages and is independent from the type of excitation (i.e. q_v). However, the method assumes the change in area to be small. Moreover, using this method requires a large number of eigen-frequencies to guarantee an accurate area reconstruction.

The comparison between the results of the blockage identification methods in the case of inaccurate identification of the eigen-frequencies is shown in Fig. (4).

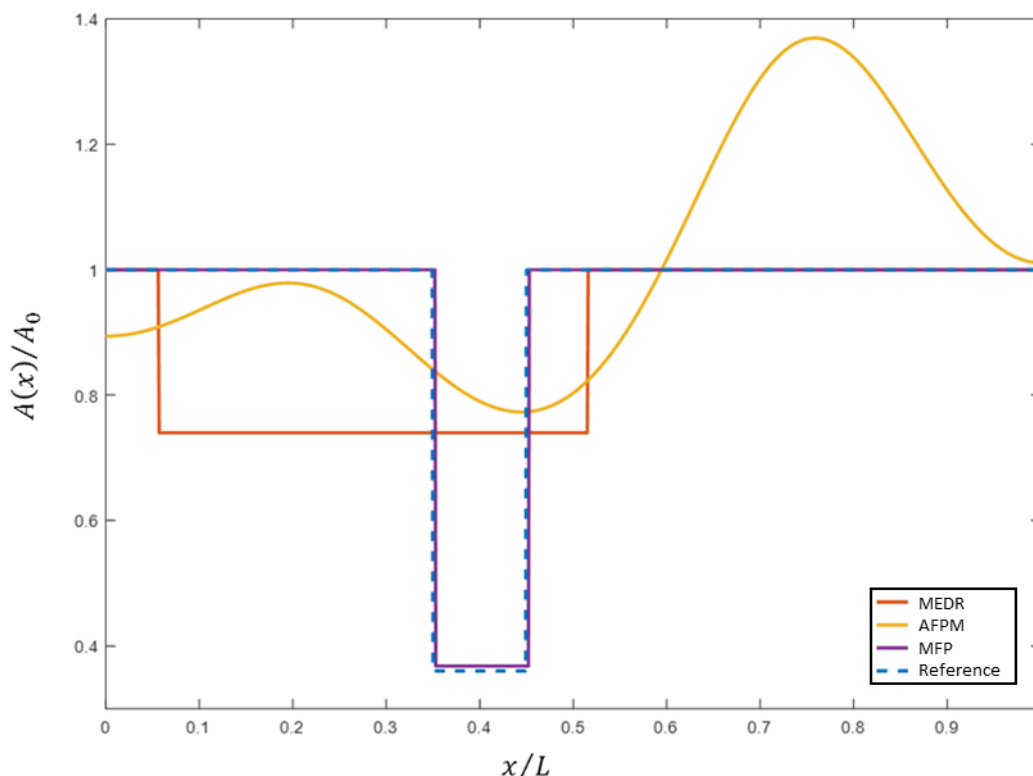


Figure 4. Comparison of the Matched-field processing with other methods in the literature.

Fig. (4) shows that the MFP method has more accurate result than the other two methods. The results found using the AFPM (DeSalis and Oldham, 2001) shows large discrepancy between the reconstructed cross-sectional area and the reference pipe's area. This is because only 3 resonant and 3 anti-resonant frequencies are used for the area reconstruction. Furthermore, the results of MEDR method (Duan et al., 2012) shows a non-accurate prediction of the blockage location and length. This is because the method is sensitive to the inaccuracy of the resonant and anti-resonant frequency identification (Duan, 2015). In contrast, the estimate of the blockage parameters was more accurate using the MFP method, this is because MFP has the ability of using frequencies other than the eigen-frequencies.

Despite the advantages of using MFP for blockage parameters estimation, this method has some limitations. The first being that the method requires a relatively accurate measurement of the frequency response in at least two measurement locations, it also requires a good knowledge of the input and of the boundary conditions. The second limitation is that the general form of the blockage size $\hat{\alpha}$ used in this method (Eq. (8)), to solve for the blockage location and length independently from the blockage size, does not necessarily satisfy the feasibility condition. This is because the least square solution does not necessarily satisfy the condition $A_0 \hat{\alpha}_1 = A_0 \hat{\alpha}_2 / (1 + \hat{\alpha}_2)$, and this is the reason why more than one estimate for the area is obtained by this method. In progress research is conducted to solve these limitations.

4 CONCLUSION

A new method for blockage detection is proposed. The method has the advantage of using information not only from the resonant frequencies but also from other frequencies, this is a key advantage especially when the signal is contaminated with a zero-mean Gaussian noise, and when the identification of eigen-frequencies is not accurate. The proposed MFP-based method solves for the location and the length of the blockage independently from the blockage's area. This gives the advantage of visualizing the overall objective function for all possible blockage parameters which cannot be achieved by other methods. However, an accurate knowledge of the input and the boundary conditions is required for the robustness of the proposed model-based MFP method.

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