

On the design of a digital filter to compensate for the shaker dynamics in a virtual pipe test rig

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Abstract: The waste of drinking water is one of the main concerns in modern society. Leakages from buried pipe distribution systems is the main contributing factor. To help overcome this problem, water industries around the world have put a lot of effort into locating and repairing leaks. Leak-noise correlators are used extensively to find and locate leaks. Although it is considered a straightforward and accurate technique, conventional leak-noise correlators require extensive field tests and training of the workers in their use. This cost both time and money. A virtual pipe, which is the subject of this paper, could help reduce costs and provide a more consistent way of testing these devices. One way to generate vibration that resembles leak noise as measured on a buried pipe, is to use an electrodynamic shaker. However, a shaker is a dynamic system, and its dynamic behavior could result in contamination of the leak noise related vibration. The aim of this paper is to determine a way to compensate for the shaker dynamics and the associated instrumentation, so that representative pipe vibration due to a leak can be generated in the laboratory. An investigation is carried out into design of a digital filter, which is able to compensate for the shaker dynamics. The approach is first described and then the compensator is placed in series with the shaker, and its efficacy is demonstrated in a laboratory test.

Keywords: *Compensator, digital filter, pure delay, buried pipe*

INTRODUCTION

A large amount of water is lost in many water distribution systems between the treatment plant and the consumers. In developing countries, the loss of water can reach alarming levels. In Brazil, for example, 38% of the total potable water is lost before reaching residences and industries, with some states, such as Amapá, losing about 70% of its potable water (O Globo, 2018). Conversely, in developed countries such as Japan, where the water loss is about 2% (O Globo, 2018), acoustic techniques such as listening devices and leak-noise correlators are widely used to detect and locate leaks (Hunaidi et al., 2000). Listening devices include instruments such as listening rods and geophones, which are capable of detecting leak-induced sound and vibration (Hunaidi et al., 2000). Leak noise correlators have become extremely popular in the leak detection field over the past decades. They are generally considered to be state-of-art portable computer-based device that can pinpoint leaks automatically. Generally, the leak is located by estimating the time delay between measured leak signals by calculating the cross-correlation function (Gao et al., 2004). Furthermore, some works related to such technique have been conducted in order to evaluate the soil effects on the wave responsible for leak noise propagation (Brennan et al., 2018; Scussel et al., 2018).

Since the cross-correlation technique is considered to be a straightforward and accurate method, especially for metallic pipes, it is widely used by water industries to detect leaks in their water distribution systems. However, these companies have to decide which noise-correlator is more suitable for each pipe network. It is thus necessary to carry out some field tests in order to assist this decision. In addition, these devices require training personnel in their use and, ideally, they must be exposed to different conditions, different pipe geometries and leak strengths, to gain knowledge and experience (Brennan et al., 2016). Both of these issues motivate the development of a bench-top test-rig which is capable of generating vibrations similar to the pipe vibrations generated by a leak in the field. However, power amplifiers and shakers, which are used to generate the vibration, have an important effect on the cross-correlation function and time delay estimate, since their dynamic characteristics can also affect the response of the system.

The main aim of the work described in this paper is to design a virtual pipe test rig which is capable of reproducing the pipe vibration at the measurement positions. It is important to note that robust vibration exciters need to be chosen in order to provide a consistent vibration, which is independent of the loading effects of the sensors of different leak noise correlators.

Furthermore, it is necessary to compensate for the dynamic effects of the associated instrumentation required to generate pipe vibration due to a leak. To achieve this a digital filter is designed as a compensator. The type of filter was selected because of its simplicity and robustness (Elliott, 2000).

Measurement arrangement used in acoustic correlation

The cross-correlation technique applied to leak detection in buried water pipes is based on the arrangement shown in Fig. 1, where a sensor is positioned on either side of a suspected leak at distances d_1 and d_2 . The distance d between the sensors is equal to $d_1 + d_2$. Accelerometers or hydrophones which measure vibration or acoustic signals are usually used. Signals from the sensors are transmitted to the leak noise correlator, which calculates the cross-correlation function of the two signals and hence the time delay, and presents the estimation results to an operator (Gao et al., 2004).

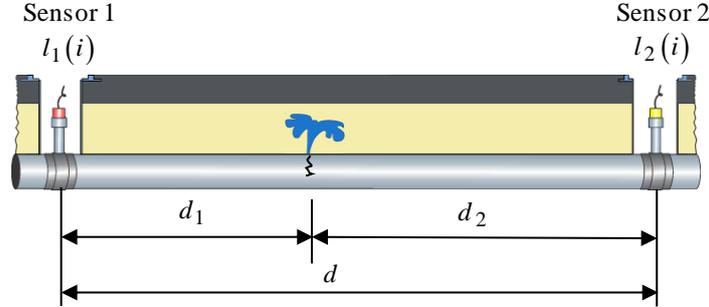


Figure 1 - Schematic of the arrangement used in leak detection based on cross-correlation technique.

It is assumed that the distance d between the sensors is known. It is necessary to estimate either d_1 or d_2 in order to detect the location of the leak in such a buried water pipe. Considering the arrangement in Fig. 1, the distance d_1 can be calculated by (Gao et al., 2004)

$$d_1 = \frac{d - c\tau_{peak}}{2}, \quad (1)$$

where c and τ_{peak} are the wavespeed (speed of leak noise propagation) and time delay between the arrival times of the leak noises at sensor positions 1 and 2. In Fig. 1, $l_1(i)$ and $l_2(i)$ are the leak noise signals in terms of discrete time from sensors 1 and 2 respectively.

The time delay can be estimated through the lag m between $l_1(i)$ and $l_2(i)$, and is associated with the maximum value of the cross-correlation function. Since the leak noise at the two measurement positions are considered to be two jointly random processes, the discrete cross-correlation function of the leak noise $R_{l_1 l_2}(m)$ is given by (Stoica and Moses, 2005)

$$R_{l_1 l_2}(m) = E[l_1(i)l_2(i-m)] = E[l_1(i+m)l_2(i)], \quad -\infty < i < \infty, \quad (2)$$

where $E[\]$ is the expectation operator. However, since the calculation of such a function can only consider a finite segment of one realization of the infinite-random process, the biased discrete correlation estimator $\hat{R}_{l_1 l_2}(m)$ is used and is given by (Stoica and Moses, 2005)

$$\hat{R}_{l_1 l_2}(m) = \begin{cases} \sum_{i=1}^{I-m} l_1(i+m)l_2(i), & m \geq 0, \\ \hat{R}_{l_1 l_2}(-m), & m < 0. \end{cases} \quad (3)$$

where I is the finite number of measured samples.

If a leak exists between the two sensor positions in the system depicted in Fig. 1, a distinct peak may be found in the cross-correlation function which provides the difference in arrival times between the signals at each sensor (Gao et al., 2004).

Response of the actuators in the time and frequency domains

The experimental arrangement for the virtual pipe rig is shown in Fig. 2. It consists of a PC, a dual-channel power amplifier and two LDS V101 shakers, which are used to generate vibration representative of measured leak noise. There are also two PCB 352C22 piezoelectric accelerometers and an LMS SCADAS data acquisition system to measure and record the signals which are used to estimate the Frequency Response Functions (FRFs) and Impulse Response Functions (IRFs) of the system.

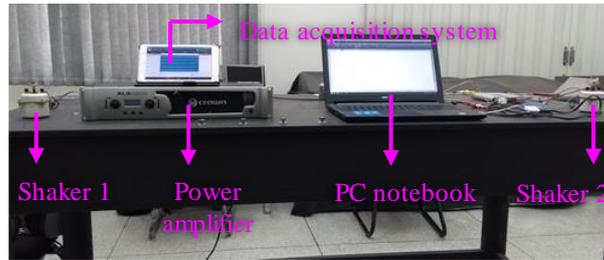


Figure 2 - Virtual pipe test rig.

To generate $l_1(i)$ and $l_2(i)$, the arrangement shown in Fig. 2 was divided into two independent systems, named here as virtual pipe system 1 and virtual pipe system 2, which are shown schematically in Fig. 3. To determine the FRFs, 60-second-long white noise signals $x_1(i)$ and $x_2(i)$ were used as input sequences to the virtual pipe systems 1 and 2 respectively. The FRFs of both systems are denoted as $H_s(\omega)$, in which s is used to denote systems 1 and 2. A sampling frequency of 8,192 Hz was used together with an 8,192-point FFT and a Hanning window with 50% overlap to give a frequency resolution of approximately 1 Hz.

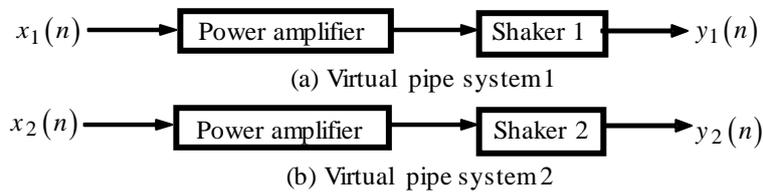


Figure 3 – Schematic of the two sub-systems of the virtual pipe system.

The FRFs for the systems in Fig. 3 are shown in Fig. 4 in terms of magnitude and unwrapped phase.

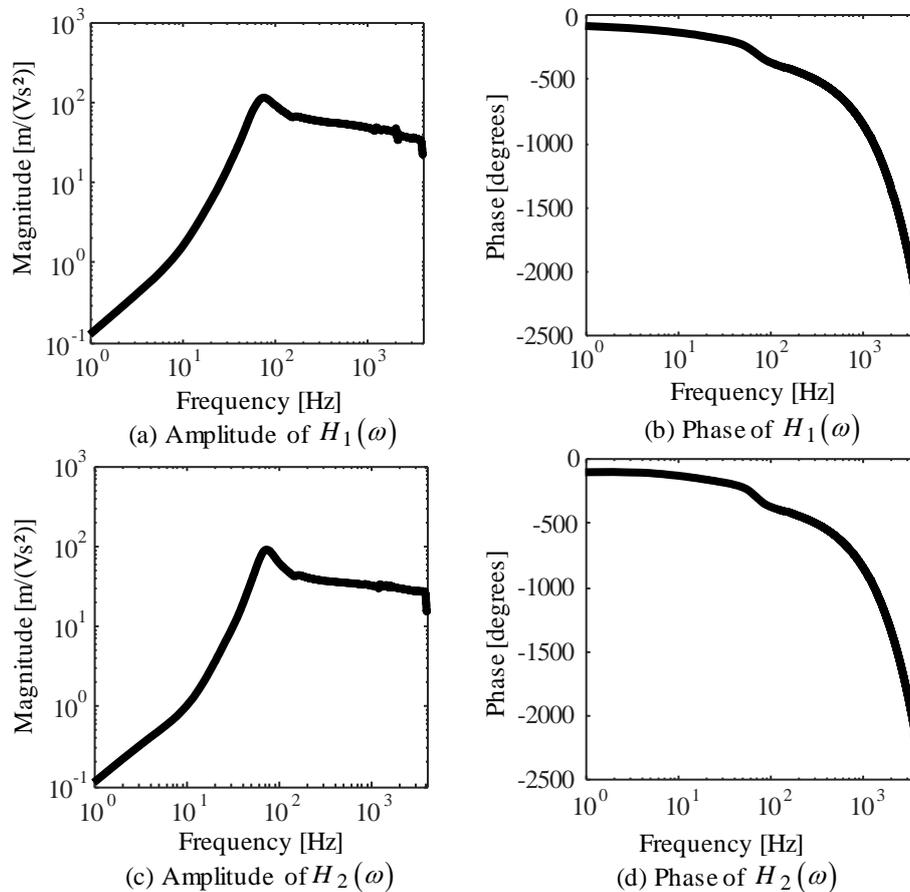


Figure 4 - FRFs $H_1(\omega)$ and $H_2(\omega)$ of the two systems of the virtual pipe test rig.

Examining Fig. 4, it can be seen that the two systems have similar behavior, which is to be expected because they consist of nominally the same equipment, but there are some small differences due to manufacturing.

Using the measured FRFs in Fig. 4, the IRFs are calculated using the discrete Fourier transform. These IRFs are needed to determine the compensators, the details of which are described in the next section. Note that the time resolution for the IRFs is approximately 0.12 ms and the total number of samples is 400 which corresponds to a time series of approximately 48 ms.

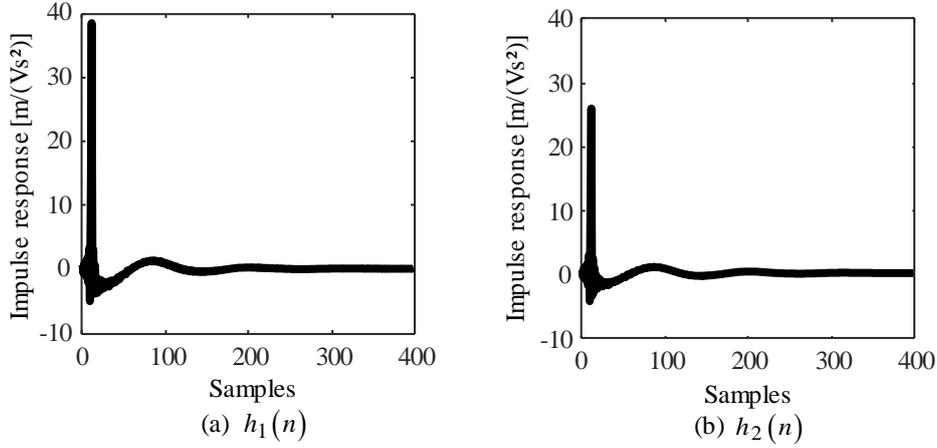


Figure 5 - IRFs $h_1(n)$ and $h_2(n)$ of the two branches of the virtual pipe test rig.

Examining Fig. 5, it can be seen that, as with the FRFs, the IRFs of the two systems have similar behavior, which is to be expected, but there are some small differences.

Compensator design

The aim of each compensator is to compensate for the dynamics of each shaker and amplifier when it is cascaded with these devices in series. However, each shaker and amplifier have a time delay associated with them because of the finite time it takes for a signal to pass through each component. It is not possible, therefore, to completely compensate for the effects of the dynamics unless a time delay is added to the compensator. This added time delay is to ensure that the compensator has a time delay rather than a time advance and ensures that the compensated system is causal. To design the compensator, the FRFs $H_s(\omega)$ are first inverted to give the compensator FRF $\bar{H}_s(\omega)$, i.e.,

$$\bar{H}_s(\omega) = H_s^{-1}(\omega). \quad (4)$$

The IRFs $\bar{h}_s(n)$ of the compensators are then calculated through the inverse discrete Fourier transform, where $1 \leq n \leq N$ in which N is the size of the FFT. A delay of α samples is then added. If N is an even number, then the modified IRFs are given by

$$\begin{cases} \bar{h}_s(n) = \bar{h}_s(n + \alpha)w(n), & \text{if } n \leq \alpha; \\ \bar{h}_s(n) = \bar{h}_s(n - \alpha)w(n), & \text{otherwise;} \end{cases} \quad (5)$$

where $\alpha = N/2$ and N is even. If N is an odd number, then the modified IRFs are given by

$$\begin{cases} \bar{h}_s(n) = \bar{h}_s(n + \alpha)w(n), & \text{if } n \leq \alpha + 1; \\ \bar{h}_s(n) = \bar{h}_s(n - \alpha - 1)w(n), & \text{otherwise;} \end{cases} \quad (6)$$

where $\alpha = (N-1)/2$ and N is odd. To ensure that the beginning and end of the modified IRFs are zero, they are multiplied by a Hanning window. In the experiments reported here N was equal to 8,192 and the delay was set so that $\alpha = 4,096$. The IRFs $\bar{h}_s(n)$ of the compensators for each system are shown in Fig. 6.

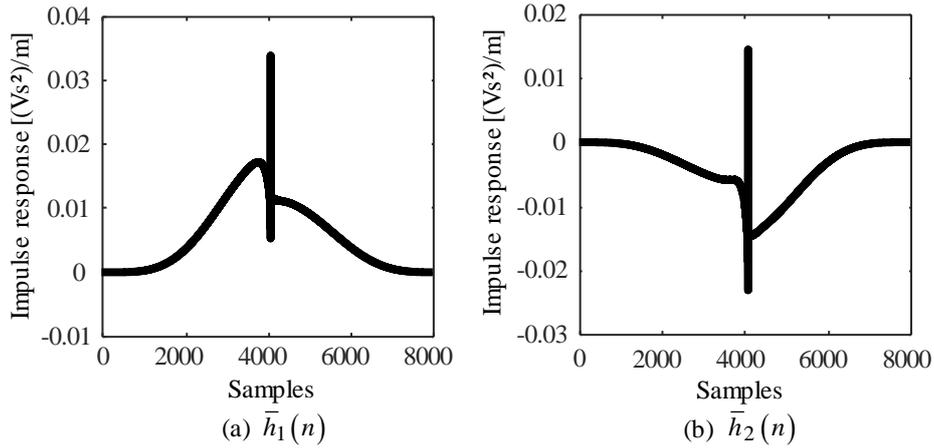


Figure 6 – IRFs of the compensators $\bar{h}_1(n)$ and $\bar{h}_2(n)$.

Modified compensator design

Although the compensators described in the previous section could be used in the practical system, they contain 8,192 points. This is thought to be inefficient as they could be represented accurately by much fewer points. In the work conducted here, the reduced number of points is 1,024, with 512 delay samples, removing the first part and last part of the IRFs $\bar{h}_s(n)$, and further applying a Hanning window to ensure the beginning and end of the IRFs are zero. Such an operation resulted in the modified IRFs $\hat{h}_s(i)$, where $1 \leq i \leq 1,024$, shown in Fig. 7.

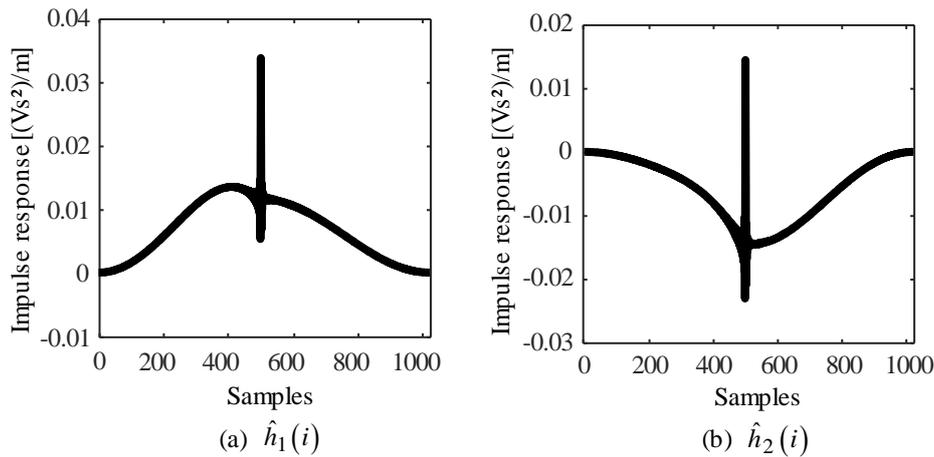


Figure 7 – Modified IRFs $\hat{h}_1(i)$ and $\hat{h}_2(i)$ of the compensators.

To verify if the new IRFs $\hat{h}_s(i)$ are able to compensate for the systems depicted in Fig. 3, the modified IRFs of the two compensated systems of the virtual pipe test rig $h_{com_s}(n)$ are calculated through the convolution of $\hat{h}_s(i)$ and $h_s(n)$ within the computer, i.e., $h_{com_s}(n) = \hat{h}_s(i) \otimes h_s(n)$, where \otimes denotes the convolution operator. The result should be a delayed *sinc* function (note that if the bandwidth was infinite then the result would be a delayed delta function). The results are shown in Fig. 8. Also shown in each graph is the uncompensated FRF of the amplifier and shaker alone. It can be seen that $h_{com_s}(n)$ is apparently a delayed unitary impulse, which means that the compensator is working as expected. Note that $h_{com_s}(n)$ is not a pure delayed delta function because of the finite bandwidth, which is effective from approximately 10 Hz to 3,800 Hz.

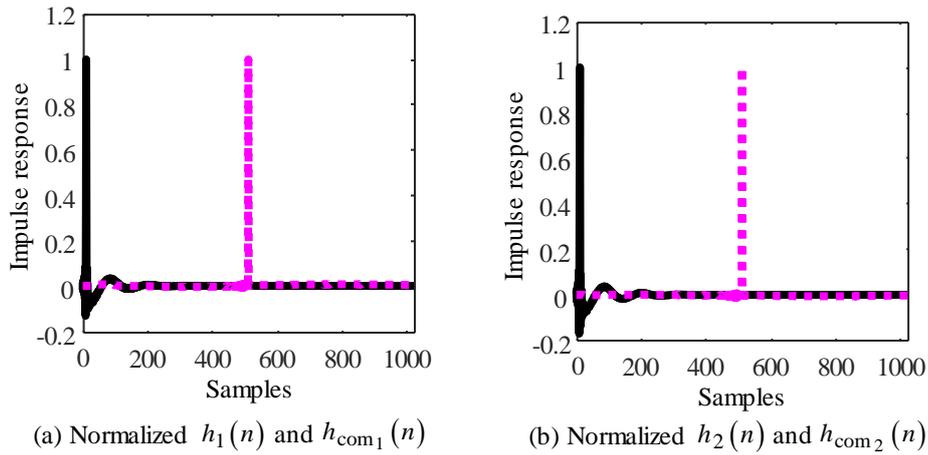


Figure 8 - Normalized IRFs $h_1(n)$ and $h_2(n)$ and IRFs $h_{com_1}(n)$ and $h_{com_2}(n)$ of the two compensated systems of the virtual pipe test rig. $h_1(n)$ and $h_2(n)$ are represented by the line — and $h_{com_1}(n)$ and $h_{com_2}(n)$ are represented by the line - - - .

Given the encouraging results shown in Fig. 8 where the cascading of the IRFs of the compensator, and the amplifier and shaker was carried out entirely in the computer, it was decided to verify whether the compensator would work in practice. To do this, the shakers were excited, through the amplifiers by white noise excitation $x_1(i)$ and $x_2(i)$ were used as input sequences to the compensators of virtual pipe systems 1 and 2 respectively. A sampling frequency of 8,192 Hz was again used together with an 8,192-point FFT and a Hanning window with 50% overlap to give a frequency resolution of approximately 1 Hz.

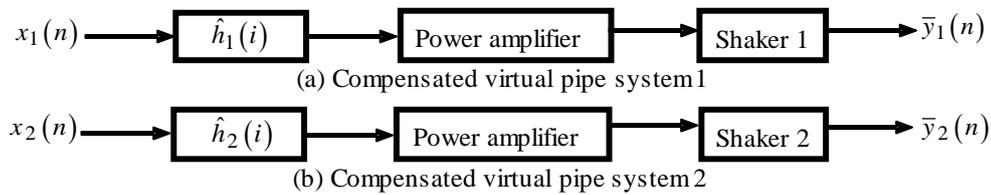


Figure 9 - Schematic of the two compensated systems of the virtual pipe system.

The FRFs for the systems in Fig. 9 are shown in Fig. 10 in terms of magnitude and unwrapped phase. Also plotted are the FRFs corresponding to the IRFs in Fig. 8.

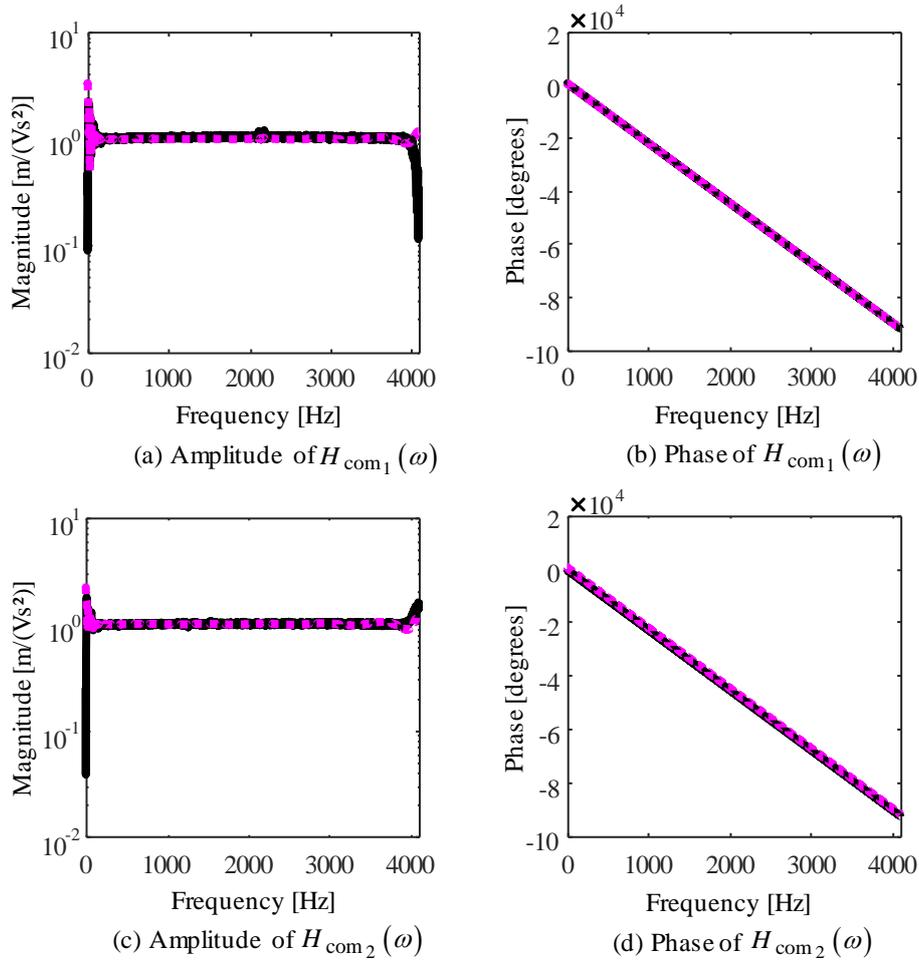


Figure 10 – FRFs $H_{\text{com}_s}(\omega)$ of the two compensated systems of the virtual pipe test rig. $H_{\text{com}_s}(\omega)$ in real time are represented by the line \blacksquare and $H_{\text{com}_s}(\omega)$ in non-real time are represented by the line \blacksquare .

It can be seen from Fig. 10 that the magnitude and phase of both FRFs for both systems are given approximately by a constant and straight line with a constant slope respectively, which suggests that such systems provide pure delay signals. Some differences between the two FRFs are apparent at low frequency and at frequencies close to the Nyquist frequency. The low frequency discrepancies are probably due to the poor frequency responses of the accelerometers and associated instrumentation and the shaker dynamics. The high frequency discrepancies are probably due to the limited bandwidth.

CONCLUSIONS

This paper has described the way in which shaker dynamics can be compensated by designing a suitable digital filter that can be cascaded in series with the amplifiers and shakers. The particular application for these systems is the generation of vibration that is representative of pipe vibration due to a leak in buried plastic water pipes. The compensators were designed by manipulating measured FRFs of the systems that require compensation and by applying delays, to ensure causality of the complete systems. The resulting compensators were first tested through simulation in the computer, and then were verified by carrying out an experiment in the laboratory. In the experiment, a white noise signal was first passed through the compensators before exiting the computer and driving the shakers through amplifiers. The FRFs of the composite systems were then evaluated and the results showed that the compensators, in the form of digital filters, were capable of compensating for the dynamics of the shakers and amplifiers. The next step of this work is concerned with incorporating them into a virtual pipe test rig.

ACKNOWLEDGMENTS

The authors would like to thank the financial support provided by the São Paulo Research Foundation (FAPESP) under Grant numbers 2013/50412-3, 2017/16953-8 and 2017/14432-0.

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