On The Investigation of Flow Rate Measurements Using Tap Noise and Variational Mode Decomposition

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Abstract. Currently, conventional flow measurement methods are intrusive, and flow meters need to be installed on pipelines conveying fluid. Some investigations have already been conducted to develop non-intrusive flow measurement techniques, mainly via using vibro-acoustic signals acquired straight on the pipe, where the flow induced vibration can be used to estimate the flow rate. However, such techniques are very accurate for high flow rate values which are related to the level of vibration specially when the flow is turbulent. This is not the case when considering tap noise vibration associated with the water flow, which is much smaller than for industrial cases. Here, for tap noise, the induced vibration is measured in a valve next to the tap. Variational Mode Decomposition Method is then used to give an estimation of the frequency bandwidth over which the tap noise can be found. The signals are filtered out using such band to attenuate background noise to enhance the flow rate estimation. This is conducted using classical vibration measures such as the RMS value and Power Spectral Density for the time and frequency domain, respectively. Actual tap vibration signals were collected at different flow rates by using two different accelerometers with different sensitivities to validate the methodology. It was found that the methodology is effective in selecting the bandwidth over which induced vibration due to tap noise is concentrated, and also estimating the flow rate for tap usage. The sensor sensitivity, however, indicates that for low flow rates the higher the better for tap flow estimation.

Keywords: tap noise, flow rate estimation, variational mode decomposition

1 Introduction

Flow rate is a property of fluid kinematics that is present in many applications, and in many cases its measurement, monitoring and control is extremely important. There are a variety of flow meters available and the majority of them are installed in pipes through which fluids are conveyed. Hence, such measurements are conducted in an intrusive way.

Some investigations have been carried out with the objective of providing alternative ways to perform flow measurements in a non-intrusive manner, in which there is no need to install the meter in the pipe wall, for example. Barbosa et al [1] published an investigation on water flow measurement on pipes, through vibration caused by the passage of fluid on the surface of the pipe. The flow rate used were from 10 m^3/h to 110 m^3/h. Vibration signals were acquired using piezoelectric accelerometers coupled on the external surface of the pipe, in a straight section. Barbosa et al [2] presented a water flow measurement method using the pipe itself as an intrinsic flow meter. The pipe was a PVDF - polyvinylidene fluoride type. This polymer has a piezoelectric property caused by the extrusion process during its manufacture, without the need for any specific treatment. A flow range of 1.14 m^3/h and 6.90

m^3/h was applied in the experiment. Bento et al [3] presented a method of measuring water flow using piezoelectric sensors incorporated near the inner surface of the pipe (straight section and long radius and short radius curves), which measure the vibrations caused by the passage of fluid due to Flow Induced Vibration (FIV) phenomenon. A piezoelectric ceramics of lead zirconate titanate (PZT) was used in this case. The flow rate range used was from 0.108 m^3/h to 10.8 m^3/h. The cited research presents an alternative of non-intrusive flow measurement via pipe vibration induced by the conveying fluid. In this work, however, there is also an alternative for measuring the water flow in a non-intrusive way, which is made via a valve, which vibrates due to the excitation caused by a tap (noise), with water flow ranging from 0.05 m^3/h to 1.30 m^3/h, that is, from laminar to turbulent flow.

Signals acquired by piezoelectric sensors are processed in the time and frequency domain. Then, the method presented by Dragomiretskiy and Zosso [4], called Variational Mode Decomposition (VMD) is used. VMD is a self-adaptive decomposition method through the construction and solution of constrained variational problems. The VMD decomposition process is done through an optimal solution. The method decomposes a signal into modes and determines its frequencies and bandwidth for each component, so that the sum of the modes reconstructs the input signal. Bai et al [5] and Feng et al [6] used the VMD to eliminate noise in the signal, aiming to identify leaks in natural gas pipelines. Zhang and Zheng [7] used the VMD to eliminate noise in the magnetic flux leakage signal, thus allowing to develop a non-destructive testing device for wire rope by unsaturated magnetic excitation, classifying broken wires. Parey and Sharma [8] used empirical mode decomposition (EMD) and VMD to detect leakage in a reciprocating compressor valve and compared the results, proving the performance of the VMD was better than that of the EMD.

Hence, for this work, VMD is applied as an alternative way to define frequency bandwidths representative of the vibration response of a shutoff valve due to a tap noise excitation. Hence, regions over which the flow rate can be defined as low, moderate and high consumption can be estimated using the raw data together with the modes given by the VMD in the time domain via de Root Mean Square (RMS) value and, in the frequency domain via the PSD, which is used to estimate the frequency bandwidths together with their central frequencies and the frequency at which the signals peak for each mode.

2 Overview on the Variational Mode Decomposition technique

As mentioned previously, the Variational Mode Decomposition (VMD) was developed by Dragomiretskiy and Zosso [4] based on the theory related to the Empirical Mode Decomposition (EMD) developed by Huang et al. [9]. These can be described as one way to rewrite any signal $x(t)$ via the summation of Intrinsic Mode Functions (IMFs) $u_k(t)$, i.e. $x(t) = \sum_k u_k(t)$, which are in turn amplitude-modulated-frequency-modulate signals written as

$$u_k(t) = A_k(t)\cos(\phi_k[t]), \tag{1}$$

where k is the mode, $A_k(t)$ is the non-negative envelope, i.e. $A_k(t) \geq 0$ and $\phi_k[t]$ is the non-decreasing phase, i.e. $\phi_k[t] \geq 0$. The VMD uses the optimization procedures by applying the augmented Lagrangian [10] with the Fourier Transform of $\Lambda(f)$, which in turn leads to a Wiener filter responsible for decomposing the signals into the pre-defined number of modes, so that the Fourier Transform $U_k^{n+1}(f)$ of the k mode due to the $n+1$ ith interaction is given in the frequency domain as

$$U_k^{n+1}(f) = \frac{X(f) - \sum_{i \neq k} U_k^n(f) + \Lambda^n(f) / 2}{1 + 2\alpha\left(2\pi(f - f_k^n)\right)^2}, \tag{2}$$

where $X(f)$ is the signal $x(t)$ in the frequency domain and α is the so-called penalty factor, which is the variance of the white noise responsible to tune the search for the modes. Moreover, the modes can be given in the time domain using the inverse Fourier Transform of Eq.(2), i.e. $F^{-1}\left(U_k^{n+1}(f)\right)$, so that any classic signal processing can be applied to it such as Root Mean Square (RMS) and Power Spectral Density (PSD).

3 Experimental Set-up and Description

The measurements were carried out in an ordinary residential area in the city of Tupã, located countryside of São Paulo State. The aim was to obtain similar actual conditions as the ones found in ordinary residential houses, such as background noise, pipe systems and tap characteristics. Fig.1 shows the measurement set-up used to collect the vibration response of a control/shutoff valve when a tap is opened. These control/shutoff valves are the ones used to allow water flow to the house pipe system, which generally controls the water supply to different rooms, bathrooms, faucets and others.

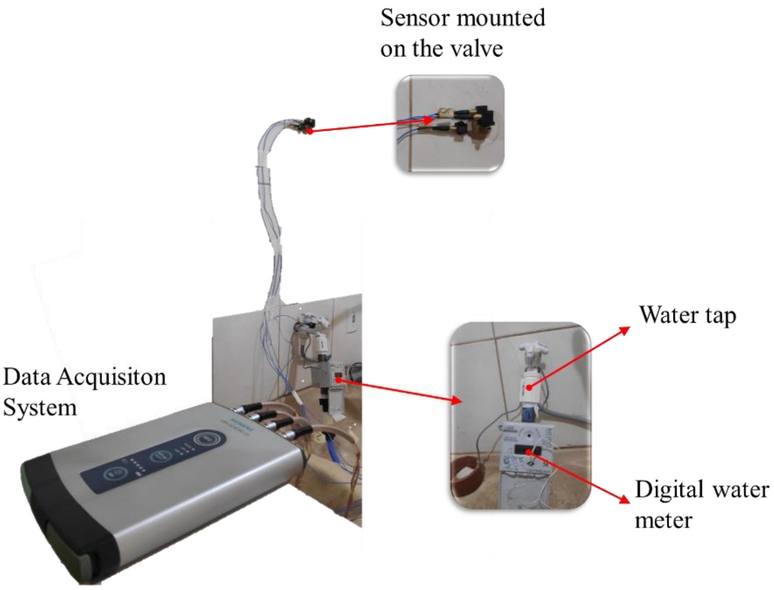


Figure 1. Measurement set-up used to collect the vibration response of a valve due to tap water excitation.

The equipment used to conduct the measurements are summarized in Table 1, for convenience. The signals were recorded at a sampling rate of 12.8kHz for 10 seconds. A Butterworth band-pass filter with low and high frequency limits set at 10 Hz and 3kHz, respectively, were applied to the raw data prior to any signal processing. This limit was set based on the linear frequency response range of the accelerometers used.

Table 1. Equipment used for the measurements

Description	Manufacturer	Type	Sensitivity
Data Acquisition System	SIEMENS	SCADAS XS	-
Flow Meter	DIEHL	HYDRUS	1×10^{-3} m^3/h
Sensor (accelerometer)	PCB	356A17	500 mV/g

Although tri-axial sensors were used, the valve axial response was the only measurement under investigation in this work as it presents the higher vibration severity level in the frequency range of analysis. Background noise (BN) and 25 vibration flow-induced measurements were carried out. The vibration flow-induced measurements were conducted at an increment of 0.05 m^3/h by opening an ordinary water tap next to the valve as shown in Fig.1. Hence, the smallest flow rate measured was 0.05 m^3/h and the highest was 1.25 m^3/h with the valve fully opened (FO). Fig.2(a) shows the one-second-long time histories of the background noise (magenta thinner solid line), the smallest flow rate measured, which is 0.05 m^3/h (blue thicker solid line), highest vibration level, which is around 0.65 m^3/h (dashed red line) and the valve fully opened presenting a flow rate of about 1.25 m^3/h (black dotted line). The data suggest that the tap noise excitation has a white noise characteristic and also that the severity level, i.e. RMS (root mean square) does not increase continuously with the increment of the flow rate, as observed by the vibration level drop from 0.65 m^3/h to 1.25 m^3/h. Fig.2(b) shows the Power Spectral Density (PSD) of these signals estimated via the Welch's method considering a frequency resolution of 1Hz, overlap of 50% and windowing hanning type. The colors used are the same as for the time histories. The background noise can be interpreted as the baseline below which no data can be collected. It is possible to observe that the frequency content when the tap is opened (tap noise) excites the whole frequency range where the sensor has a linear response (from 10Hz to 3kHz), so that a band-limited white-noise characteristic can be assumed. Furthermore, there are frequency ranges over which the signals present a higher vibration level dependent upon the flow rate. The PSD for the smallest flow rate of 0.05 m^3/h has a very similar behavior as for the flow rate of 0.65 m^3/h. This perhaps is due to the fluid interaction with the tap mechanism responsible for controlling the water flow. However, the latter has much higher amplitude over the depicted frequency range. This is not the case for the fully open situation, where the water flows through the tap without any resistance. For this case, the low frequency content (below 1kHz) has a much higher energy as depicted in the spectrum.

(a) (b)

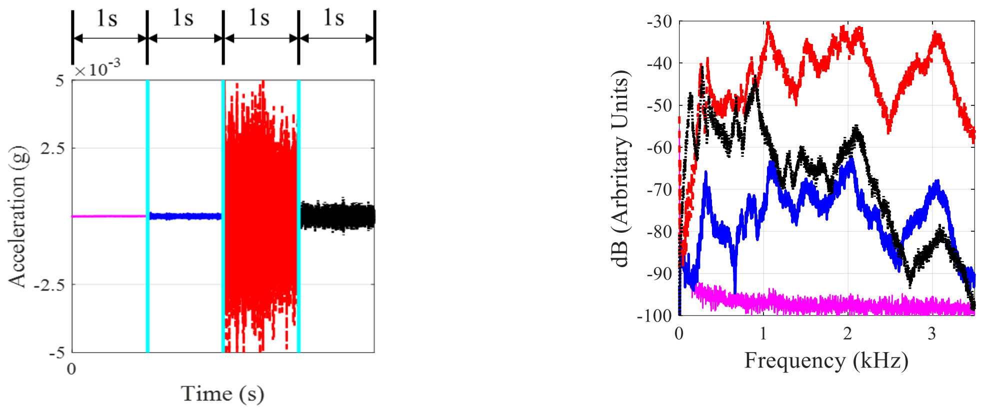


Figure 2. The measured vibration response of the valve considering the background noise (purple thin line), the flow rate of 0.05 m^3/h (blue thick line), 0.65 m^3/h (red dotted line) and fully opened tap (black dashed line). (a) One second time history. (b) The Power Spectral Density (PSD).

4 Results

As mentioned previously, there are frequency ranges over which the vibration response of a tap due to different flow rate has different characteristic. Hence, the variational mode decomposition (VMD) method is used to select automatically 3 frequency ranges in an attempt to select low, mid and high frequency contents. This is highlighted in Fig. 3. The grey thick line shows the normalized PSD of the signal considering the cases already presented in Fig.2. Here, however, the PSD is normalized by to its highest peak o that:

$$\bar{S}_{xx}(\omega) = \frac{S_{xx}(\omega)}{\max \ S_{xx}(\omega)}, \tag{3}$$

where $S_{xx}(\omega)$ is the PSD and $\max \ S_{xx}(\omega)$ is its maximum amplitude (peak) in the depicted frequency range. The PSDs are plotted in linear scale to emphasize the peaks presented in the signals and to facilitate the visualization of the three regions (frequency ranges) selected by the VMD. These are highlighted by the PSDs given in blue dashed line (VMD 1), black solid line (VMD 2) and red dotted line (VMD 3). The labels "i", "ii" and "iii" are related to the flow rate of 0.05 m^3/h, 0.65 m^3/h and 1.25 m^3/h (fully opened), respectively. The frequency bandwidth depicted by the green shaded area is calculated when the peak in the PSD for the "a" raw data, "b" VMD 1, "c" VMD 2 and "d" VMD3 is higher than the threshold value of 0.01, i.e. $\bar{S}_{xx}(\omega) \geq 0.01$. This follows the criteria used by [11] when dealing with leak detection problems. It is possible to observe that the frequency bandwidth for the raw data starts covering the region over which the VMD calculates its three components for the lower flow rate. Moreover, it is also possible to observe that the frequency bandwidth changes its frequency position (central frequency) as a function of the flow rate too. This perhaps, can be used as additional information to estimate the flow rate of the tap.

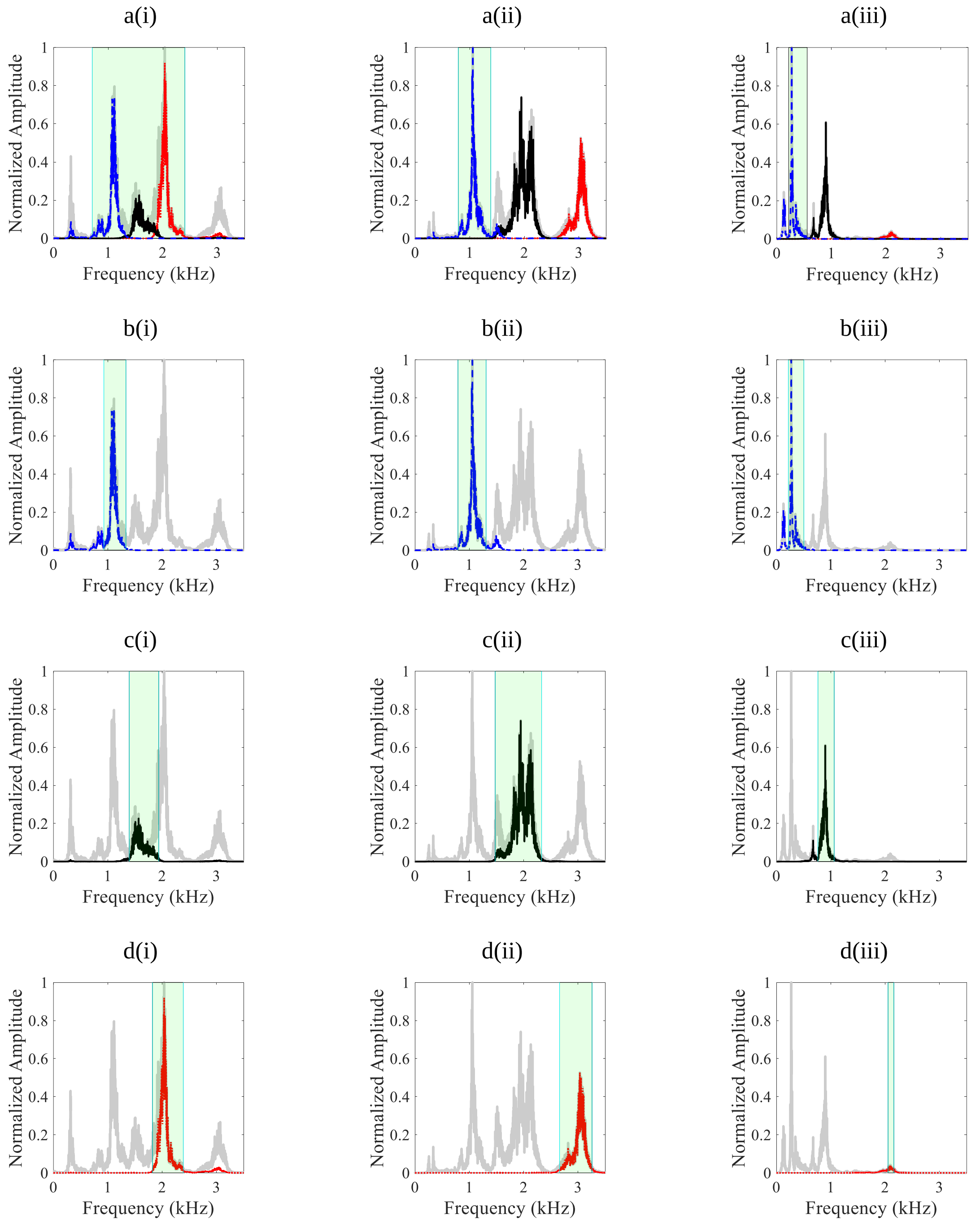
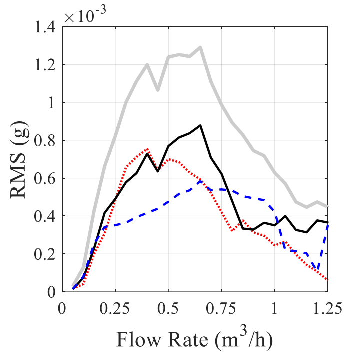


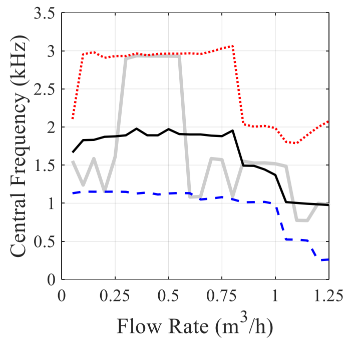
Figure 3. The normalized PSD and the frequency bandwidth calculated for the (a) raw data (grey solid line), (b) VMD 1 (blue dashed line), (c) VMD 2 (black solid line), (d) VMD 3 (red dotted line), considering a flow rate of “i” 0.05 m^3/h, “ii” 0.65 m^3/h and “iii” 1.25 m^3/h (fully opened).

Fig. 4 shows the time and frequency domain analysis to summarize the results given by the measured data for each flow rate. Fig. 4(a) shows the RMS value (time domain analyses) for the raw data (grey think solid line) considering the frequency range over which the sensor presents a flat response (10Hz-3kHz), and for the VMD1 (blue dashed line), VMD2 (black solid line) and VMD3 (red dotted line). The RMS values evaluated for the VMDs are performed over the frequency bandwidth given in Fig.3. The central frequency of these bandwidths and the frequency at which each VMD peaks are shown in Figs. 4(b) and 4(c) respectively. The RMS values for the VMDs have similar behavior as for the raw data, especially for the VMD2 and VMD3. It is possible to delimitate a region before and after the peak, which can be used to estimate the flow rate in low and high for example. This peak perhaps is due to the higher interaction between the water flow and the tap mechanism, which decays away when the tap is opened for higher flow rates (less vibration level). These two regions (low and high) can be even more enhanced if the frequency domain data is used. The central frequency and the frequency at which the signal presents its higher value is a bit erratic for the raw data. This, however, is not the case for the VMDs. They present a flat behavior in the region where there is low and moderate consumption, but reduces when the flow starts to have a high consumption, which is something about 1 m^3/h. Hence, the time and

(a)



(b)



(c)

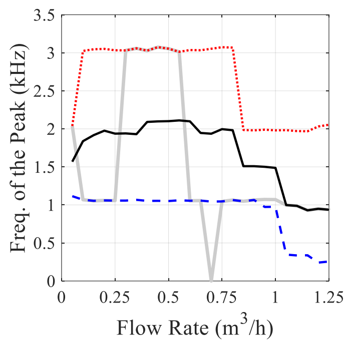


Figure 4. The domain analysis given by the (a) RMS value and the frequency domain analysis given by (b) The central frequency and (c) the peak of the PSD withing the frequency limit range. Grey solid line – raw data; Blue dashed line – VMD1; Black solid line – VMD2; Red dotted line – VMD3.

5 Conclusions

Actual vibration response of a control/shutoff valve induced by an ordinary water tap is measured. This response is investigated as one way to estimate the water flow rate through the tap. The Variational Mode Decomposition is used to aid in the estimation of flow rate by automatically selecting three frequency bands over which the vibration severity and central frequency can be estimated. The frequency bandwidths are calculated using a PSD normalized by its peak, so that the frequency range is defined when the modulus of the PSD is higher than threshold value of 0.01. These frequency ranges can be addressed to regions where the flow rate is defined as low, moderate and high. It is clear that the use of VMD is prominent specially when using the information given by the frequency bandwidth (central frequency or frequency at which the peak of the PSD withing the frequency limits occur). This can be used to define the flow rate at which the high consumption is likely to happen. The RMS value, however, can be used to estimate the flow rate limit in which the low and moderate consumption occurs.

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