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The uncertainties induced by internal pipe wall roughness on the measurements of clamp-on ultrasonic flow meters

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***Abstract*—Clamp-on ultrasonic flow meters (UFMs) have lower accuracy compared with spool piece UFMs because of the uncertainties introduced during the in-field installation process. Internal pipe wall roughness, one of these uncertainties, distorts the flow profile and causes the scattering of ultrasound. The objective of this paper is to carry out a parametric study to quantify the effect of scattering of ultrasound on the uncertainties of clamp-on UFM measurements without considering the flow disturbances. 2D finite element analysis was used to simulate the upstream and downstream signals of the clamp-on UFM based on some simplifying assumptions which were made about the effect of the flow. This simulation method was then verified by experiments which measure the uncertainties relating to the placement of ultrasonic probes at different separation distances. The simulation and experimental results were in good agreement. Then we applied this verified simulation method to investigate the uncertainties caused by the internal pipe wall roughness on the flow measurements. For ultrasonic waves at a frequency of 1 MHz and corroded internal pipe wall surfaces (0.2 mm RMS) it was found that systematic errors of 2 percent can result from the roughness induced scattering. This is a significant part of the measurement uncertainty range (1-5 percent) that is often quoted by manufacturers of clamp-on UFMs. This study therefore demonstrates that the accuracy of the clamp-on UFMs can be limited by the effects of internal pipe wall roughness.**

***Index Terms*—Flow measurements, ultrasound, clamp-on flow meters, roughness**

I. Introduction

CLAMP-ON ultrasonic flow meters (UFMs) measure the velocity of fluid flow in many industrial sectors, such as chemical industry, water distribution etc. The biggest advantage of clamp-on UFMs is the ease of installation, non-invasiveness and little maintenance cost [1].

However, the disadvantage is that there are uncertainties during the in-field installation process [2]. These uncertainties may come from a number of sources such as the installation of measurement probes, pipe properties. Some of these sources have been studied such as transducer separation distance [3], frequency of transducers [4] etc.. However, there is little information available on pipe wall roughness related effects on the uncertainties. The pipe wall roughness induces uncertainties with regards to two main aspects, flow profile and scattering [5]. Mori [6] and Calogirou et al [7] have studied the effect of flow profile but limited studies appear on the effect of scattering of ultrasound due to rough pipe surface on the flow measurements. The scattering causes attenuation [8] and phase modulation of the ultrasonic signals. This reduces the SNR (signal to noise ratio) and results in waveform distortion of the signals. Hence, the impact of this wave scattering from rough pipe surfaces on the flow measurements needs to be investigated and quantified.

To achieve this, Section II presents a reference simulation method. Section III then verifies this method experimentally by measuring the uncertainties as a function of horizontal separation distance errors between transducer probes. This method is then used to quantify the uncertainties induced by internal pipe wall roughness for different roughness profiles (Section IV).

II. Reference simulation method

A. FE model of the reference setup

The FE model of a reference setup of a typical clamp-on UFM is shown in Fig. 1. Commercial software, Abaqus/Explicit [9] was used to setup the simulation. The size of the steel pipe follows the industrial standard [10]. The transducer probes are placed on the perspex wedge which are clamped onto the pipe wall.

The angle of the wedge was chosen to be 50 degrees. This angle maximises the propagation angle (θ) of ultrasound in water and ensures that only shear waves exist in the pipe wall [4]. The value is similar to those in industrial applications [11]. The wedge on the top was modelled as the generator and the one on the bottom as the receiver. A more detailed record of the work can be found in [12].

B. Flow simulation and signal processing method

The upstream and downstream signals are simulated by simulating the effect of the flow. Many simulation methods were published for simulating the flow in UFMs using FEM [13] and CFD [14]. However, these methods are time and computationally demanding and it could take days to finish

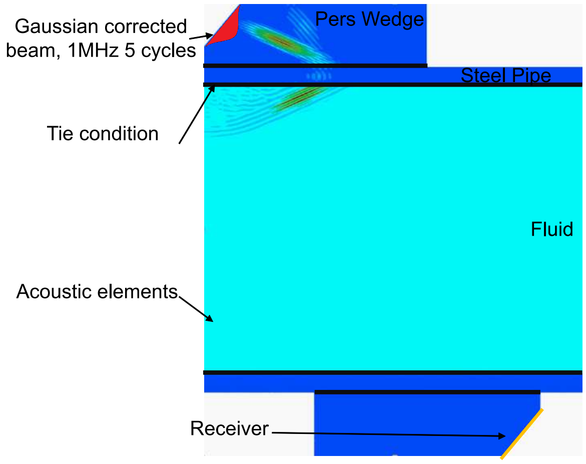
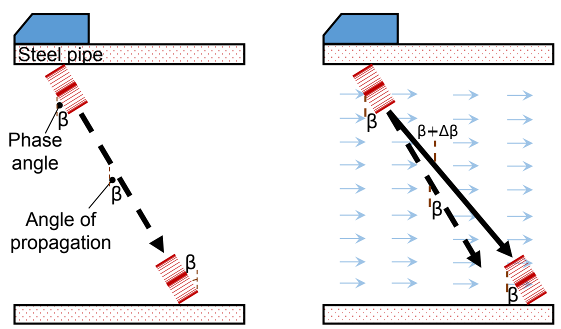


Fig. 1: FE model in Abaqus, the stress wave is 18 μs after the transducer generates the signal.

one simulation. In addition, this paper aims to quantify the roughness related effects by carrying out parametric studies (a large number of simulations), so a simplified method is used to simulate the upstream and downstream signals based on what happens in the fluid. As shown in Fig. 2, the angle of propagation changes with the flow. However, to a first approximate, the phase angle remains the same because the impedance of water and pipe remains unchanged. This was also observed in [14].



(a) Ultrasound propagation Without flow

(b) Ultrasound propagation with uniform flow

Fig. 2: Ultrasonic wave propagation with and without flow. To a first approximation, the propagation angle changes but the phase angle remains the same

Based on this assumption, the upstream and downstream signals are simulated by moving the receiver wedge at a distance dx calculated by Equation 1. This method is illustrated in Fig. 3.

$$dx = V_f \frac{l_w}{c_w} \tag{1}$$

where V_f is the velocity of flow, l_w is the distance of travel in the fluid and c_w is the ultrasonic velocity in water.

The upstream and downstream signals simulated are shown in Fig. 4.

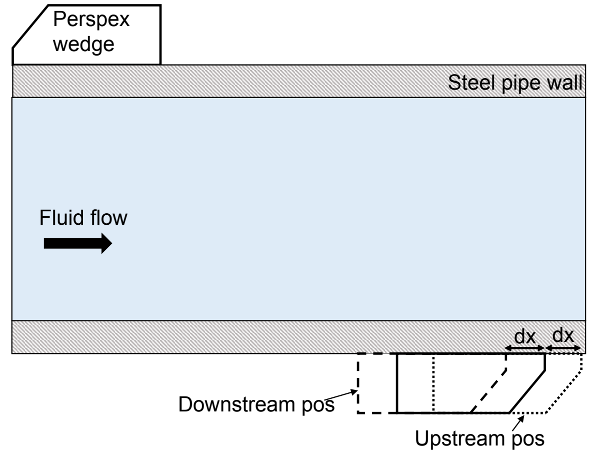


Fig. 3: The receiver wedge was moved at a distance dx to simulate the effect of flow and the upstream and downstream signals

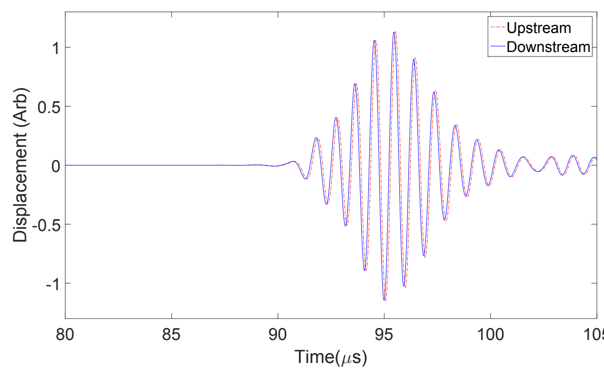


Fig. 4: The reference up and downstream signals simulated

This method takes into account the complexity of signals but also reduces the time to simulate the signals. This is based on the assumption that the phase angle of the ultrasonic wave packet remains the same across the pipe with and without flow.

To process the upstream and downstream signals and calculate the arrival time difference, cross-correlation and linear interpolation were used [15] [16]. This processing method is used in the parametric study so that the signals can be processed using the same method.

III. Verification Experiments

A. The experimental setup

The experimental setup is shown in Fig. 5. The transducers (1 MHz, B28069, Aerotech, United States) were fixed onto the pipe with a clamp. A micrometer is used to move the wedge by small distances horizontally as shown in Fig. 3. An LVDT (VG/2/s, 54.1mV/V/mm sensitivity, Solartron Metrology, West Sussex, UK) was used in order to measure accurately the position of the wedge (repeatability of 0.018μm). Therefore to move approximately 300μm (equivalent of generating 2 m/s in Equation 1), the repeatability of the measurement is better than 0.1%. To transmit (1MHz, 5 cycles toneburst, 12

V) and receive the ultrasonic signals (14 bit ADC at 50 MHz sampling frequency, amplifier at 40dB), Handyscope HS5 (Tiepie Ltd, Sneek, The Netherlands) was used. The signal

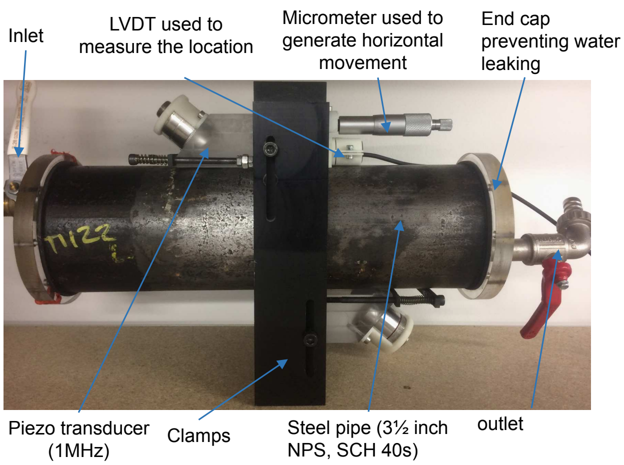


Fig. 5: Photo of the experimental setup showing the transducer and the steel pipe

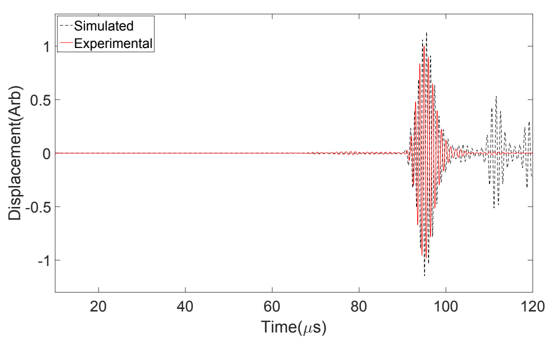


Fig. 6: Reference signal obtained experimentally compared with the simulated reference signal

obtained experimentally is shown in Fig. 6. A good agreement is achieved between the experimentally obtained and simulated signal. It was observed that low amplitude waves arrive before the main signal arrives. This is due to waves travelling around the pipe circumference. In addition, followed by the main signal, there are signals arriving later. This is due to reflections within the wedge (the wedge where the generator is attached). These additional signals are attenuated in the experiment.

B. Probe placement experiments

In order to verify the simulation method, experiments were carried out to measure the uncertainties related to horizontal separation distance between the probes.

The procedure to carry out the test is to deliberately introduce errors on horizontal distance between the ultrasonic probes. For each of the positions, to generate the upstream and downstream signals, the method described in Section II-B is used. Then the reference signal processing methods were used to calculate the estimated flow velocity.

Horizontal errors from -40 (negative means smaller separation distance between the probes) to 30 mm were tested and simulation was also carried out following the same procedures.

The result of this test is shown in Fig. 7. Between -15 and 15%, the estimated flow velocity error is small in comparison to the repeatability (error bar). However, outside this horizontal distance error, the experimental results show agreement with the simulation results. This indicates that this simulation method yields valid results.

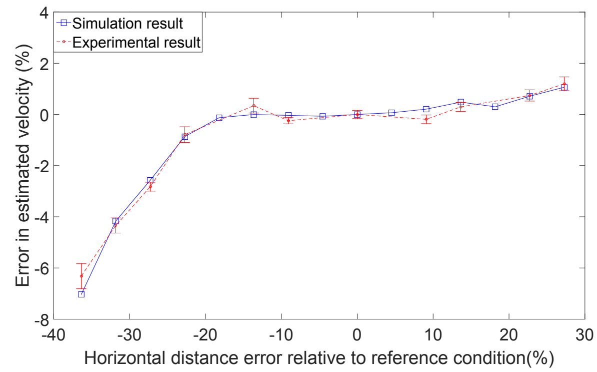


Fig. 7: The effect of horizontal separation distance between the transducer probes on the estimated flow velocity error. The repeatability is represented by the error bar

IV. Pipe roughness uncertainty simulation

After the reference simulation method was verified by the experiments, the method was then used to carry out the parametric study on quantifying the uncertainties of estimated flow velocity relating to pipe wall roughness. Only the internal pipe wall roughness is investigated.

To define the surface roughness, RMS height and correlation length were used [17]. [18] indicates the 0.05 mm is approximately the RMS height for the new pipe and 0.2 mm represents the roughness of a pipe that is moderately corroded. Correlation length measures the horizontal variation of the roughness profile. 1, 3 (wavelength of the shear ultrasonic wave in steel) and 5 mm correlation length are chosen.

In this paper, 12 different combinations of RMS and correlation lengths were simulated. For each of the combinations, 10 realizations of roughness profile were generated. This is because even for profiles that have the same combination of parameters, the actual profile that ultrasonic wave transmitted through is different.

For each of the roughness profile, the simulation method shown in Section II was carried out. An estimated flow velocity is generated for each of the simulation and each of the realization. Fig. 8 presents the mean and standard deviation of the 10 realizations for each parameter combination.

The mean of the estimated velocity errors is approximately 0 while the standard deviation increases with the RMS height. This means to evaluate the impact of roughness on the uncertainties of UFM, the mean error of the estimated flow

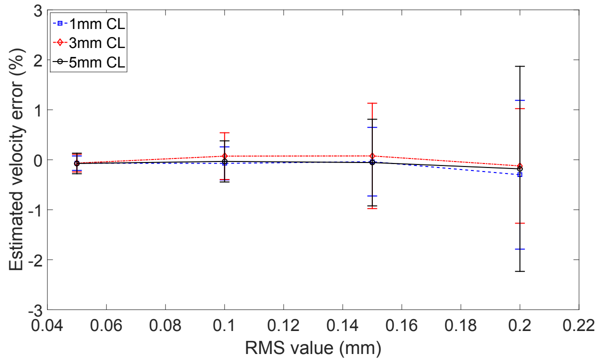


Fig. 8: For different parameter combinations, the mean and standard deviation are calculated for 10 realizations of the estimated flow velocity error and their error is shown

velocity is not representative. Therefore, the standard deviation of the estimated flow velocity shows how much influence the pipe roughness has on the uncertainties [19].

The RMS height of the roughness profile has a large impact on the scattering of ultrasound and therefore on the roughness induced uncertainties of clamp-on UFMs. [20] [21] describe the expected effects of the rough profiles on the ultrasonic measurements. The relative RMS height to the ultrasonic wavelength determines how large the impact is. If the RMS height is much larger than the wavelength, the phase of the beam that enters the fluid from steel pipe varies spatially along the pipe wall. This changes the phase and amplitude of the received ultrasonic wave and causes an error in the travel time.

For a moderately corroded pipe (0.2 mm RMS height and 5 mm correlation length), the standard deviation reaches about 2% for estimated flow velocity uncertainty. This means, the systematic errors could reach the order of 2% for clamp-on flow meter on moderately corroded pipes. This number is a large proportion of the uncertainties claimed by manufacturers (1-5%).

V. Discussion and Conclusion

The aim of this paper is to quantify the measurement uncertainties of clamp-on UFMs induced by the internal pipe wall roughness (non-flow related effects). A reference simulation method was presented and experimentally verified. Then this method was applied to investigated the measurement uncertainties caused by internal pipe wall that has different roughness parameters for a particular setup. It was found that the systematic error could reach as much as 2% for a moderately corroded pipe (0.2 mm RMS height and 5 mm correlation length). Since the manufacturers quote the accuracy of the clamp-on UFM to be approximately 1-5%, these results indicate that roughness of the internal pipe surface is an important parameter that needs to be considered during the installation.

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