Studies on Attenuation in Ultrasonic Flow Meter

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Introduction

Ultrasonic technology is used for various crucial measurements in the industry; few of the most popular uses are in Non-destructive testing, flow measurement, level measurement etc. Like every other energy waveform the ultrasonic waveforms also suffers attenuation while travelling through a medium. This attenuation is a function of the square of resonant frequency of the ultrasonic waveform, thermal coefficient of the medium, bulk and shear viscosity of the medium. If the attenuation is high the received signal becomes almost undetectable, hence transducer frequency is a very important criterion for choice of ultrasonic transducer to be used in desired medium.

In order to design an in-house ultrasonic flowmeter, it was necessary to determine the transducer frequency for the given flow medium and pipeline dimension. For this purpose, a model was prepared using Computational Fluid Dynamics module and Acoustic module of COMSOL. In order to achieve coupling between the flow and acoustic, thermoviscous acoustic transient interface have been used. This interface aided in studying the effects of attenuation due to frequency of waveform, the thermal co-efficient of medium and bulk viscosity of the medium.

Literature Survey

The attenuation suffered by acoustic waveform while travelling in a medium can be given by equation 1.

$$I = I_0 \exp(-2x\alpha_{abs}) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Where,

- I is net acoustic pressure received at the end
- I_0 is initial acoustic pressure
- x is distance travelled by the waveform
- α_{abs} is absolute value of attenuation/ absorption co-efficient

$$\alpha_{abs} = \alpha_S + \alpha_T + \alpha_B \quad \ldots\ldots\ldots\ldots\ldots (2)$$

$$\alpha_S = \frac{8\,\pi^2 f^2\, n_S}{3\,\rho\, c^3} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

$$\alpha_T = \frac{2\,\pi^2 f^2\, K}{\rho\, c^3}\left(\frac{\gamma-1}{c_p}\right) \quad \ldots\ldots\ldots\ldots\ldots (4)$$

$$\alpha_B = \frac{2\,\pi^2 f^2}{\rho\, c^3}\left(\frac{4\,n_S}{3} + \frac{(\gamma-1)K}{c_p} + n_B\right) \quad \ldots\ldots (5)$$

Where,

- α_S is attenuation/absorption co-efficient due to shear viscosity of the medium
- α_T is attenuation/absorption co-efficient due to thermal conductivity of the medium
- α_B is attenuation/absorption co-efficient due to bulk viscosity of the medium.

It can be concluded from above equations that the pressure of the acoustic wave received at the end of the duct will be a function of the frequency of the ultrasonic transducer and size of the pipe.

Simulation and Governing Equations

The Geometric model shown in figure 1 was prepared. The central cylindrical part signifies the main flow pipe line and the duct aligned at an angle of 45° is the transducer duct. Both of the ends of the main pipe line are suffixed with Perfectly matched layer to absorb any acoustic wave form going through them and therefore removing the chances of false reflections from inlet and outlet of the pipe line.

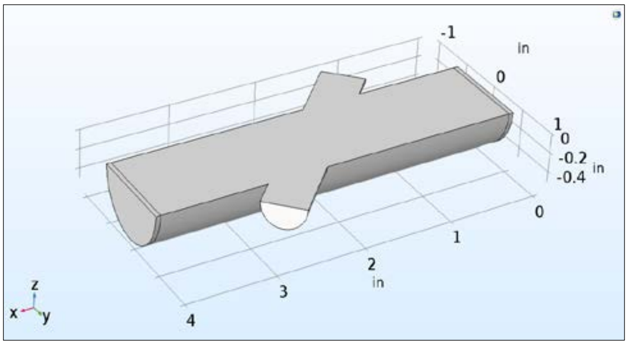

Figure 1: Geometric Model

Figure 2 shows the meshed geometry. Meshing of the geometry was done with tetragonal element type. The largest size of the element/mesh was chosen as λ/4, to better resolution.

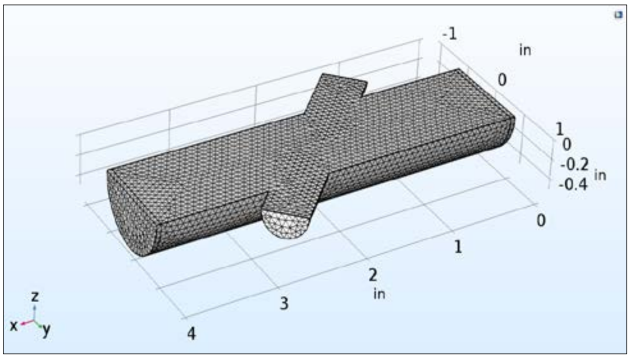

Figure 2: Tetragonal meshing over the geometric model

Turbulent flow k-ε model in Computational Fluid Dynamics module has been used to simulate various flow rates. Since the flow is considered constant for a given simulation stationary study has been used in this module. Figure 3 shows the surface velocity of the fluid at any given time instant.

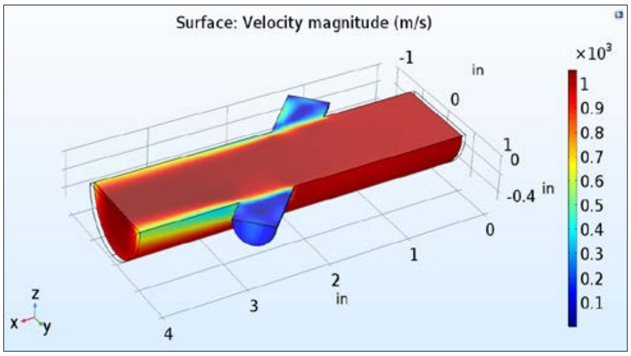

Figure 3: Velocity magnitude via CFD computation

At one end of the transducer duct is the source (pressure source) and the other end acts as the pressure receiver. Pressure Acoustics, Transient model of acoustics module has been utilised to develop a normal entering pressure waveform from the source side of the duct.

The thermos-viscous model under pressure acoustics was utilised to study the waveform received at the receiver end of the transducer duct after suffering attenuation (depending on the medium properties and frequency of the transducer). Time dependent studies were done with pressure acoustics and thermos-viscous acoustics to arrive at the results. Figure 4 shows a screenshot of the acoustic pressure arising from the transmitter and moving towards receiver at a time instant of 2.3e-5 seconds.

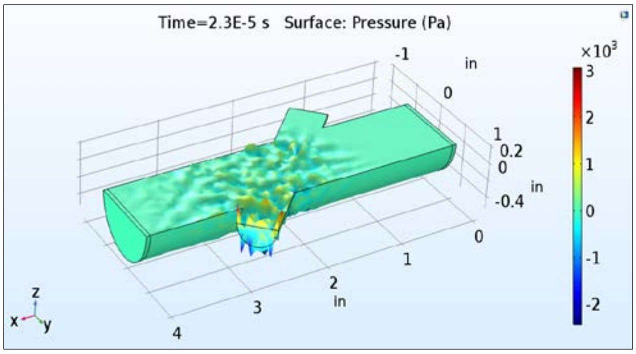

Figure 4: Acoustic pressure on the surface via Thermo-Viscous Module

The model was executed with water as the medium and amount of attenuation was studied at various transducer frequencies. Further, studies were done with water as medium at different flow rates. The results obtained with these simulations were used to arrive at an acceptable value of transducer frequency to be used in ultrasonic flowmeter prototype for a given pipe line size.

The following governing equations were used to arrive at the pressure attenuation results.

$$\frac{\partial \rho_t}{\partial t} + \nabla\cdot(\rho_0 \mathbf{u}_t) = 0 \qquad ....(6)$$

$$\rho_0 \frac{\partial \mathbf{u}_t}{\partial t} = \nabla\cdot\left[-p_t\mathbf{I} + \mu\left(\nabla\mathbf{u}_t + (\nabla\mathbf{u}_t)^T\right) - \left(\frac{2}{3}\mu - \mu_B\right)(\nabla\cdot\mathbf{u}_t)\mathbf{I}\right] \qquad (7)$$

$$\rho_0 C_p\left(\frac{\partial T_t}{\partial t} + \mathbf{u}_t\cdot\nabla T_0\right) - \alpha_p T_0\left(\frac{\partial p_t}{\partial t} + \mathbf{u}_t\cdot\nabla p_0\right) = \nabla\cdot(k\nabla T_t) + Q \qquad ....(8)$$

$$\rho_t = \rho_0(\beta_T p_t - \alpha_p T_t) \qquad ....(9)$$

$$\alpha_p = -\frac{1}{\rho_0}\left[\frac{\partial \rho_0}{\partial T_0}\right]_{p_0} \qquad ....(10)$$

$$\beta_T = \frac{1}{\rho_0}\left[\frac{\partial \rho_0}{\partial p_0}\right]_{T_0} \qquad ....(11)$$

Simulation Results

The model was simulated for 4 different pipe sizes with transducers of different frequencies and the acoustic pressure at the transmitter and receiver end of the duct was monitored. Figure 5 and figure 6 shows the pressure variation at transmitter and receiver when a transducer of 2MHz and 1MHz is used respectively at the end of transducer duct.

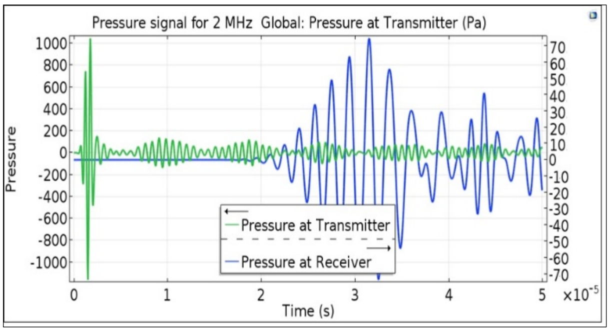

Figure 5: Pressure signal at transmitter and the Receiver when 2MHz transducer is used

It can be seen that the ratio of magnitude of pressure wave at receiver to magnitude of pressure at transmitter is around 0.07 whereas the same ration in case of 1MHz transducer comes around 0.2.

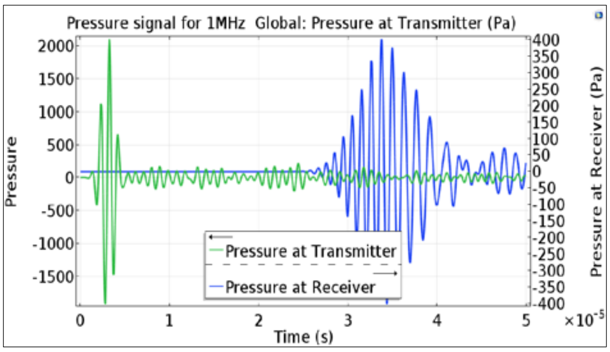

Figure 6: Pressure signal at transmitter and the Receiver when 1MHz transducer is used

Various other simulations were done on similar lines and the results are plotted in the graph in figure 7. It can be seen that as the frequency of the ultrasonic transducer increases the ratio of pressure magnitude at the Receiver to that at the transmitter decreases exponentially.

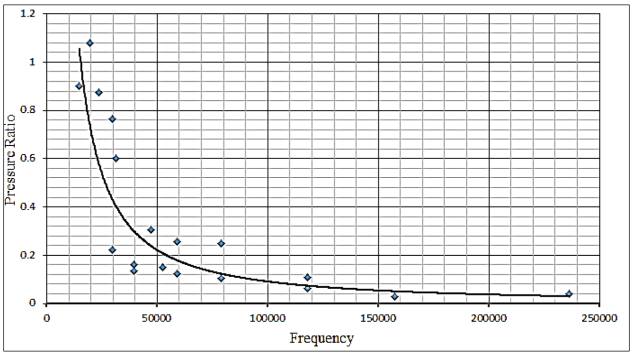

Figure 7: Variation in pressure ratio (Received versus Transmitted) with frequency of the transducer

Conclusions

The Study clearly shows that frequency of the transducer plays an important factor for choice of transducer in ultrasonic related applications.

Studies done till now are for ultrasonic flowmeter with water as a medium, however the same approach can be effectively used to do attenuation studies for other mediums too. The model for Non-destructive testing and level measurement can also be made on similar lines.