Simulation of Sound Wave Propagation Inside a Spherical Ball Submerged in a Pipeline

Wadie R. Chalgham*[1], Abdennour C. Seibi[1], and Mehdi Mokhtari[1]
[1]University of Louisiana at Lafayette
*P.O. Box 40029, Lafayette, LA 70504, wadie.chalgham@gmail.com

Abstract: One of the limitations of pipelines performance and structural integrity assessment is the continuous inspection of possible leaks due to corrosion or other types of failure mechanisms. Efforts to develop new technologies started several decades ago where different inspection techniques were used to enhance pipelines structural integrity. Although available technologies present some advantages, they still have some limitations in practice. This paper presents preliminary numerical simulation results of a research effort aiming at developing a new inspection technique consisting of inserting an autonomous self-recharging spherical ball, equipped with multiple sensors, and moving inside the pipeline. The simulation initially focused on the fluid flow around the spherical ball and noise level propagating inside the pipeline. In addition, COMSOL was used to study the effect of fluid type, ball material, leak location and initial leak noise on the sound pressure level propagation inside the pipe and through the ball. The main goal of this paper is to use the simulation results to calibrate the control system embedded inside the mobile inspection ball.

Keywords: Leak Detection, Fluid Flow, Pipeline Inspection, Safety, Environment

1. Introduction

Undetected leaks present major financial, environmental, and human threats. Every day, more than 7 billion gallons of clean drinking water are lost due to pipeline failure leading to a loss of $11 billion per year from water leaks only (James, 2011). Moreover, the U.S. Department of Transportation reported that 623 gas and hazardous liquid pipeline incidents happened in 2013 resulting in 10 fatalities, 47 injuries and an estimated cost of $336 million in property damage (Calder, 2014). Thereby, leak detection is essential to mitigate any future incidents from occurring, which require the development of innovative and advanced inspection techniques.

2. Objectives and Scope

This paper presents simulation results of the fluid flow around a mobile spherical ball inside a pipeline as well as the leak noise propagation inside the ball. This preliminary study aims at developing a new inspection tool consisting of a mobile ball detecting leaks inside pipelines using acoustic signals. The velocity and pressure profiles will be used to calibrate the control system inside of the ball. The control system relates sound pressure levels to leak detection and accounts for the perturbations caused by the fluid flow around the ball.

3. Use of COMSOL Multiphysics® Software

3.1 Purpose of Use

COMSOL Multiphysics was first used to create the geometry of this autonomous ball, which presents a novel design in mobile inspection tools. Then, COMSOL Computational Fluid Dynamics (CFD) module was used to simulate the velocity and pressure propagation around the ball located inside the pipeline for two cases: i) no leak along the pipe and ii) induced leak. The goal of using the CFD module is to find the velocity and pressure profiles around the moving ball. Next, the Acoustics and Vibrations module was used to simulate the leak noise propagation generated when a leak occurs. This module was used to check how leak noise travels inside a pipeline and how it propagates inside the mobile ball.

The intended results will be used to provide enough data to build a control system able to detect leak sizes and locations with higher precision. Moreover, COMSOL was used to conduct a sensitivity analysis that compared results for different fluid types, ball materials, leak locations and initial leak noises. The aim of the sensitivity analysis is to provide a better calibration of the control system.

3.2 Initial and Boundary Conditions

The model under study consists of a fluid flow around a stationary spherical ball placed inside a pipeline as well as the sound propagation generated from an induced leak. In order to accurately understand the collected results, several assumptions were made in the model design: i) single phase laminar flow was considered, ii) constant fluid temperature, iii) constant heat capacity of the fluid (as long as the measurements are at the same depth with the same flow rate then the heat transfer of the fluid will remain the same without random changes to the heat capacity of the fluid), iv) negligible friction-induced heat, and v) the pipe walls are assumed to be sound insulators since this study does not account for external noise.

4. Numerical Model

In order to simulate the fluid flow around the ball, a section of a typical cylindrical pipeline model was developed having a 10 in. diameter as shown in Figure 1. Water was used as the flowing fluid, which was given an initial inlet velocity of 1 mm/s. The ball has a diameter of 6 in. A 0.5 in. diameter leak was induced at an initial location of 25 in. from the pump, which was varied to conduct a sensitivity analysis for a 40 in. pipe section.

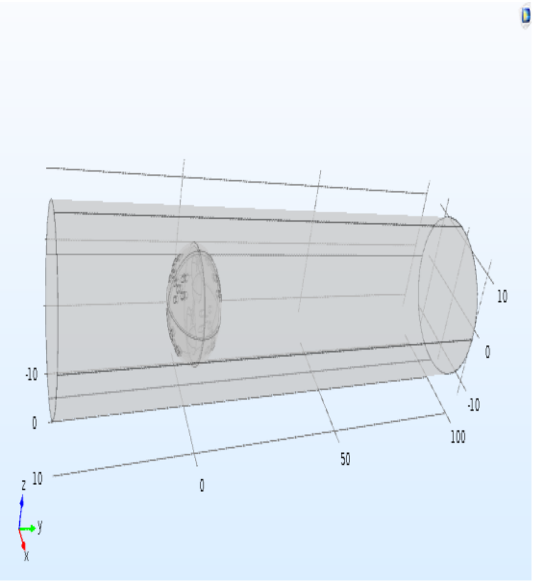

Figure 1. Mobile Ball Flowing inside the Pipeline

5. Simulation Results

5.1 Numerical Simulation of Velocity Profiles

This simulation used the Computational Fluid Dynamics (CFD) module. Figure 2 shows the velocity profile of the fluid flowing inside the pipe with the leak. The simulation shows how the velocity magnitude of the fluid inside the pipe increases around the ball from the upper and lower sides. This increase is caused by the reduction in area of the flowing water. In fact, at a distance of 12 in. from the inlet, the fluid has a flow surface of $\pi/4*(10^2 - 6^2)$ or 16π in.^{2} compared to an initial flow surface $\pi/4*10^2$ or 25π in.^{2}.

To better visualize the velocity profile around the ball, five vertical sections along the pipe are considered. Figure 3 shows five vertical pipe sections equally spaced starting from the location of 6 in. from the pump to study the change of fluid velocity before, around and after the ball.

Figure 4 describes precisely the change in velocity by plotting the magnitude of the velocity along the vertical direction at the five different sections.

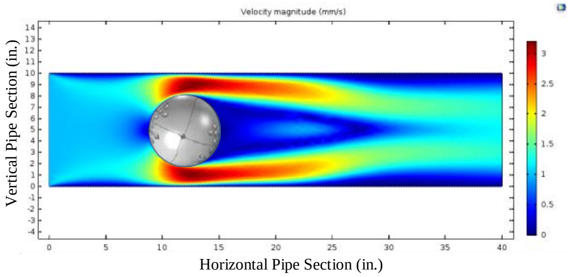

Figure 2. 2D Velocity Distribution of the Fluid around the Ball in Case of a Leak

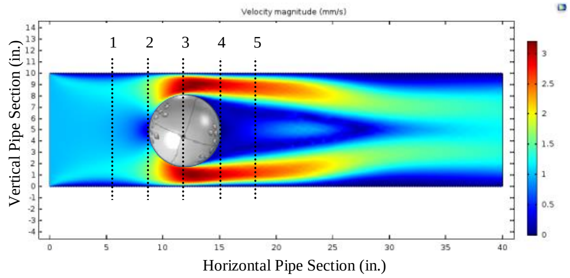

Figure 3. Five Vertical Sections of Pipe

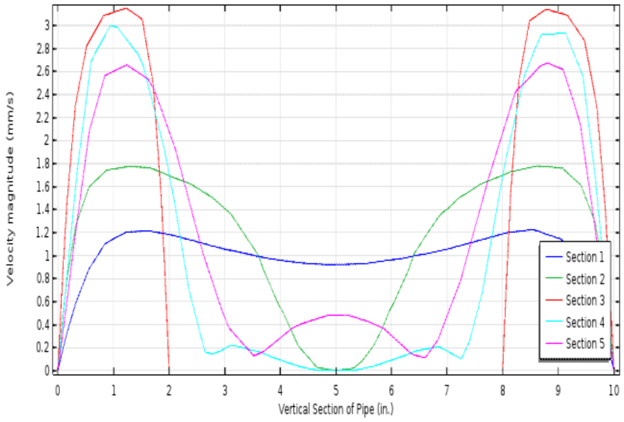

Figure 4. Average Horizontal Velocity Magnitudes of the Fluid along five Vertical Sections inside the Pipe

The results show how the velocity peaks on the upper and lower sides of the spherical ball. As expected, the highest velocity peaks are observed at the Section 3 with magnitudes of 3.1 mm/s, more than 3 times the initial inlet velocity of 1 mm/s.

5.2 Numerical Simulation of Pressure Profiles

This simulation used the Computational Fluid Dynamics (CFD) module. Figure 5 shows the pressure profile of the fluid flowing inside the pipe in the case of a leak. The simulation shows how the pressure reduces significantly when the fluid flows around the spherical ball. In order to understand the effect of the leak on the pressure distribution of the fluid inside a pipeline, another simulation was performed without a leak.

Figure 6 shows a plot of the pressure distribution along a horizontal section below the ball, at an elevation of 2 in.

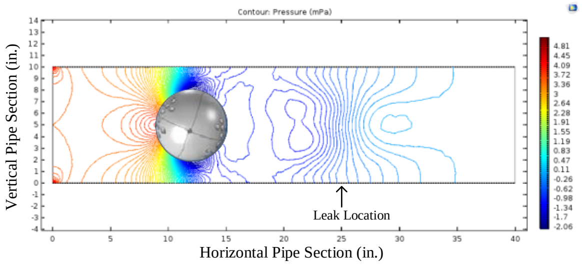

Figure 5. Pressure Distribution in Case of a Leak

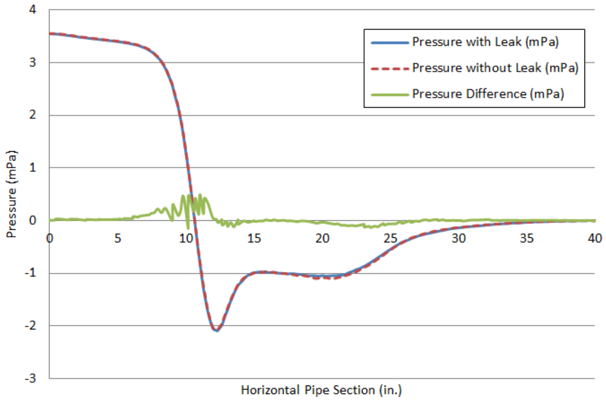

Figure 6. Pressure Distribution around the Mobile Ball without a Leak

The plots show that the pressure difference is negligible inside the pipe except around the ball and near the leak location of 25 in. Also, the plots illustrate how the pressure magnitudes decrease significantly around the ball location, from 9 to 15 in., reaching negative magnitudes which could be explained by the high fluid velocity at this location. Moreover, the pressure tends to increase after the ball location reaching a positive magnitude again after 25 in.

The results from Figure 6 confirm Bernoulli's equation. In fact, the increase in velocity observed in Figure 4 around the ball (from 1 to 3.1 mm/s) resulted in a significant reduction in pressure of more than 5 mPa.

5.3 Numerical Simulation of Sound Pressure Level Propagation inside the Pipeline

To simulate a leak noise generated from a leak size of 0.5 in., a point source was created at a location of 25 in. where the leak centerline is located. The spherical ball has a steel layer of 0.5 in. thickness filled with air. An initial leak noise power of 8.5e-11 W was assigned at this location to study sound propagation along the pipe and inside the ball.

Figure 6 shows the simulated results of acoustic propagation from the leak location and how the magnitude of the sound pressure level decreases as it gets away from the leak location.

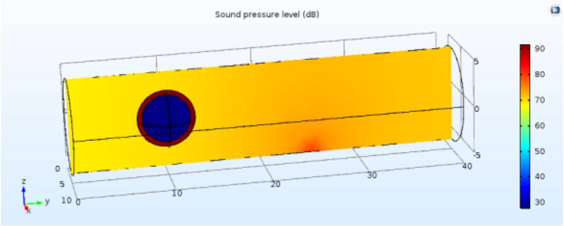

Figure 6. Sound Pressure Level in dB in the Presence of a Leak at a location of 25 in.

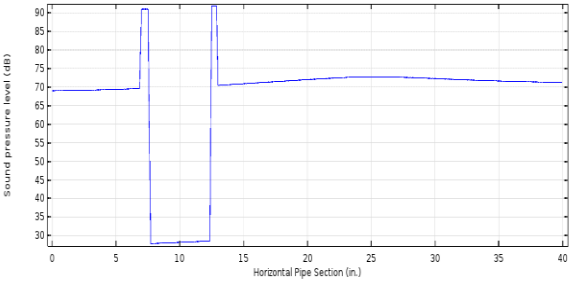

Figure 7. Sound Pressure Level Propagation Inside the Ball Only

In addition, this simulation shows how the sound pressure level increases in the steel layer and decreases inside the spherical ball. In fact, steel has higher density compared to water and air, which allows it to have higher pressure levels. Figure 7 presents a plot of the sound pressure level propagation in decibel (dB) at the centerline of the pipe.

The results from Figure 7 show how the sound level increases at the leak location of 25 in. and then decreases and peaks again at the ball location. At the steel outer layer of the ball, the sound pressure level increased by 20 dB from 72 to 92 dB, an increase caused by the higher density of steel. It is important to also note that the sound pressure level at the rear side of the ball has a magnitude of 91 dB, a 1 dB lower than the value at the front side of the ball. These results are significant since they will be used to correctly calibrate the control system, which will be designed in the next phase of this research effort.

For instance, for this particular case scenario, an increase of 20 dB detected at the ball location describes that the leak is at a distance of 10 in., calculated by subtracting the ball front location of 15 in. from the leak location of 25 in.

In addition, the calibration magnitude for this case scenario is ± 1 dB, calculated by subtracting the sound pressure level at the front side of the ball of 92 dB from the rear side having a magnitude of 91 dB. Thus, the expression that will be implemented in the control system for this case scenario is 20 ± 1 dB.

6. Sensitivity Analysis on Leak Noise Propagation

The obtained results so far represent an initial study of one case and needs to be investigated for more scenarios where the fluid type, ball outer layer material, leak noise intensity and leak location are different. This section describes the effect of these parameters.

6.1 Effect of Fluid Type

In order to understand the effect of fluid type on the sound propagation inside a pipe, a different fluid medium such as oil was used using the same conditions as for water. Figure 8 shows the effect of the flowing fluid type on the sound pressure level propagation. The results show that the sound pressure levels are lower when using oil as the flowing fluid than when using water. The difference is explained by the difference in density; oil is less dense than water. The maximum recorded difference between the water and oil plots is 1.2 dB. As a result, the calibration for fluid type is not negligible and has a magnitude of ± 1.2 dB.

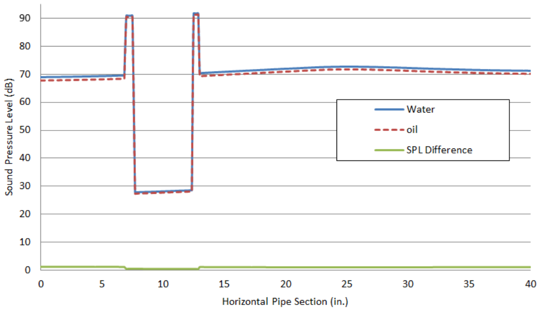

Figure 8. Fluid Type Effect on Sound Pressure Level Propagation inside a Pipeline

6.2 Effect of Ball Material

In order to understand the effect of the ball outer layer material on the sound propagation inside a pipe, different simulations were conducted where aluminum and polypropylene were used instead of steel. For comparison purposes, the fluid type was maintained as water.

Figure 9 shows the effect of the ball material on the sound pressure level propagation. The results show that the sound pressure level varies with respect to the material type where the sound decreases in aluminum and polypropylene as compared to steel. The difference is explained by the difference in density; aluminum is less dense than steel and polypropylene is less dense than aluminum.

The maximum recorded difference between the steel and aluminum/polypropylene is 2.7 and 17.2 dB; respectively. As a result, the calibration for ball material is not negligible and has a peak magnitude of ± 17.2 dB. This calibration parameter depends on the material type used for the ball.

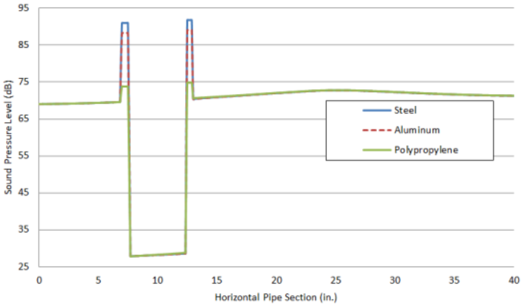

Figure 9. Ball Material Effect on Sound Pressure Level Propagation inside a Pipeline

6.3 Effect of Initial Leak Noise Power

The initial leak noise power used in the previous simulations was assumed to be constant at 8.5 e-11 W. To understand the effect of different initial leak noise powers on the sound pressure level, various simulations with different leak noise magnitudes were compared. A spherical steel ball flowing in water was used.

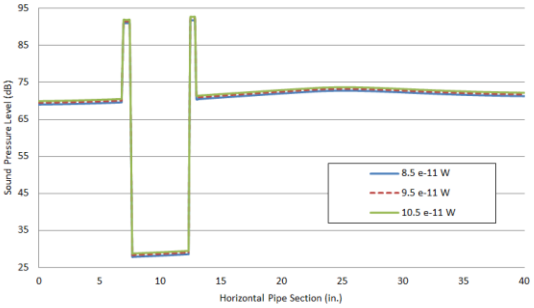

Figure 10. Leak Noise Power Effect on Sound Pressure Level Propagation inside a Pipeline

Figure 10 shows the different sound pressure level magnitudes for various audible initial leak noises. The results show that when the initial leak noise power increases, the sound pressure levels increase as well.

The maximum recorded difference in magnitude is 0.48 dB, describing an increase of leak power of 1 e-11 W (from 8.5 to 9.5 e-11 W). As a result, the calibration for initial leak noise is not negligible and has a peak magnitude of ± 0.48 dB per 1e-11 W change in initial leak power.

6.4 Effect of Leak Location

The previous simulations used a fixed leak location of 25 in., which is located at a distance of 12 in. (1 ft.) from the center of the ball. In order to understand the effect of leak location on the sound pressure distribution, different leak locations were used.

Figure 11 shows the simulation results of sound pressure level propagation inside the pipe when leak locations are at distances of 13, 25 and 37 in. from the inlet or at distances of 0, 1, and 2 ft. respectively from the front side of the ball. For this sensitivity analysis, the fluid type is water, the ball outer material is steel and the leak initial power is 8.5 e-11 W. The results show that when the leak location is 1 ft. farther from the front side of the ball (i.e., from 13 in. to 25 in.), the recorded sound pressure level magnitudes decrease by a peak value of 23.6 dB.

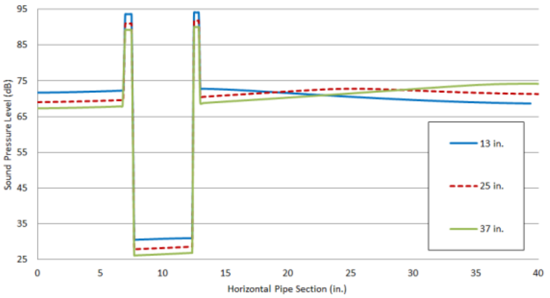

Figure 10. Leak Location Effect on Sound Pressure Level Propagation inside a Pipeline

As a result, the calibration for leak location is very important and has a peak magnitude of ± 23.6 dB per 1 foot change in leak location. This sensitivity analysis showed that the calibration of the control system embedded inside the ball is primarily affected by the leak location since it has the highest calibration magnitude of 23.6 dB when compared to the other calibration parameters.

8. Conclusions

The simulation results provided data to calibrate the control system of the ball with respect to the flowing fluid type, ball material, initial leak noise power, and leak location inside a pipeline. The following calibrations were found and represent peak values to have more accurate results:

- The fluid type has an effect of ± 1.2 dB on the sound pressure level.
- The ball outer layer material has an effect of ± 17.2 dB on the sound pressure level received at that outer shell of the ball where the acoustic sensors will be placed.
- The leak noise has an effect of ± 0.48 dB per 1e-11 W change in power on the sound pressure level.
- The leak location has an effect of ± 23.6 dB per 1 foot change distance on the sound pressure level.

These calibration values represent the noise level threshold below which any noise level will be detected by the sensors.

9. References

1. Chalgham, W. R., Seibi, A. C., and Boukadi, F., Simulation of Leak Noise Propagation and Detection Using COMSOL Multiphysics, *ASME Proceedings of the International Mechanical Engineering Congress & Exposition, Phoenix, Arizona, USA* (2016)

2. Chalgham, W. R., Seibi, A. C., and Lomas, M., Leak Detection and Self-Healing Pipelines Using Twin Balls Technology, *SPE Annual Technical Conference and Exhibition, Dubai, UAE* (2016)

3.Ariaratnam, S.T. and Chandrasekaran, M., Development of an Innovative Free-Swimming Device for Detection of Leaks in Oil and Gas Pipelines, *Proceedings of the 2010 ASCE Construction Research Congress "Innovation for Reshaping Construction Practices", ASCE, Banff, Alberta* (2010)

4. Bond, A., Deployment of equipment into fluid containers and conduits. *United States Patent and Trademark Office, U.S. Patent No. 5,889,703, USA* (2005)

5. Bond, A., Mergelas, B. and Jones, C., Pinpointing Leaks in Water Transmission Mains, *Proceedings of ASCE Pipelines 2004, San Diego, California, USA* (2004)

6. Calder, B., Technologies Mimic the 5 Senses to Monitor Pipelines, *Intel Free Press* (2014)

7. Chapman, H., Development of a Successful Internal Leak Detection and Pipeline Condition Assessment Technology for Large Diameter Pipes. *6th Annual WIOA NSW Water Industry Engineers & Operators Conference* (2012)

8. Chatzigeorgiou D., Khalifa A., Youcef-Toumi K. and Ben- Mansour R.. An in-pipe leak detection sensor: Sensing capabilities and evaluation. *ASME/IEEE International Conference on Mechatronic and Embedded Systems and Applications* (2011)

9. Dancer, B., Shenkiryk, M. and Day, S., Leak Detection Survey for a Large Diameter Transmission Main: City of Calgary, *Proceedings of the 2009 Pipelines Conference, ASCE, San Diego, CA* (2009)

10. James, A., The U.S. Wastes 7 Billion Gallons of Drinking Water a Day: Can Innovation Help Solve the Problem? *Climate Progress, Think Progress* (2011)

11. Khalifa A., Chatzigeorgiou D., Youcef-Toumi K., Khulief Y. and Ben-Mansour R., Quantifying acoustic and pressure sensing for in-pipe leak detection, *ASME International Mechanical Engineering Congress & Exposition* (2010)

10. Acknowledgements

The author is grateful to the University of Louisiana at Lafayette and to the advisor Dr. Seibi, who supported the simulation work and provided continuous support to this research study.

11. Appendix

GEOMETRY

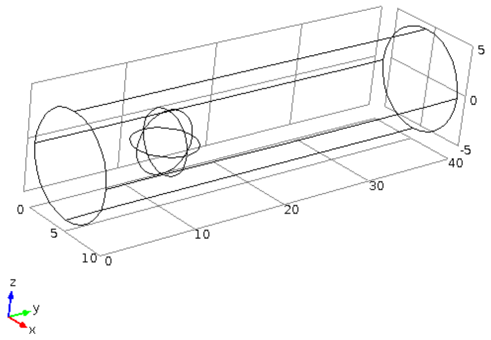

Figure A1. Solid Model of Pipe/Ball System

ACOUSTIC DIFFUSION MODEL

The acoustic diffusion model is based on the assumption that the volumes studied contain scatters that uniformly scatter the sound field and that the sound field is diffuse (large number of reflections). Using the diffusion of light in a scattering environment as an analogy one can express a diffusion equation for the sound-energy density w = w(x,t) (SI unit: J/m3). The diffusion equation describes the energy flow from high to low energy regions.

DOMAIN EQUATIONS

The domain diffusion equation for the sound-energy density $w = w(\mathbf{x}, t)$ is given by :

$$\frac{\partial w}{\partial t} + \nabla.\boldsymbol{J} + c\, m_a\, w = q(\boldsymbol{x}, t)$$

where the local energy flux vector **J** (SI unit: $J/m^2/s = W/m^2$) is defined in the usual way, as:

$$\boldsymbol{J} = -D_t\, \nabla w$$

The equation is simplified as:

$$\nabla.(-D_t\, \nabla w) + c\, m_a\, w = q_p \delta(\boldsymbol{x} - \boldsymbol{x_0})$$

The total diffusion coefficient is $D_t = D = \lambda c/3$ (SI unit: m^2/s), λ is the mean free path (SI unit: m), c is the speed of sound (SI unit: m/s), and m_a is the volumetric absorption coefficient (SI unit: 1/m).

MESH

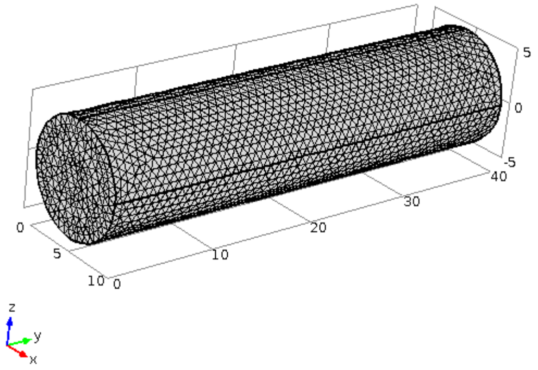

Figure A2. Finite Element Model of Pipe/Ball System