Modeling Low Frequency Axial Fluid Acoustic Modes in Continuous Loop Piping Systems

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Abstract

Industrial fluid systems often involve continuous piping loops. Hydraulic and heating/coolant systems are common examples. These systems consist of varying lengths of pipes and hoses connecting multiple components together. The fluid passes from a starting point along a supply path to a location where the quantity within the fluid is transferred into another process through a component such as a heat exchanger, separator or hydraulic actuator. Once the quantity of interest has been transferred, the fluid is recirculated through a return leg to the original location forming a "continuous" loop of fluid. Figure 1 shows a schematic representation of one such continuous loop piping system. Fluid resonances can detrimentally affect the operation of fluid systems and components. The unwanted impacts of the fluid resonances include increased system noise, excessive component fatigue, interference with test measurements and monitoring instrumentation, improper system and potentially system or component failure. The analysis of axial fluid resonances within a system loop of piping is an acoustic problem that incorporates elastic effects [1,2]. These resonances are sometimes simply referred to as "acoustic" resonances as opposed to structural resonances, even though the fluid and structural resonances are not independent of each other. The objective of this work was to investigate the frequency and mode shapes of axial fluid resonances within a system of piping and components that form a continuous loop. Finite element models were generated using the Acoustic Module in COMSOL Multiphysics to investigate the behavior of axial fluid resonances in various continuous loop piping systems, including the example system shown in Figure 1. Water was used as the working fluid flowing inside a metallic pipe. The frequencies and mode shapes of the pressure modes were calculated with an eigenvalue analysis of the model. Similar calculations were performed using the Transfer Matrix Method and the results of both approached were compared. The baseline model consisted of a uniform continuous loop. Analysis was done for rigid wall conditions and considering the effect of elasticity. Figure 2 shows representative computed mode shapes. For the elastic pipe, frequencies of the axial loop modes occurred at lower values than those calculated for the axial modes within a rigid wall loop of the same fluid and dimensions. However, the pressure and displacement mode shapes remained sinusoidal. The corresponding pressure mode shape for a continuous loop system with three cavities along its length is shown in Figure 3. In general, the pressure modes are similar, occurring at slightly different frequencies and showing small differences in the amplitudes of the mode shape. However, the displacement mode shapes are not continuous (Figure 4). The axial displacement within the component cavities decreases due to the increase in cross sectional area and changes in the phase velocity. The volume displacement was continuous for each of the mode shapes calculated

indicating that the TMM and FEA modes satisfy the continuity of volume velocity. It was shown that at the location of sudden changes in impedance in continuous loop piping systems, the conditions of continuity could cause a discontinuity in the phase angle or imaginary portion of the axial mode. The discontinuities in phase angle can cause each of the axial loop modes to shift lower or higher in frequency, depending on the net change in phase angle. The net change in phase angle was found to be specific to each axial mode resulting in a unique change in frequency for all of the axial loop modes. The unique shifting in frequency resulted in a non-harmonic spacing of the axial modes. The modes of each whole wavelength axial mode pair also shifted uniquely. This resulted in two modes for each integer multiple of whole wavelength occurring at different frequencies in the same physical system. The pressure mode shapes were found to have kinks at the locations of impedance and phase angle discontinuities. While the real portion of the pressure remained continuous, the slope of the pressure mode shape was not continuous. The discontinuities in the slope of the pressure resulted in mode shapes that were not purely sinusoidal and had amplitude variations within a single mode. The variation in magnitude and the discontinuity in the slope of the pressure modes were related to the phase angle discontinuity. Moreover, the changes in the frequency and mode shapes of the axial loop modes were much larger due to the impedance discontinuities than the changes in phase velocity due to the elasticity of the cylindrical components and piping. The frequencies and modes shapes of the axial loop modes calculated by COMSOL Multiphysics were in good agreement with acoustic theory and with the results obtained from the TMM models.

Reference

1. F. Axisa and J. Antunes, Modeling of Mechanical Systems Fluid-Structure Interaction, First Edition, Elsevier, Boston, 2007.
2. K. Baik, J. Jiang, and T. G. Leighton, “Theoretical investigation of acoustic wave propagation in a liquid-filled cylinder,” ISVR Technical Report No. TR 329, The Institute of Sound and Vibration Research, University of Southampton, Southampton, UK, 2009.
3. E.R. Marderness, Low Frequency Axial Fluid Acoustic Modes in a Piping System that Forms a Continuous Loop, Thesis, Master of Science in Mechanical Engineering, Rensselaer Polytechnic Institute, Hartford, Connecticut, April 2012.

Figures used in the abstract

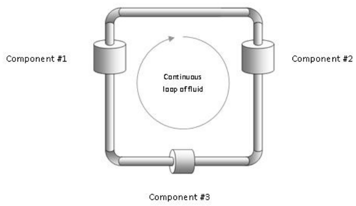

Figure 1: Schematic of a continuous loop piping system with cavities.

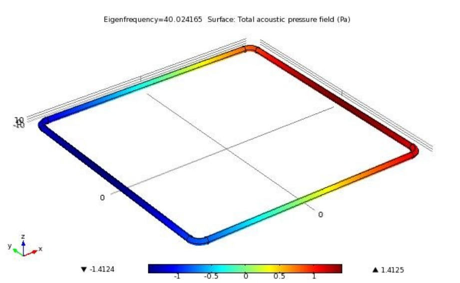

Figure 2: Computed Pressure Mode Shape. Continuous uniform loop.

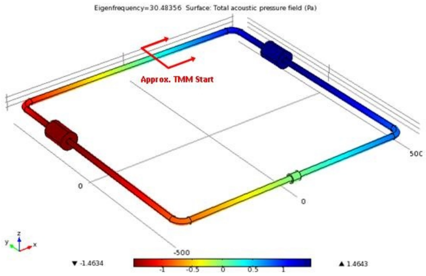

Figure 3: Computed Pressure Mode Shape for Mode A. Continuous loop with three cavities.

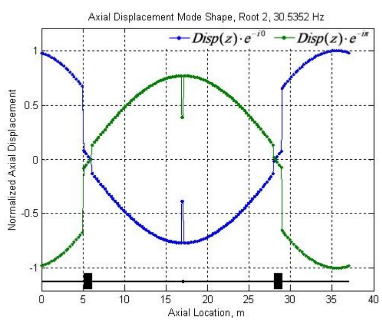

Figure 4: Axial Displacement Mode Shape for Mode A . Continuous loop with three cavities.