OpenPulse: An Open Source Software for Acoustically Induced Vibration Analysis of Piping Systems

Olavo M. Silva * Jacson G. Vargas André S. Fernandes Vitor V. Slongo
Rodrigo Schwartz Gildean. N. Almeida Vinícius H. Ribeiro Gustavo C. Martins

Federal University of Santa Catarina, Florianópolis, Brazil

Abstract

Acoustically Induced Vibration (AIV) represents a critical risk to the integrity of gas piping systems pressurized by reciprocating compressors in the oil and gas industry. This article introduces *OpenPulse*, an open-source Python software developed to facilitate the numerical modeling of low-frequency AIV. With the aid of a graphical user interface (GUI), the modeling process begins with the definition of system geometry, material properties, and cross-sectional parameters, followed by the application of boundary conditions such as displacement constraints, nodal pressure, acceleration, and external forces. These loads can be either experimental or derived from theoretical models. A thermo-fluid-dynamic model of a reciprocating compressor is also implemented. Time-harmonic acoustic analysis is then performed within the one-dimensional acoustic domain, under the assumption of plane waves and using the Finite Element Transfer Method (FETM). The resulting pressure field is subsequently applied as an equivalent internal distributed load to the structural piping model, modeled based on the Timoshenko beam theory and solved using the Finite Element Method (FEM). Visualization tools, including animations, colormaps, and frequency-domain plots assist users in analyzing the computed AIV results.

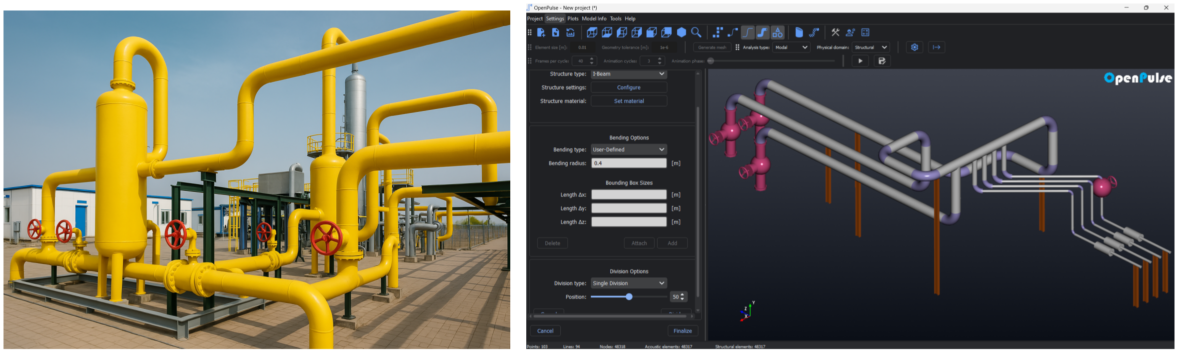
Keywords: Acoustically-Induced Vibrations, Low-Frequency Pulsation, Reciprocating Compressors, Finite Element Transfer Method, Piping systems, Timoshenko Beam, Finite Element Method

1 Introduction

Reciprocating compressors represent an important excitation source for gas piping systems in oil refinery plants. The structural behavior of the pipes can be strongly affected by the acoustic response of the internal acoustic field represented by the gas flow. This kind of excitation is known as Acoustically Induced Vibration (AIV) and is an important vibration mechanism in piping structures, which respond to both unsteady and pulsating flow fields [1]. Acoustic and structural responses of pipes arise from low-frequency internal distributed loads induced by acoustic pulsations at low-order harmonics of typical compressor discharge and suction pressure spectra.

When acoustic and structural natural frequencies coincide, vibrations can amplify dramatically, especially for reciprocating compressors where harmonic energy is concentrated below 100 Hz [2]. To mitigate these effects, standards such as the API 618 [3] guide the design and analysis of safe and reliable pipeline systems that ensure adequate structural and acoustic performance [4]. These

*Corresponding author, Email address: olavo@lva.ufsc.br



(a) Virtual representation of a piping system. **(b)** OpenPulse interface.

Fig. 1: Illustrative figures of a typical piping system and software interface. Source: authors.

analyses compare predicted values to allowable limits to prevent fatigue failures, in accordance with, for instance, the Energy Institute guidelines [2].

Refineries commonly have kilometers of piping and hundreds of components such as pulsation chambers, valves, and others, as illustrated in Fig. 1a. In this context, methodologies to predict the vibration behavior of such systems must be both simplified and representative. Approximate 1D acoustic models can be applied to calculate time-domain solutions for AIV [5]. The most common methods are the Method of Characteristics (MOC) [6] and the Finite Element Method (FEM) [7]. On the other hand, the structural response of the pipes is often obtained by FEM [8].

Assuming that the most energetic pulsation harmonics of reciprocating compressors occur at frequencies below 100 Hz, one can assume the associated structural wavelengths are long enough to represent only global vibrations, rather than local wall vibrations. It is reasonable that most structural analyses of such systems assume that the pipes are made of elastic-isotropic materials, with lengths much greater than their diameters and relatively low deflections. This fact enables one to consider the piping system as a set of beams.

Regarding acoustic-structure interaction, most engineers estimate equivalent shaking forces at elbows based on acoustic pressure, applying point forces aligned with the direction of the corresponding equivalent force area. This procedure is generally not automated and typically involves a manual calculation of the forces to be applied to the structural model.

In this article, the authors present *OpenPulse* [9], an open-source Python software that numerically models low-frequency AIV. Through a graphical user interface (GUI), the software allows users to define the pipeline route and geometry, material properties, cross sections, and loads. It performs a time-harmonic acoustic response analysis of the one-dimensional acoustic domain using the Finite Element Transfer Method (FETM)[10], and automatically applies the resulting pressure field as internal distributed loads to the structural piping system (weak coupling), which is modeled using Timoshenko beam theory and FEM [8]. A screenshot of the GUI used for pipeline input is shown in Fig. 1b.

2 Theoretical background

For a given pipe element (see Fig. 2) and considering acoustics only, the FETM arranges the nodal pressures p_1 and p_2, and volume velocities q_1 and q_2, obtained from the Transfer Matrix Method [10], into separate vectors and transforms the transfer matrix of the acoustic element into a mobility matrix.

This mobility matrix depends on fluid and geometric properties such as sound speed c_f, density ρ_f, and cross-sectional area S_f. It can be written, for a given angular frequency ω, as [10]

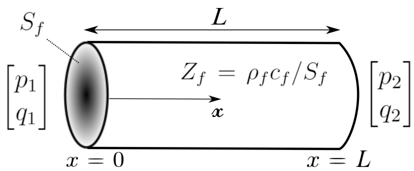


Fig. 2: Uniform tube, 1D acoustic element, with length L (adapted from [10]).

$$\begin{bmatrix} -\mathrm{j}\cot(kx)/Z_f & \mathrm{j}/Z_f \sin(kx) \\ \mathrm{j}/Z_f \sin(kx) & -\mathrm{j}\cot(kx)/Z_f \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}, \quad (1)$$

where $k = \omega/c$ is the wavenumber, $Z_f = \rho_f c_f / S_f$ is the impedance, and j is the imaginary unit.

To enable a programmable implementation, it is advantageous to combine FETM with numerical strategies from FEM [10]. In *OpenPulse* acoustics approach, only the "concept of element" and the prescription of boundary conditions – such as nodal pressure, volume velocity, and impedance – are inherited from FEM. Meanwhile, the mobility matrices are derived analytically using FETM, based on wave propagation theory in time-harmonic response. The resulting formulation yields a two-node element with one degree of freedom per node (pressure). In *OpenPulse*, Eq. (1) is further refined by using dissipation models such as the Low-Reduced Frequency (LRF) model [11] and other models for dissipation at low Mach numbers. In addition, the software contains various "pre-modeled" elements, such as perforated plates, pulsation suppression devices, and other components. The reciprocating compressor is modeled using a transient thermodynamic approach, whose time-domain response is processed via FFT and applied as a frequency-dependent volume velocity boundary condition.

The objective of *OpenPulse* is to predict the harmonic acoustic response of piping systems using FETM, as well as their global vibration response under low-frequency distributed loads, represented by internal acoustic pulsations corresponding to the first harmonics of typical reciprocating compressor spectra. The methodology assumes that the pipes can be modeled through the well-known Timoshenko beam theory with FEM (two-noded element, with three translations and three rotations per node).

A weak coupling between structural and acoustic fields is considered, where axial stress, σ_1, radial stress, σ_r, and circumferential stress, σ_c, on the structure pipe wall, derived analytically from cross-section dimensions and internal pressure [12, 5], are converted into axial forces. In this case, for a given structural element, the axial equivalent forces acting at both ends can be found, and the additional element load vector $\mathbf{f}_p^e$, which must be added to the external forces vector, is given by, assuming ν as the Poisson coefficient of material,

$$\mathbf{f}_p^e = \big[-F_x, 0, 0, 0, 0, 0, F_x, 0, 0, 0, 0, 0\big]', \quad \text{where} \quad F_x = S_f\big[\big(\sigma_1 - \nu(\sigma_r + \sigma_c)\big)\big]. \quad (2)$$

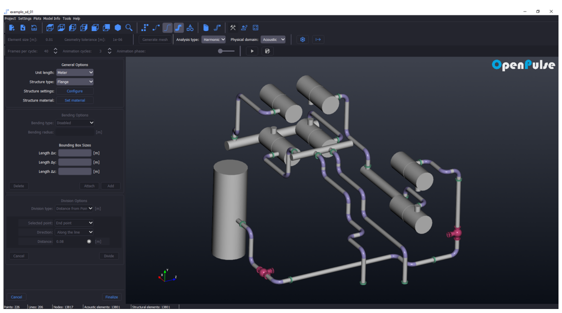
The "weak" (one-way) coupling is assumed based on the following hypotheses: the fluid is a gas; the acoustic plane wave propagates axially; the pipe is thin-walled and linearly elastic; the radial inertia of the pipe wall is neglected for low frequencies; and the acoustic wave speed c_f in the gas is influenced by the mechanical compliance of the pipe wall, given by $c_f = \sqrt{\left(\frac{\rho_f}{K_f}\left(1 + \frac{D_i K_f}{Et}\right)\right)}$, where K_f is the bulk modulus of the fluid, E is the Young's modulus of the pipe material, D_i is the internal diameter, and t is the pipe wall thickness. In *OpenPulse*, the same mesh is utilized for both the acoustic analysis (solved first) and the structural analysis.

3 Python implementation

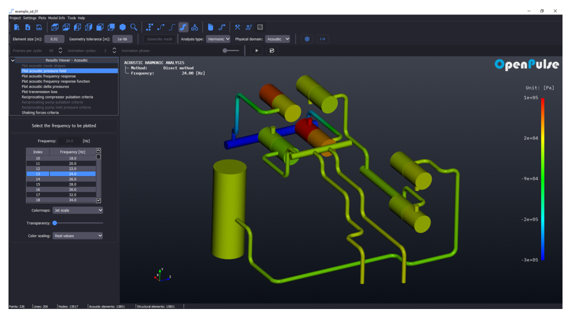
OpenPulse is developed in Python, leveraging a range of libraries to ensure functionality and efficiency. The GUI and application control are implemented using PySide6, while VTK is employed for 3D graphical rendering. Gmsh serves as the mesh processor, enabling the creation and manipulation. Numerical computations are handled by NumPy, SciPy, and PyPardiso. For visualization of data, Matplotlib is used to generate 2D plots, while data interfaces rely on Pandas and H5py to manage and store structured datasets. Finally, dependency management and environment configuration are performed with Poetry. The source code of *OpenPulse* is available on GitHub (https://github.com/open-pulse/OpenPulse) and published under GPL v3 license. For each release, an installation file is provided, eliminating the need to interact with Python code if the user prefers to work this way.

4 Some screenshots of application

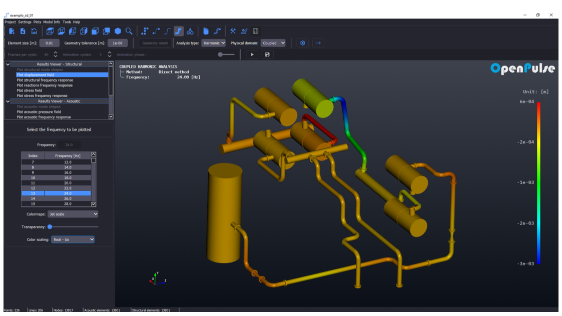
The screenshots in Fig. 3 illustrate the application of *OpenPulse* to the analysis of a piping system subjected to excitation by three-stage reciprocating compressors.



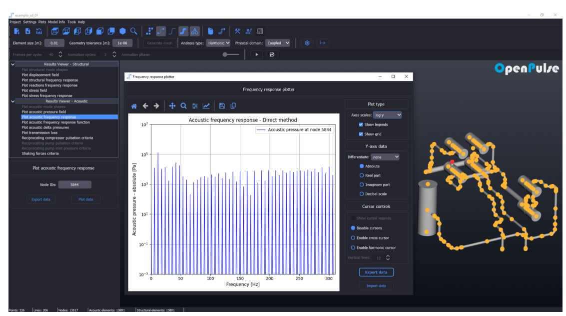
(a) Geometry and component design.



(b) Resultant pressure field.



(c) Resultant structural field.



(d) Frequency response of pressure at a node.

Fig. 3: Some screenshots of *OpenPulse*.

5 Conclusions

This manuscript introduces the main physical and methodological foundations of *OpenPulse*, an open-source software designed to analyze low-frequency AIV in piping systems. While it remains under development, initial results obtained by partners like PETROBRAS have shown reliable accuracy and can be validated against commercial FEM software. Future research will focus on comparisons with experimental data.

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