Chapter 4
Test-vs-Simulation Correlation of Noise Emission in a Bent-Axis Pump

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Abstract This work presents a detailed methodology for simulating the noise emissions of a bent-axis pump using an integrated approach with Multibody Dynamics, Structural and Acoustic Finite/Boundary Element, and Psychoacoustic solvers leading to a Harmonic Acoustics simulation. Be leveraging the capabilities of these simulation tools, we demonstrate the precise modeling of the bent-axis pump dynamics, and housing surface velocity to estimate the Equivalent Radiated Power (ERP) and its impact on noise level and quality at a specified distance. An initial correlation of the simulation model against real-world measurements, including microphone data, at the time of this abstract shows promise in the accuracy and reliability of the simulation process. The advantages of employing such a comprehensive model extend beyond technical precision, offering significant benefits in design optimization, manufacturing efficiency, and product development cycles. For pump manufacturers, this approach not only enhances product quality and compliance with noise regulations but also provides a faster go-to-market strategy. Furthermore, this work explores future avenues, including the integration of additional physics to refine the model's accuracy, positioning this methodology as a template for innovation in pump design and manufacturing.

Keywords NVH Workflow · Bent-Axis Pump · Test-vs-Simulation · Multibody Dynamics · Acoustics

Introduction

Accurate numerical models are crucial for the engineering industry for several reasons. These include:

Design prediction and optimization: Engineering simulations enable precise modeling of complex systems, allowing engineers to fine-tune designs and improve product performance [1].

Faster time-to-market: A comprehensive simulation approach accelerates the product development cycle, helping manufacturers bring products to market more quickly by reducing the need for iterative physical prototyping and testing [2].

Regulatory compliance and quality: Simulations ensure that products meet regulations (e.g., noise regulations) and maintain high-quality standards, reduce costs involved in certification testing, reducing potential manufacturing issues and enhancing overall product reliability [3].

The objective of this publication is to propose an effective NVH workflow for modeling the acoustic emissions of mechanical systems, with a focus on the bent-axis pump as a case study. This workflow integrates multiple physics-based solvers into a cohesive simulation strategy, providing accurate predictions of noise behavior and its psychoacoustic impact. Through this approach, we aim to present a robust methodology that can be extended to other complex machinery, offering insights into both the quantitative and qualitative aspects of noise emissions, while enhancing design optimization, product development cycles and compliance with noise regulations.

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Overview of the NVH Workflow

The NVH workflow comprises a structured approach divided into three key components: excitation, vibration response, and acoustics.[4] The process begins with excitation, which can stem from various sources such as electromagnetic analyses, dynamic outputs, or fluid pulsation. This excitation generates the necessary input for the subsequent step, where we calculate the vibration response of the enclosure (i.e. the physical structure or casing surrounding the system). This response is crucial, as it serves as the foundation for understanding how sound waves propagate through the surrounding air. Finally, this vibration response is fed into the acoustic domain to assess sound pressure levels at critical frequencies and to generate the far-field acoustic response spectrum. This comprehensive workflow allows for an in-depth analysis of sound power and sound pressure levels across a wide frequency range, providing valuable insights for optimizing NVH performance. One aspect of this workflow is that it accounts for excitations in the mid frequency range where the modal density of the structure is low enough to capture the vibro-acoustic response. For high frequencies (>5kHz), energy-based formulations such as SEA should be employed.

Excitation Stage

Ansys Motion Multibody Dynamics analysis (MBD) serves a pivotal role in the ”excitation stage” of the NVH workflow of the bent-axis pump mechanism. This tool models the complex interactions and motion of various components within the pump, capturing the reaction forces acting at the interfaces between the mechanism and its housing, see Figure 1. By accurately simulating the kinetic behavior of the pump, MBD provides essential data on dynamic forces, which are critical inputs for subsequent stages of the workflow.

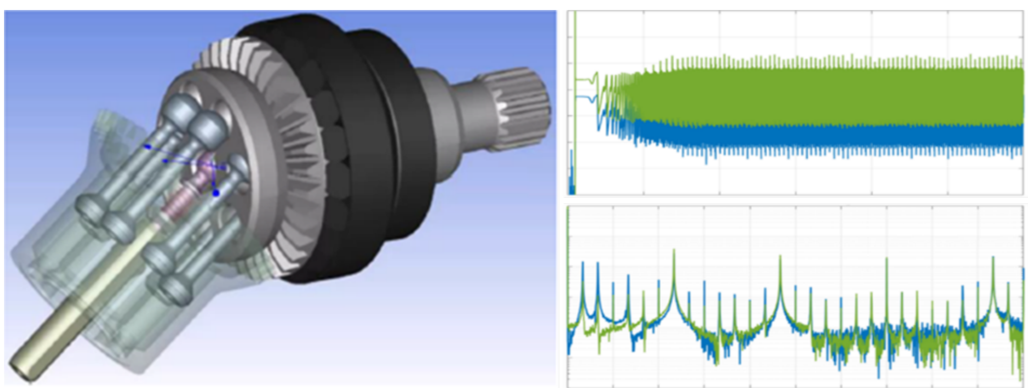

Fig. 1 Image of the bent-axis pump model (left) and a sample reaction force signal acting on interfaces between the mechanism and housing expressed in the time and frequency domains (left).

Vibration Response

The vibration response of the enclosure was calculated by performing a modal superposition using the modes of vibration and excitation forces to analyze the enclosure’s behavior under dynamic conditions. The Modal Solver simplifies the enclosure’s dynamic characteristics by expressing it as reduced model coordinates which efficiently captures its vibrational modes (see Figure 2). This reduced model, along with the reaction forces calculated during the excitation stage, serves as the input for the Harmonic Structural Solver. The Harmonic Solver then computes the velocity response of the enclosure’s outer surface (see Figure 2), quantifying how the pump’s operation affects the structure’s vibrations. This critical output provides foundational data for the subsequent acoustic analysis.

Acoustics

In the Acoustics part of the NVH workflow, the velocity response of the enclosure’s outer surface, obtained from the Harmonic Structural Solver, is utilized to assess sound emissions around the operating bent-axis pump. This data is input into acoustic solvers, which calculate the sound pressure levels (SPLs) at critical frequencies and evaluate the far-field acoustic

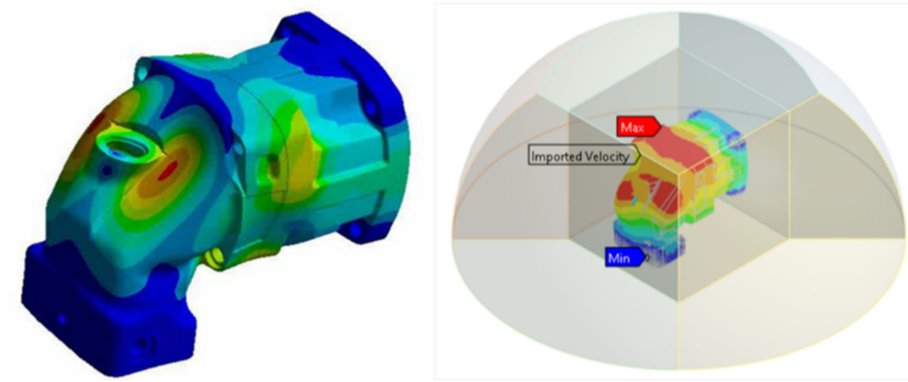

Fig. 2 One of the mode shapes computed by Ansys-Modal (left), and the velocity response of the enclosure's outer surface calculated by the Harmonic Structural solver and imported to the Acoustic solver (right).

response spectrum (as presented in Figure 3). By analyzing how the vibrations translate into sound, these solvers help quantify the noise impact of the pump on the environment, enabling engineers to identify potential areas for noise reduction and improve overall acoustic performance. This comprehensive analysis is essential for ensuring that the pump meets industry standards for noise, vibration, and harshness.

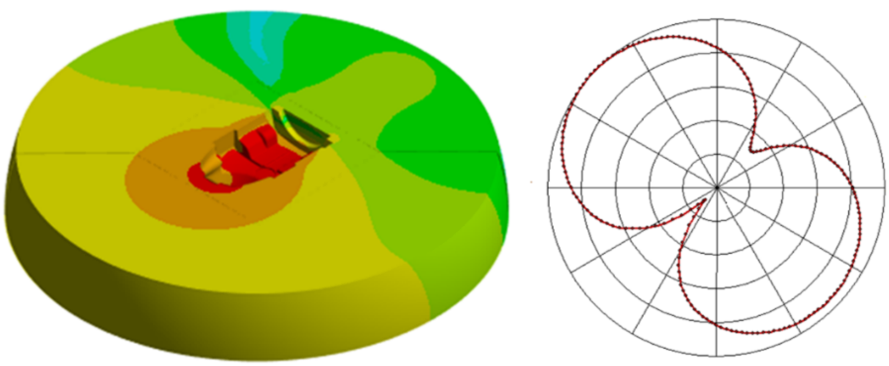

Fig. 3 Sample results from the acoustic solver. (Left) Sound pressure level at certain frequency and (right) the far-field directivity, which determines how focused the acoustic signal is.

Experimental Set-up

Experimental investigations were conducted in a semi-anechoic acoustic chamber at Parker Hannifin in Trollhättan, Sweden. Adjacent to this chamber is a separate room housing all the fixed equipment necessary to operate the pump of interest, including the drive motor, electric motor, and the pump shaft, as shown in Figure 4. The acoustic chamber contains the pump being tested, along with a microphone and amplifier (Brüel & Kjaer), as shown in Figure 4. Sound pressure data was acquired using the National Instruments system with a 50 kHz sampling rate.

The chamber is designed to be isolated from the surrounding environment, as illustrated in Figure 5. This separation helps minimize noise contributions from the factory and adjacent rooms. The acoustic chamber is lined with sound-absorbent materials that form a cone-like shape, as shown in Figure 5. Note that the floor does not have sound-absorbent materials; hence, it is a reflective surface (semi-anechoic room).

The room and measurements adhere to the International Standard ISO/DIS 3745, dated 1977-05-15. The microphone is placed 1 m away from the pump of interest. The facility can measure sound pressure with an accuracy of 1-3 dB for a frequency range of 125-10000 Hz. For the measurements and comparison against the NVH model, an F12-080 pump was used; F12 is a bent-axis fixed displacement pump (can operate as a motor) used for both open and closed-loop circuit applications (Figure 6).

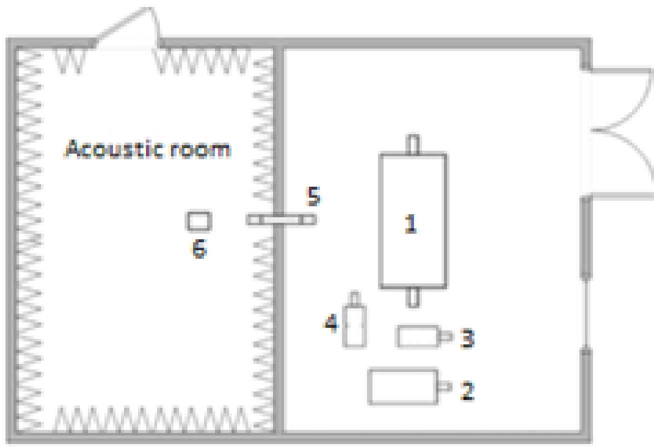

Fig. 4 Schematic view of facility to measure sound pressure. 1 – Drive motor; 2, 3, 4 – Electric motors with pumps; 5 – Shaft to acoustic room; 6 – Microphone and amplifier.

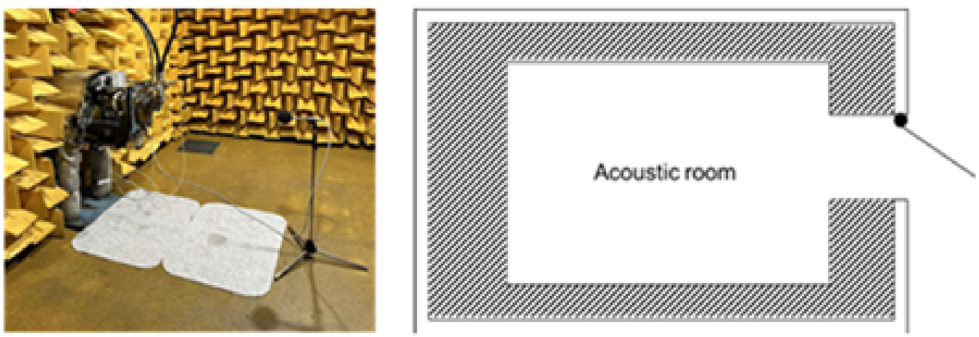

Fig. 5 (Left) Picture of test set-up and (right) Illustration of the acoustic room.

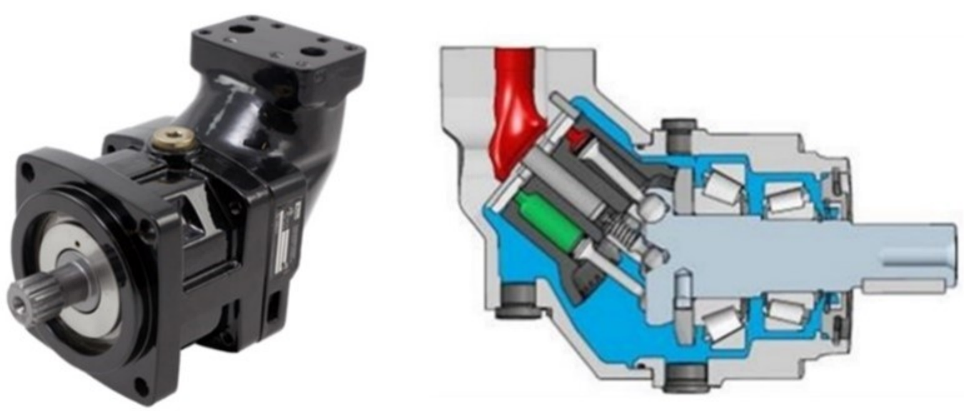

Fig. 6 Bent-Axis Fixed Displacement Pump - Series F12, Parker Hannifin.

A static and a speed sweep measurement were conducted. The static measurement involved recording sound pressure at several operating points; however, for the comparison, only data from operating points 2000 RPM and 200 Bar (outlet pressure) were used. The sound pressure was recorded with a sampling time of five seconds and a sampling rate of 50 kHz, and each operating point was measured twice. In the speed sweep campaign, measurements were carried out over approximately one minute, during which the outlet pressure remained constant (50 Bar and 200 Bar) while the speed varied from 100 to 2200 RPM and then back.

Test Data Interpretation

As previously covered in the experimental setup section, the acoustic chamber has a lower cut-off frequency of 125 Hz. The test cell also has ventilating fans and electronics that contribute to the overall acoustics of the chamber. An empty room run was conducted and the noise floor of the room was measured. It was determined that frequencies below 200 Hz have contributions from the chamber auxiliary components. The measured microphone data revealed there was a presence of both pump and motor orders present in the data. The test data used for this correlation was restricted only to the frequencies excited by the pump.

Preliminary Results Comparison and discussions

The boundary conditions of the test ensured that none of the initial excitation orders matched the resonant frequencies of the pump. Thus, the response obtained is purely forced for the frequency range of interest. The results for the major pump orders are compared. Initial results indicate that the difference between the test and simulation amplitudes for SPL are consistent across all frequency points, see Figure 7.

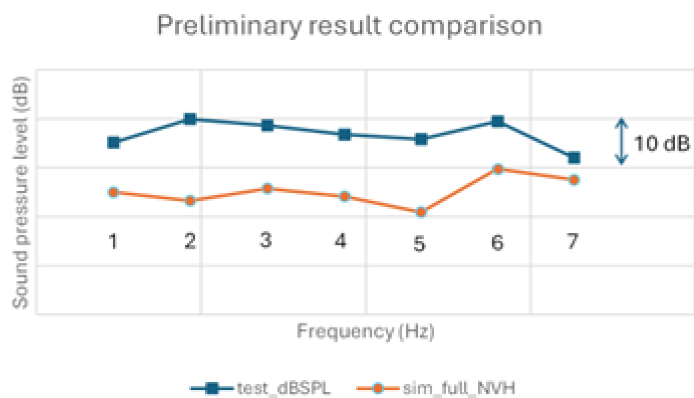

Fig. 7 Preliminary results comparison.

The higher frequency trends seen in the simulation model are in alignment with the test data obtained. For lower frequencies (Data point 1 and 2) the values follow opposite trends. The test cell floor as mentioned in the previous section is a reflective surface. At lower frequencies, the incident and reflected waves are in phase with each other since the wavelengths are large enough to constructively interfere with each other giving a higher amplitude. This phenomenon is not captured by the simulation model. At higher frequencies, the incident and reflected waves are out of phase with each other and hence do not amplify. Thus the behavior at high frequencies matches the simulation trends.

Future Work

Based on the results obtained from the preliminary correlation strategies to understand design sensitivity to acoustic response are conceptualized. Those are described below:

Impact of flexibility: The current simulation captures the forces and moments from the multi-body dynamics model when all inner parts are assumed to be rigid. This contributes to a conservative estimate of the dynamic interaction and thus the overall vibration response obtained at the enclosure. The impact on the acoustic response by considering crucial parts inside the mechanism as flexible is being studied.

Acoustic boundary conditions: As discussed in the preliminary results section, the impact of the reflective floor in the test cell amplifies the lower frequencies more in comparison to the higher frequencies. This can be studied by considering different acoustic mesh that captures the acoustic chamber conditions. A balance between acoustic domain size for accuracy vs computational resources available is important for this action.

Load and static pressure sensitivity: The current model setup considers the force interactions between individual components as well as an approximate force to capture the fluid pressure imparted on the fluid-structure interface. A load and pressure sensitivity analysis will help capture the impact of the load change on acoustic response change.

Fluid pressure fluctuations: The fluid pressure inside a positive displacement pump is a function of the rotational speed and the translational speed of the pistons. The fluid excitations will follow the same operating orders of excitations as the kinematic analysis. Due to the closed nature of the system, the fluid excitations can be used to study the vibrational response on the enclosure and the impact on the sound pressure level measured.

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