An Approach for Evaluating Structure-Borne Noise Emission of Axial Piston Units Using Blocked Forces

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Abstract

In the context of electrification and the development of quieter internal combustion engines, the noise generated by axial piston units is becoming more prominent. While established methods and standards exist for evaluating airborne and fluid-borne noise of hydraulic pumps, the structure-borne noise emitted by the pump and transferred to mobile machinery has been rarely investigated. A method that has gained popularity in recent applications for characterizing structure-borne noise sources is the in situ blocked force method. Blocked forces are receiver-system-independent interface quantities, allowing for a component-specific assessment of structure-borne noise. This publication introduces the fundamental approaches for determining blocked forces and presents the results of a metrological assessment of blocked forces for an axial piston pump. Besides evaluating the hydraulic unit using blocked forces, these forces can also be applied to any machine structure as they are receiver-system-independent. This enables the prediction of how structure-borne noise emitted by the axial piston pump propagates in a mobile working machine. The findings demonstrate promising outcomes according to common validation methods for blocked forces and provide a simple single-value metric for evaluating the emitted structure-borne noise of an axial piston pump.

Keywords: Structure-Borne Noise, Axial Piston Pumps, Source Characterization, Blocked Forces

1 Introduction

The development of increasingly quieter internal combustion engines, along with the growing adoption of considerably quieter electric motors, has heightened the demand for low-noise components in mobile machinery [1]. This trend presents a significant challenge for component manufacturers, but it also offers substantial potential to reduce overall noise levels of mobile machines. A key aspect in the development of low-noise mobile machinery is the ability to accurately assess and evaluate the contribution of individual noise sources. One of the primary sources of noise in mobile machinery are axial piston units. These units are widely used due to their high power density, the adjustable displacement volume, and the achievable high pressure level [2]. The challenge in assessing the contribution of axial piston pumps to the overall noise lies in the fact that these pumps emit all three types of sound: airborne noise (ABN), fluid-borne noise (FBN), and structure-borne noise (SBN). To enable a comprehensive assessment of the acoustic behavior of a pump, all three types of noise must be evaluated separately.

Figure 1 presents a schematic illustration of the noise transfer paths within a mobile machine, assuming the axial piston pump is the sole noise source and the SBN transmitted through the tubing can be neglected. SBN vibrations that directly affect the driver, such as those transmitted through the seat, are also not considered here. The primary excitation mechanisms within an axial piston pump can be divided in a SBN excitation and a FBN excitation, often referred to as flow ripple or fluid pulsation. These excitation mechanisms lead, on the one hand, to an ABN directly emitted from the pump housing ① ④ (see Figure 1) and, on the other hand, to FBN and SBN transmitted via the pump discharge port ③ and the pump mounting ② to the vehicle. The following section briefly describes the most important excitation mechanisms within an axial piston pump.

The FBN excitation or fluid pulsation in an axial piston pump can be divided into kinematic pulsations, due to the finite number of displacement elements, and pulsations resulting from compressibility of the hydraulic oil. It occurs during the transition of a piston from the suction port to the discharge port, when the pressure in the piston chamber differs from that in the discharge port. [2–4]

Since fluid pulsation can lead to not only noise issues but also other problems within the hydraulic system, various studies

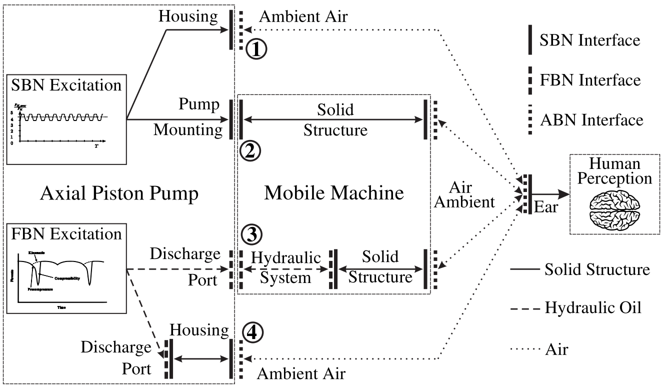

Figure 1: Noise transfer paths of a mobile machine with axial piston unit as the only source

have been conducted to characterize the FBN excitation of hydraulic units. The most common methods are the "High Impedance Pipe" Method [5], the "Reflectionless Termination (RaLA)" Method [3,6], the "Secondary Source" Method [7,8], and the "Two Pressures Two Systems" Method [9, 10]. Some of these methods have also been standardized in ISO 10767, enabling a comparable source characterization of hydraulic pumps with respect to FBN. Concerning the ABN caused by high-pressure pulsations in the discharge port of the pump ④, Haarhaus [11] demonstrated that this plays a minor role in the noise emission of axial piston pumps.
Regarding SBN excitation mechanism, previous studies [2, 11–14] have indicated that the primary excitation is due to the axial force resulting from pressure fluctuations in the cylinder chambers of the pump's power unit. These forces lead to two primary effects: firstly, they induce vibrations in the pump housing, causing the pump to directly radiate ABN ①; secondly, the SBN is transmitted at the pump's mounting points to the mobile working machine, thereby exciting the entire machine structure ②.
For the characterization of ABN radiated from the housing of hydraulic pumps and motors, a test procedure is described in the ISO 4412-1/2 standard. This standard defines necessary properties for the test setup to ensure comparable results that are independent of external boundary conditions.
In contrast to FBN and ABN, there is currently no standard or established method for the source characterization of hydraulic pumps with respect to SBN. Hence, this publication presents an approach that enables the evaluation of SBN based on so-called blocked forces, which provide a receiver-independent description of the source at the interface to the receiving structure. In addition to evaluating the pump, source characterization using blocked forces also enables the prediction of vehicle noise resulting from SBN excitation.
The publication is structured as follows: First, various methods of transfer path analysis are introduced, focusing on component-based transfer path analysis. Next, the application of the in situ blocked force method to an axial piston pump is presented, and a metric for evaluating SBN is derived. Subsequently, the results of the in situ blocked force measurement and the evaluation metric are discussed. Finally, the findings are summarized, and an outlook is provided.

2 Methods

The method used to investigate the transmission paths through which noise is transferred from a source to a receiver is referred to as Transfer Path Analysis (TPA). The description of a source using blocked forces is one method of source characterization within the framework of TPA. Therefore, an introduction to TPA will be provided in this chapter.
According to [15] a typical TPA workflow aiming to identify critical noise sources or transmission paths can be divided into four steps:

1. Operational measurement of the active component
2. Determination of the structural dynamic behavior of the passive receiver
3. Calculation of interface quantities between the source and the receiver
4. Assessment of the contribution of individual sources and paths to the overall noise

Depending on the TPA method used, only some of these steps may be performed, or they may be carried out in different order. Since this publication focuses on evaluating the SBN transmitted from an axial piston pump to a mobile working machine, the emphasis is on the third step, the calculation of interface quantites. An overview of the different TPA methods can be found in [15]. The notation and theoretical framework introduced in the following are also based on this work. In the next sections, the TPA methods most relevant to this publication will be introduced.
Figure 2 illustrates the general transfer path problem applied to hydraulic pump **A** connected to a receiver system **B**, such as the engine flange in a mobile working machine. In addition to the mounting points, the pump is also connected to the receiver via hydraulic hoses or pipes. These interfaces are not considered here. The system consists of three nodes: the excit-

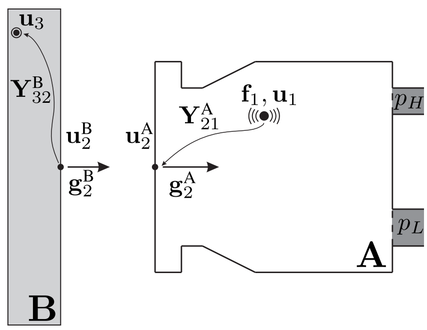

Figure 2: General transfer path problem applied to a hydraulic pump

ation point within the source **1**, the interface **2**, and an arbitrary point on the receiver **3**. The excitation at node **1** is described by the force $\mathbf{f}_1$ and the displacement quantity $\mathbf{u}_1$. As displacement quantities, accelerations, velocities and displacements can be considered, as these can be directly converted into one another. In the following, it is assumed that $\mathbf{u}$ represents a velocity. The response at the receiver point to the excitation at **1** is denoted by $\mathbf{u}_3$. At the interface, the displacement quantities on the source and receiver sides are described by $\mathbf{u}_2^{\mathrm{A}}$ and $\mathbf{u}_2^{\mathrm{B}}$, respectively, and the interface forces by $\mathbf{g}_2^{\mathrm{A}}$ and $\mathbf{g}_2^{\mathrm{B}}$. At this point, it is important to note that the superscript indicates the component to which the quantity refers. Accordingly, $(\cdot)^{\mathrm{A}}$ represents a source quantity, while $(\cdot)^{\mathrm{B}}$ denotes a receiver quantity. The superscript $(\cdot)^{\mathrm{AB}}$ indicates that the quantity is associated with the assembled system. The structural dynamic behavior of a node, as well as the transfer behavior between two nodes, is described using admittances $\mathbf{Y}$. Admittance, also known as mobility, is a measure of how a structural dynamic system responds to external forces. It is defined as the ratio of the system's velocity response to the applied force in the frequency domain. Since the systems under investigation are typically multi-input multi-output (MIMO) systems, forces and velocities at the nodes are described by column vectors, and the transfer behavior is represented using admittance matrices.

The described transfer path problem can be represented by the following system of equations, where the subsystem admittance matrices $\mathbf{Y}^{\mathrm{A}}$ and $\mathbf{Y}^{\mathrm{B}}$ are arranged in a block-diagonal format. The admittances matrices with identical indices describe the point admittances at the nodes, while those with different indices represent the transfer admittances between the nodes.

$$\underbrace{\begin{bmatrix}\mathbf{u}_1\\ \mathbf{u}_2^{\mathrm{A}}\\ \mathbf{u}_2^{\mathrm{B}}\\ \mathbf{u}_3\end{bmatrix}}_{\mathbf{u}} = \underbrace{\begin{bmatrix}\mathbf{Y}_{11}^{\mathrm{A}} & \mathbf{Y}_{12}^{\mathrm{A}} & \mathbf{0} & \mathbf{0}\\ \mathbf{Y}_{21}^{\mathrm{A}} & \mathbf{Y}_{22}^{\mathrm{A}} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{Y}_{22}^{\mathrm{B}} & \mathbf{Y}_{23}^{\mathrm{B}}\\ \mathbf{0} & \mathbf{0} & \mathbf{Y}_{32}^{\mathrm{B}} & \mathbf{Y}_{33}^{\mathrm{B}}\end{bmatrix}}_{\mathbf{Y}} \underbrace{\left(\begin{bmatrix}\mathbf{f}_1\\ \mathbf{0}\\ \mathbf{0}\\ \mathbf{0}\end{bmatrix} + \begin{bmatrix}\mathbf{0}\\ \mathbf{g}_2^{\mathrm{A}}\\ \mathbf{g}_2^{\mathrm{B}}\\ \mathbf{0}\end{bmatrix}\right)}_{(\mathbf{f}+\mathbf{g})} \quad (1)$$

For an assembled system, assuming a rigid behavior of the interface, the compatibility condition and the equilibrium condition at the interface must also be satisfied. The compatibility condition states that the velocities on both sides of the interface must be identical, i.e., $\mathbf{u}_2^{\mathrm{B}} = \mathbf{u}_2^{\mathrm{A}}$. The equilibrium condition, which is fundamentally based on Newton's Third Law, asserts that the interface forces on the receiver side must be equal in magnitude and opposite in direction to the forces on the source side, i.e., $\mathbf{g}_2^{\mathrm{B}} = -\mathbf{g}_2^{\mathrm{A}}$. By employing equation 1 in conjunction with the compatibility and equilibrium conditions, it is possible to forecast the response at the receiver $\mathbf{u}_3$ to an excitation **1**, provided that the excitation and the admittances of the subsystems are known.

Although predicting the response at the receiver using the internal excitation, as just described, is theoretically possible, it presents certain practical issues. In particular, the internal forces $\mathbf{f}_1$ are typically unknown with regard to their position, orientation, and magnitude. Consequently, it is not possible to define the transfer behavior, i.e., the admittances $\mathbf{Y}_{11}^{\mathrm{A}}$ and $\mathbf{Y}_{21}^{\mathrm{A}}$. A solution to this problem is to find an alternative description of the source activity that: a) is capable of physically representing the internal forces (i.e., inducing the same vibration in the structure), b) has known positions, and c) has magnitudes that can be practically determined [16]. Such a description of the source activity can be achieved using the interface quantities at interface **2**, which makes these interface quantities also suitable for evaluating the source with respect to SBN.

The TPA approaches presented in the following differ primarily in the interface quantities used to describe the source and how the response at the receiver $\mathbf{u}_3$ can be predicted based on these interface quantities.

2.1 Classical TPA

In the first investigations in the field of TPA, the objective was to describe the source activity using the forces acting at the interface $\mathbf{g}_2^{\mathrm{A}}$ and $\mathbf{g}_2^{\mathrm{B}}$, whereby $\mathbf{g}_2^{\mathrm{A}}$ and $\mathbf{g}_2^{\mathrm{B}}$ differ only in sign due to the equilibrium condition. From the fourth row of Equation 1, we obtain:

$$\mathbf{u}_3 = \mathbf{Y}_{32}^{\mathrm{B}} \mathbf{g}_2^{\mathrm{B}} \quad (2)$$

From this, it can be directly seen that the response at the receiver $\mathbf{u}_3$ is determined by the interface force $\mathbf{g}_2^{\mathrm{B}}$ and the transfer behavior from the interface to the receiver point $\mathbf{Y}_{32}^{\mathrm{B}}$. This type of TPA is referred to as "Classical TPA".

In practice, the transfer behavior is often determined using impact hammer or shaker measurements. When measuring $\mathbf{Y}_{32}^{\mathrm{B}}$, the source must be decoupled, as only the transfer behavior of the receiver itself (denoted by the superscript $(\cdot)^{\mathrm{B}}$) is required. The interface forces $\mathbf{g}_2^{\mathrm{B}}$ can be determined using various methods, namely the "Direct Force" method or the "Mount Stiffness" method. While the interface forces in the "Direct Force" method are directly measured using force transducers placed between the source and the receiver, the "Mount Stiffness" method determines these forces by measuring the displacement, assuming the stiffness of the mounting is known. Another well-studied method is the "Matrix Inverse" method, which shares many similarities with the later introduced "In situ Blocked Force" method. In this method, it is assumed that the transfer admittance $\mathbf{Y}_{42}^{\mathrm{B}}$ from the interface to additional receiver points $\mathbf{u}_4$ positioned on the receiver can be determined in an initial step, for example, through an impact hammer measurement. In the second step, an operational measurement of the assembled system is conducted to determine $\mathbf{u}_4$ when the source is running. Using the relationship from Equation 2 and replacing $\mathbf{u}_3$ with $\mathbf{u}_4$, it follows that

$$\mathbf{g}_2^{\mathrm{B}} = \left(\mathbf{Y}_{42}^{\mathrm{B}}\right)^{-1} \mathbf{u}_4 \quad (3)$$

which allows the interface force $\mathbf{g}_2^{\mathrm{B}}$ to be computed. Since the receiver points $\mathbf{u}_4$ are not used as target quantities for purposes such as predictions, but rather for determining the interface forces, they are often referred to as indicator points.

Although classical TPA is a useful tool for many applications and still used in practice, it has a fundamental drawback: the interface forces $\mathbf{g}_2^{\mathrm{B}}$ used in this approach are influenced not only by the internal excitation but also by the structural dynamic behavior of the receiver. As a result, these forces do not represent a pure source quantity, making them not transferable to other receiver systems and unsuitable for evaluating the source itself.

2.2 Component-based TPA

The limitations of classical TPA are overcome in component-based TPA (cTPA). In this approach, the source is described using receiver-independent interface quantities, which offers several advantages. Firstly, a receiver-independent source description allows the prediction of the vibration response $\mathbf{u}_3$ for different receivers, assuming the transfer behaviour of the receiver can be determined. Secondly, and particularly relevant for this publication, the receiver-independent interface quantities enable the evaluation of the source itself in terms of SBN emission. Figure 3 shows an overview of the most important source characterisation methods, which are introduced in the following.

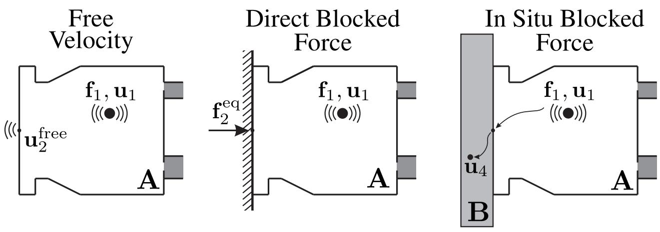

Figure 3: Source characterisation methods in cTPA

2.2.1 Free velocity

The most obvious method to characterize a source without receiver system influence is to determine an interface quantity when the source is freely vibrating, i.e., not connected to any receiver system. In this case, the force at the interface vanishes, i.e., $\mathbf{g}_2^{\mathrm{A}} = 0$. The velocity at the interface is referred to as the free velocity, $\mathbf{u}_2^{\mathrm{free}}$. Under this condition, the second row of Equation 1 becomes

$$\mathbf{u}_2^{\mathrm{free}} = \mathbf{Y}_{21}^{\mathrm{A}} \mathbf{f}_1 \tag{4}$$

from which it is evident that the free velocity depends solely on source quantities, thereby allowing for a description of the source excitation at the interface. Although the characterization of SBN sources using free velocities is theoretically possible, this method is not applicable to every kind of source. This is primarily because the source must be operated under free conditions. For hydraulic pumps in particular, this is not practical, as it would eliminate any means of driving the pump.

2.2.2 Direct blocked force

Another method for eliminating environmental influences is to theoretically attach the source to an infinitely stiff receiver. In this scenario, the velocity at the interface vanishes, i.e., $\mathbf{u}_2^{\mathrm{A}} = \mathbf{u}_2^{\mathrm{B}} = 0$. The force at the interface is then referred to as the blocked force, $\mathbf{f}_2^{\mathrm{eq}}$ (The superscript $(\cdot)^{\mathrm{eq}}$ denotes "equivalent," as the blocked forces offer an equivalent representation of the source excitation). Under these conditions, the second row of Equation 2 becomes:

$$\begin{aligned} 0 &= \mathbf{Y}_{21}^{\mathrm{A}} \mathbf{f}_1 + \mathbf{Y}_{22}^{\mathrm{A}} \mathbf{g}_2^{\mathrm{A}} \quad \text{for} \quad \mathbf{f}_2^{\mathrm{eq}} = \mathbf{g}_2^{\mathrm{bl}} = -\mathbf{g}_2^{\mathrm{A}} \\ \Rightarrow \mathbf{f}_2^{\mathrm{eq}} &= \left(\mathbf{Y}_{22}^{\mathrm{A}}\right)^{-1} \mathbf{Y}_{21}^{\mathrm{A}} \mathbf{f}_1 \end{aligned} \tag{5}$$

From this, it can be seen that the blocked forces depend solely on the source itself, making them an appropriate interface quantity as well. Furthermore, by substituting the term $\mathbf{Y}_{21}^{\mathrm{A}} \mathbf{f}_1$ in Equation 4 with the relationship from Equation 5, it can be seen that the blocked forces and the free velocities are directly related through the equation

$$\mathbf{u}_2^{\mathrm{free}} = \mathbf{Y}_{22}^{\mathrm{A}} \mathbf{f}_2^{\mathrm{eq}}. \tag{6}$$

As with the interface forces in the classic TPA, there are several methods for determining the blocked forces. The most obvious method is direct measurement using force transducers between the source and a receiver with sufficient stiffness. Nevertheless, previous studies [17, 18] have demonstrated that the condition of sufficiently high receiver stiffness can only be met within a limited frequency range. Furthermore, mounting force transducers between the source and the receiver presents several of challenges. Firstly, the stiffness of the force transducers must be sufficiently high to meet the stiffness requirements. Secondly, the sensors must not alter the interface itself. While this is less of an issue for point contacts, it becomes a significant challenge for surface-like interfaces, as is typically the case for hydraulic pumps. Moreover, directly measuring torques and in-plane forces is difficult to achieve due to the complex sensor alignment. Consequently, direct measurement of blocked forces is impractical for many applications, including hydraulic pumps.

2.2.3 In situ blocked force

Another method, first introduced by Moorhouse et al. [19], is the so-called "In Situ Blocked Force" method. This approach is comparable to the "Matrix Inversion" method of classical TPA but allows for the determination of blocked forces "in situ," meaning in the typical installation condition of the source. This method has gained popularity in recent years, particularly in the automotive industry, leading to numerous scientific publications in this field [20, 21]. Additionally, the procedure for conducting an in situ blocked force measurement has been defined in the ISO 20270 standard since 2019. In [19], Moorhouse et al. demonstrated that the blocked force can be determined using the following relationship (for a detailed derivation, see [19] or [15]):

$$\mathbf{f}_2^{\mathrm{eq}} = \left(\mathbf{Y}_{42}^{\mathrm{AB}}\right)^{-1} \mathbf{u}_4 \tag{7}$$

Analogous to the matrix inversion method, $\mathbf{u}_4$ denotes additional indicator points on the receiver structure. The right-hand side of of Equation 7 differs from that of Equation 3, which describes the "Matrix Inversion" method of classical TPA, in that it requires the admittance of the assembled system, $\mathbf{Y}_{42}^{\mathrm{AB}}$, instead of the admittance $\mathbf{Y}_{42}^{\mathrm{B}}$ of the receiver only. From Equation 7, it follows that the measurement process for determining the blocked forces consists of two steps. In the first step, the admittance matrix $\mathbf{Y}_{42}^{\mathrm{AB}}$ from the interface to the indicator points for the assembled system is determined. For this purpose, the structure is excited close to the interface using an impulse hammer or shaker, and the response at the indicator points is measured using accelerometers. In the second step, the response at the indicator points $\mathbf{u}_4$ is measured while the source is operating, with the accelerometers remaining at the same locations as during the impulse hammer measurement. The blocked forces are then determined via Equation 7 at the positions where the excitation was applied in the first step using the impulse hammer. By following these steps, the source and receiver do not need to be separated at any stage of the measurement process. This allows the blocked forces to be determined in the coupled state (in situ).

Figure 4, adapted from [22], visually highlights the crucial difference between describing the interface excitation using actual interface forces $\mathbf{g}_2^{\mathrm{A}}$ (classical TPA) and blocked forces $\mathbf{f}_2^{\mathrm{eq}}$ (component-based TPA). When the source is fully characterized by the corresponding interface quantity, both methods ultimately lead to the original vibration response at the receiver. In classical TPA, the interface forces are combined with the admittance $\mathbf{Y}_{32}^{\mathrm{B}}$ of the receiver only, whereas in component-based TPA, the blocked forces are applied to the coupled system $\mathbf{Y}_{32}^{\mathrm{AB}}$.

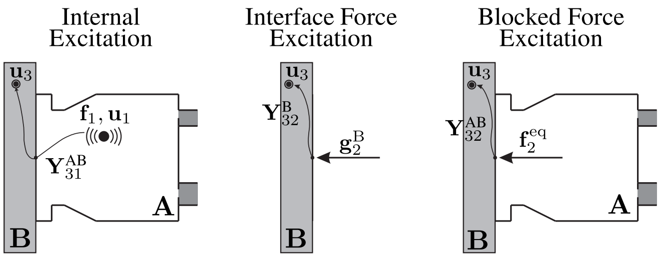

Figure 4: Description of the source excitation with Interface Forces and Blocked Forces

Although "in situ" can be translated to "in its original place," the blocked forces, due to their independence from the receiver system, do not necessarily need to be determined in the target application. Instead, they can also be obtained on a specially designed test bench. The main advantage here, besides the measurement under controlled laboratory conditions, is primarily the accessibility of the interface. The receiver can be designed in such a way that the interface, or the area around the interface, can be easily excited with an impact hammer or a shaker. This is often not possible in a mobile machine with limited space. Once a test bench for the in situ method is developed, the blocked forces for any operating point of the pump can be determined under controlled test conditions.

Additionally the in situ blocked force relationship from Equation 7 not only allows for the determination of blocked forces but also opens up possibilities for Virtual Acoustic Prototyping (VAP). Since the blocked forces $\mathbf{f}_2^{\mathrm{eq}}$ are independent of the receiver system, they can be combined with any arbitrary receiver. More specifically, once a source is characterized by blocked forces, it can be virtually combined with various receiver systems to simulate the resulting noise for those receivers. This opens up possibilities such as the virtual investigation of how noise mitigation measures, tested on the test bench, affect the noise in a mobile working machine. The transfer behavior $\mathbf{Y}_{32}^{\mathrm{AB}}$ required for this purpose can be determined either through an initial measurement in the vehicle or by employing dynamic substructuring approaches.

2.3 Quality criteria in situ blocked force method

The quality of the results when determining the blocked forces using the in situ method can be evaluated using various criteria. A fundamental prerequisite for achieving satisfactory results according to these quality criteria is that the transfer admittance $\mathbf{Y}_{42}^{\mathrm{AB}}$ can be determined with sufficient accuracy. There are specific quality criteria for this, which will not be discussed here, as they are general criteria for the experimental determination of transfer functions, as elaborated upon in [16]. In the following, the criteria of On-Board Validation and Transferability, which are specifically suitable for the in situ blocked force method, are introduced.

2.3.1 On-Board Validation

The most straightforward and particularly easy-to-apply method for in situ determination of blocked forces is the On-Board Validation (OBV). In this approach, the blocked forces, determined using indicator points in conjunction with Equation 7, are used to make a prediction for the receiver points $\mathbf{u}_3$:

$$\mathbf{u}_3 = \mathbf{Y}_{32}^{\mathrm{AB}} \mathbf{f}_2^{\mathrm{eq}} \tag{8}$$

The required transfer admittance $\mathbf{Y}_{32}^{\mathrm{AB}}$ and vibration response $\mathbf{u}_3$ are typically obtained simultaneously with the determination of $\mathbf{Y}_{42}^{\mathrm{AB}}$ and $\mathbf{u}_4$, making it an easy-to-apply method. To evaluate the source description, the predicted vibrations $\mathbf{u}_3$ at the receiver points are compared with the directly measured ones. The OBV method can be particularly useful for assessing whether the number of interface degrees of freedom (DOFs), and thus the number of blocked forces, is suitable to accurately describe the source. Additionally, OBV can help identify errors or issues in the inversion of the admittance matrix $\mathbf{Y}_{42}^{\mathrm{AB}}$.

In addition to OBV during the operation of the source, an OBV for so-called artificial excitations is typically conducted. In this case, the source itself is not in operation, and artificial excitations are applied to the source using an impact hammer or shaker. This approach offers the advantage that the artificial excitations provide a broad-band excitation and do not contain complex features like the operational response, which can complicate the inspection of agreement [16]. Consequently, the description of the interface can be evaluated more easily.

2.3.2 Transferability

As mentioned, OBV is a straightforward method for evaluating blocked forces. However, a good result in OBV is a necessary but not sufficient condition. While OBV can assess the description of the interface and the matrix inversion, it does not verify whether the blocked forces are independent of the receiver system, which is a fundamental requirement for a reasonable source description in cTPA. To evaluate this, the concept of transferability is used, which examines whether the determined blocked forces can be transferred to another receiving system. For this purpose, the blocked forces are determined for an identical source excitation in two different assemblies **AB** and **AC**. If the condition of receiver independence is satisfied, the response at the receiver points $\mathbf{u}_3$

of assembly **AC** can be predicted using the blocked forces determined in assembly **AB**. Or mathematically expressed:

$$\mathbf{u}_3^{AC} = \mathbf{Y}_{32}^{AC}\mathbf{f}_2^{eq,AB} \tag{9}$$

It should be noted that deviations can arise not only due to nonlinearities, insufficient interface description, or numerical errors but also from variations in the excitation mechanism. Because of this, it is crucial to ensure that the operating conditions are as similar as possible in both operational tests. For hydraulic pumps, this particularly includes pressure and rotational speed. Additionally, the passive properties on the source side, such as the hosing, should be as identical as possible for both systems.

2.4 In situ blocked force determination for an axial piston pump

As with many SBN sources, the in situ method is considered the most suitable source characterization method for hydraulic pumps. The determination of free velocities and the direct measurement of blocked forces are less suitable due to the aforementioned practical reasons.
In the case of the axial piston pump examined in this section, the blocked forces were not determined in a typical application, such as a mobile machine; instead, a test bench was specifically developed for this purpose, which offers the aforementioned advantages. Additionally, for a comprehensive characterization of the source excitation at the interface, it is crucial to excite various interface Degrees of Freedom. This means that excitation with the impulse hammer or shaker should be possible in different directions and at various positions around the interface. In practical applications, especially excitation in the plane direction is often not feasible. These challenges can be mitigated by conducting measurements on the test bench, thereby enhancing the quality of the results.

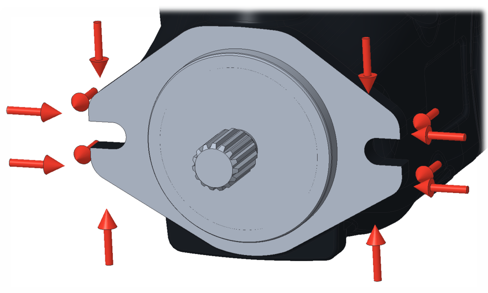

Figure 5: Possible Impact Positions for an Axial Piston Pump (Receiver not shown)

Figure 5 illustrates a potential positioning of excitation points for an impulse hammer or shaker in proximity to the mounting of an axial piston pump, which features a two-bolt mounting flange according to DIN ISO 3019-1 and is typically used in 6-ton mini excavators. It should be noted that the coupled receiver is not shown in Figure 5, as the design of the receiver can theoretically be arbitrary. However, this only applies when the internal excitation mechanism of the source is not influenced by the the receiver. Since in an axial piston pump the main SBN excitation is caused by pressure fluctuation within the power unit and this is not directly influenced by the external movement of the pump, it is assumed that this condition is met.
To measure $\mathbf{Y}_{32}^{AB}$ and $\mathbf{Y}_{42}^{AB}$, the pump and receiver must be coupled, making direct excitation at the interface infeasible. Therefore, excitation points must be positioned around the interface. In the illustrated case, six impacts are arranged around each of the two mounting points, based on the assumption that the excitation from the source is primarily transmitted to the receiver through the mounting points. In order to excite all interface DoF, impacts are applied in the normal direction and the in-plane directions.
The accelerometers used to determine the admittance matrices can theoretically be positioned anywhere downstream of the interface on the receiver. However, in practice, they should be placed in close proximity to the interface to achieve a good signal-to-noise ratio (SNR) and to minimize sources of error such as nonlinearities along the transmission path. To solve Equation 7, it is necessary to measure at least as many response signals (indicator DoFs) as there are excitation points (interface DoFs). However, according to ISO 20270-1-2019, it is recommended to overdetermine the system by using more indicator DoFs than interface DoFs. This results in an overdetermined system, and the inverse matrix $\left(\mathbf{Y}_{42}^{AB}\right)^{-1}$ in Equation 7 is replaced by the pseudoinverse $\left(\mathbf{Y}_{42}^{AB}\right)^{+}$. Consequently, the matrix inversion becomes a least-squares optimization, which reduces the influence of measurement errors and noise (for a detailed explanation, see [16]). For the measurement setup of the axial piston pump, seven triaxial indicator sensors ($\mathbf{u}_4$) were used, resulting in an approximately twofold overdetermined system of equations. Additionally, two triaxial receiver sensors ($\mathbf{u}_3$) were employed for evaluation using OBV and transferability.

2.5 Evaluation of structure borne noise emission of axial piston Pumps

In the previous section, the procedure for determining the blocked forces of an axial piston pump was explained. The following introduces a metric for evaluating an axial piston pump's SBN emission based on the blocked forces.
The characterization of structure-borne sound sources has been a subject of investigation for many years. The Technical Committee on Acoustics TC43 of the International Organization for Standardization (ISO) has defined four requirements in [16, 23] that should be met by a characterization method:

1. Comparison of structure-borne sound emissions of similar machines
2. Examination of compliance with limit values
3. Determination of input data for acoustic planning (e.g. prediction of sound levels when installed)
4. Collection of necessary data for the development of quiet machines

In addition to the listed requirements, the Committee also

proposed various characterization methods. These methods, along with many subsequently developed approaches such as the Source Descriptor method [24] and the Characteristic Power method [25], aim to fulfil the aforementioned requirements using one or two frequency-dependent single-value parameters. In these approaches objective is to facilitate a straightforward characterization of the source, analogous to the use of sound power in the characterization of ABN.
However, it has been demonstrated that, unlike ABN, a complete characterization of SBN sources using one or two frequency-dependent single-value parameters is hardly feasible. This is due to the significantly different nature of SBN (for a detailed explanation, see [16]). To specifically address the third requirement, which is the prediction of noise levels when the source is installed, the mentioned single-value-based methods are rather inadequate, particularly when an accurate prediction is required. Consequently, new approaches such as the in situ blocked force method have been developed in recent years [16]. These methods provide a more comprehensive description of the source, thereby enabling advanced concepts like cTPA and VAP, which are particularly relevant in later stages of development when specific applications for the source are known or for root cause analysis in a vehicle exhibiting poor noise performance.
However, in an early stage of hydraulic pump development, these concepts are of less interest. This is primarily due to the wide range of applications for a hydraulic pump, which vary significantly in their dimensions and acoustic properties. At an early stage of pump development, it is particularly important to investigate the effectiveness of measures, compare different pump designs, and identify critical operating points (1st and 4th requirement for a source characterization method). For this purpose, a straightforward evaluation method is needed, which may not provide a complete source description but offers a simple assessment that is independent of a receiving system.
To provide both a comprehensive source description for application-specific investigations and a straightforward evaluation method for early-stage development, the evaluation metric should be derived from a complete source description. In the case of the axial piston pump described above, the evaluation quantity should be derived from the twelve determined blocked forces.
There are various methods [25–27] to combine interface forces such as blocked forces. In the evaluation method introduced here, the forces are aggregated in a straightforward manner by calculating the vector norm of the resultant force vector of the blocked forces $\mathbf{m}_2^{\mathrm{eq}} = \begin{bmatrix} m_{2,X}^{eq} & m_{2,Y}^{eq} & m_{2,Z}^{eq} \end{bmatrix}^T$. In the first step, all blocked forces are combined into three resultant blocked forces $m_{2,X}^{eq}, m_{2,Y}^{eq}, m_{2,Z}^{eq}$, one for each coordinate direction. The combined blocked forces are denoted by the variable m in accordance with the Virtual Point Transformation, which will be briefly described in the subsequent paragraph. Assuming that the interface behaves like a rigid body, no information is lost during this combination step; however, this condition is only met within a limited frequency range. In the second step, the vector norm of the resultant blocked forces vector is calculated as follows:

$$\|\mathbf{m}_2^{\mathrm{eq}}\| = \sqrt{\left(m_{2,X}^{eq}\right)^2 + \left(m_{2,Y}^{eq}\right)^2 + \left(m_{2,Z}^{eq}\right)^2} \tag{10}$$

yielding a single-valued, frequency-dependent force quantity. This combination using the vector norm results in the loss of phase information, rendering the combined force is unsuitable for cTPA and VAP.
It should be noted that the aggregation of the blocked forces into three resultant forces in the first step corresponds to the so-called Virtual Point Transformation (VPT), without considering the torques. A detailed discussion of the VPT is beyond the scope of this paper and can be found in [17, 27]. However, it should be mentioned that neglecting the torques also represents a significant simplification and, as previous studies have shown, can lead to substantial errors. Nevertheless, they are not considered here for the sake of simplicity as a complete VPT would be required, which need additional information. Moreover, since the resultant forces and torques of a comprehensive VPT are physically different quantities, they cannot be directly combined into a single evaluation metric. To achieve this, an advanced approach, such as a power-based method, would be required.

3 Results

In this chapter, the first part presents the results of the in situ blocked force measurement for the axial piston pump described above and evaluates them using the introduced quality criteria. The second part demonstrates the behavior of the introduced evaluation metric for two characteristic operating points of the pump.

3.1 Results in situ blocked force determination

Before presenting the results in the following section, it should be noted that, although velocities and admittances were used to describe the physical relationships in the previous chapter, the subsequent analysis will compare predicted and measured acceleration signals. This is because accelerations were directly measured and contain the same information. Thus, the measured transfer functions, also known as Frequency Response Functions (FRFs), describe the relationship between the resulting acceleration and the applied force excitation.
Figure 6 shows the result of the OBV for an artificial excitation using an impulse hammer impact on the pump housing. Specifically, the vector norm of the acceleration signal from all three measurement channels of a triaxial accelerometer at a receiver point in the frequency domain is depicted. The y-axis represents the acceleration in decibels (dB), with a reference value of $10^{-6}\,\mathrm{m/s^2}$. This reference value is uniformly used in all subsequent figures where the acceleration in dB is shown. It can be observed that for the frequency range $150\ \mathrm{Hz} < f < 2500\ \mathrm{Hz}$, the prediction and measurement of the signal at the receiver point match very well. Beyond 2500 Hz, the signal becomes significantly noisier, indicating a poorer SNR. This can be attributed to the decreasing frequency response of the impulse hammer with a plastic tip at higher

frequencies. This outcome indicates that, in further analysis, good results can only be expected for the frequency range of 150 Hz $< f <$ 2500 Hz. Therefore, this frequency range will be examined in more detail in the following.

Figure 7 shows the OBV for a typical operating point with $n = 1500$ rpm, $p = 200$ bar, and $V_d = V_{d,max}$ for a frequency range up to 2500 Hz. As can be seen, the prediction and measurement align very well across the entire frequency range.

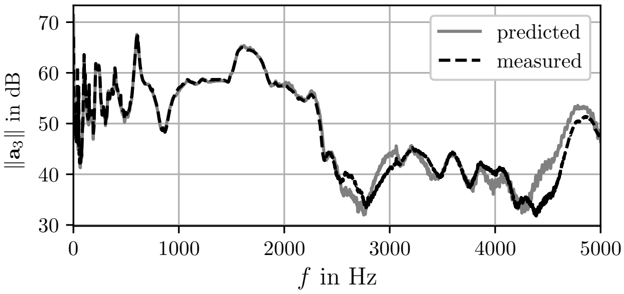

Figure 6: Result OBV for an artificial excitation

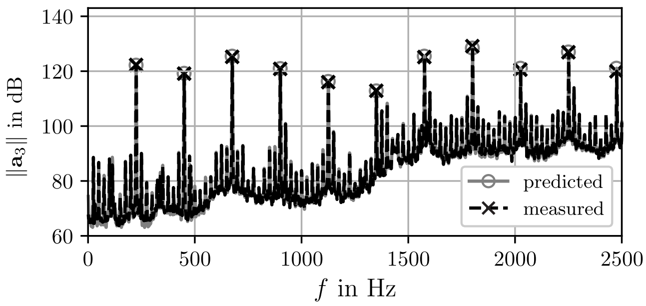

Figure 7: Result OBV for the stationary operating point: $n =$ 1500 rpm, $p = 200$ bar, $V_d = V_{d,max}$

As explained in the section on OBV, the result demonstrates that a set of twelve blocked forces is suitable for describing the source in this frequency range. However, what the OBV cannot yet demonstrate is whether the determined blocked forces are independent of the receiver system. To address this, the next step involves investigating the transferability of the blocked forces. For this purpose, the blocked forces determined in system **AB** are applied to another system **AC**. To ensure a valid transferability check, systems **AB** and **AC** must differ in their structural dynamic behavior. For the axial piston pump under investigation, the behavior of the receiver was influenced by varying the number of mounting screws on the receiver flange. The extent to which the admittance matrices $\mathbf{Y}_{42}^{\mathrm{AB}}$ and $\mathbf{Y}_{42}^{\mathrm{AC}}$ differ can be estimated by the mean magnitude difference of the indicator FRFs, as shown in Figure 8. The plot illustrates the percentage difference between the mean magnitude of all FRFs in system **AB** and those in system **AC**, relative to the values from system **AB**, as a function of frequency. From the plot, it can be observed that the deviation is relatively small for the frequency range 150 Hz $< f <$ 450 Hz. It is only at frequencies above 450 Hz that the dynamic behaviour of the structure can be expected to be significantly affected, making the investigation of transferability only meaningful beyond this frequency.

Figure 9 presents the transferability check for the same operating point as in Figure 7. The insights from Figure 8 can also be observed when comparing Figure 7 and 9. While the peak values at the harmonics for frequencies up to 1000 Hz are nearly identical in Figures 7 and 9, they diverge more significantly at higher frequencies.

Examining the transferability check, it is evident that the measured and predicted accelerations align well for $f <$ 1300 Hz, with greater deviations occurring beyond this point. These discrepancies can be attributed to various factors, such as measurement errors during the impulse hammer test, numerical errors, or nonlinearities. It is also important to note that, unlike the OBV, the transferability check pertains to the same operating points but not exactly the same operational measurement. Consequently, differences in operating conditions, such as variations in oil temperature or air content in the oil, can also influence the results.

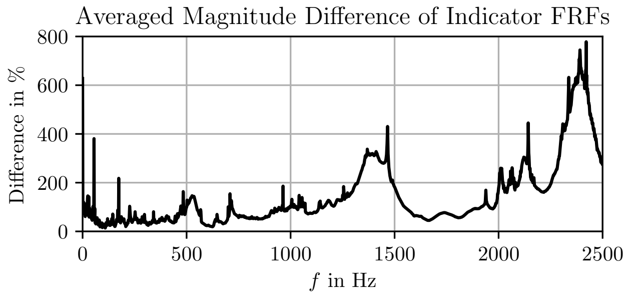

*Figure 8: Averaged magnitude difference of the indicator FRFs of System **AB** and **AC***

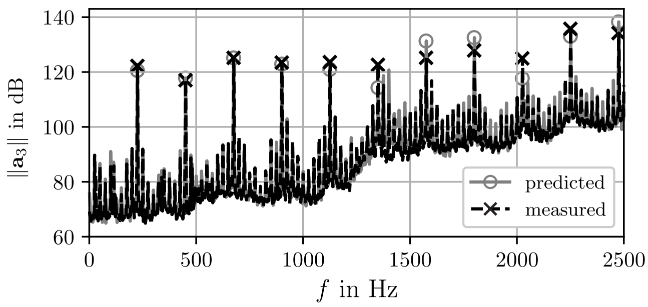

Figure 9: Result Transferability for the stationary operating point: $n = 1500$ rpm, $p = 200$ bar, $V_d = V_{d,max}$

3.2 Results evaluation metric

As the results of the in situ measurements demonstrate, the structure-borne noise excitation by an axial piston pump can be described for a using twelve blocked forces. Based on the blocked forces, the evaluation metric introduced in the previous chapter can be computed. Figures 10 and 11 illustrate the behavior of the evaluation metric for maximum and minimum displacement volumes ($V_{d,min}$: minimum displacement to maintain the target pressure), with values obtained from both system **AB** and system **AC**. Since the evaluation metric is an aggregation of the blocked forces, it has the unit Newton. For the determination of the decibel value, a reference value of 10^{-6} N is used.

When analyzing Figure 10, it is noticeable that the qualitative behavior of the evaluation metric significantly differs from that of the acceleration at the receiver points in Figures 7 and 9. This difference is primarily due to the rigid test setup, which causes the receiver sensors to experience stronger vibrations only at higher frequencies. Instead, Figure 10 clearly shows that the structure-borne noise excitation at this operating point is mainly dominated by the first harmonic, with the influence of higher harmonics generally decreasing. Comparable values of the evaluation metric are obtained for both systems **AB** and **AC**, confirming the independence from the receiver system.
Figure 11 shows the evaluation metric for the operating point with the same rotational speed and pressure but with minimal displacement volume. As can be seen, the spectrum does not fundamentally change due to the same rotational speed; however, the quantitative values of some harmonics in Figure 10 and Figure 11 differ significantly. While the evaluation metric for maximum displacement is clearly dominated by the first harmonic, the peaks at minimum displacement are at a similar level over a broader frequency range. The evaluation metric for both systems also aligns well for this operating point.

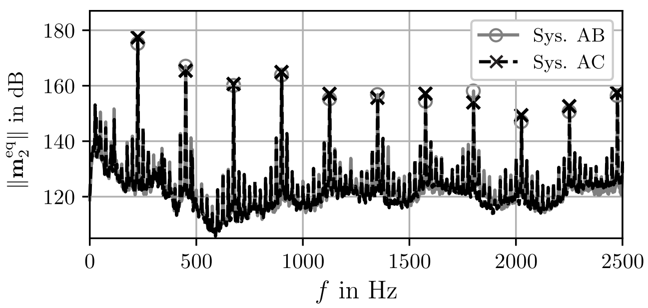

Figure 10: Evaluation quantity $\|\mathbf{m}_2^{eq}\|$ for the operating point: $n = 1500$ rpm, $p = 200$ bar, $V_d = V_{d,max}$

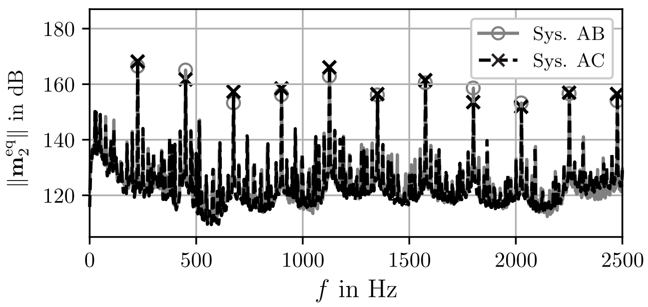

Figure 11: Evaluation quantity $\|\mathbf{m}_2^{eq}\|$ for the operating point: $n = 1500$ rpm, $p = 200$ bar, $V_d = V_{d,min}$

4 Discussion

The presented results demonstrate that the in situ method is suitable for determining the blocked forces of an axial piston pump. According to the OBV results, the pump can be characterized using 12 blocked forces within a frequency range of 150 Hz $< f <$ 2500 Hz. However, the analysis of transferability indicates that these forces can only be transferred to another receiver system up to a frequency of approximately $f <$ 1300 Hz. This limitation could be attributed not only to insufficient source characterization but also to measurement errors or variations in the operational measurement.
Given that the frequency range up to approximately 5000 Hz is particularly relevant for the acoustics of axial piston pumps [28], the procedure for determining the blocked forces must be further optimized to enable reliable source characterization within the relevant frequency range. To achieve this, sufficient energy must be introduced into the system across the entire frequency range of interest during the FRF measurement. This can be accomplished by using different impact hammer tips or a shaker. Additionally, an investigation of the required interface degrees of freedom could help analyze whether the twelve blocked forces used are adequate for characterizing the axial piston pump.
The introduced single-valued evaluation method significantly simplifies the source description using twelve blocked forces. However, it facilitates a straightforward comparison of different operating points or potential pump measures.The suitability of this evaluation method for assessing the SBN emission of axial piston pumps remains to be ascertained, as it necessitates validation through additional measurements. Nevertheless, it represents an initial approach to evaluating the emitted SBN independently of a receiver system and provides a foundation for further investigations.

5 Conclusion and outlook

To meet increasing noise requirements for mobile machinery, it is crucial to evaluate the acoustic behavior of axial piston pumps. Unlike ABN and FBN, no established method exists for assessing SBN emissions from hydraulic pumps. Therefore, a method has been introduced that derives a single-valued evaluation metric based on a comprehensive source description using blocked forces, enabling a straightforward assessment of the pump's SBN characteristics.
As the investigation shows, the in situ blocked force method is a suitable approach for the comprehensive source characterization of axial piston pumps with respect to SBN. However, to accurately describe the pump across the entire relevant frequency range, the procedure for determining the blocked forces must be further optimized. This particularly requires improvements in the measurement procedure.
The single-valued evaluation metric derived from the source description using blocked forces represents a significant simplification of the source characterization. However, it enables straightforward comparisons of operating points and measures, which is essential in early stage pump development.
The validity of the evaluation method cannot be conclusively assessed at this stage and must be examined in further studies. Additionally, the metric should be compared with other approaches for summarizing interface quantities like power-based methods.

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