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Blocked forces characterization of an air-conditioning compressor – Application to the norm ISO-21955

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ABSTRACT

SANDEN is an automotive equipment manufacturer specialized in Air Conditioning Compressor (ACC). Acoustical comfort is a strategic topic and, as the new generation of vehicles becomes more and more silent, noise generated by accessories as ACC is going to contribute in a large part of the global radiated noise of powertrain.

The component integration problems on the vehicle appear often late in the project development. Thus, SANDEN worked with CETIM to develop a new methodology for a better NVH characterization of their products. SANDEN wanted to predict the blocked forces of their compressor. Blocked force is intrinsic data, *i.e* independent of the host structure of the compressor.

The proposed methodology in this study is based on the Pr norm ISO 21955 used to transpose dynamic forces from a bench to a vehicle. The method uses the measured inertances of the source/host structure and the operational accelerations to predict the blocked forces. This paper presents the methodology, and some results about this indirect method on different receiving structures.

Keywords: Blocked forces, Compressor, Matrix inversion
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1. INTRODUCTION

1.1 Background

SANDEN Automotive Components Corporation is an automotive equipment manufacturer specialized in Air Conditioning Compressor. In Tinténiac (Brittany, France), SANDEN manufactures mechanical piston-type compressors of two technologies, « wobble-plate » and « swash-plate ». The internal parts of the compressor are invariants. Only the external casings are adapted for each customer and each engine. Therefore, SANDEN delivers many compressors models whose interfaces differ from one another.

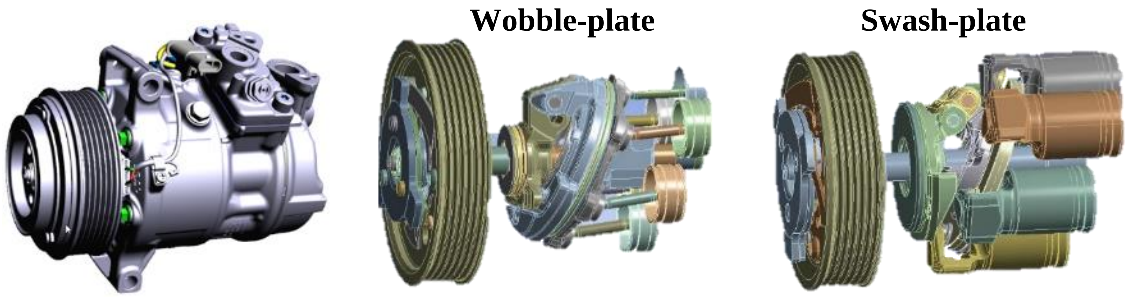

Figure 1 - Compressor and mobile assembly types

Because of ever more restrictive specifications from the customers (OEMs), there is a need for a continuous improvement of the performances of the products. Especially, acoustic comfort is a strategic topic and, as the new generation of vehicles becomes more and more silent (downsizing approach, hybrid or 100% electric vehicles); the noise generated by accessories like those that the A/C compressor contributes even more to the overall noise perception into the car cabin.

The compressor is a source of air-borne noise, structure-borne noise and fluid-borne noise, respectively transferred through the chassis, the AC pipes and the refrigerant. While the air-borne noise generally has a low effect on the noise into the car cabin, the structure-borne noise and the fluid-borne noise play major roles.

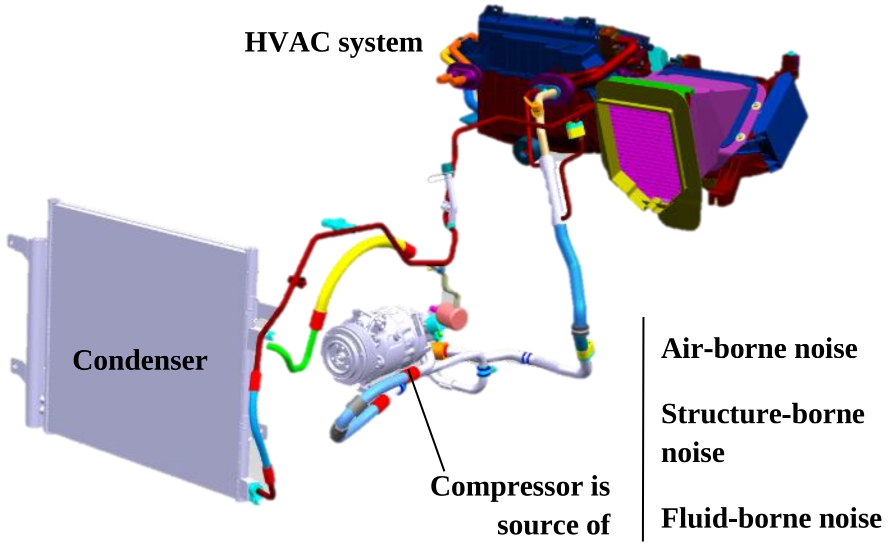

Figure 2 - Noise transfer from the compressor to the car cabin through the A/C system

For years, SANDEN has been providing test measurements obtained on benches following technical specifications from each OEM. Nevertheless, most of the specifications do not guarantee an optimised implementation of the compressor in the final host-structure (vehicle) for noise performances. Indeed, the host-structure used for the measurements on bench is mistakenly supposed rigid and is not representative to the vehicle one. Consequently, the measured forces on bench are neither the blocked forces, nor the forces that are injected to the vehicle host-structure. At the end, SANDEN faces noise issues when the compressor is installed in the vehicle.

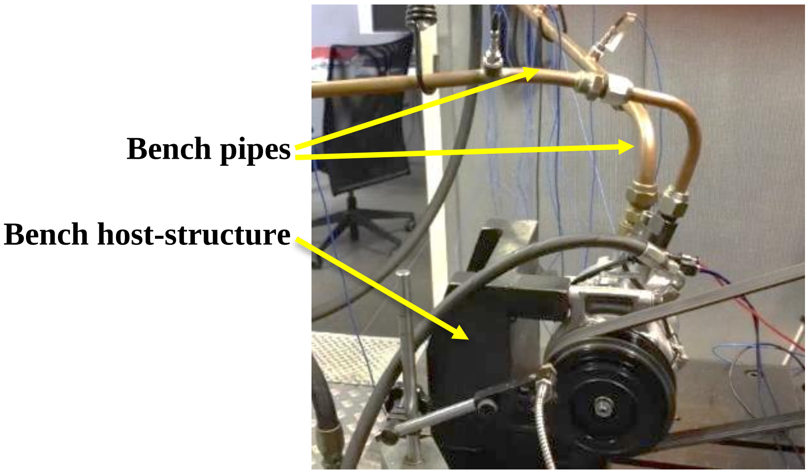

Figure 3 - Compressor mounted on a bench

In addition, SANDEN is equipped with several benches worldwide and it is always verified that one compressor, tested at different sites of the company, delivers different results. The explanation is also coming from the compressor environment. Host-structures and pipes differ between Sanden sites. It results on variability of the measured NVH responses.

Based on this evidence and the fact that the component integration problems on the vehicle appear often late in the project development, SANDEN asked for the development of a new method for a better NVH characterization of their products, right at the beginning of each project.

1.2 **Objectives**

As the final goal was to shorten the development process, ensure an optimised implementation of the compressor on the vehicle and reduce development costs, the method had to:

- deliver the adapted NVH response for each customer,
- facilitate the integration of compressor parts,
- reduce waste of money and time in case of mistakes during development,
- encourage dialog between manufacturers and suppliers.

SANDEN firstly focused the activities on the structure-borne noise and decided to work with CETIM to extract the blocked forces of the compressor based on the experimental norm Pr ISO 21955 [1].

Specifically, SANDEN wanted to develop and to set up the new method with the following main objectives:

- To have a unique test specification and to allow compressors comparison delivered to different customers,

- To allow the data comparison between results obtained with different test benches worldwide SANDEN sites (Germany, USA, Japan),
- To determine the blocked forces which characterize the compressor as a source of structure borne-noise. It will offer robust technical arguments to share with OEMs for NVH trouble-shooting.

In details, it was specified:

- To estimate the blocked forces at each compressor fixture point: the mounting bosses as well as the discharge and suction ports (refer to bench presentation for details),
- To make the study in the frequency range [0-1500] Hz.

As a constraint, the proposed method had to be adapted to the current SANDEN qualification process with restricted modifications from the existing test bench.

2. BENCH PRESENTATION – CURRENT SITUATION

Figure 4 shows an example of a compressor set up in the NVH semi-anechoic room. The compressor is, on one hand, directly fixed on a host structure and, on another hand, connected to the rest of the AC loop by two pipes. To secure that annoying noise coming from the AC loop does not interfere with the compressor noise, all the other elements of the loop (condenser, evaporator and expansion valve) are located outside the compressor room.

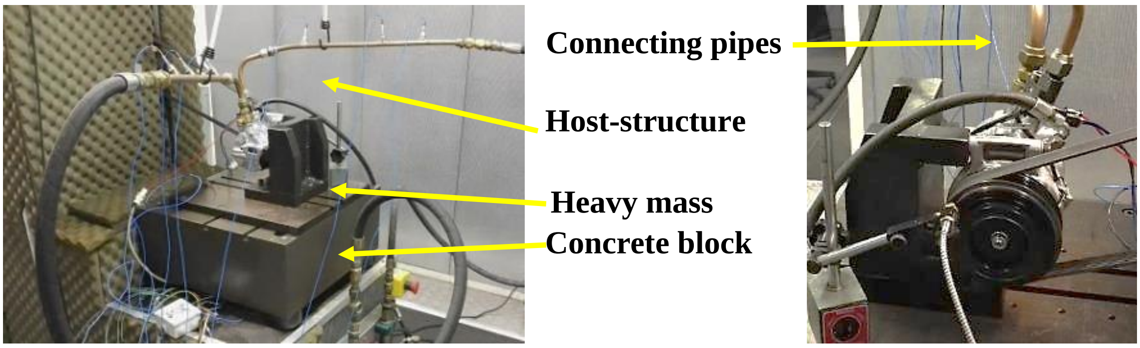

Figure 4 - Example of a compressor mounted on a bench

The compressor is driven by an electric motor through shafts, pulleys and belts. The electric motor is located outside the room and part of the driving system is insulated in the room. The host structure is attached to a heavy mass (called the passive support) which is decoupled from the rest of a concrete block. This decoupling prevents from any other structure excitation coming from other benches next to the NVH room. Three fixture points are identified on the host structure and two on the connecting pipes (see Figure 5).

The bench input command parameters are:

- the compressor rotation speed,
- the pressure (Ps) and the temperature (Ts) at the compressor inlet,
- the pressure (Pd) at the compressor outlet,
- the cam angle defining the compressor displacement.

The current customer specifications request to track NVH data not only in stationary conditions (stable speed) but also during run-up conditions. Indeed, in real life, the car engine, through the accessory belt, drives the compressor. As a result, the rotation speed of the compressor directly depends on the engine speed.

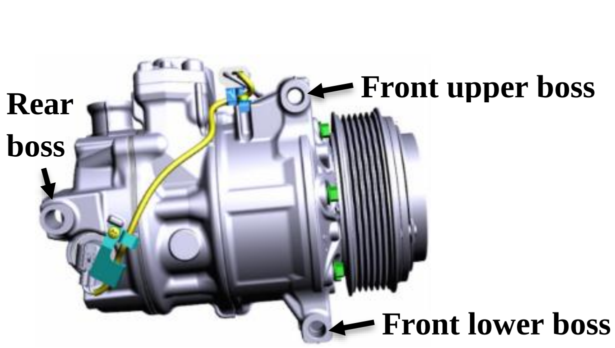

Figure 5 - Identification of the fixture point

The following pictures show examples of sensors required by the customers to record acceleration and force levels. These pictures show a large variety of sensors installation which makes difficult any comparison of the acceleration and force levels between all SANDEN compressors.

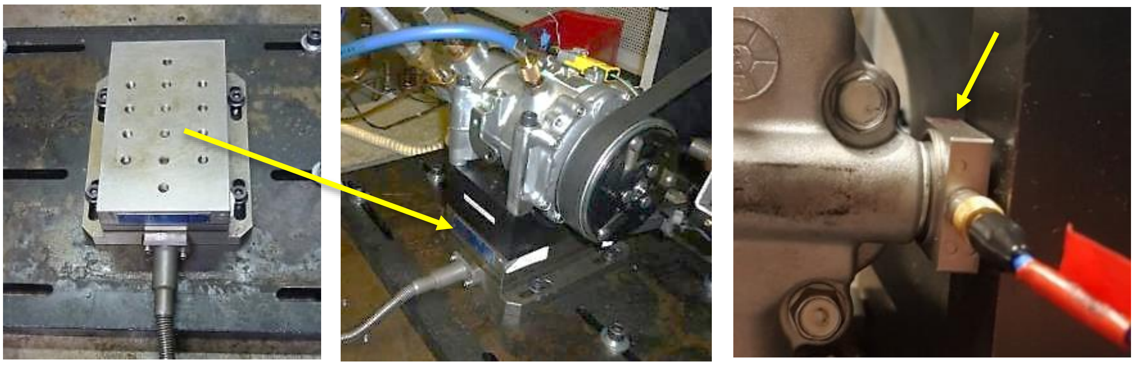

Figure 7 - Examples of force sensors installation

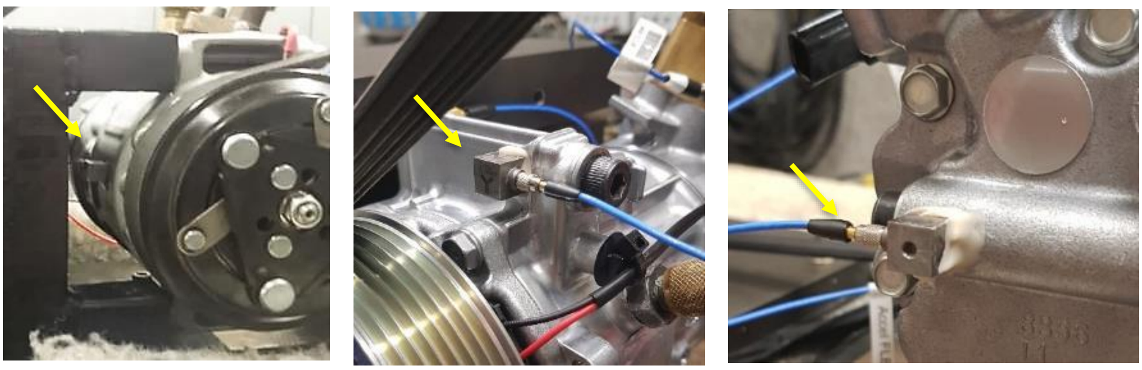

Figure 6 - Examples of accelerometers installation

In most cases, the host structure is wrongly considered as an infinitely-rigid structure that would allow to directly measure the blocked forces of the compressor. However, it is not the case and that is why SANDEN decided to develop a new method in collaboration with CETIM.

3. PROPOSED APPROACH TO PREDICT BLOCK FORCES

3.1 Principle based on the norm Pr ISO 21955

Usually, two structures coupled by both rigid and elastic connections are considered (see Figure 8). AC structure is called Active Component or source structure and PC1 is called Passive Component or receiving structure (test bench). For this study, the interface connections are considered as rigid.

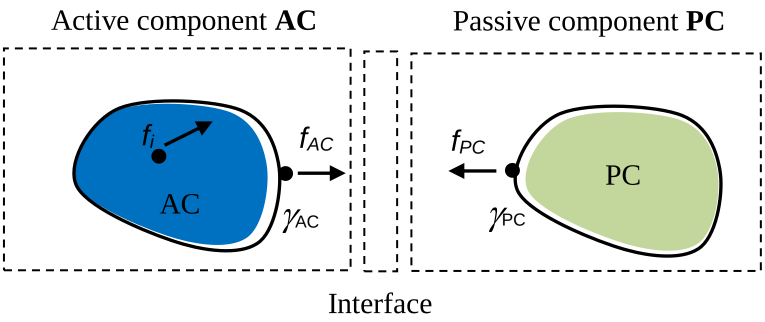

Figure 8- Coupling between the source structure and the passive component

The proposed approach is an experimental methodology based on the norm Pr ISO 21955 [1], the goal of which is to predict the forces generated by a source structure (called AC) on a receiving structure (called PC) through interface points. This method requires dismounting the active component from the assembly for the measurement of the inertance (ratio acceleration/force).

$\boldsymbol{Y^i_{AC}}$ is considered as a matrix describing the transfer functions between the internal points and the interface points of the source structure. $\boldsymbol{Y_{AC}}$ is a matrix describing the transfer functions at the interfaces of the source structure. $\boldsymbol{Y_{PC}}$ is a matrix describing the transfer functions of the host structure PC at its interfaces. The terms of these matrices Y are equivalent to inertance. The vector $\boldsymbol{\gamma_{PC}}$ is considered as the acceleration at the interface when the active and passive component are connected.

One can apply the mechanical equilibrium expressed at the interfaces. Thus, the force vector applied to the host structure PC, noted $\boldsymbol{f_{PC}}$, is connected to the force vector due to internal excitation in the source structure noted $\boldsymbol{f_i}$ in harmonic regime by the equation:

$$\boldsymbol{Y^i_{AC} f_i - Y_{AC} f_{PC} = \gamma_{PC}} \quad (1)$$

$$\boldsymbol{Y_{PC} f_{PC} = \gamma_{PC}} \quad (2)$$

This internal force vector $\boldsymbol{f_i}$ and the $\boldsymbol{Y^i_{AC}}$ inertance matrix are not directly measurable, but they are intrinsic data, *i.e.* independent of the host structure. The interface force $\boldsymbol{f_{PC}}$ is measurable, by a direct method (force sensors) or by an indirect method (using the accelerations), however it is dependent on the receiving structure behavior through $\boldsymbol{Y_{PC}}$.

Without information about the final host structure PC (for example: customer bracket, or a new test bench), it can be useful to have an estimation of experimental intrinsic data of the source. The blocked forces of an active component are often used to get intrinsic data of the source. They can be defined considering that the final host structure PC is infinitely rigid, meaning that $\underline{\mathbf{Y}}_{\mathbf{PC,blocked}} = \mathbf{0}$ and $\gamma_{PC,blocked} = \mathbf{0}$.

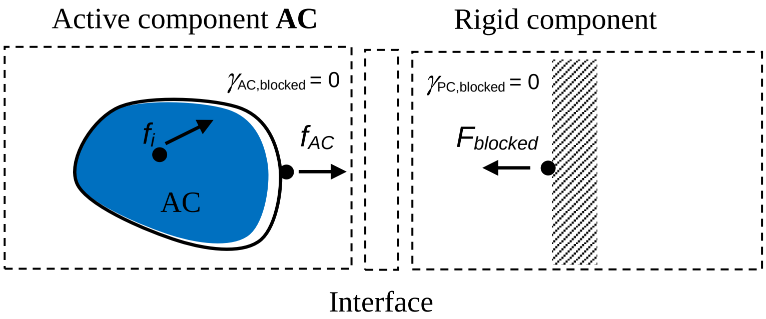

Figure 9 – The analogy of the blocked forces

By expressing the dynamic equilibrium at the interface, considering the acceleration and the inertance matrix equal to zero, one can find that [2]:

$$\boldsymbol{f_{blocked}} = [\boldsymbol{Y_{AC}}^{-1} + \boldsymbol{Y_{PC}}^{-1}]\boldsymbol{\gamma_{PC}} \tag{3}$$

3.2 Experimental protocol

First, the inertance matrices of the disconnected compressor and host structures were measured using an impact hammer. Three tri-axial accelerometers were set up around fixation points to average the translational acceleration at the contact point. The inertance measurements were made on the boss points and the port points (see Figure 5).

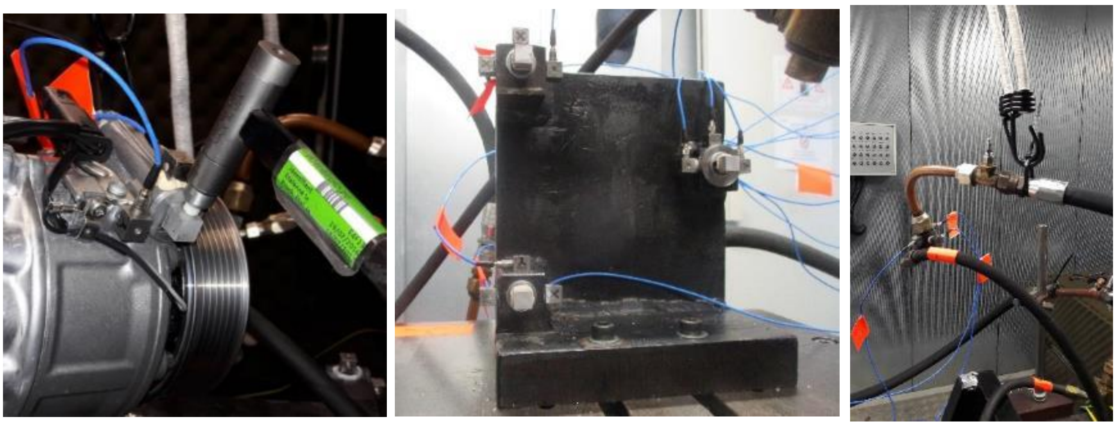

Figure 10 – Inertance measurements with an impact hammer (left: Source structure; middle: Passive component PC1 for the boss points; right: Passive component PC1 for the port points).

Then, the compressor was screwed on a receiving structure. Force sensors were set up at the boss point interfaces to measure the injected forces into the host structure. It was impossible to set up force sensors at port points, thus the comparison between the direct and indirect method will only be made at boss points.

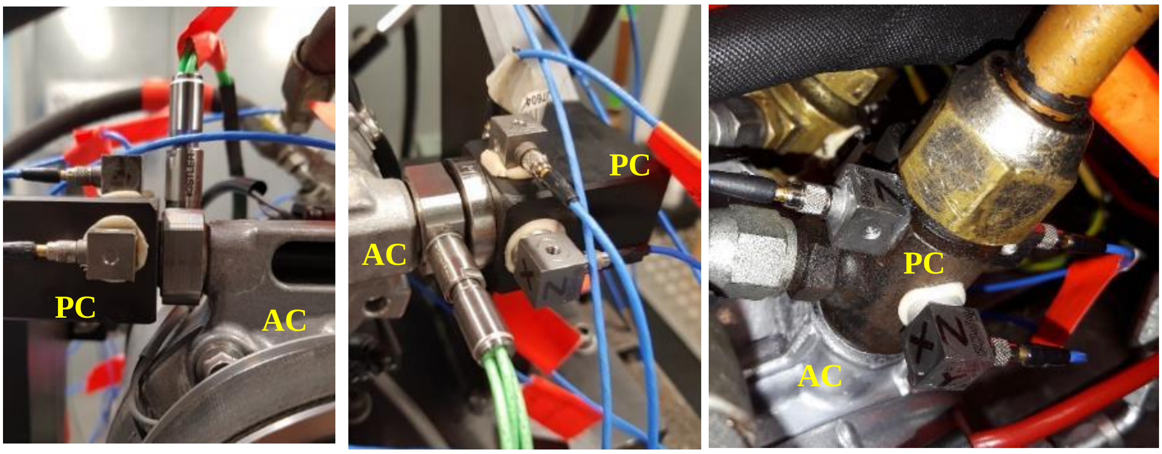

Figure 11 –Accelerometers and force sensors set up for the blocked forces method

4. RESULTS

4.1 Inertance matrices

The inertance measurements were arranged in inertance matrices as a $\boldsymbol{Y_{PC}}$ matrix and a $\boldsymbol{Y_{AC}}$ matrix. The goal of the study is to validate the blocked forces methodology, so two receiving structures were tested PC1 and PC2. They have different mechanical behaviour such that PC1 is stiffer than PC2 (see Figure 12). The PC1 inertance measurement was made by two different operators during the Phase 1 and the Phase 2 of the project.

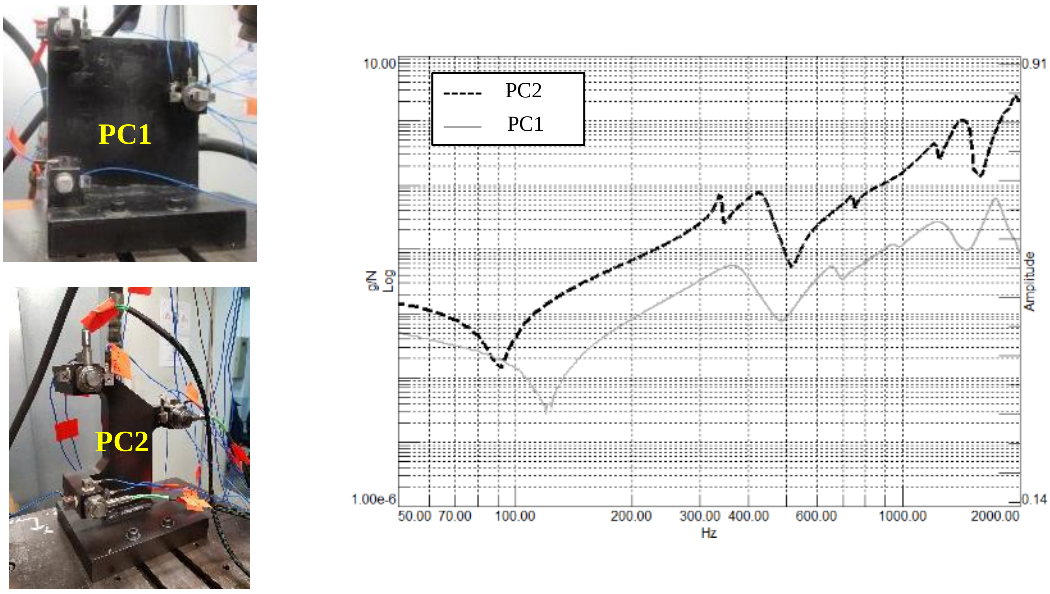

Figure 12 – Inertance measurements on the same point for PC1 and PC2

The Equation (3) implies inverting these matrices, this can be directly applied if the experimental matrices are not too ill-conditioned. The condition number represents the ration between the largest and the smallest singular value. The higher the ratio will be, the worst the matrix inversion will be done. The Figure 13 represents the condition number of the two receiving structures.

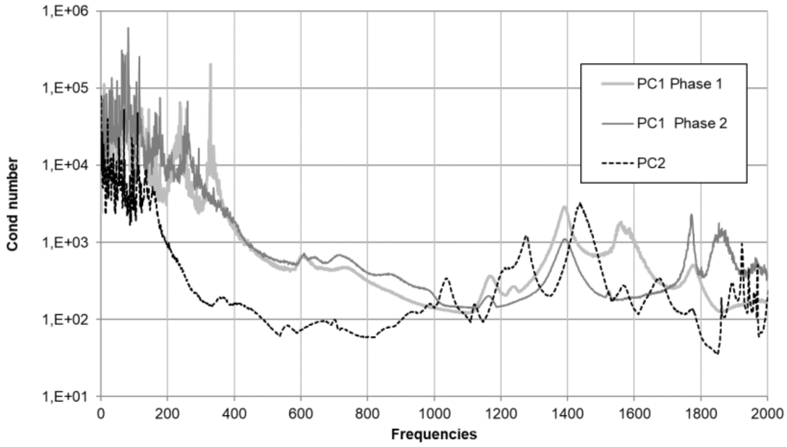

Figure 13 - Condition number of the passive components

It is obvious that the ratio is high in low frequencies, especially for the PC1 structure, which is due to its very low accelerations making the matrices ill-conditioned. So, the use of matrix regularization is highly advised to invert these ill-conditioned matrices. The regulation has been made by using the Moore-Penrose pseudoinverse in MATLAB. One can then set a threshold to only select the greatest singular values and reducing the ill-condition.

4.2 Comparison between the direct and the indirect method

Before computing the blocked forces of the active component, a comparison has been made between an indirect and a direct method to validate the matrix inversion (see Equation (3)). As force sensors were set up at the interfaces, it is possible to compare the injected force measurements (direct method) with an indirect method derived from the Equation (2):

$$\boldsymbol{f_{PC}} = \boldsymbol{Y_{PC}}^{-1}\boldsymbol{\gamma_{PC}} \tag{4}$$

The Figure 14 represents the quadratic mean of the boss points forces for the 30 first compressor harmonic orders. The indirect and the direct method are compared. The source was set up on the PC2 host structure and its stationary speed was 2000 rpm. The top graph has been obtained without SVD regularization. It is obvious that the calculated injected forces are overestimated, especially in low frequencies where the conditioning number is high (see Figure 13). The use of the SVD regularization (threshold 1E-4) clearly improves the low frequency results. It is to be noted that it has no influence on the higher frequencies results. This threshold will be used for the other configurations to predict the blocked forces of the compressor.

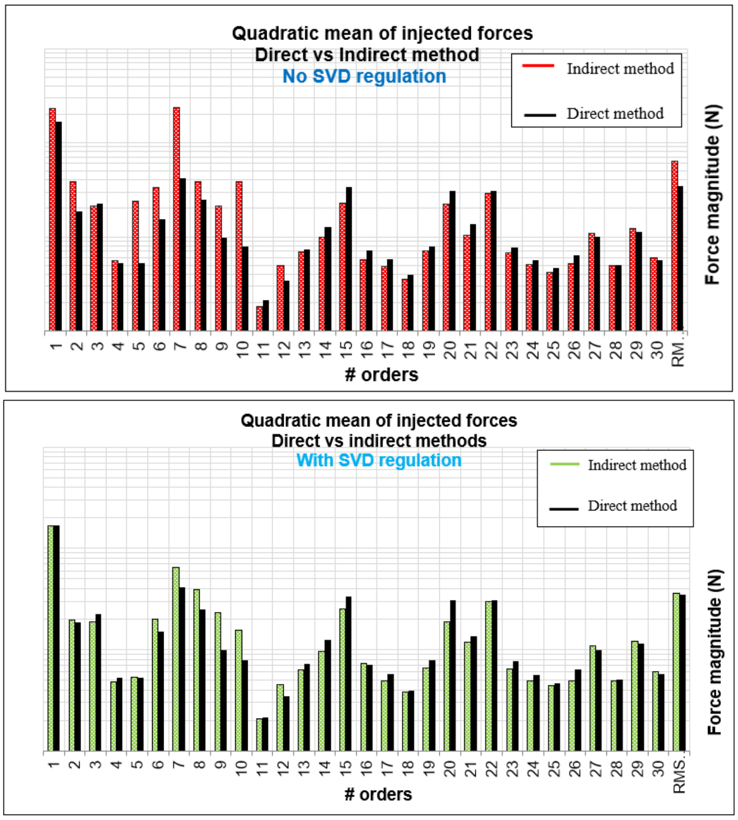

Figure 14 – Comparison of the indirect and direct method at a stationary speed of 2000 rpm (Source on PC1 Phase1; top: without SVD regularization; bottom: with SVD regularization)

4.3 Blocked forces prediction

4.3.1 Reproducibility of the method

The blocked forces methodology, using the Equation (3) was applied on the compressor mounted on the passive component PC1. To evaluate the reproducibility of the method, two mountings were made with the same active and passive component. The Figure 15 represents the quadratic mean of the blocked forces for the two mountings. The results clearly show a good consistency between the two test configurations. However, slight discrepancies can be seen, especially in high frequencies. These differences have also to be considered when comparing the blocked forces of the same AC on two different supports. They can be due to mounting errors or to test parameters which are slightly different.

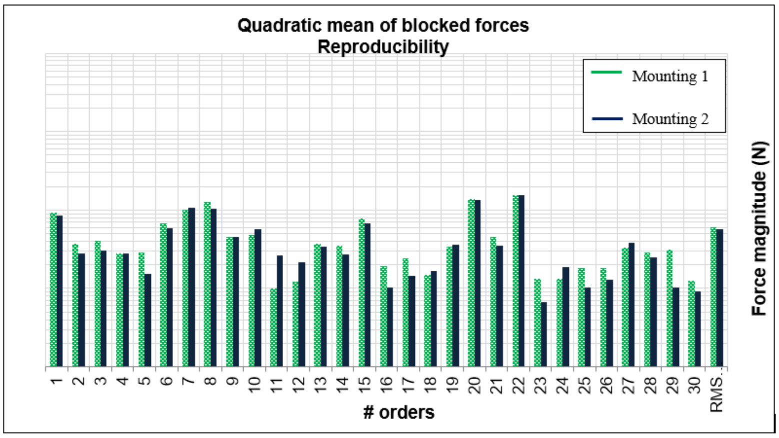

Figure 15 – Influence of the mounting reproducibility on the method at a stationary speed of 2000 rpm (Source on PC1 Phase1)

4.3.2 Comparison on two different supports

To evaluate the methodology, the blocked forces have been calculated on two different host structures (PC1 and PC2). Some results are sum up in the Figure 16. It shows a good consistency between the blocked forces evaluted for the two receinving structures. Some discrepancies can be seen on the whole spectrum, they can be explained by test parameters (see 4.2.1) or by the ill-conditioning of the passive/active inertance matrices.

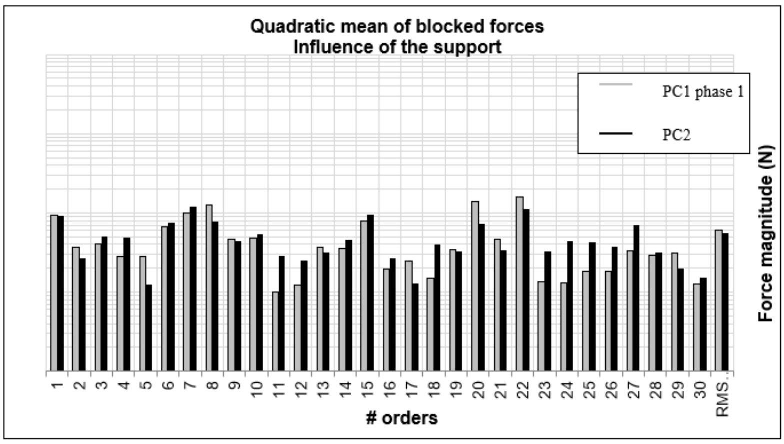

Figure 16 – Comparison of the blocked forces of the AC on two different supports

5. CONCLUSION

SANDEN wanted to develop a unique NVH test specification and to allow compressors comparison delivered to different customers. The goal was to be able to compare results obtained with different test benches. SANDEN decided to determine the blocked forces which characterize the compressor as a source of structure borne-noise. Thus, SANDEN worked with CETIM and apply the norm Pr ISO 21955 methodology to predict the blocked forces of the compressor.

The blocked forces methodology was applied on two kind of host structures. Their dynamic stiffness was different such that PC1 was stiffer than PC2. There was a good consistency between an indirect and direct method to get the injected forces in the host structure. However, one needed to use matrix regulation to improve the ill conditioning of inertance matrices. The comparison between the forces obtained on the two receiving structures show close results. However, results could be enhanced by improving matrix regulation or the test parameters reproducibility.

6. REFERENCES

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