ACOUSTIC OPTIMIZATION OF A SERVO-HYDRAULIC PUMP UNIT AND AI EVALUATION OF THE SUBJECTIVE SOUND PERCEPTION

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ABSTRACT

As part of the development of a new type of primary-controlled press drives (direct mounted servo-hydraulic pump unit on the manifold), various concepts were designed and acoustically optimized with the help of the finite element method. In this study, sound measurements were carried out on a hydraulic press. The aim was to analyse the influence of different designs of the pump unit on the sound power of the overall system. In addition to this state-of-the-art procedure, the recorded sounds were played back to participants in listening tests (> 1000) and the subjective perception of the sounds was assessed and evaluated. Psychoacoustic metrics were also analysed. With the aim of replacing time-consuming jury tests in ongoing developments, an artificial intelligence (AI) was developed and trained with the help of the data obtained. This AI helps to accelerate the development process. The results are compared based on the different investigated development stages of the servo-hydraulic pump unit.

Keywords: acoustics, nvh, servo-hydraulic pump, fem, sound power, listening tests, subjective sound perception, psychoacoustics, artificial intelligence, ai

1. OBJECTIVE OF THE STUDY

1.1. Primary-Controlled Press Drive with Servo-Hydraulic Pumps

To develop a space-saving, energy-efficient primary-controlled press drive with high power density and excellent robustness, a classical hydraulic approach with a proportional directional control valve is replaced by a servo-hydraulic pump (SHP) [1]. A SHP is a combination of synchronous servomotor and an axial piston pump and generates the volume flow required for the axis movements adjusting the two control variables: rotational speed and swivel angle [2].

As part of the development of the primary-controlled press drive, three different axial piston pumps were compared with each other as direct drives for the upper and lower pistons on a PA200HE powder press of the company Frey, as shown in **Figure 1**. Pump A and pump B are standard axial piston pumps. The A4VZA with a displacement of 71 ccm is a newly developed axial piston pump, designed for direct block mounting.

1.2. Acoustic Measures and Investigations

To ensure, that the development of the A4VZA71 will meet the acoustic requirements the following steps were taken:

1. Acoustic optimisation of the servo-hydraulic pump using finite element analysis techniques.
2. Measurements of the sound power generated by the servo-hydraulic pumps.
3. Calculation and evaluation of the psychoacoustic parameters characterizing the sound produced by the pump.
4. Determination of the human sound perception and training of an artificial intelligence model.

These objectives guide the research and analysis presented in this paper, allowing for a comprehensive understanding of the various aspects related to the servo-hydraulic pump and its acoustic characteristics.

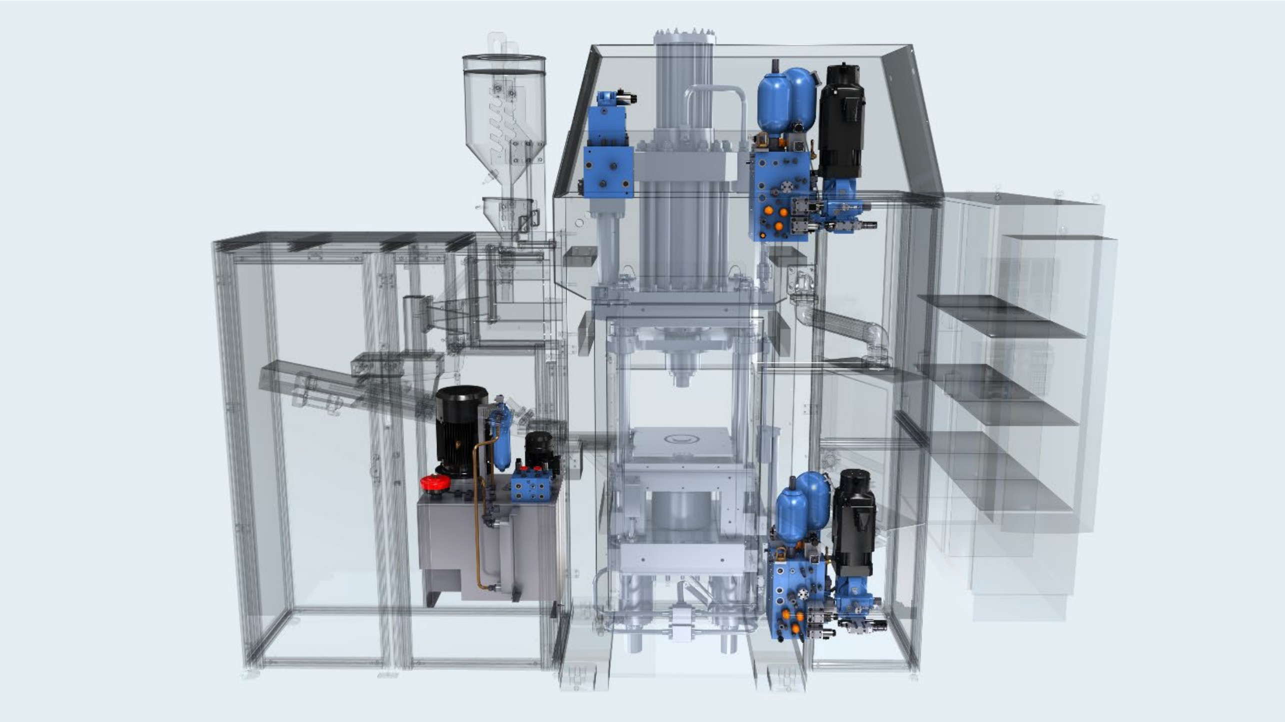

Figure 1: Schematic representation of the powder press with servo-hydraulic upper and lower piston drive

2. METHODOLOGY

2.1. Finite Element Optimisation of the Servo-Hydraulic Pump

After it had been shown that the primarily-controlled drive concept for the press meets the requirements of the market, the development of a pump especially designed for direct block mounting was started.

To meet the acoustic requirements of the market even better, the pump was investigated and optimized during the design phase by means of acoustic finite element simulations. In addition to the airborne sound power of the servo-hydraulic pump, the structure-borne sound excitation at the interface to the press was evaluated in order to diminish both quantities significantly.

Figure 2 illustrates the application of the finite element method in the acoustic optimization of the servo-hydraulic pump.

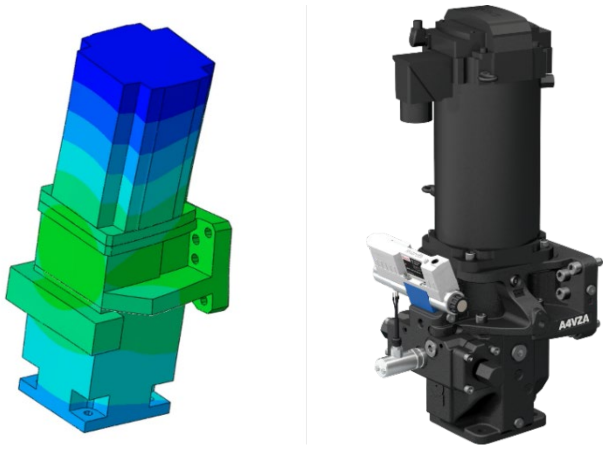

Figure 2: Finite element model (left); SHP with A4VZA71 and servomotor (right)

2.2. Sound Power Measurements

In this study, sound power measurements were carried out on a hydraulic press. The aim was to analyse the influence of different designs of the pump unit on the sound power of the overall system.

The travel speed of the cylinder piston was set as the operating parameter, and the operating modes *rapid traverse* and *press traverse* were investigated. Additionally, the different servo-hydraulic pumps were all operated with the same operating parameters. This means that a pump with a lower displacement is operated at significantly higher speeds than a pump with a larger displacement at the same cylinder piston speed.

To evaluate the influence of the servo-hydraulic pumps on the sound radiation of the entire press, all sound power measurements were conducted according to DIN 45635-1 [3]. The microphones were arranged on a parallelepiped measurement surface with a distance of 1 m from the reference box of the press, matching accuracy class 3, as shown in **Figure 3**.

During the investigations, the press was located in a test hall and could not be set up in a qualified hemi-anechoic test room. For this reason, various measures have been taken to ensure that the installation conditions affect the investigations as little as possible.

To minimize influences from the installation environment, the background noise correction K_1 was determined before each series of measurements. The environmental correction K_2 was determined using a reference sound source based on DIN 45635-1 [3]. Additionally, care was taken in all measurements to minimize disturbances from the test hall.

The diagram in **Figure 4** shows the sound power of the press equipped with different pumps. The distance between the horizontal lines in the diagram is 5 dB.

In the case of pump A, and pump B, which were not developed for the "direct block mounting" application, the sound power starts at low values, but increases significantly at different cylinder piston speeds. The sound power of the press equipped with the A4VZA71 shows a rather flat, continuously increasing trend. This was achieved through the acoustically optimized design of the SHP using the finite element method. As a result, both the structure-borne sound excitation of the press and the airborne sound radiation of the SHP could be significantly reduced. In several operating points, the sound power of the press equipped with the A4VZA71 is 10-12 dB lower. On average, the use of the A4VZA71, which has been especially developed for the "direct block mounting" application, results in a 5 dB lower sound power of the press. Since the sound power is already halved with a reduction of 3 dB, this can be considered a significant reduction. The fact that the sound power fluctuates significantly less over the increasing cylinder speed is also regarded as a sign of quality.

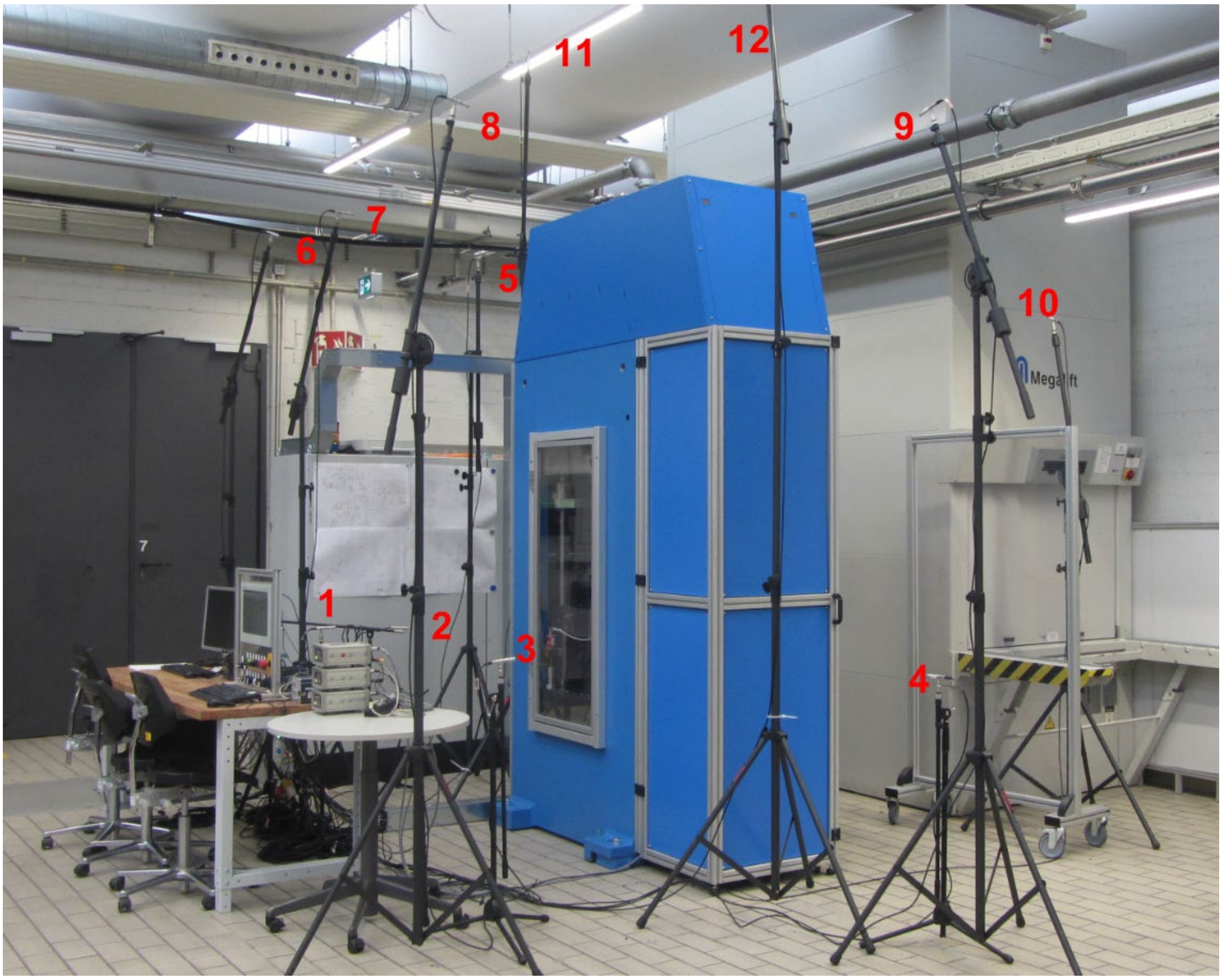

Figure 3: Parallelepiped microphone array and the powder press

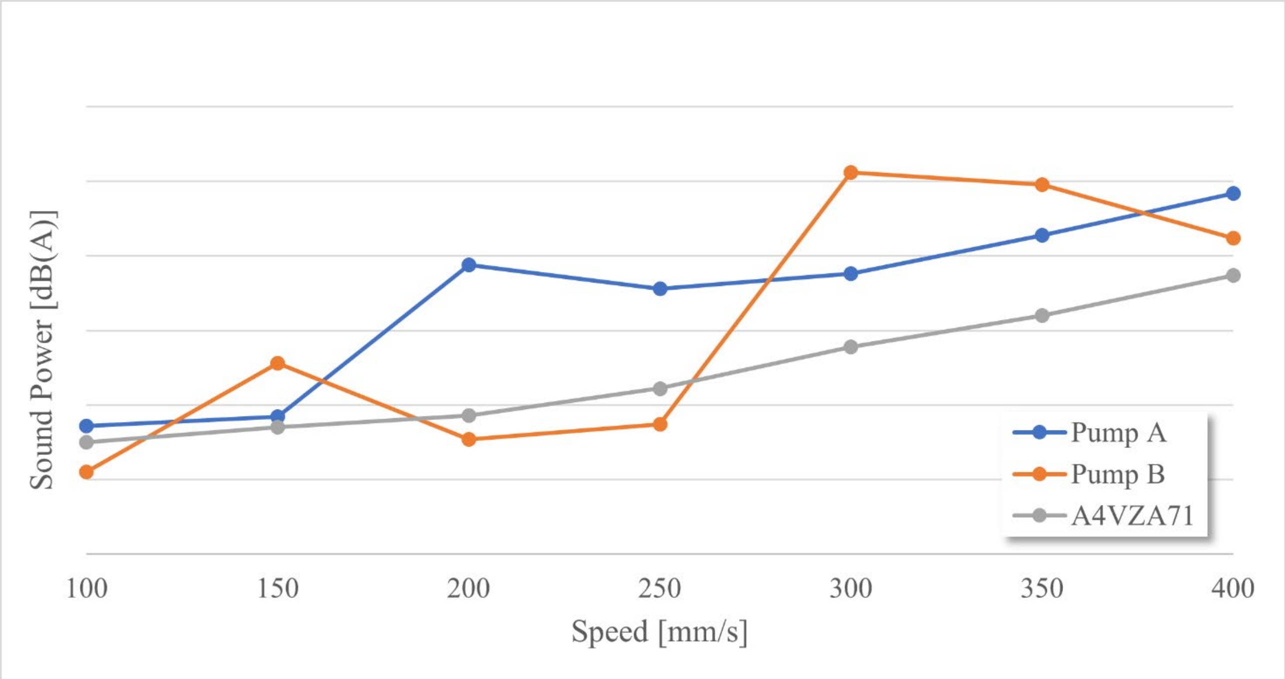

Figure 4: Sound power of the press, equipped with different pumps

2.3. Psychoacoustic Parameters

In addition to the sound power also the psychoacoustic parameters of the airborne sound emitted by the press was investigated. Since the influence of the servo-hydraulic pumps on the sound of the press is of special interest in this study, a suitable microphone position within the microphone array was selected. This position is determined by finding a balance between placing the microphone as close as possible to the operator's ear position and in a position suited to detecting the influence of the SHP. Using the sound pressure time signals recorded at this microphone position, the psychoacoustic parameters of loudness [4], sharpness [5] and tonality [6] were evaluated and compared for the different SHPs.

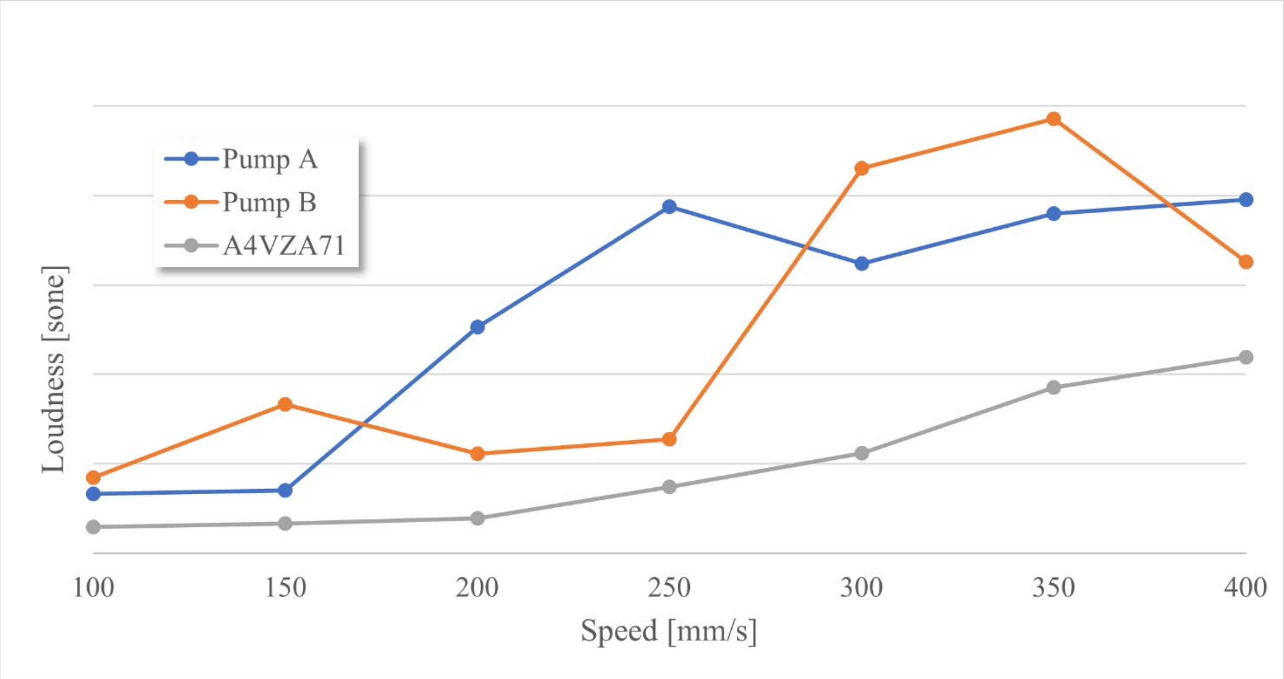

Figure 5: Loudness at microphone 4 at the press, equipped with different pumps

Loudness is the "perceived magnitude of a sound, which depends on the acoustic properties of the sound and the specific listening conditions, as estimated by that the average human listener with normal hearing" [6].

Figure 5 shows the loudness in relation to the cylinder piston speed, evaluated at microphone position 4, recorded on the press equipped with various pumps. The distance between the horizontal lines represents 5 sone.

Similar to the sound power in **Figure 4**, the loudness of pump A and pump B, which were not especially designed for the "direct block mounting" application, starts at low values and increases significantly at different cylinder piston speeds. Operating the A4VZA71 the loudness shows a rather flat, continuously increasing trend. The difference between the highest and lowest amplitude for the A4VZA71 is more than 50% less than for pump B.

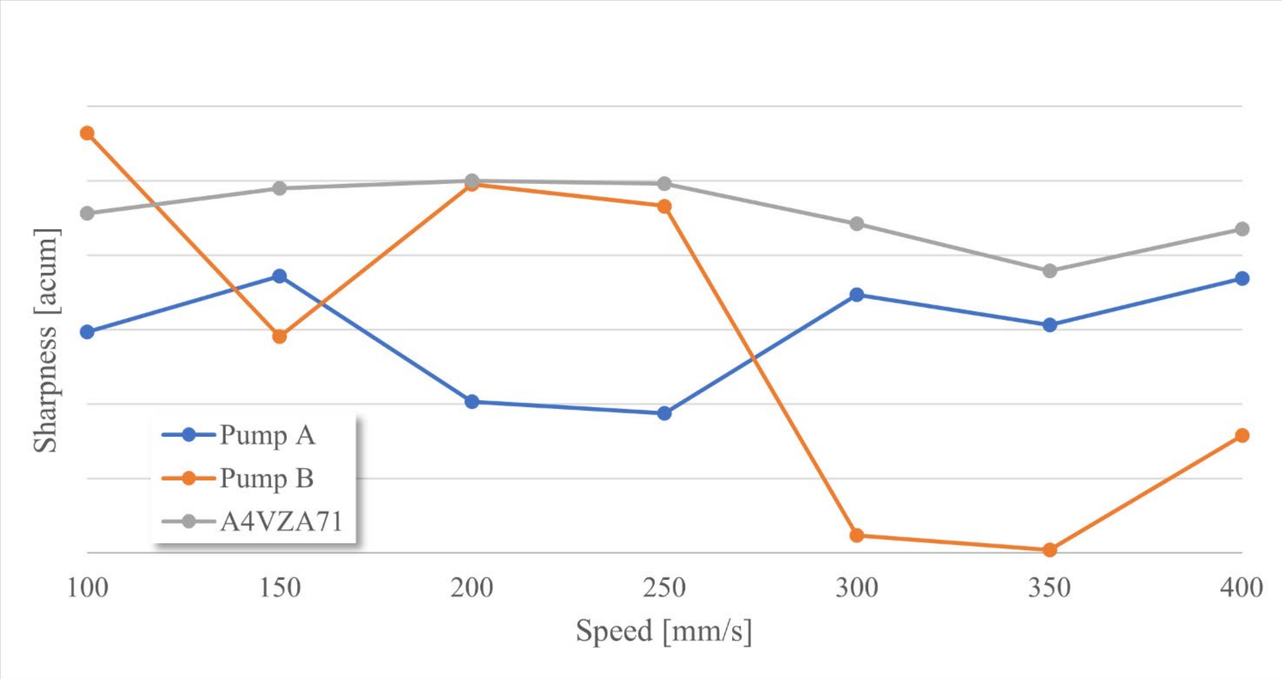

Figure 6: Sharpness at microphone 4 at the press, equipped with different pumps

Figure 6 shows the sharpness in relation to the cylinder piston speed, evaluated at microphone position 4, recorded on the press equipped with different pumps. The distance between the horizontal lines represents 0,1 acum. “Sharpness is the ratio of the loudness of the higher-frequency spectral components to the total loudness” [6].

In terms of sharpness, the behaviour is different compared to loudness and sound power. While the sharpness changes only slightly when operating the A4VZA71 over wide operating ranges, it fluctuates much more when operating the other two pumps.

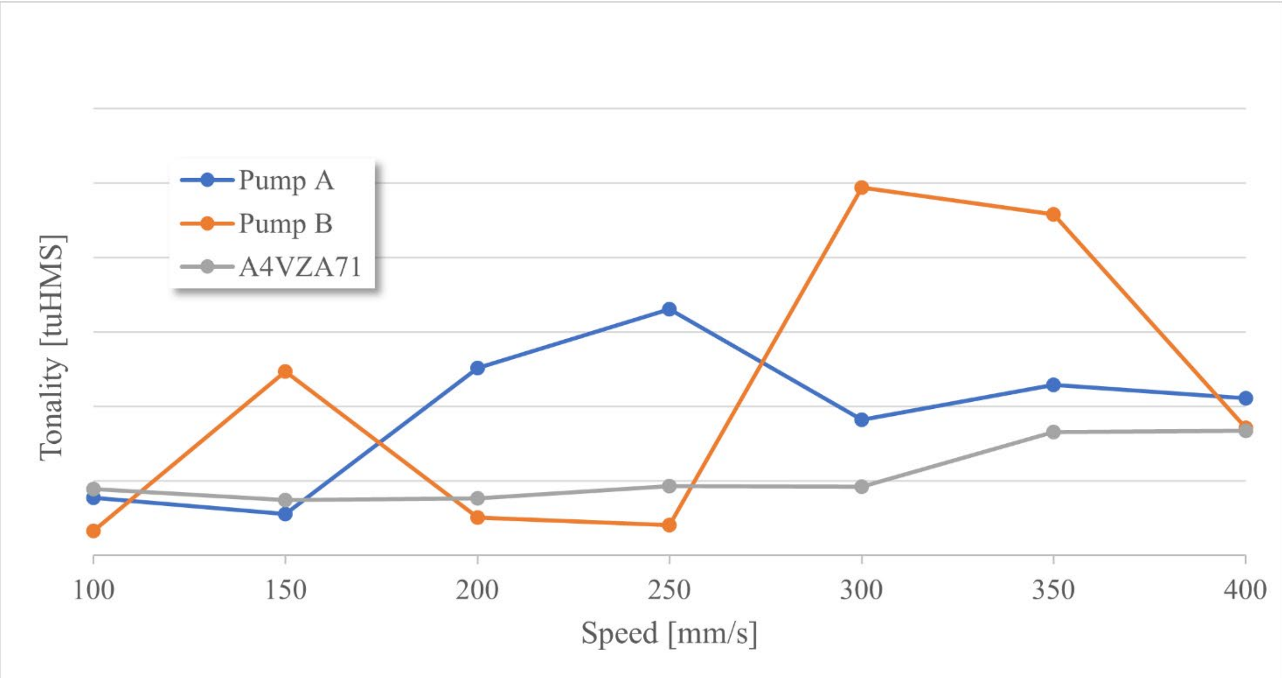

Figure 7: Tonality at microphone 4 at the press, equipped with different pumps

Figure 7 shows the tonality in relation to the cylinder piston speed, evaluated at microphone position 4, recorded on the press equipped with various pumps. The distance between the horizontal lines represents 0,5 tuHMS. The tonality is “a characteristic of sound containing a single-frequency component or narrow-band components that emerge audibly from the total sound” [7].

The evaluation of the tonality shows that the values change only slightly during the operation of the A4VZA71 over the entire operating range and only increase slightly at 300 m/s cylinder piston speed. For the other two pumps, major changes are caused by the increase of the cylinder piston speed and higher values are reached.

2.4. Human Sound Perception and AI Training

In addition to this state-of-the-art procedure, the recorded sounds were played back to participants in listening tests (jury tests) and the subjective sound perception was assessed and evaluated. For this purpose, the sounds played back to the participants were the same as already used for the analysis of the objective psychoacoustic parameters (sounds recorded on the microphone 4). The sounds used are thus as close as possible to product sounds as is customary for listening tests [8].

Since jury testing is time-consuming and requires the involvement of a larger group of people, a solution had to be found that would save time and effort in future. With the objective of replacing time-consuming jury tests in the future and in ongoing developments, an artificial intelligence (AI) model was built and trained using the data obtained. Therefore, the number of listening test (> 1000) was chosen to be significantly larger than usual. The sounds were collected over the entire operating range of the pumps and not only focused on particularly noticeable operating points. The training and test data were split in a ratio of 80:20, as is often the case [9].

This AI model helps to accelerate the development process [10, 11].

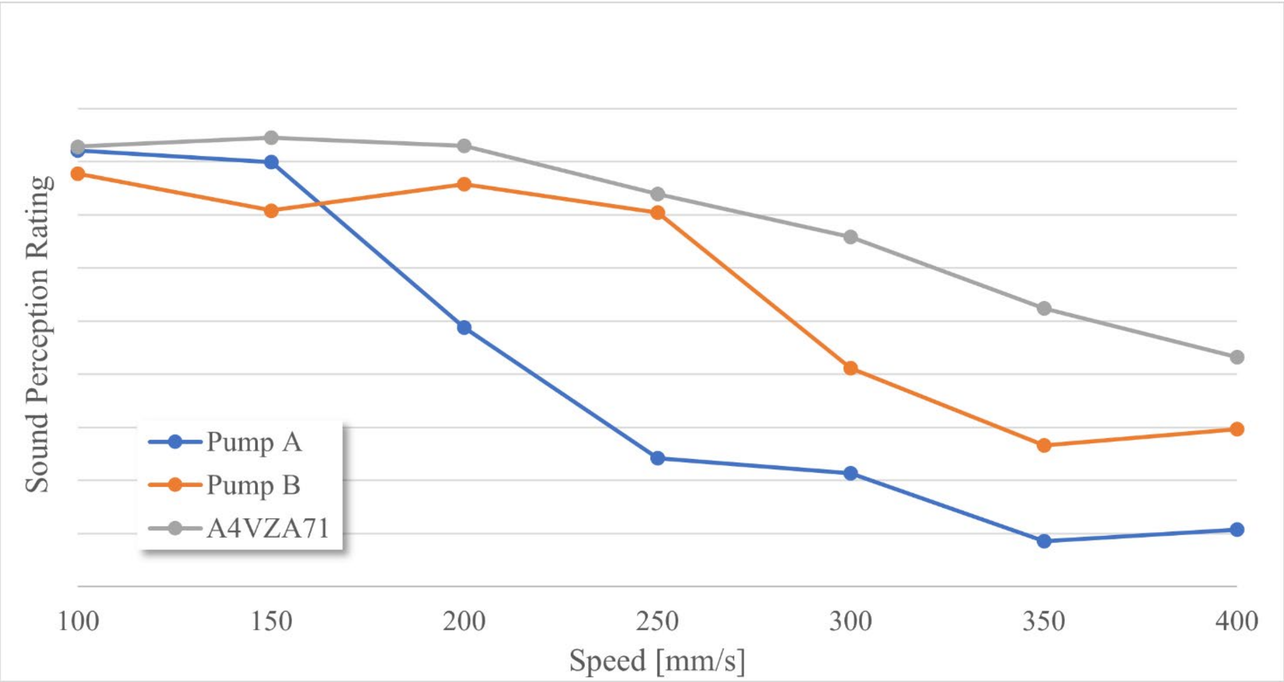

Figure 8: Sound perception rating at microphone 4 at the press, equipped with different pumps

Figure 8 shows the sound perception rating in relation to the cylinder piston speed. The values shown are the results of the AI trained to evaluate the sound signals based on human sound evaluation. The higher the values, the higher the agreement with the sounds, indicating a more positive evaluation.

It can be clearly seen that the sound perception rating remains at a high level up to medium cylinder speeds when using the A4VZA71. The rating also drops less significantly at very high cylinder piston speeds than the rating of pumps that were not developed for the direct block mounting. Since the human perception of the machine sound is an important quality criterion, the approach described leads to an acoustical optimization of the system.

3. CONCLUSION

By developing a new servo-hydraulic pump for direct mounting on a valve block and optimising its acoustics by means of the finite element method, the acoustics of a press application could be significantly improved compared to standard axial piston units. In addition to the significant reduction in sound power, a noticeable improvement of the psychoacoustic parameters loudness and tonality could also be achieved.

Besides these objective quantities, the human perception of the sounds was also investigated. Comprehensive listening tests show that also the subjective sound perception of the machine was significantly improved due to using an acoustically optimised servo-hydraulic pump.

In order to reduce the effort of future developments noticeably, an AI was trained using the recorded data, which reflects the subjective evaluation of the test persons. The trained AI reduces the number of necessary listening tests for further development steps in the future significantly.

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