A Model-Based Approach to Optimize the Noise Harmonics of Internal Gear Pumps by Reducing the Pressure Pulsation

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Abstract

Regarding hydraulics, the reduction of noise emissions is one of the main topics researchers and manufacturers are working on. Even after many years of experience, this field represents a big challenge, because, on the one hand, the transmission of oscillations from fluid to air is influenced by many components and numerous parameters. Finally, it is the operator's perception that decides which kind of sound has to be regarded as noise. On the other hand, manufacturers are forced to generate quick solutions that focus directly on the customer's benefit. Concerning noise reduction, this is hard to achieve, not just by test rig experiments but even more on a full theoretical basis.

This paper presents a semi-theoretical approach to model the generation, transmission and judgement of sound of an internal gear pump in one special application. A basic principle of this work is the analysis of pump harmonics in the frequency spectra of pressure and sound signals. The aim is to set up the pre-conditions for an optimization process, which allows reducing the machine noise by modifications of the pump affecting the pressure pulsation.

KEYWORDS: noise reduction, pump model, pressure pulsation

1. Introduction

Noise emission of hydraulic drives is a subject many researchers and manufacturers have been working on and it remains current as it still represents one of the major drawbacks of hydraulics in general. Reducing noise emissions poses a challenge, as the noise emitted by a machine is a result of interactions between many components. Therefore, it is necessary to take the whole system into account as well as to locate components which significantly influence the noise of the system. Regarding hydraulics, two mayor kinds of noise sources can be defined. The first kind, so called “structure born”, sums up all effects that cause mechanical vibration directly at the displacement machine. The second kind, further called “fluid born” noise sources, is defined by the flow ripple and the pressure pulsation, which is brought into the system and leads to vibrations of other components. **Figure 1** gives a popular illustration of this transmission path. An appropriate method to examine the relations between noise sources and noise emissions is to take a look at the harmonics of the pump, which can be identified in the noise spectra of the whole system and of the pump itself as well as in the spectrum of the pressure pulsation.

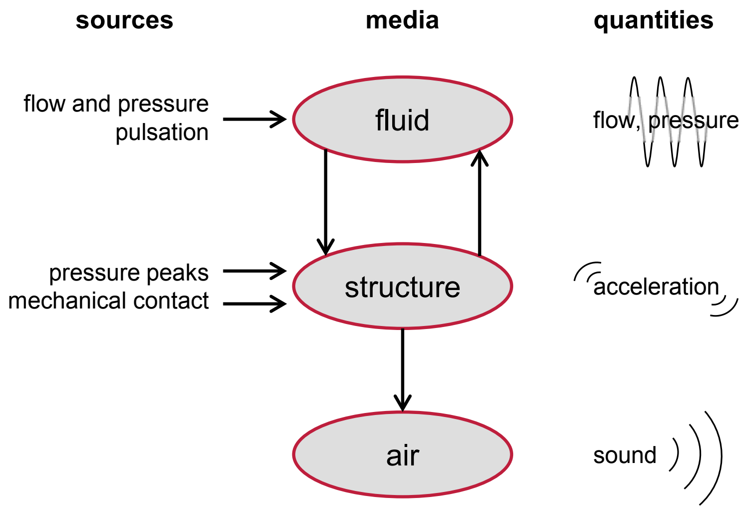

Figure 1: Transmission of oscillations in hydraulic systems (acc. to /1/)

During the years, numerous methods of noise reduction have been developed, ranging from additional damping-components (so called “secondary measures”) to changes in the design or even the in functional principle of displacement machines (“primary measures”). In addition, the methods can also be divided into groups that address different mediums in the process of transmission shown in figure 1. Sound reflection or absorption boards and noise cancellation as an active method directly address oscillations of the air. Structure oriented techniques include for example flexible attachments of pipes, special designs of bearings and gears or grooves in the area between suction and discharge port of pumps in order to avoid squish oil and pressure spikes. A reduction of flow ripple and pressure pulsation is often approached by increasing the number of displacement chambers, a bigger displacement angle or by hydraulic dampers as secondary measures.

Although many of these approaches have been established decades ago, the layout still poses a challenge even if it is supported by the use of simulation tools. Especially the noise reducing effect of measures which address oscillations early in the transmission path is influenced by numerous parameters throughout the whole system. When it comes to defining directions and criteria for the optimization of these measures, it often remains unclear, how the machine noise is being changed by judgement of the operator. The only solution to this problem is to take the operator's perception into account upfront in the optimization process.

The objective of this industrial project is to develop a simple method that allows estimating the effect of modifications of hydraulic components on the operator's judgement concerning noise emissions. In the first stage, which is being presented here, the work was focused on design modifications of an existing internal gear pump, mainly serving as lube oil and power supply for small actuators in different mobile applications. With the help of this kind of primary measure, the noise reduction effect is achieved by optimizing the pump harmonics in the frequency spectrum of the pressure signal.

2. Basic structure

According to the requirement of describing both, the generation of oscillations and the complete path of transmission, a procedure has been developed that consists of four steps, shown in **figure 2**.

The first task is to derive the parameters needed by the simulation model from the given internal gear pump. In order to build a tool which is easy to handle, the parameterization process has been programmed in Matlab. Pump model and parameterization are based on geometric attributes like the relation between driveshaft angle and volume of a single displacement chamber. Forces and mechanical friction are not part of the simulation.

In the next step, the simulation is run at several operating points that represent the range being critical for the operator's noise perception. The simulation has been set up in a modular way, including the pump model itself, a simple model of the line connected to the discharge port of the pump and a small signal processing unit that analyses the pressure pulsation. As result of the simulation runs, the amplitude of the pressure pulsation regarding the fundamental frequency and several harmonics are documented for the different operating points.

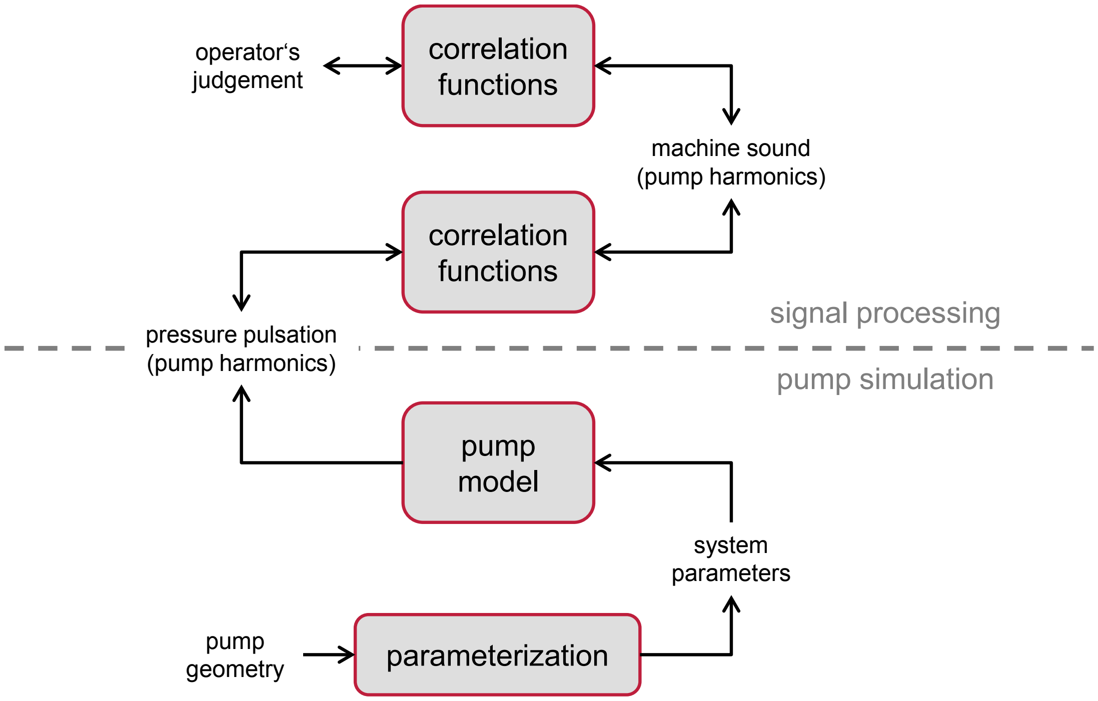

Figure 2: Basic structure of the process

Once the prospective pressure pulsation of a pump with a certain design has been calculated for certain operating points, the corresponding sound at the operator's ear has to be estimated. This is done in the third step of the procedure by the help of correlation functions that have been established on the basis of measurements. As the transmission of oscillations is influenced by numerous parameters throughout the whole system, these correlations have to be regarded as machine-specific.

In the last step, it has to be estimated, how the machine sound, represented by the amplitudes of the pump harmonics, is judged by the operator. Again, this is achieved by the use of correlation functions. These are based on sound experiments, which have been evaluated by different operators.

Regarding the input of the first and the output of the last step, the procedure allows estimating the effect of changes in the pump geometry on the operator's judgement of the machine sound. This is meant to be the basis for the development of an optimization tool.

In the following, the work that has been and is still being done to build up the procedure shown in figure 2 will be presented. This affects, in a first place, the development of correlation functions in order to process the output data of the pump simulation. Afterwards, the structure and implementation of the simulation model will be explained as well as the parameterization tool. This paper will close with a presentation of early results and an outlook on further steps.

3. Signal processing

As already mentioned, the correlation between the pressure pulsation and the operator’s judgement of the resulting machine sound is described with the help of two kinds of functions: one dealing with the operator’s judgement and another representing the transmission of pressure pulsation to sound.

This part of the project has not been finished yet. For this reason, the section will focus on structures, showing how the detection of correlations is being approached.

3.1. Judgement of sound

Sound becomes noise by judgement of a person. This conclusion results from the common definition of the term “noise” as “unwanted sound”. Following this argumentation, “noise reduction” can be circumscribed as a modification of sound in order to increase its acceptance. In turn, the acceptance of sound by a person is affected by more than only one criterion and hard to describe theoretically.

Within this project, the aim is to detect criteria for the sound acceptance of the operator that can be expressed in a simple mathematical way. The idea is, not only to look at the absolute values of amplitudes but to examine the amplitude ratio of different harmonics. Correlation functions that address multiple criteria should provide more options when it comes to finding solutions for noise reduction.

Figure 3 gives an overview of the measurement and evaluation process that has been build up in order to define criteria for noise perception. It can be divided into two stages. First, test runs have been performed with certain modified pumps that show significant differences in pressure pulsation and sound. The sound spectra have been measured in the operator’s cabin and at the same time, the sound has been evaluated by different operators, indicating if it had been more or less acceptable. Afterwards, this data has been used to roughly define acceptance criteria, representing first stage correlation functions.

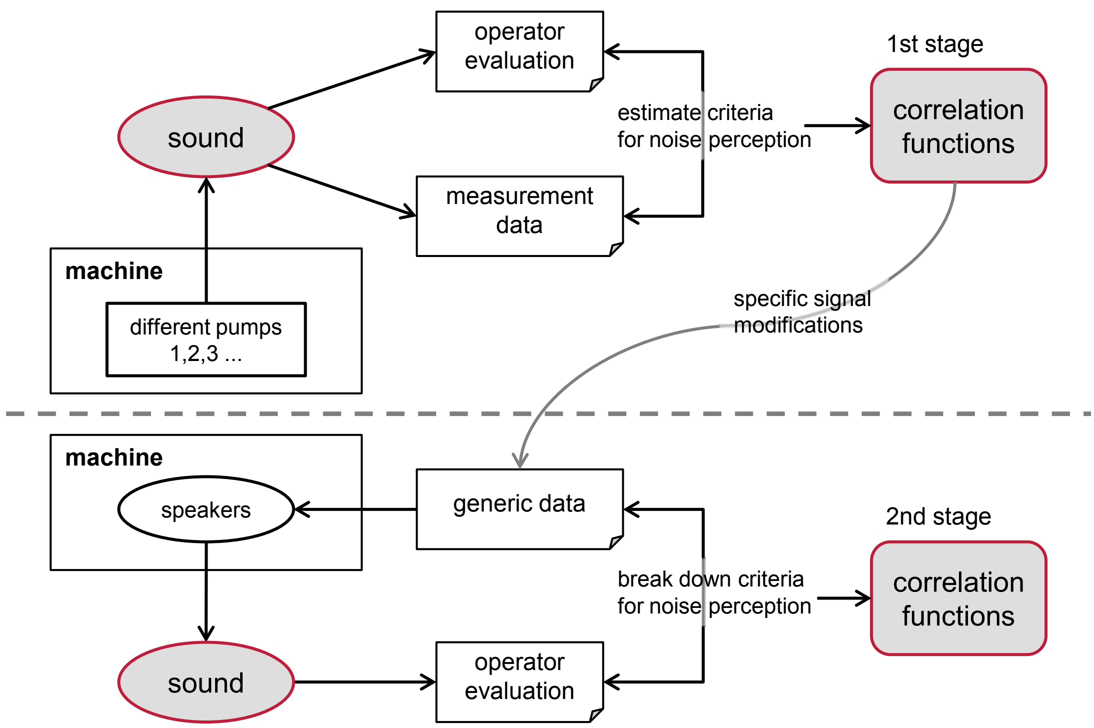

Figure 3: Measurement and evaluation process

One result of this first step is depicted schematically in **figure 4**. Here, the sound amplitudes of four frequencies have been plotted for different pumps at two speeds. The marker symbols indicate how the sound has been rated by the operator. Based on the measurements behind this graphic, it can be assumed for example, that in the area below the dotted line in figure 4, the amplitude ratio between second and first pump harmonic are more critical to the operator's perception than the absolute values. In the area above, the operator's acceptance seems to correlate directly with the absolute values of amplitudes.

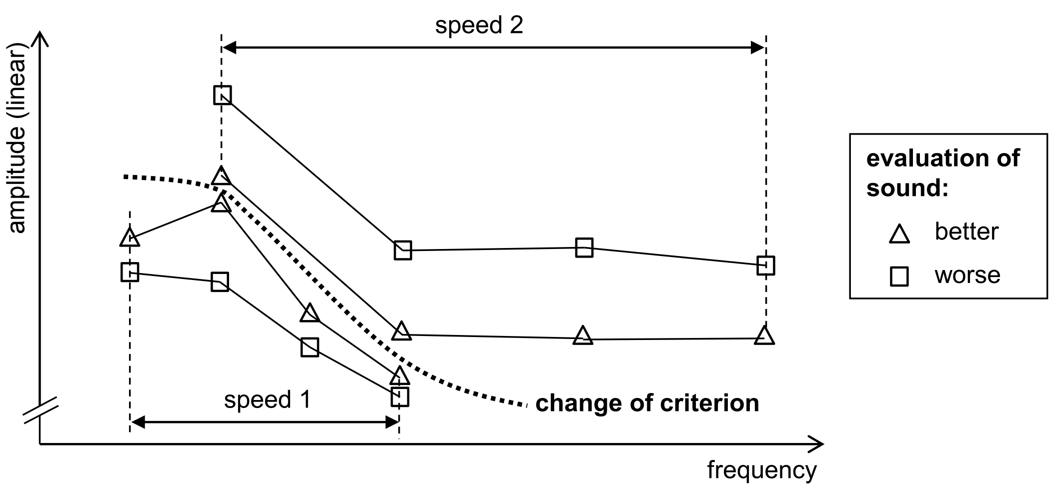

Figure 4: Detecting criteria for noise perception by evaluated sound spectra

In the second stage of the process presented in figure 3, these results are being used to digitally generate specific modified sound spectra. The operator is confronted with this artificial sound via headset speakers while he is sitting in the cabin of the original machine used in stage one. The objective of this approach is not to influence the evaluation results by any effects that another environment may have on the perception of the operator. By comparing the evaluation results with the generated sound spectra, the criteria out of stage one are broken down systematically.

3.2. Sound transmission / Transmission of oscillations

The correlation functions concerning the transmission of oscillations from fluid ($\rightarrow$ pressure pulsation) to air ($\rightarrow$ sound) are being established by the help of measurements performed on a test rig. This is necessary, because on the real machine, it is impossible to measure the pressure pulsation generated by the pump without any influences of lines and other hydraulic components. On the test rig, the hydraulic system has been equipped with a low reflection line termination that allows a clear measurement of the pump harmonics in the pressure signal. These measurements are being performed with the same pumps that have been used one step earlier for the sound evaluation on the real machine. By comparing the results with the sound spectra measured in the operator's cab, correlations are being detected and documented. **Figure 5** gives an overview of this process.

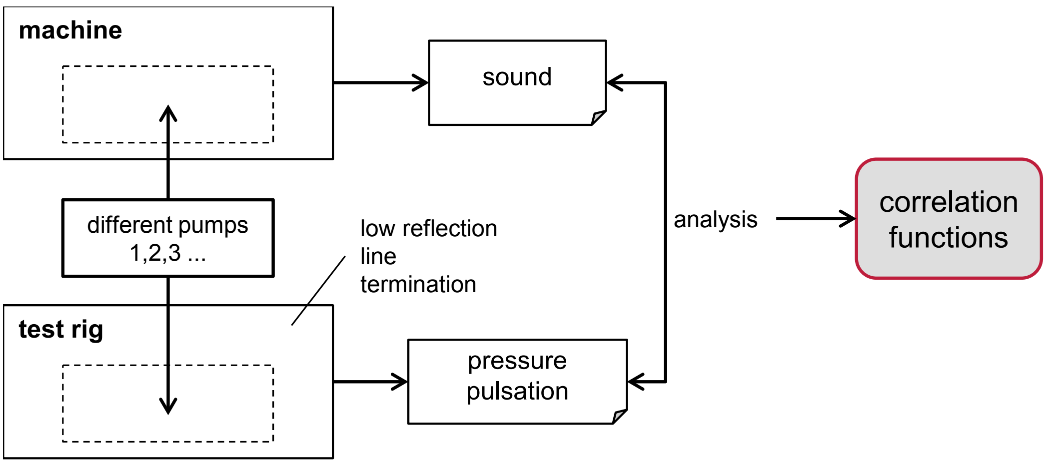

Figure 5: Analysis of sound transmission

4. Pump simulation

The pump simulation and the parameterization tool have been developed on the basis of three main requirements:

First of all, both, pump model and parameterization tool, have to be easy to use in order to get quick solutions. Next, the pump model has to be of a general type and very variable, so that it can easily be adopted to other pumps with a different number of displacement chambers or even different functional principles. Regarding the parameterization tool, the main requirement is a high degree of robustness, because in many industrial applications, engineers have to work with incomplete databases. At the beginning of this project, for example, the exact geometry of the internal gear pump has not been available in a digital manner.

4.1. Model

The simulation model has been implemented in Matlab Simulink by means of a model library which allows the user to quickly set up a model of the pump he wants to simulate. As already mentioned in section 2, the model can be divided into three parts: the pump itself, a hydraulic line and a signal processing unit.

Figure 6 shows the structure of the pump model. It consists of multiple displacement units, each containing one displacement chamber. The connection between chamber and the two ports for suction and discharge is regulated by one orifice each. The main input signal of the displacement units is the driveshaft angle which is used to calculate the current chamber volume and cross sectional areas of the port connections by the help of look-up tables. Besides the number of displacement chambers, these assignments of driveshaft angle and geometric quantities represent the model parameters. Leakage between displacement chambers and ports has been neglected in this model because the accuracy of the database was not sufficient. In return, working only with functional parameters leads to an even simpler model, which is able to perform very quick simulation runs.

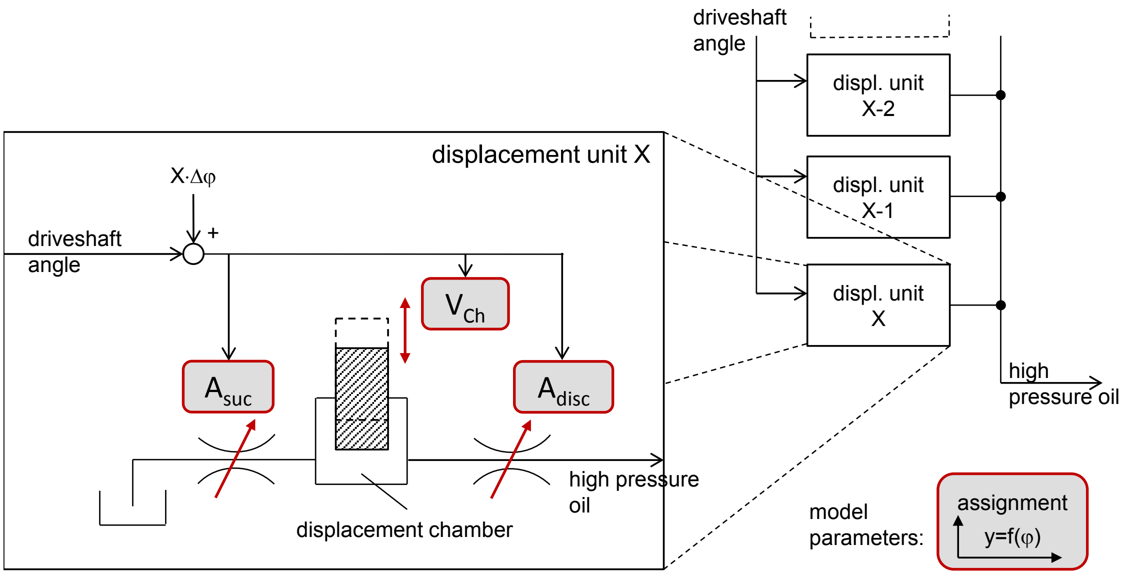

Figure 6: Structure and parameters of the pump model

The output of each displacement unit is the instantaneous flow of oil into the high pressure line. For being able to calculate this flow through the discharge orifice, the displacement unit needs a feedback from the hydraulic line concerning pressure. This second input to the unit is not depicted in figure 6 as it shows just the basic structure of the model.

The hydraulic line model used in the simulation is given in **figure 7**. As the hydraulic capacitance C_{oil} is the only parameter, the line model is reflection free and it is not necessary to implement a special line termination. The hydraulic resistance is represented by an orifice. In Simulink, the orifice is combined with a controller for being able to examine the pressure pulsation for different speeds at the same pressure level.

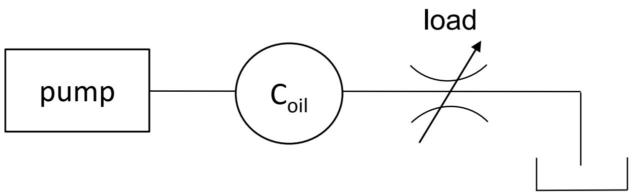

Figure 7: Simple model of a hydraulic line

The last part of the simulation model is a signal processing unit, which reads the pump harmonics out of the pressure signal. The pressure is sensed at the inlet of the load orifice. In a first step, the frequency spectrum of the pressure signal is identified by the use of a Fast Fourier transform. After this, the different pump harmonics can be extracted and taken to further calculations.

4.2. Parameterization

The job of the parameterization tool is to set up the model parameters for a given pump geometry. The tool has been implemented as a Matlab script that puts out the model parameters as 2-D vectors, which can be addressed directly by the look-up tables in the pump model.

Because, at the beginning of this project, there was no CAD data available for the given pump, the parameterization tool had to be able to gather the required information from image data. Basically, the parameterization process consists of two steps, like it is shown in **figure 8**. First, digital images of the pump are being processed by the help of the Matlab Image Toolbox. Within this step, coloured pictures are converted to grayscale in order to define a threshold that allows detecting the contours of ports and gears as functional elements of the pump.

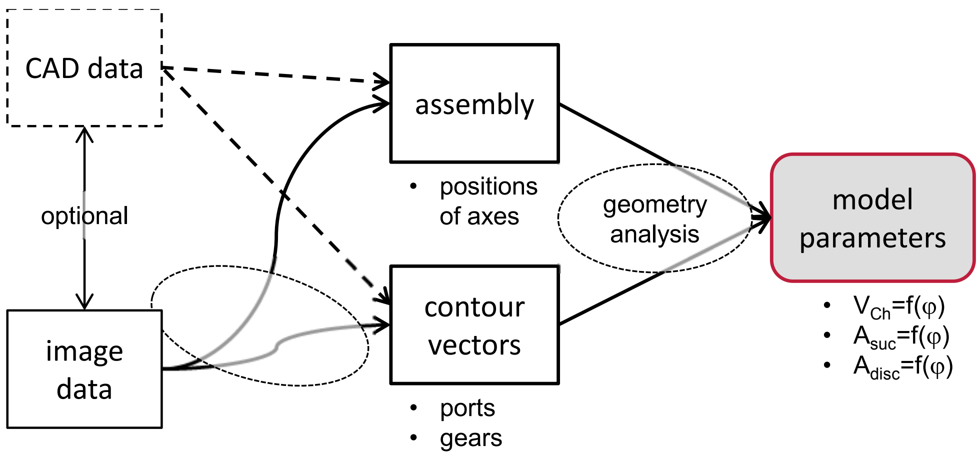

Figure 8: Structure of parameterization process

In the second step, the pump geometry represented by the contour vectors and information about the pump assembly is analysed with respect to the model parameters (**figure 9**). This means, the pump contours are assembled virtually and a full revolution of the inner gear (which is attached to the driveshaft) is being performed stepwise, while the model parameters are calculated for each step.

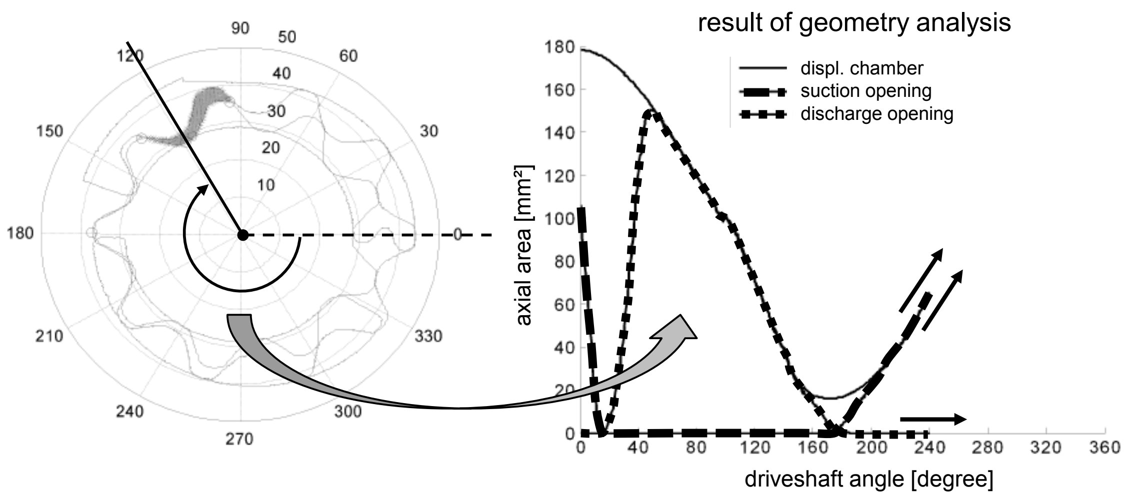

Figure 9: Analysis of pump geometry

Figure 9 shows two pictures out of the parameterization process. The axial area of displacement chamber depicted on the right side has to be multiplied with the width of the gears in order to get the displacement chamber volume as the third model parameter.

5. Variation of parameters

As an advantage of the image based model parameterization, the user has the opportunity to perform quick parameter variations by modifying the pump geometry just in the image. This can be done with any drawing software. **Figure 10** and **figure 11** show two examples out of the variations performed within this project. One aim was to vary the slope of the discharge opening. Therefore, the shape of the discharge port in the entry zone, where the oil-filled displacement chambers get connected to the port, has been modified in several steps. Figure 10 shows two variations of the opening slope.

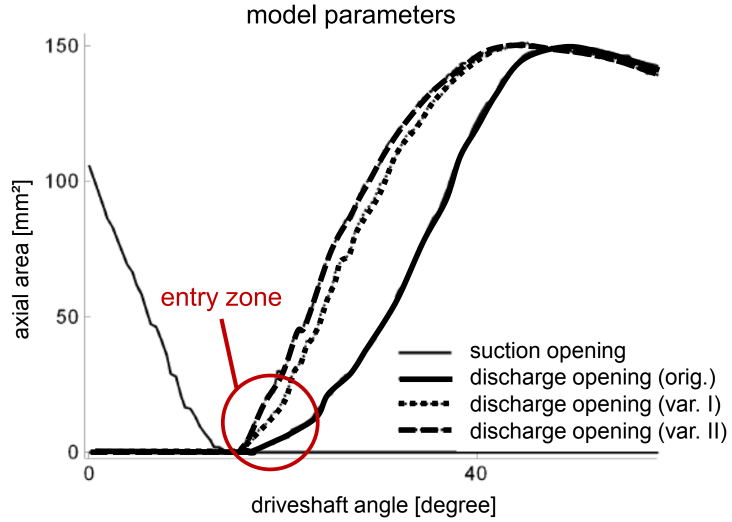

Figure 10: Variation of discharge opening slope

Depicted in figure 11 is the amplitude ratio of fundamental frequency and first harmonic of the pump as one result of the simulation. It is obvious, that the slope of the discharge opening in the entry zone has great influence on this amplitude ratio. Slopes greater than variation I show a smaller ratio. Variation II, which is depicted as well in the figures, seems to have no influence at all. The absolute amplitude of the fundamental pump frequency is barely affected by any of the performed slope variations.

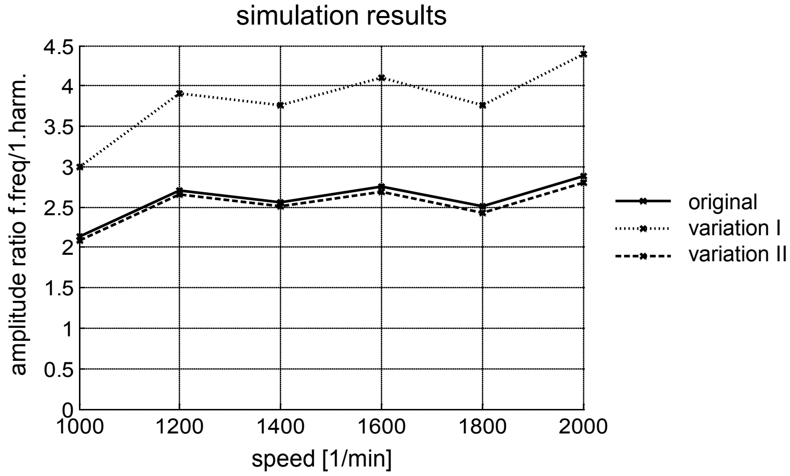

Figure 11: Result of parameter variation

6. Conclusion

In this paper, a concept has been presented that aims on building up a model based tool for noise reduction of hydraulic systems with respect to the complete path of oscillation transmission and noise perception of the operator. In the presented case, the simulation model and parameterization tool have been set up for an internal gear pump, regarding a maximum of robustness and user comfort as main requirements.

Although a lot of work still has to be done, first results show a good perspective. The analysis of sound spectra evaluated by different operators suggests that it is possible to define different criteria regarding noise perception, some of them being amplitude ratios of different pump harmonics. At the other end of the process, even a simple pump model is able to demonstrate correlations between modifications of the port geometry and the ratio of different frequencies in the pressure pulsation. First results of parameter variations like those presented in section 5 show potential for optimization processes. The parameterization which has been built offers several opportunities for parameter variations, image based as well as by direct modifications of the assignments that represent the model parameters.

7. References

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8. Nomenclature

V_{Ch}	volume of displacement chamber	mm^3
A_{suc}	axial area of suction opening	mm^2
A_{disc}	axial area of discharge opening	mm^2
C_{oil}	hydraulic capacitance	m^5/N
CAD	Computer Aided Design	