Structure-borne Sound Generation in Hydraulic Valves due to Needle Impacts

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Introduction

Modern electro-magnetic valves have to fulfil the requirement for rapid actuation and are therefore characterized by fast valve dynamics. Impacts of the moving bodies of the valve lead to structure-borne sound. In this work the impact dynamics of the valve needle at the end stops is investigated by numerical and experimental methods.

Within the computer aided design process, the system behaviour is simulated in the time domain by using lumped parameter models. Hereby, multi-physics aspects such as hydraulics, mechanics, and electromagnetics are considered.

In order to investigate the time dependent contact force the lumped parameter approach in the system simulation is not sufficient. Transient 3D Finite Element simulations give a better understanding of the dry contact dynamics and the contact force. Coupling of the contact dynamics with hydraulic and magnetic effects in the 3D domain is a time consuming task. Therefore the lumped masses of the impact bodies are replaced by flexible bodies. By using a modal model order reduction, the elastodynamic aspects are captured in the system simulation tool AMESim.

These modifications improve the prediction of the coefficient of restitution, impact time, and impact force in time domain simulations. The contact parameters influence the needle dynamics, whereas the time dependent impact force is an important criterion for further assessment of the acoustic noise generation. Coupling the impact model with simple fluid dynamic effects leads to improved models for predicting the noise design and the functionality of electro-magnetic valves.

Calculation of the Dry Contact Force

In a first step ANSYS Workbench is used to perform a transient 3D-FE simulation in order to understand the dry contact dynamics. Figure 1 shows the displaced upper half of a sectional view of the impact bodies. Here the spring force is responsible for the needle movement and an initial velocity is prescribed. In Figure 1 the needle initially moves to the left. The valve body is represented partially and is fixed at different circumferential areas corresponding to the real build-up situation.

Model Order Reduction

Clearly a lumped approach in the system simulation with one spring and one dashpot element is not capable to capture the contact force. Therefore the following procedure is used to transfer the flexible properties of the impact bodies to the system simulation. The meshed needle and the valve body are exported from ANSYS Workbench into a Matlab based toolbox [1]. Here, an appropriate reduction basis for the model order reduction is created from the first few low-frequency eigenvectors. The number of eigenvectors depends on the frequency range of interest. In the present case a maximum frequency of several hundred kHz is employed which results in 20 retained modes for the needle and 40 modes for the valve body.

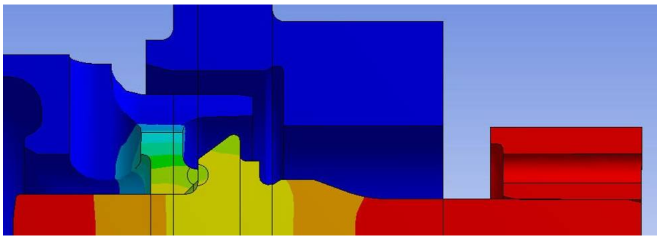

Figure 1: Displacement of the upper half of the valve body and the valve needle in the transient 3D FE impact calculation.

In order to account for the discarded modes above the maximum frequency of interest, the concept of static correction is used [2]. Thus residual attachment modes are added to the matrix of eigenvectors to create the reduction basis. The valve body has no rigid body modes. Therefore the static correction can be represented with one residual attachment mode. The valve needle on the other side is a free floating structure. Here, two shifted attachment modes [2] are used for static correction.

Further on, the contact area of both impact partners is considered as force load in the direction of the movement, while for the sake of simplicity the displacement of one node of the contact area is chosen as output point. Figure 2 depicts the magnitude of the transfer function for the needle with the contact force as load input. In order to compare the reduced model, the transfer function for a reduction basis with 50 retained modes is also plotted in Figure 2. As expected, the curves correspond quite well for the retained modes.

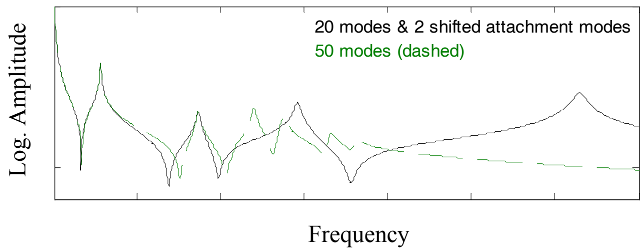

Figure 2: Magnitude of the transfer function from the force load on the contact area of the valve needle to one displacement output point in the contact surface.

After the reduction process the matrices are normalized and transformed to state space models. These are then imported into AMESim. In the system simulation a simple dry contact model is created in order to compare the results to the 3D-FE calculation.

The necessary local contact stiffness, resulting from the geometric relation in the contact area between the impact partners is also calculated with ANSYS. In this case only the structures close to the contact region are calculated with a static force displacement simulation [3]. The resulting force displacement relation up to the maximum displacement is linear at a value of 1e9 N/m.

Figure 3 compares the time dependent contact force and the corresponding FFT from the ANSYS simulation with the results from AMESim. In the time domain the maximum contact force amplitude and contact time fit quite well, whereas the higher harmonics show minor deviations because of the frequency truncation in the reduced model. The frequency transformation supports this statement and shows good agreement for all retained modes.

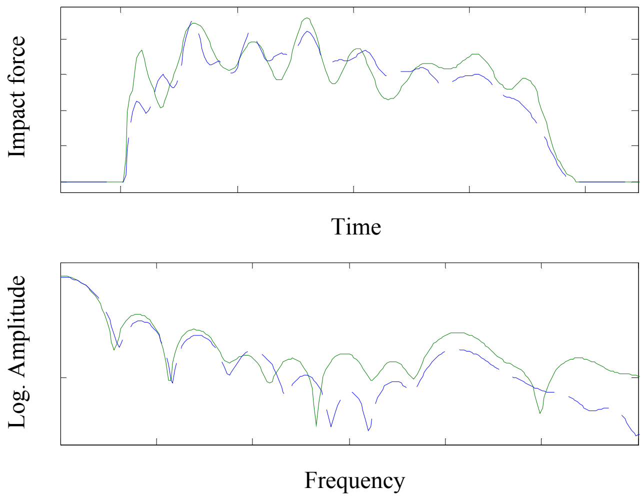

Figure 3: Time dependent contact force and corresponding FFT for the transient simulation with ANSYS in 3D (green) and with reduced models in 1D AMESim (blue, dashed).

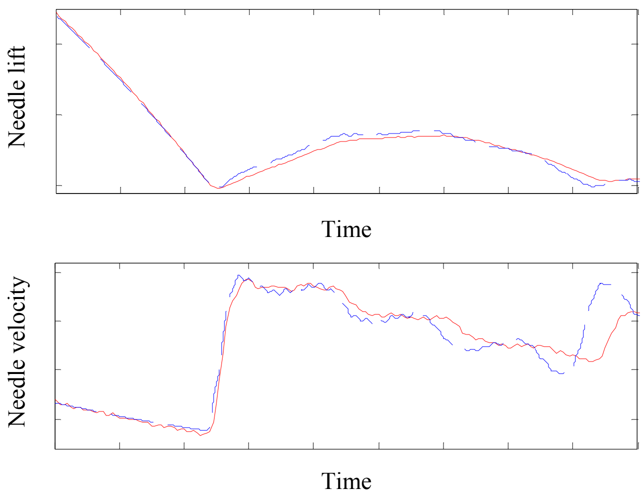

Figure 4: Measurement (red) and reduced order AMESim calculation (blue, dashed) of the valve needle lift and velocity at 5 bar with T16 as fluid.

Validation with Measurements

In order to validate the simulations, the results are compared to measurements. In the measurements the needle lift at the needle tip is determined by means of an inductive displacement sensor. The needle attains always the same velocity before the contact. In the case without fluid there is a quite high stochastic deviation for the velocity after the impact and the rebound height. This is because of a possible eccentric impact in combination with friction and multiple contacts. Therefore the highest rebound from a set of 50 single measurements is considered the ideal centric impact with the minimum portion of friction. The needle displacement over time as well as the coefficient of restitution fit well when the reduced AMESim simulation and measurements are compared.

In a field application the fluid is present around the valve needle and the model in AMESim needs to be extended in order to capture all relevant fluid dynamic effects like hydraulic resistance, water hammer and squeeze film damping in the contact region. The deviation between the single needle strokes because of the fluid is hardly noticeable. The needle lift measurements and the multi-domain simulation with the reduced order models in AMESim are in excellent agreement as depicted in Figure 4. Compared to the dry measurements the hydraulic resistance is responsible for the lower impact velocity. Squeeze film damping occurs right before the structural impact and alters the impact force. The water hammer effect is a result of the step-like deceleration of the fluid columns and causes pressure peaks. The resulting forces can be noticed as “stairs” in the rebound velocity of the needle in Figure 4.

Conclusion

A procedure to use modal reduced flexible bodies in a multi-domain system simulation focusing on contact dynamics is presented. Static correction is used to improve the quality of the reduced models in the selected frequency range. The reduced order flexible impact bodies are imported into AMESim as state-space models. The comparison to a transient 3D-FE calculation shows good agreement and the calculation time is improved from several hours to a few seconds.

Only the coupling of the reduced impact model with simplified fluid dynamic effects allows a realistic prediction of the acoustic excitation and system behaviour of the valve. This leads to improved models for the noise design and optimization of electro-magnetic valves.

References

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