2014

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A Comparative Study Of Different Numerical Models For Flapper Valve Motion

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ABSTRACT

Flapper valve design is critical for the reliability of a compressor and the performance of a compressor further the valve has to perform well under several operating conditions. However the movement of a valve is difficult to measure in a compressor running with refrigerant. For that reason numerical models of valve motion are inevitable when designing a new flapper valve. Probably the most promising and accurate way for simulating valve motion is 3D-Fluid-Structure-Interaction (FSI), however due to the large computational effort it is so far impossible to cover the whole operating range of a compressor. For this purpose so called 1D lumped-models are often used. In this study we compare a full 3D-FSI model and a valve dynamics simulation program, which is based on a 1D lumped model, with laser trigonometric measurements of the movement of a suction valve. Further we will discuss the advantages and disadvantages of the different simulation approaches.

1. INTRODUCTION

Reciprocating compressor valves have to fulfill several requirements in order to contribute to compressors functionality. To ensure reliability the maximum stresses when bending over the suction or discharge hole must not exceed a certain value, also at maximum lift height the stresses in the valve must not be too high. A further important criterion for reliability of a valve is the impact velocity at the valve-seat or limiter. Besides reliability of a compressor, valve design is also critical for the performance of a compressor. Pressure drop over the valve system should be as low as possible as it has a direct influence on capacity and COP (Coefficient Of Performance). Valve timing is also extremely important – late closing of the valve leads to backflow which directly influences capacity and COP. In addition suction valves are one of the primary sound sources in compressors (Soedel 2007). Taken together valves strongly influence the two most important features for marketability of household compressors: efficiency and sound radiation.

Due to the importance of valves for the reliability and performance of a compressor a proper knowledge of valve-dynamics is a condition precedent to design a valve which performs well in the whole operating range. Accordingly significant effort has been made to predict valve motion by numerical studies (Boeswirth (1984, 1990a, 1990b, 1996), Rigola *et al.* (2008), Soedel (1984, 1992)). In principal three different modelling approaches can be distinguished: lumped models, CSM (for the valve) and CFD (see Figure 1). In this work we will introduce a 1D-lumped model suggested by Böswirth (1990a, 1990b, 1996) and a model which includes 3D-FSI, i.e. a combination of CFD and CSM simulation for the movement of a suction valve similar to the study done by Takemori (2010). To verify our simulation approach we will compare the results with laser trigonometric measurements of the movement of a suction valve as done for example by James *et al.* (2010).

Method	Description	Simulation tools
CFD	**Computational Fluid Dynamics** uses numerical methods to solve and analyze problems that involve fluid flows. Almost all algorithm work with spatial discretization called **finite volume method (FVM)**	CFX, Fluent, OpenFoam…
CSM	**Computational Structural Mechanics** uses numerical methods to investigate the behavior of structures under mechanical loads. The method of choice is the **finite element method (FEM)**	Ansys, Solidworks…
Lumped Models	**Lumped Models** simplify the description of the behaviour of spatial physical system into a low dimensional system. Typically the differential equations are solved with Runge-Kutta Method	KV-DYN, Matlab…

Figure 1: Different modelling approaches used for flapper valve simulations for compressors

2. MODELLING OF FLAPPER VALVE MOVEMENT

2.1 A Lumped for Valve Dynamics Simulation

In the lumped model introduced by Böswirth (1990a, 1990b, 1996) and used in the valve dynamics simulation program worked out by Leopold Böswirth (1996) and Heinz Stegbauer the valve is assumed to work as a spring-damper-mass system and the fluid is assumed to be incompressible and inviscid. Further a potential flow is assumed, accordingly eddies and viscous effects are neglected.

Roughly, the behavior of a valve can be described as follows. The movement of the piston, changes the volume in the cylinder and such leads to a pressure difference ΔP, if we consider the suction valve, between the suction side V_{suc}, and the cylinder volume, V_{cyl}. When the P_{cyl}<P_{suc}, the force on the surface of the valve, denoted as the plate force, F_{pl} starts to open the suction valve. As a consequence gas is flowing inside the cylinder with velocity W_2(t) and interacts with the valve. The lift height as function of time, X(t), is determined by the Equations of Motion (EOM) of the mass-spring-damper system. By applying potential flow theory, continuity law and conservation of energy with some algebra (for details see Böswirth (1990a, 1990b, 1996)) we get the following equations of motion for the valve.

Valve: $$M\ddot{X}(t)+\gamma\dot{X}(t)+M\omega^2X(t)=F_p \tag{1}$$

Gas flow: $$\frac{\Delta P(t)}{\rho}=\frac{w_2^2(t)}{2}+J(\dot{X}(t)w_2(t)+X(t)\dot{w}_2(t))+\frac{c_pA_p}{2C_DL}\frac{w_2(t)\dot{X}(t)}{X(t)} \tag{2}$$

Massflow: $$\dot{m}=\rho C_DA_2w_2=\rho C_DLX(t)w_2(t) \tag{3}$$

Pressure: $$\Delta P=P_{suc}-P_{cyl}=P_{suc}-\frac{m}{V_{cyl}}\frac{R}{M_{molar}}T \tag{4}$$

Where the term $J(\dot{X}(t)w_2(t)+X(t)\dot{w}_2(t))$ describes the gas inertia effect on the suction side and J is the gas inertia parameter; M is the mass of the Valve, m of the refrigerant, w_2 is gas velocity, X(t) is valve lift, ρ is the gas density, P_{suc} is the suction-pressure, P_{cyl} is the pressure in the cylinder, R is gas constant, T the Temperature, L is the circumference at the narrowest part of suction hole, M_{molar} is molar mass, C_D is the discharge factor and describes the flow through the suction or discharge hole and A_p is the effective area of the valve being subjected to the refrigerant flow. The results of the lumped model shown in 4 are based on the dynamics described by equation (1) to (4).

2.2 3D Fluid-Structure-Interaction

Numerical simulations are always based on a mathematical modelling of the reality. In case of 3D-FSI the movement of a fluid volume and a solid volume are modelled. The solution of FSI requires co-simulation between CFD and structural CSM. For a numerical solution the boundary conditions have to be spatio-temporal discretized. Here are a partitioned approach to solve the FSI-problem is used, i.e. the flow of the refrigerant and the displacement of the valve are solved separately, with two distinct solvers. Accordingly, the FSI problem consists of several challenges of the separate problems.

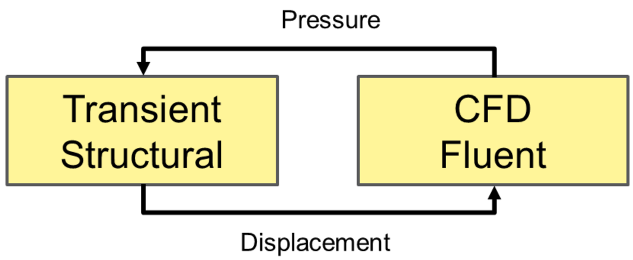


Figure 2: Exchange of boundaries in a partitioned 2-way FSI-simulation

In the CSM problem nonlinear contacts occur at the valve seat and at the limiter or piston. Due to limited computational resources and thereby limited temporal and spatial resolution in the CFD part, a special model of turbulence is necessary. Further the movement of the valve, especially near the contacts leads to complex movement and remeshing of the CFD mesh.

The interaction between the structural CSM part and the CFD part of the problem takes place, by exchanging the boundary pressure and displacement on the interaction surfaces (see Figure 2). The two-way surface pressure/displacement coupling can be realized by combining a CFD package with a CSM package (see Figure 3).

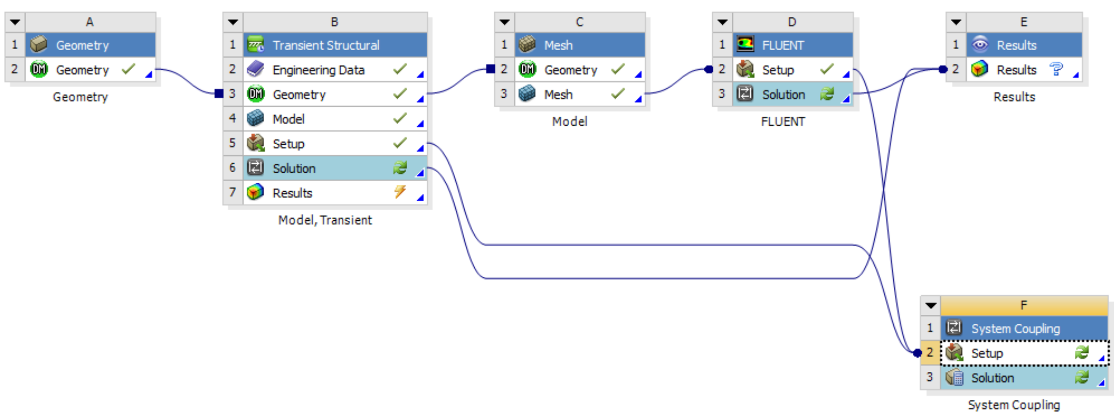
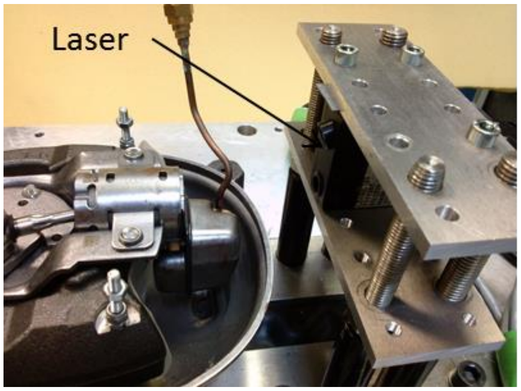


Figure 3: Combination of a CFD simulation with CSM simulation to model Fluid-Structure-Interaction

3. EXPERIMENTAL SETUP

3.1 Measurement of Valve Movement

A laser is placed in front of the suction valve to measure the valve movement via laser trigonometry, as shown on Figure 4 left. A digital output is coming from the laser which is connected to a Digital to Analog Converter (DAC) in order to get an analog voltage signal from the laser. A stable mounting of the laser and stiff connection between laser mounting and compressor is necessary to avoid relative movement between laser and compressor.



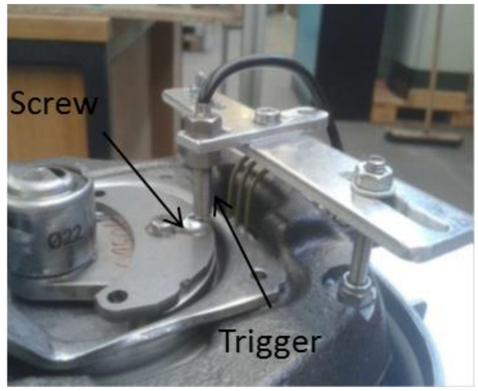


Figure 4: Left: Position of the laser in front of the suction valve. Right: Induction trigger used in combination with a screw for determining top dead center.

An inductive trigger is placed to give a time stamp when the piston reaches top dead center. The trigger is shown in Figure 4 right. As seen a screw is placed on the eccentric, so when the screw passes the inductive trigger an analog voltage signal is passed which acts as a basis for averaging. Each measurement is an average of several thousand valve movements.

3.2 Measurement of the Pressure in the Cylinder

Figure 5: Pressure sensor mounted on the valve plate

To be able to measure the pressure inside the cylinder a hole was drilled in the valve plate and a tube was welded onto the hole on which the pressure sensor was mounted (see Figure 5). The increased top clearance volume has to be taken into account in the setup of the simulations.

4. RESULTS

We performed measurements on an open XV compressor with the working condition 4000 RPM with air and a discharge pressure of 8.8 [Bar]. Additionally we conducted a 3D-FSI simulation and calculations with a program used to calculate valve dynamics where the underlying, governing equations are presented in 2.1. (Boeswirth 1984, 1990a, 1990b, 1996).

4.1 Valve Movement

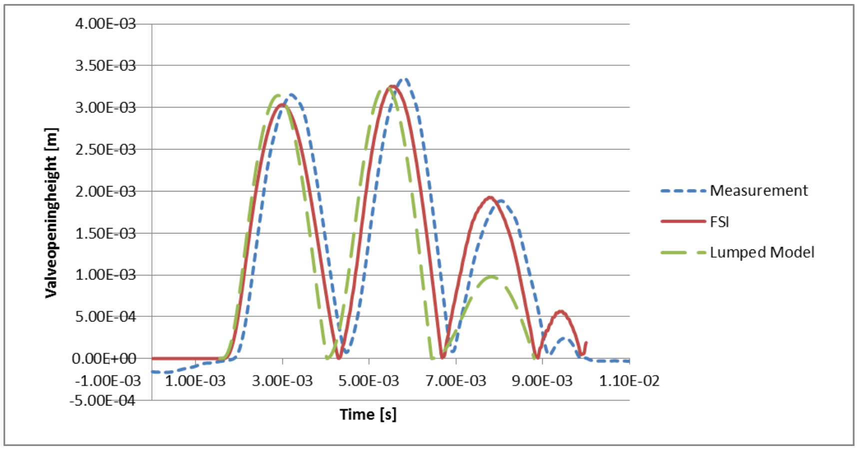


Figure 6: Valve movement with an evaporating pressure of 1[Bar] and 8.8 [Bar] condensing pressure

The results are shown on Figure 6. It is seen that the 3D-FSI simulation resembles the measured data with better accuracy than the lumped model. The difference in comparison to the measurement is mainly caused by uncertainties in estimating the initial conditions, e.g. noxious space etc.. It is prominent that the third peak in the calculation with the lumped model is a lot smaller than in the experimental acquired data and the results obtained by the FSI-simulation. This occurs due to the fact that in lumped model the valve impact at the valve plate is assumed to be absorbing.

4.2. Pressure drop over valve system

The pressure drop of the valve system is one of the most important performance indicators when designing a valve. For the case of a suction valve the pressure drop directly influences volumetric efficiency, as it decreases density of the refrigerant entering the cylinder. However, also the power consumption will be affected. For a variable speed compressor a proper suction valve design is a special challenge, as the pressure drop at low compressor speed and low mass flow must not be too high. High compressor speeds with high mass flows and opening height should not exceed a certain value in order to avoid damage to the valve. For that reason and the high effort of measurements, valid predictions of the pressure drop over the valve system, based on simulations is a useful help for valve design.

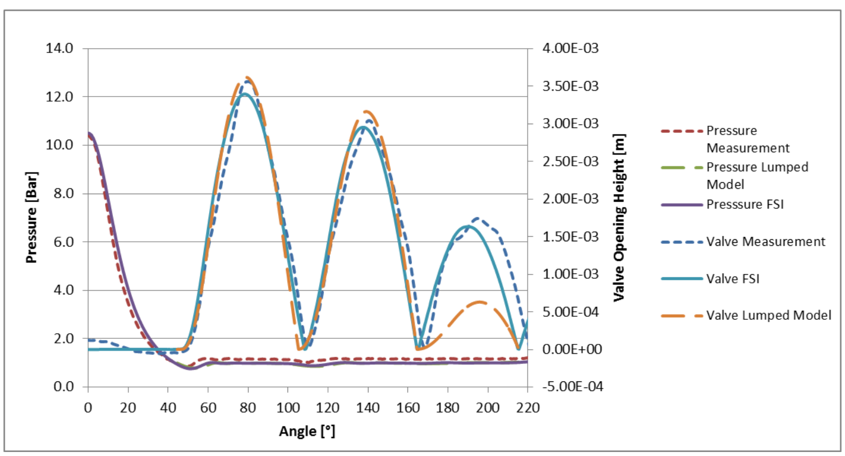


Figure 7: Valve movement and pressure in the cylinder in an open Compressor with air 1 [Bar] evaporating pressure and 10 [Bar] condensing pressure

As Figure 7 shows both the FSI-simulation and the lumped model reproduce the experimental data quite well. It is seen that the pressure in the cylinder is about 0.1 [Bar] lower in the simulations than in the measurement. It is assumed that this effect is caused by uncertainties in the measurement because the pressure in the lab was at 1.01 [Bar], and the pressure in the cylinder should be below this value. In the measurement it is at 1.1 to 1.15 [Bar], here the measurement must return to high values for the pressure.

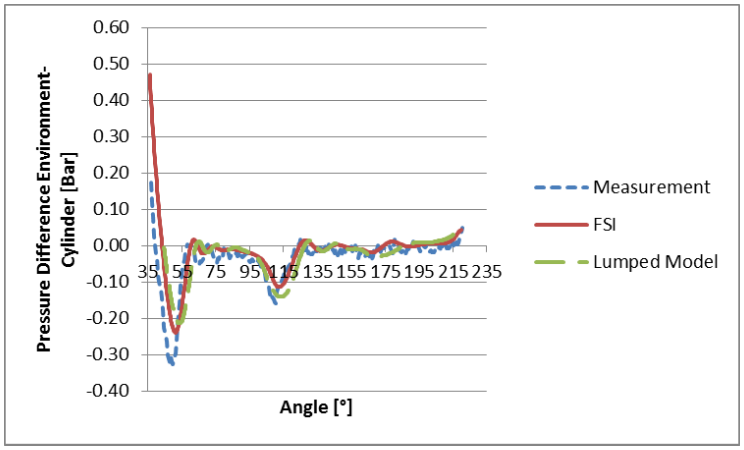


Figure 8: Pressure difference of between pressure in the cylinder and environmental pressure

As seen in Figure 8 the pressure variation is larger in the experimental acquired data than in the simulations, while the values of the lumped model simulation and the FSI-model show quite good accordance. Probably the reason for this difference is the fact that the simulations show the volume average in the cylinder while the measurement shows the pressure at the sensor which is placed at the end of a small tube as shown in Figure 5. We will perform further simulation with this small tube incorporated into our FSI-model and monitor the pressure at the end of that tube to gain further knowledge of the influence on the measured results.
If the valve movement is considered (see Figure 7) it can be seen that the eigenfrequency of the valve is smaller in the measurement than in the simulations. While for the first peak in Figure 7 we see a quite good accordance between the FSI-simulation and the measurement, at the third peak in the FSI-simulation the valve closes earlier than in the measurement. As the last peak of the valve movement in Figure 7 occurs mainly due to reflection of the valve on the valve plate. Minor uncertainties in the contact boundary with the valve plate may lead to large difference of the valve movement; therefore it is assumed that this deviation has its reason in uncertainty of the contact boundary.

4.3. Discussion of the Different Modelling Approaches

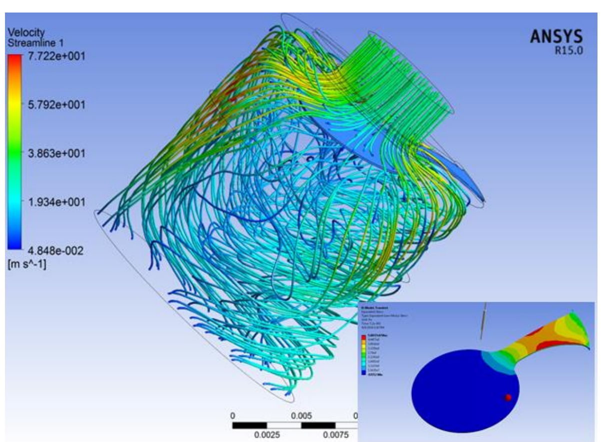


Figure 9: Flow around valve in the FSI-model and corresponding valve stress (inlet)

The results presented above show a good agreement of the numeric models with the experimentally acquired data. It seems that the lumped model by Boeswirth (1996) is almost as accurate as the FSI-model, however the lumped model needs to be tuned by some fetching factors to get the right data, while the FSI-model comes along without any fetching factors and delivers good results as long as the boundary conditions are chosen properly. Furthermore the fetching factors of the lumped model are state dependent, i.e. if the model is tuned at a certain operating state, the more this state is left, the more the results will get less accurate. Another important factor when evaluating the models is calculation time. The 3-D FSI simulation has a total calculation time of about 12 hours, using 14 cores for the fluid-dynamics part and 2 cores for the structural mechanics part. The calculation time for the lumped model is less than a second. However the flow of the refrigerant is not represented by the 1-D lumped model and such some important possibilities for valve optimizations cannot be realized. From the FSI-simulation we get the full information about the flow from the CFD part (see Figure 9) and from the CSM part of the simulation we get information about the stresses (see Figure 9 inlet) and impact velocities and such predictions about the reliability of a valve can be made.

5. CONCLUSIONS

- Valve dynamics is critical for both compressor reliability and compressor efficiency
- Numerical tools are a great help for valve design
- FSI simulations are the tool of choice for compressor simulations as they cover the details of fluid and valve behavior and resemble experimental data with high accuracy, however FSI is computational costly
- 1-D lumped models are able to give good results but the model presented here needs to be tuned, so an FSI simulation or measurements are needed to tune the model

NOMENCLATURE

CFD	Computational Fluid Dynamics	
CSM	Computational Structural Mechanics	
FSI	Fluid Structure Interaction	
COP	Coefficient of Performance	[W/W]
V_{suc}	Suction Side Volume	[m^3]
V_{cyl}	Cylinder Volume	[m^3]
P_{suc}	Suction Pressure	[bar]
P_{cyl}	Cylinder Pressure	[bar]
C_D	Discharge Coefficient	[1]
F_{pl}	Valve Plate Force	[N]
A_{pl}	Effective Valve Area	[m^2]
W_2	Gas velocity	[m/s]
J	Gas Inertia Parameter	[1]

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ACKNOWLEDGEMENT

The authors would like to acknowledge Joergen Houe Pedersen of Secop Compressors GmbH for fruitful discussions and careful cross reading