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MODELLING THE DYNAMICS OF RING PLATE VALVES IN RECIPROCATING COMPRESSORS USING COUPLED CFD-FEM SIMULATIONS

Åsmund Ervik[(a)], Afaf Saai[(b)], Torodd Berstad[(b,c)], Ole Meyer[(a)], Takuma Tsuji[(d)], Tatsuya Oku[(d)], Kazuhiro Hattori[(d)], Kazuya Yamada[(d)], Virgile Delhaye[(b)], Petter Nekså[(a)]

[(a)] SINTEF Energy Research, 7034 Trondheim, Norway, asmund.ervik@sintef.no
[(b)] SINTEF Industry, 7034 Trondheim, Norway, afaf.saai@sintef.no
[(c)] Norwegian University of Science and Technology, Norway, torodd.berstad@ntnu.no
[(d)] Mayekawa MFG Co., LTD., Botan Koto ku, Tokyo, Japan, kazuhiro-hattori@mayekawa.co.jp

ABSTRACT

Improving the efficiency and reliability of valves in the reciprocating compressor is important for future refrigeration systems. A model for valve dynamics that links the fluid- and solid-dynamic effects can give fundamental insight and enable improvement of design. We developed such a model that combines computational fluid dynamics with finite element modeling. By computing gas flows and pressures during the valve actuation cycle using CFD, and computing the corresponding plate motion and impact at opening/closing using FEM, we are able to predict salient features of this system. We find that the damping at impact strongly affects the valve motion and the stress and strain on the ring plate. We observe that inhomogeneities in the pressure acting on the valve plate lead to small changes in plate orientation, that can be amplified through the impact into tumbling motion. Our findings are compared against experimental measurements obtained from instrumenting a real compressor.

Keywords: Reciprocating compressor, Ring plate valves, Valve dynamics, CFD, FEM, Experiments

1. INTRODUCTION

The compressor is the heart of the refrigeration cycle, providing the driving force for moving heat from the cold to the hot side. For many medium capacity systems, the reciprocating compressor (Figure 1) remains the optimal choice. The reciprocating compressor needs to meet many demands to have high performance and value. This has been the focus of many investigations since the days of early pioneers such as Lorentzen (1950). The compressor should have a high capacity, work across a wide range of operating conditions, have high efficiency and high reliability, and be compact, lightweight, and cost-efficient. Furthermore, it must be capable of working with refrigerants that have low climate impact. The natural refrigerants are excellent choices in this regard. In the current work, we focus on ammonia systems, see e.g. Palm (2008) and Pearson (2008) for overviews.

The reciprocating compressor needs one-way valves to control the suction and discharge flows. Focusing on the discharge valve, this component enables high pressure gas to leave the cylinder when the piston has compressed the gas to the desired pressure and is approaching top-dead center (TDC). The most common solutions are the reed valve and the ring plate valve. The current work investigates the dynamic behaviour of a ring plate valve using experimental and numerical studies. This valve consists of a ring made of a durable material such as steel, which covers an annular outlet at the top of the cylinder. A set of springs force the ring plate to close over the outlet, until the pressure difference from the cylinder to the discharge chamber is large enough to overcome the spring force. This arrangement is illustrated in Figure 1.

The dynamic response of valves has received a lot of attention in the literature for several decades. Early works predominantly include experimental or 1D numerical studies, e.g. Adams et al. (1974), Bredesen (1974), Elson and Soedel (1974). More recently, detailed CFD computations have been applied to study the flow through valve plates (e.g. Cyklis, 1994; Habing, 2005; Ruman et al., 2014; Zhao et al., 2018). The combination of CFD and FEM has been applied to the study of reed valves (Kim et al., 2008, Tan et al., 2014). However, to the best of our knowledge the combination of CFD and FEM has never been used for studying ring plate valves so far.

In this work, we investigate the three-dimensional dynamics of the ring plate discharge valve, using loosely coupled computational fluid dynamics (CFD) and finite element method (FEM) simulations. The CFD simulation computes the flow of gas and the pressure acting on the ring plate, while the FEM simulations compute the corresponding motion of the ring plate and the resulting forces, stresses and strains during the impact.

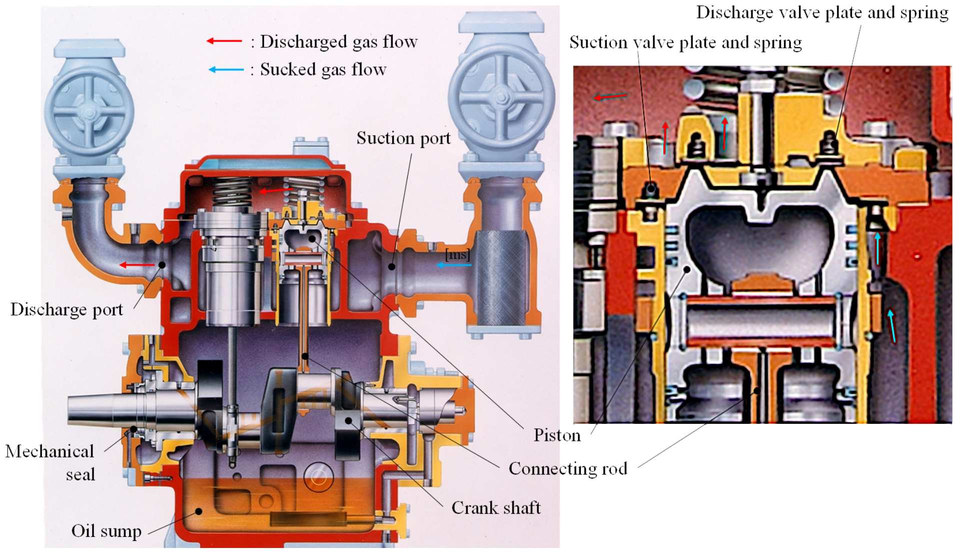

Figure 1:Illustration of the piston compressor and valves.

2. MAIN SECTION

2.1. Computational fluid dynamics modelling

The computational fluid dynamics (CFD) simulations considered in this paper are of compressible gas at high pressure, flowing at subsonic velocities around a plate that is moving due to pressure and spring forces. The governing equations are the conservation of mass, momentum and energy in the form of the Navier-Stokes equations,

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho u_j\right] = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left[\rho u_i u_j + p\delta_{ij} - \tau_{ji}\right] = 0, \quad i = 1,2,3 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho e_0) + \frac{\partial}{\partial x_j}\left[\rho u_j e_0 + u_j p + q_j - u_i \tau_{ij}\right] = 0 \tag{3}$$

Here u_i are the velocity components, ρ is the density, p is the pressure, τ_{ij} are the components of the stress tensor, e_0 is the specific enthalpy and q is the heat flux. To close these equations, a thermodynamic Equation of State (EoS) is required to specify the relation between energy, pressure, temperature, and density. It is also necessary to employ some form of turbulence model, using a Reynolds-averaging of these equations together with additional transport equations for turbulence quantitites.

In this work, we employ the cubic Peng-Robinson EoS with parameters representing ammonia, together with a Sutherland model for gas viscosity and JANAF polynomials for heat capacity. The k-omega SST turbulence model is used. The CFD simulations were performed using the OpenFOAM software v.1912 with a custom solver based on the "rhoPimpleFoam" solver with dynamic mesh capability. This is a compressible single-phase pressure-based solver suitable for flow of gas at subsonic and transsonic speeds, neglecting sound waves that are presumed to be unimportant for the problem at hand.

The equations are integrated in time using the backward Euler method and the finite volume discretization is used to approximate the spatial derivatives. The geometry used for CFD was a simplified version of the real valve system, illustrated in Figure 2. The regions where the gas can flow are discretized using a structured mesh in the CFD simulation. The ring plate is represented as an annular hole in the mesh. This hole can move according to the pressure and spring forces acting on the plate, using the dynamic mesh six degree of freedom capability of OpenFOAM. The motion of the plate was constrained such that the center of mass could only move vertically.

Figure 2: Cross-section of the valve cage geometry used in the CFD. The inlet from cylinder is shown in blue, and the outlets are shown in red.

A simplified impact model was implemented as a nonlinear contribution to the spring force, given as:

$$F_{elastic} = \left(1001\,\mathrm{k} + 1000\,\mathrm{k}\tanh\frac{\mathrm{L_s} - \mathrm{L_p} - \mathrm{z_{max}} - \mathrm{z}}{2*10^{-5}}\right)(\mathrm{L_s} - \mathrm{z}), \quad \textbf{(4)}$$

where, L_s is the spring rest length, L_p is the preload, z_{max} is the maximum lift, z is the lift, and v_z is the vertical velocity. k is the real spring stiffness, while the factors 1001 and 1000 ensure that the impact force is three orders of magnitude larger than the spring stiffness.

2.2. Finite element modelling

The simulations of valve ring motion and deformation were performed using LS-DYNA software for nonlinear dynamic analysis (Livermore Software Technology Corporation, version R10.1.0). Using the Finite Element (FE) method for spatial discretization and an explicit time integration, the FE model solves the motion of the valve ring that results from the pressure and spring forces. The impact forces occur when the ring contacts the cage or plate. The deformation of the ring was determined during one cycle of the piston, and the resulting stresses and strains were extracted. As illustrated in Figure 3, a complete valve assembly was generated in the FE model. In this fully 3D model, the displacement and rotation of the valve ring is possible, and the applied pressure force distributions

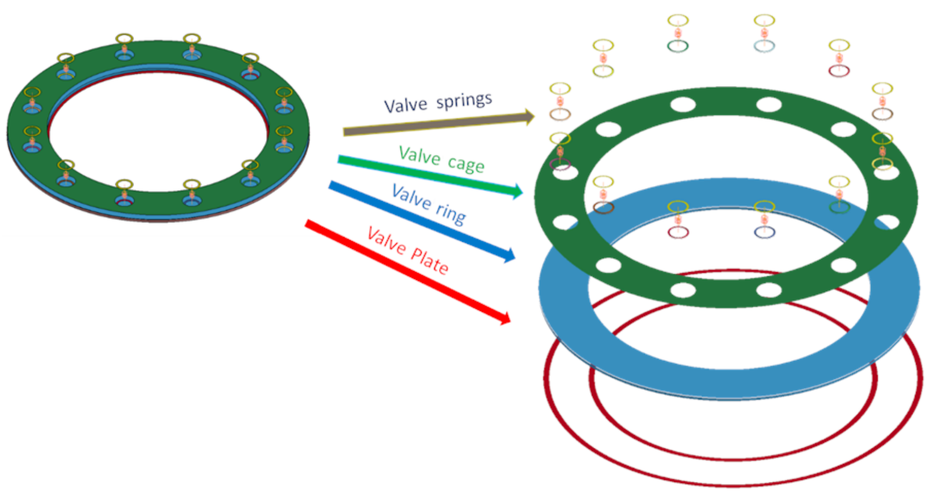

Figure 3: Illustration of the geometry and setup of FE model.

can be specified as functions of time, either homogeneously distributed or spatially varying across the ring. The cage and the plate are modelled as rigid undeformable bodies, and the model computes the forces due to impact between the deformable ring and the undeformable bodies. The displacement of eight nodes homogenously distribuated on the ring surface (see Figure 7) are analysed to identify bending, oscillation and tumbling of the valve ring.

2.3. Experimental measurements on compressor in real conditions

To provide insight into the three dimensional motion of the ring plate under real conditions in the compressor, instrumentation was placed into a Mycom M-series compressor, where measurements were taken with real refrigerant (ammonia) at real conditions, i.e. -15°C evaporating temperature, 35 °C condensing temperature, and 1500 rpm rotational speed. The discharge valve displacement was measured at three points on the ring surface using eddy current sensors (AEC, PU-05). Miniature pressure transducers (Kulite, XTME-190L-500A) were installed in the discharge chamber and in the cylinder to measure the relationship between pressure and valve motion. Care was taken to protect all sensor electronics from the corrosive ammonia atmosphere.

The result from experimental measurement during one cycle of the piston is shown in Figure 4. The abscissa represents the piston phase angle going from zero at top dead center to 360 at the next top dead center. The ordinate represents the non-dimensional pressure and displacement. The pressure is normalized by the average discharge pressure, and the displacement is normalized by the maximum designed displacement. When the cylinder pressure exceeds the discharge pressure at approximately 300 degrees, the discharge valve opens rapidly, then remains close to fully open for some time before closing gradually. A small tilt in the ring can be seen, as the lines do not overlap perfectly, but overall, the ring remains quite flat in orientation.

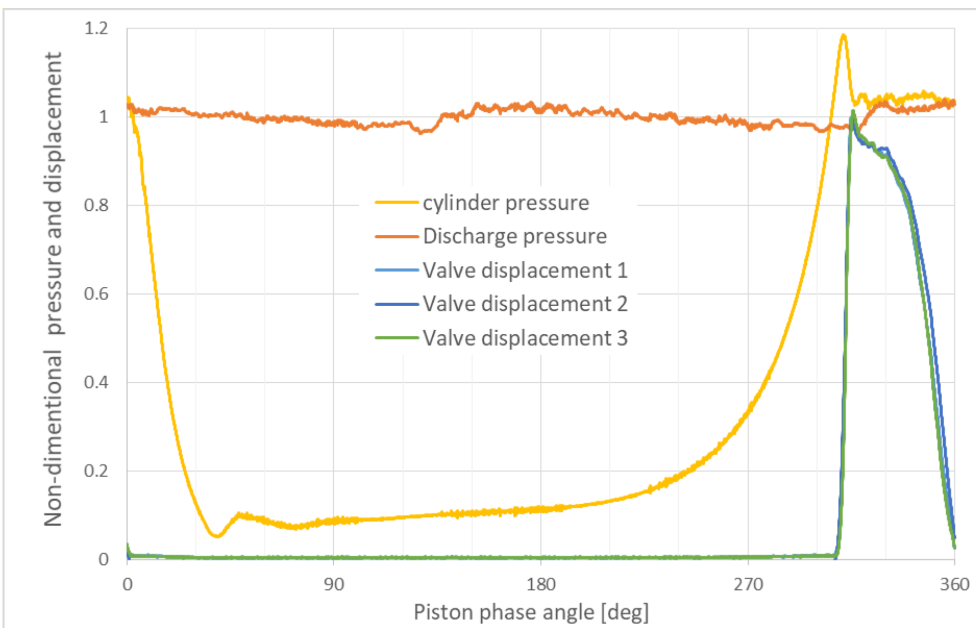

Figure 4: Measured values of cylinder pressure, discharge pressure and valve displacement at working conditions.

2.4. CFD results

The CFD simulation of a single valve cycle was performed using pressure boundary conditions based on the experimental measurements. The time evolution of pressure field, velocity field and plate motion are shown in Figure 5. The increasing pressure in the cylinder causes the plate to move rapidly updwards until it impacts the cage at maximum travel, bouncing in an elastic impact. The plate bounces two times more before closing as the cylinder pressure decreases towards the suction pressure. As can be observed by Figure 5, the pressure at the top of the plate is strongly influenced by the impact, while the pressure below the plate is largely unaffected by the impact and plate position. The pressure on the top and bottom of the ring plate (see Figure 6) was extracted and transferred to FE simulation.

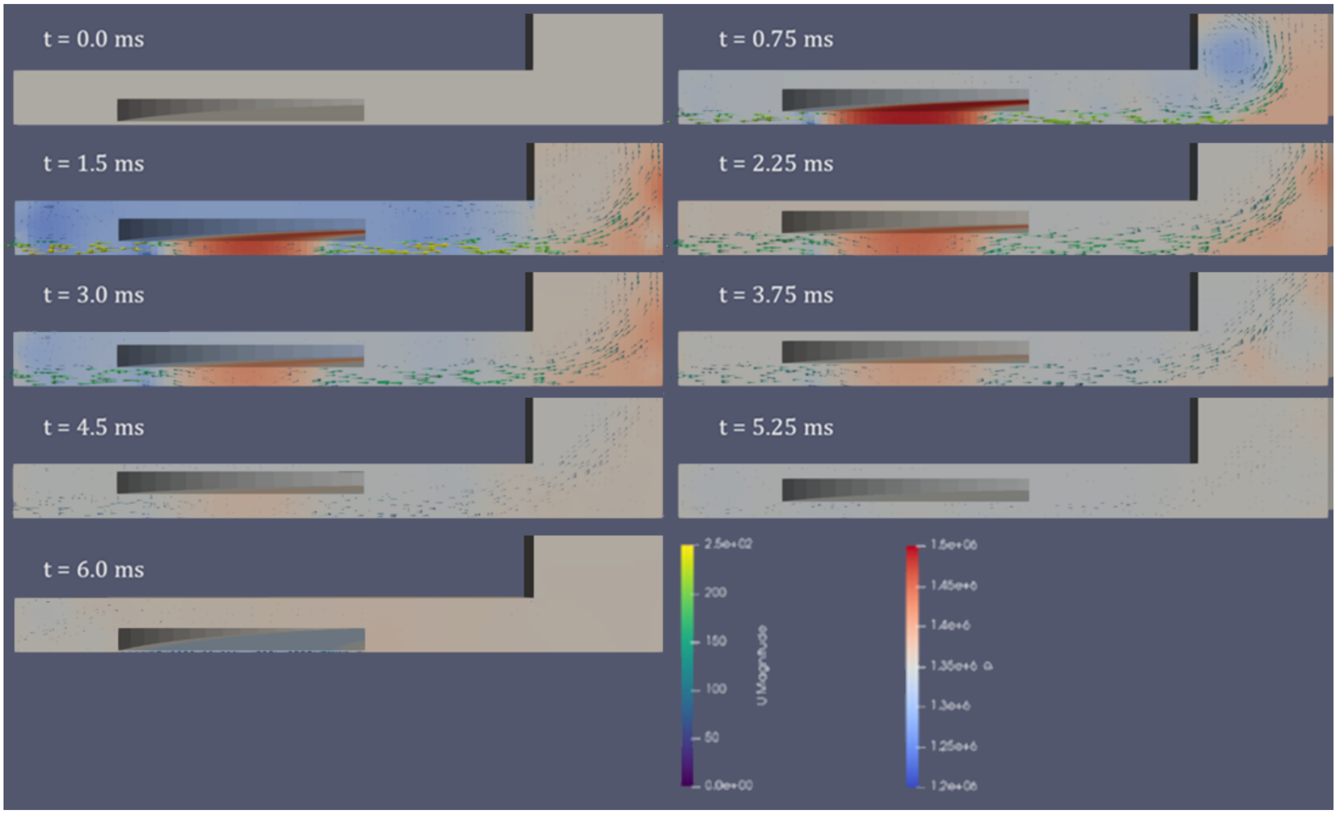

Figure 5: Plate position, pressure (red/blue) and gas velocity vectors (green/yellow) as a function of time for one cycle of the valve. The first impact occurs after 1 ms, while second impact occurs after 2.4 ms. After impact, a region of lower pressure is seen above the valve, contributing to the damping phenomenon.

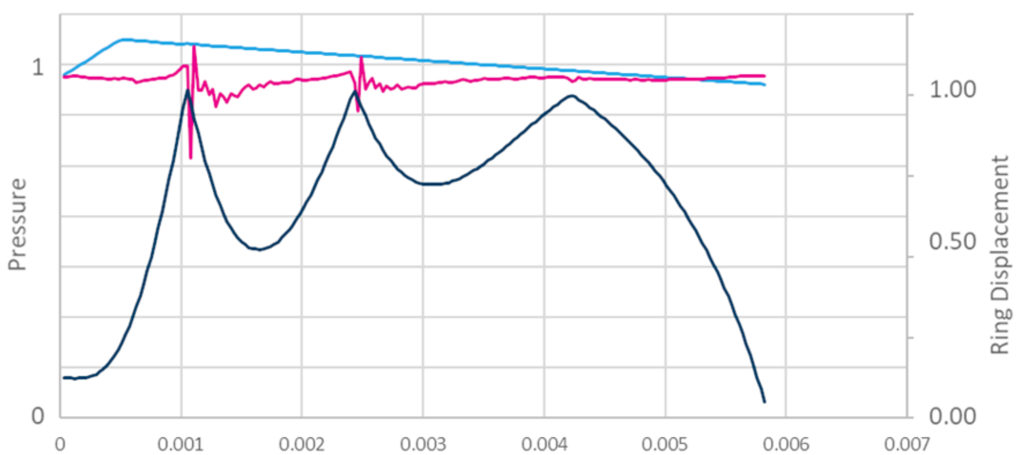

Figure 6: The normalized pressure on bottom side (light blue) and top side (purple) of the ring plate, as well as the normalized valve lift (dark blue).

2.5. FEM results

Since many coupled phenomena are ocurring in the valve system, it is desireable to separate the different effects. First, a case where no damping of any kind is included in the FE model was considered. The pressure applied to the bottom and top of the plate were determined based on experimental measurments of the cylinder and discharge plenum pressures, respectively. This results in an exaggerated (and unrealistic) plate motion, as shown in Figure 7, where the valve plate bounces strongly. The absence of any asymmetries in the applied forces means that the plate remains flat until the second impact, where oscillations (ringing) from the first impact interact with the second impact and produce a slight tumbling motion.

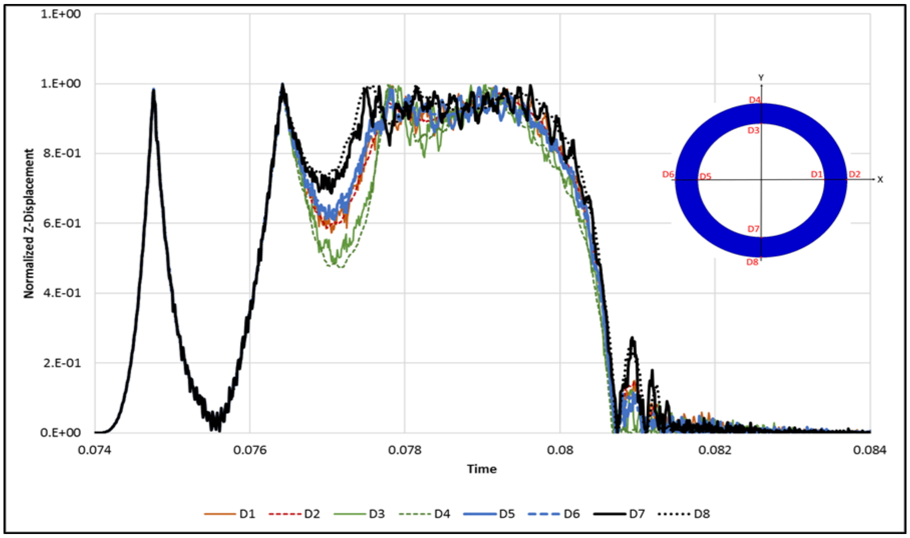

Figure 5: Displacement curves of 8 nodes distributed on the surface of the ring as illustrated in the inset figure.

In the actual compressor, the magnitude of the bounce in the valve plate is much lower, as shown in Figure 4. The difference between these two bounces give an indication of the total amount of damping present in the system. This includes the damping due to gas pressure between valve plate and cage, the mechanical damping in the impact, and other factors thought to be of secondary importance such as radiated acoustic energy and losses in the springs.

In the FEM simulations, the effect of asymmetric pressure distribution on the valve plate was also investigated. It was found that a relatively strong variation of 10% across the plate gives an almost undetectable rotation before first impact. This is because the ring has a large moment of inertia compared to this imbalance in pressure forces. However, after the impact this rotation is converted by the impact into a large amplitude tumbling motion as shown in Figure 8. Such a phenomenon, which was initially discussed by Machu (1994), highlights the importance of good valve cage design.

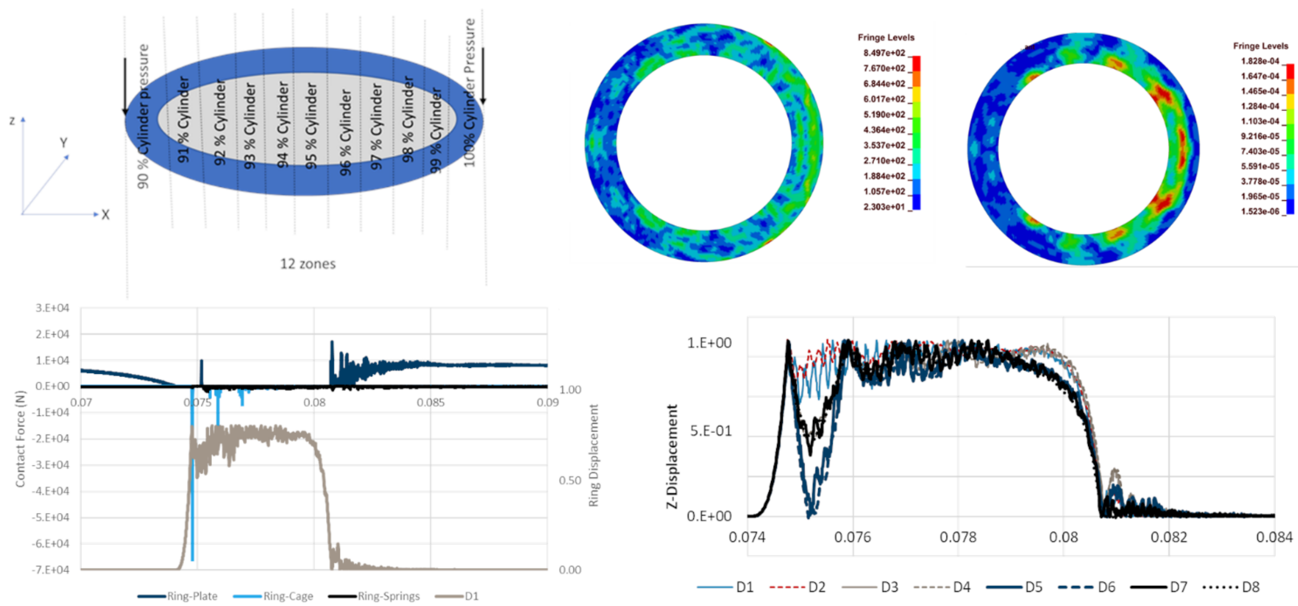

Figure 6: Response to asymmetric pressure distribution on the valve plate.

2.6. Coupled results

Since the CFD simulation gives access to the pressure distribution, it can provide the pressure in regions unaccessible to experiment. Thus, pressure at the top and bottom of the ring plate were extracted from a CFD simulation using the elastic impact model and applied to FEM simulation constituting a loosely coupled model. The results of this coupling are shown in Figure 9. By incorporating the time variations of pressure at the valve location, the amplitude of the plate bounce was decreased compared to the non-coupled case. This gives an indication of the magnitude of damping that is caused by the gas pressure rising between the ring plate and the valve cage as the valve approaches the fully open position, and the subsequent lower pressure after impact. Experimental measurements in the literature (Habing, 2005) indicate that around 90% of the kinetic energy are lost in the first bounce which is the total amount of damping due to gas pressure, absorption of energy in the impact itself, and possibly other factors. This is consistent with the observations from Figure 4. The results by coupled CFD-FEM indicate that the gas pressure alone accounts for around 1/4 of the total damping.

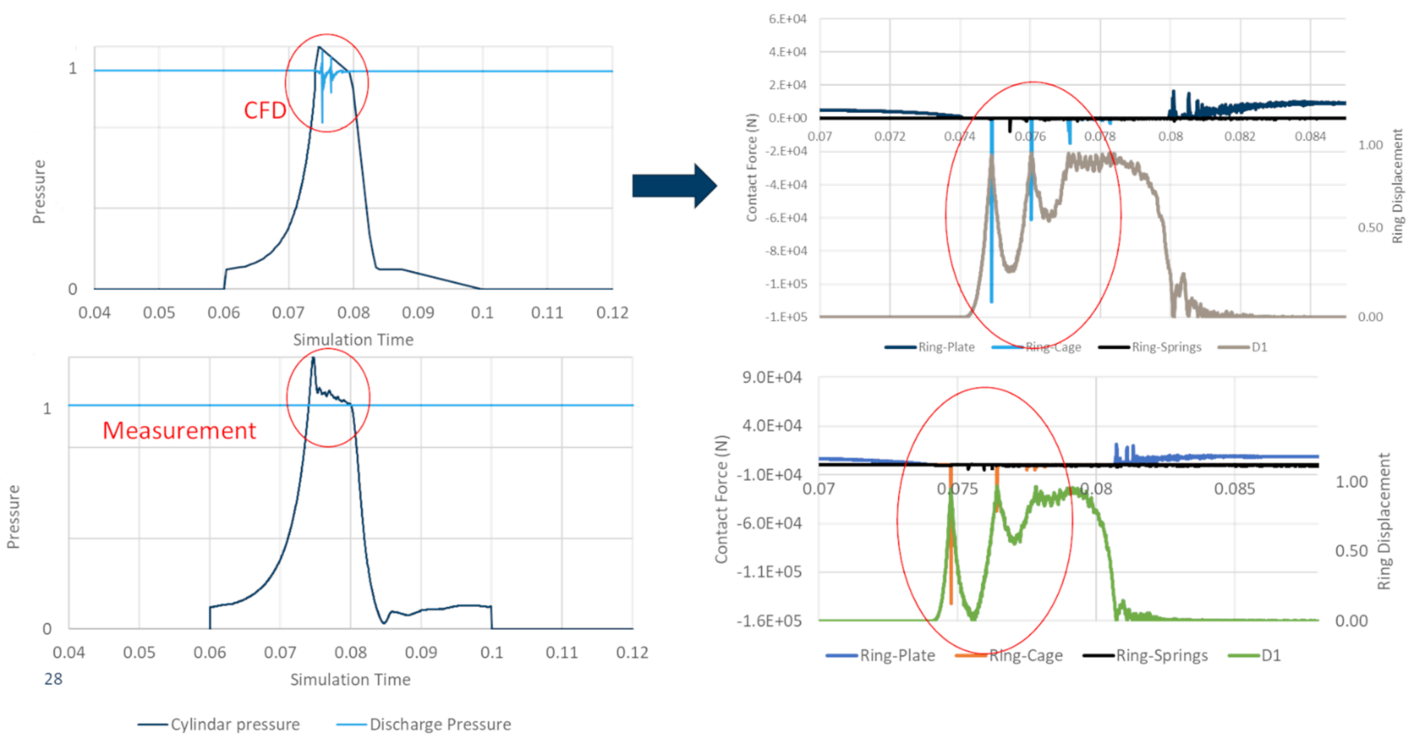

Figure 7: Using pressure from CFD in FEM (top), vs. using pressure from experimental measurements (bottom). The pressure cannot be measured at the top and bottom of the valve plate but is taken further away.

3. CONCLUSIONS

In this paper we have investigated the dynamics of ring plate valves in reciprocating compressors by CFD and FEM simulations along with field measurements from instrumenting a real compressor. We have shown that the ring plate valve is a highly complex system. The dynamic motion of the valve ring is controlled by the combined actions of forces resulting from applied pressure, spring reaction, impact with the valve's plate and cage, and damping effects. The impact between the ring plate and the valve cage is an important part of the ring plate motion and the damping is a key element of the impact. By loosely coupling CFD with FEM simulations, we have shown that the increase of pressure before impact, and decrease of pressure after impact, might represent about ¼ of the total damping. The remaining damping is mainly caused by energy absorbed into the valve cage, which is not included in the present model. We have also studied the effect of inhomogeneous pressure distribution. Even though the initial rotation due to pressure imbalance is small due to the ring's large moment of inertia, the small tilt developed is amplified in the impact into a strong tumbling motion. Thus, any pressure imbalance can have adverse consequences for both efficiency and reliability. The approach developed here gives insight into key elements of the compressor valve dynamics and enables future studies of these phenomena in greater depth.

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