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ABSTRACT

The current work directly relates valve dynamics to the compressor energy efficiency. Majority of the previous studies have focused on reducing pressure losses due to valve geometry, towards improved compressor performance. On a complimentary note, analyzing the valve 'flutter' leads to a holistic valve development methodology.

Traditionally, pressure actuated reed valves have been used in reciprocating hermetic compressors on the suction and discharge ports. A characteristic of these valve operation is the multiple opening and closing motions, during a single suction and discharge pulse, often referred to as the 'valve flutter'. This is more prominent for the suction reed considering the longer (crank-angle) duration of the suction process. The valve dynamics is a highly coupled fluid structure interaction problem. In the present work, the reed valve dynamics has been simplified to a single degree of freedom spring mass system and is captured by a mathematical model within a 15% accuracy range for displacement prediction. Considering the current stage of development, this is within acceptable limits. To validate this model, in-compressor valve lift measurements (direct strain gauge measurements) in a closed loop refrigeration rig have been used. Considering the complexity and time involved with the in-compressor measurements, a simplified framework to characterize the dynamics of reed valves outside the compressor (indirect measurements) has also been proposed and developed. Since the basis of this study is analyzing the characteristic valve dynamics, physics-based transfer functions can translate these measurements to the actual compressor reed motion leading to a faster design cycle. Also, CFD has been used to provide a detailed insight to the flow physics. With all of the above inputs, the mathematical models help identifying key design parameters and help evaluate conceptual designs towards an ideal/ chosen valve response.

Keywords: reed valve, valve dynamics, valve flutter, compressor

1. INTRODUCTION

Reciprocating hermetic compressors traditionally use pressure actuated reed valves on the suction and discharge ports. The dynamics of these valves determines the efficiency of the suction and discharge processes and strongly impacts the Energy Efficiency Ratio (EER) rating of the compressor. The pressure-volume map of the cylinder in a reciprocating compressor indicates the additional work input against the pressure losses across the suction and discharge valves. Simulations and experiments that predict the cylinder pressure-volume curve for a reciprocating compressor abound in literature. To cite a few; Ndiaye and Bernier (2010), Damle *et. al.* (2008) and Zhou *et. al.* (2001) have elaborated on simulation techniques of a reciprocating compressor. Ribas and Deschamps (2006) and Pereira *et. al.* (2008) highlight the accuracy of the simulations to capture in-compressor physics when compared to experimental measurements. Real and Pereira (2010) measured the cylinder pressure and valve lifts simultaneously so as to estimate the suction and discharge losses due to valve operation accurately.

This work proposes an alternate approach that hinges on the suction and discharge lift-map to characterize the compressor performance. There exist numerous detailed studies to minimize the losses through optimum design of the suction and discharge manifolds, optimum location and sizing of valve ports and detailed valve design. There are very limited studies which directly evaluate the influence of valve dynamics on pressure losses and efficiency of the compressor. A common approach to modeling valve behavior is to approximate them as a spring-damper system which is actuated by the evolving pressure difference across the suction/discharge manifolds and the cylinder. There have been recent efforts to capture the valve motion in a running compressor. Nagata *et al* (2010) and Kim *et. al* (2006) used strain gauges mounted at the base of the valve reed; the bending strains associated with valve movement were translated to valve deflections. Burgstaller *et al.* (2008) used Laser Doppler Vibrometry to measure valve dynamics by measuring the transient velocity of the valve. Real and Pereira (2010) also use fiber optic sensors to measure valve lifts. Some of these techniques are intrusive by way of altered clearance volumes, valve mass etc. and hence changed compressor performance. Another challenge associated with experimental studies of valve flutter is access to the reed valves in a hermetically sealed compressor under operating conditions. These efforts are thus limited by the complexity of instrumentation and time taken to evaluate a possible new concept. Characterizing the valve behavior outside the compressor – an isolated system, is a faster way to evaluate valve designs and a typical setup has been developed.

The valve design methodology starts with analyzing typical valve dynamics and projecting entitlement benefits. To isolate the main valve parameters, a 1 dimensional mathematical model (1D model) for valve behavior in the reciprocating compressor is developed. Actual measurements of the valve lifts help validate this simulation model. The flow physics can also be better understood using CFD, and these help refine the approximations in the 1D model. Once validated, the 1D model can suggest design modification towards enhanced compressor performance. The pressure-pulse setup then facilitates faster evaluation of these new designs. This is a novel test setup for valve dynamics measurement involving the measurement of valve motion in response to periodic pressure pulses. The design methodology analyzes compressor performance from a valve dynamics perspective and helps highlight the importance of reduced valve flutter as an avenue for reduced valve losses.

2. ESTIMATING EER BENEFITS

Valve design influences the power consumption of the compressor. A key observation from experimental results for valve lifts in typical compressor operation is the *fluttering motion* of reed valves. This valve *flutter* – a typical characteristic of reed valve operation, is the multiple opening and closing motions, during a single suction and discharge cycle. Flutter is more prominent for the suction reed considering the longer duration of the suction process. Existing studies, for example Soedel (2007), have looked at valve flutter as a source of noise. There are no available studies which directly look at the effect of valve *flutter* on the volumetric efficiencies. The present work addresses valve flutter as an important contributor to the power consumption of the compressor. Additionally, as highlighted by Glaeser (1999), valve flutter adversely affects the valve seat life since there are many more impacts per cycle due to flutter.

The valve dynamics is a strong fluid-structure coupling because the valve motion is a response to the pressure force it experiences, and the pressure evolves based on the mass influx/efflux through the valve at a particular lift. Valve flutter is a reason for the overpressure and under-pressure observed in a typical pressure-volume map of reciprocating compressors. Each valve lift position corresponds to a flow area opening; and depending on the pressure difference across the port, a mass flow rate. The flow rate delivered by the compressor can thus be considered to be a weighted area under the curve of the suction valve lift (or equivalently the discharge valve lift). An ideal valve operation thus, will be a valve that opens immediately (instantaneous opening) to the peak lift and stays there (no flutter) during the duration of influx/efflux.

To begin with, the entitlement available by changing the current valve dynamics was estimated using a network model created in GT-Suite™, using the valve discharge coefficient (C_d) and valve dimensions (port diameter D, valve mass etc.) as inputs. The simulation predicts the power required to operate the compressor at typical operating conditions. The objective is to relate the difference in valve dynamics to the change in C_d, which along with the

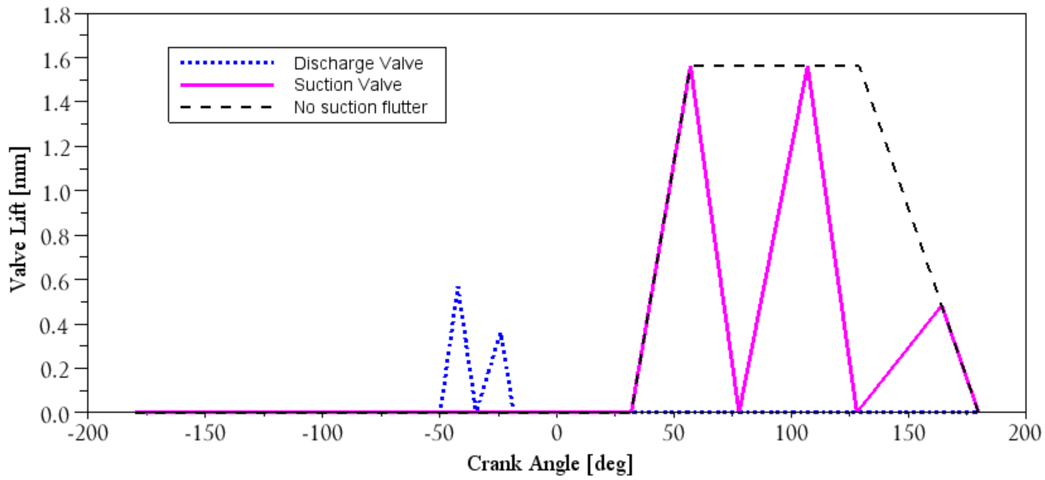

Figure 1: Sample suction and discharge valve lifts

power consumption relation translates into an EER difference (ΔEER). The maximum benefits by tuning the valve characteristics to the optimum points can thus be predicted. The methodology is demonstrated for a baseline valve lift profile shown in Figure 1. Here, the suction valve not fluttering would mean that when the reed reaches its maximum lift, it stays open until its return. Since C_d is an input requirement, its variation with the valve lift should be determined. A quick estimation can be done using an analytical model that simplifies the case to a 2 dimensional flat plate restriction with incompressible potential fluid flow (Batchelor, 2000). A better estimate uses a CFD model – a weak coupling between the fluid and structure interaction with steady state analysis at discrete valve openings (Kerpicci and Oguz, 2006). The possible EER benefit of changing valve dynamics by eliminating flutter or by having an instantaneous response is listed in Table 1. Note that these estimations are for valves with lift profiles shown in Figure 1 and indicative of the approach. Another aspect to consider is that these design changes may not necessarily be additive effects due to high interaction between the suction and discharge phenomena.

Table 1: Impact of valve dynamics on performance

Characteristic	**Analytical (ΔEER)**	**CFD (ΔEER)**
No Flutter (Suction)	0.27	0.10
No Flutter (Discharge)	0.14	0.11
Instantaneous Opening (Suction)	0.28	0.09
Instantaneous Opening (Discharge)	0.18	0.12

3. MATHEMATICAL SIMULATION

This section explains a simplified mathematical model for predicting the dynamics of reed valves in the compressor. Towards this, the piston-cylinder along with the suction and discharge reed valves constitutes the system. The compressor physics is modeled using the following assumptions. The cylinder processes are assumed to be polytropic at any instant of time. The mass flow through the valves is considered to be equivalent to an orifice flow with an effective C_d. As mentioned in Section 2, the variation of C_d with valve lift can be estimated using CFD simulations of the exact geometry. The valve is approximated to be a spring-mass-damper system with the effective mass, effective stiffness and damping dependent on the reed geometry and flow conditions. In this sense, the model is a 1D approximation considering the gas and valve dynamics assumption. The model is largely based on the iterative scheme suggested by Zhou *et. al.* (2001). The piston motion is described using the standard relation for a reciprocating compressor piston. The model requires various geometric inputs like the port diameters, crank radius, connecting rod radius, bore, stroke etc. These can be obtained by measurements of the hardware of the compressor under consideration. The effective stiffness, mass and damping constants to be used to describe the valve dynamics can be estimated using analytic beam theory. Ansys Workbench™ (on the accurate CAD geometry of the valve reed) or experimentations (described in a later section) help increase the accuracy of the analytic estimation.

The model can be improved by incorporating additional physics, as per accuracy requirements. For example, the effect of gas pulsations on the suction and discharge side could be modeled by extending the control system to the suction and discharge manifolds or by using experimental values as boundary conditions. The effect of stiction on the valve reeds can also be included using the formulation suggested by Khalifa and Liu (1998). The effect of a valve stop and/or impact of the reeds with the valve plate can be modeled as elastic collisions of the reed. Capturing additional physics will also increase the simulation parameters that may have to be empirically determined or assumed (for example the coefficient of restitution). The dimensionless suction and discharge valve lifts of a typical compressor for a pressure ratio of 10 is shown in Figure 2. The simulation model is a very useful tool to estimate the effect of valve design changes on the compressor performance.

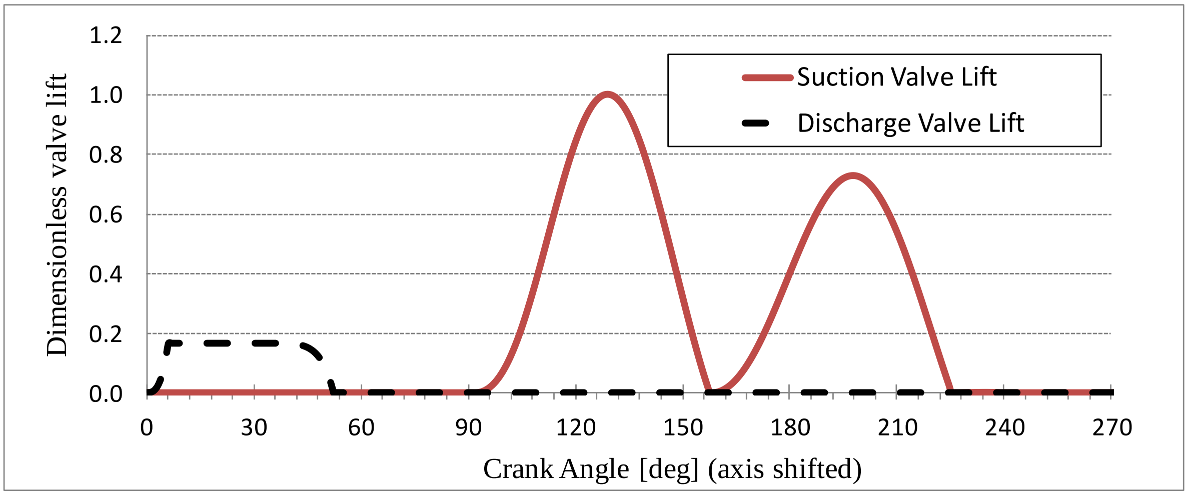

Figure 2: Predicted suction and discharge valve lifts

Before moving on to estimating design parameters for a better valve, the model needs to be baselined. The following section describes methods for experimental characterization of the valve lifts. CFD simulations of the valve dynamics also give equivalent data. These are used to determine the parameters that may have been assumed to capture the compressor physics.

4. MODEL VALIDATION

4.1 In-compressor Measurements

Measurement of reed valve displacement is paramount to the validation of 1-D model that may be used to predict the performance of the compressor valve. One of the major challenges that could be encountered is sealing the compressor with transducer cables in place. The choice of transducers that have been used range from laser, magnetic induction, electrostatic and resistance change due to strain. Of these, the resistance based strain gauge transducers are quite suitable for the experimental investigation of in-compressor valve lift characterization. These work on the principle of measurements of change in resistance of one arm of a Wheatstone bridge due to strain induced in the gauges. A similar arrangement has been made on the reed valves to be tested with the gauge balancing a Wheatstone bridge. When the gauge is strained due to the valve lifting, its resistance changes due to a change in the length, and a finite voltage proportional to this resistance change is measured across the terminals of the bridge. The gauge needs to be bonded appropriately to the reed valve. Since the reed is isolated and tucked away towards the compression zone, lead wires from the gauge can be connected to terminal pads on the valve plate sides for easy accessibility.

Conventionally, a hermetically sealed compressor shell comprises of two semi-shells welded together. Since a frequent modification of the system takes place, a modified flange shell is recommended for such experimentations. The compressor is installed within a closed refrigeration loop that simulates the refrigerator better than a calorimeter. The in-compressor measurements not only help validate the simulation, but also point towards design challenges and physics that may not have been included in the simulations. Typical compressor valve lifts that were measured at different pressure ratios are shown in Figure 3. These results show the occurrence of a back-flow and point towards the requirement of a better leakage control. Varying the pressure ratio is a good way to generate data sets for validation.

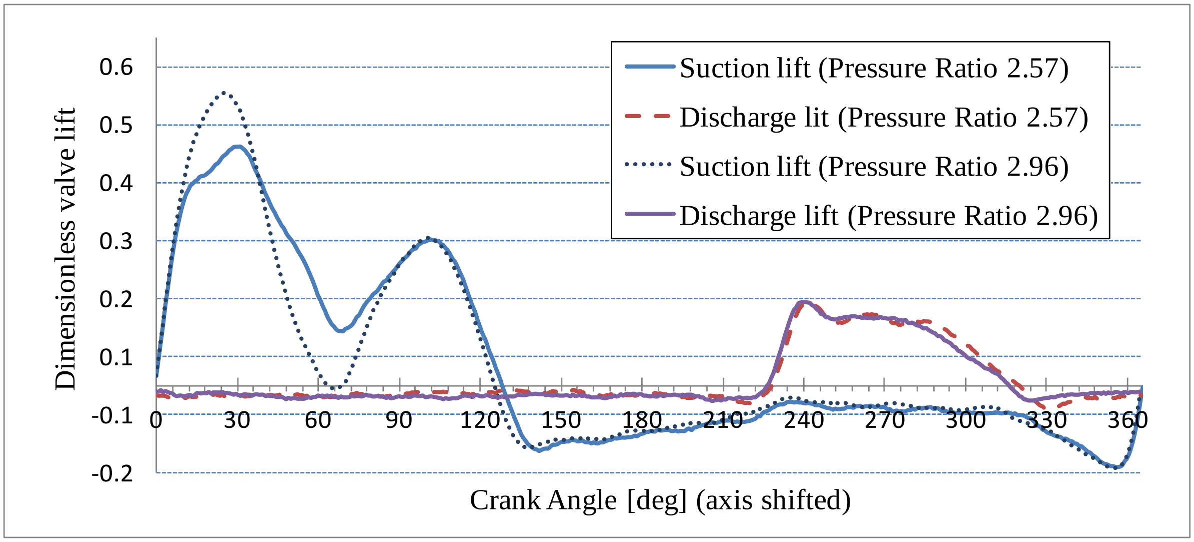

Figure 3: Experimentally measured valve lifts for typical compressor operations.

4.2 The Pressure-pulse Setup

This section describes the development of a novel test setup to characterize the influence of various geometry and operating parameters on valve flutter. The setup involves using high frequency pressure pulses to actuate reed valves. Figure 4 shows the predicted (GTSuite™ simulations) differential pressure and valve lift for a typical suction valve in compressor operating conditions. Three flutters are observed in the valve lift response; each correspond with, and lag three pressure pulsations. The width and amplitude from this simulation was utilized to decide the pressure pulse to be generated in the pressure pulse setup. The pressure pulse profiles and test setup have thus been designed to achieve a close match with compressor operating conditions.

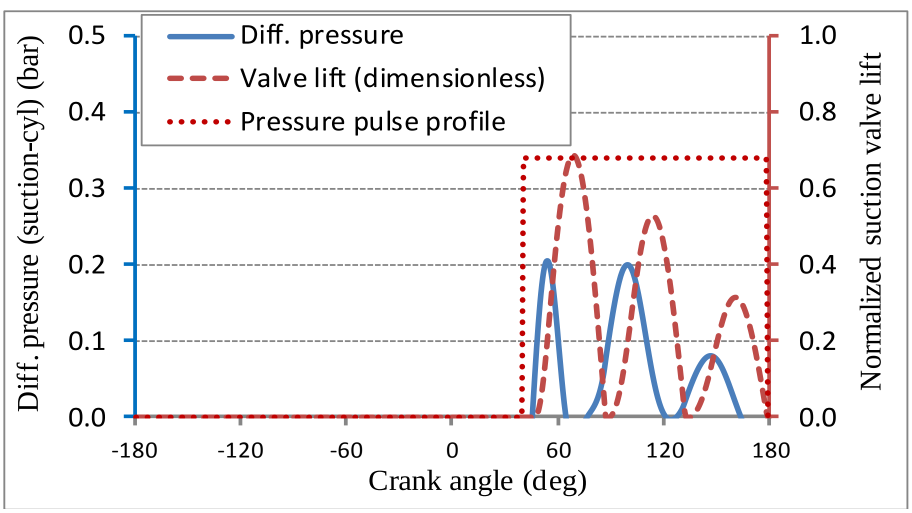

Figure 4: Pressure pulse across the suction valve reed

Details of the scheme for generating the pressure pulse are described in Figure 5. The pressure source is a nitrogen or compressed air cylinder (not shown in the figure); the outlet of the pressure source connects through a rotating disc with slits machined (Figure 6), to the valve plate and constitutes the high pressure side of the valve. When the slits align with the outlet of the pressure source, the pressure level in the manifold increases (i.e. the pulse is 'on'). The speed of rotation of the discs and the number and shape of the slits determine the pressure waveform that actuates the valve. Detailed CFD simulations were carried out to arrive at the shape of the slits to get a faithful reproduction of the desired pressure profile. The pressure downstream of the valve is atmospheric; the differential pressure actuating the valve is thus directly measured by a pressure transducer downstream of the rotating disc. The motion of the valve is measured by fixing a capacitive displacement probe above the valve as shown in Figure 5.

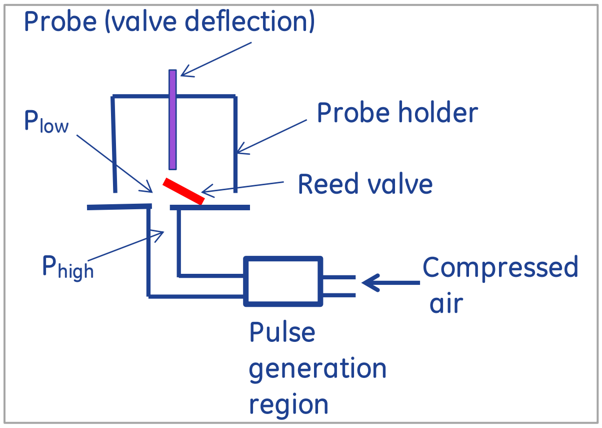

Figure 5: Pressure pulse setup schematic

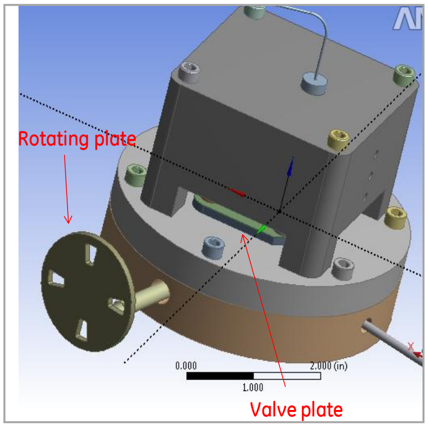

Figure 6: Pressure pulse generation concept

Figure 7 shows the measured differential pressure and valve lift profiles for a 'constant' pressure differential across the valve (no pressure pulses). It is seen that the differential pressure and valve lift are not constant; rather they oscillate about a mean position. It is also seen that the differential pressure and valve lift are strongly coupled through fluid-structure interaction, i.e. when the valve opens, the pressure on the valve face drops and vice versa. The pressure and valve lift profiles have a phase difference of almost 180°. The frequency of valve oscillation is a direct measure of the natural frequency of the valve. This information can be used to extract the mass and stiffness of the valve.

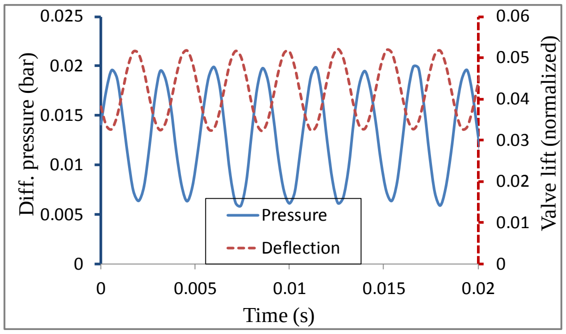

Figure 7: Transient pressure and valve lift profiles for a 'constant' applied pressure

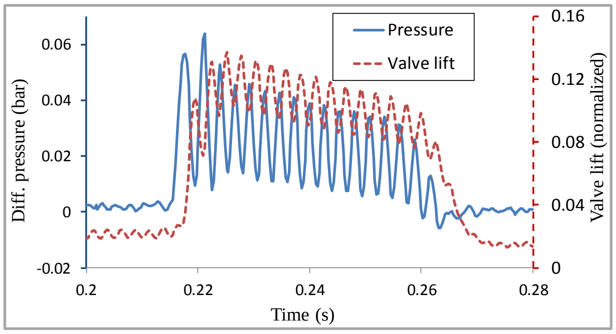

Figure 8: Measured flutter in pressure and valve lift during a single pressure pulse

The response of the baseline suction valve to continuous low frequency pressure pulses (8 *Hz*) is shown in Figure 8 (the figure shows the differential pressure and valve dynamics during one pulse). The strong coupling between the differential pressure and valve lift is again seen in the results. Also, multiple valve flutters are observed in the duration of the pulse. This flutter frequency corresponds to the natural frequency of the valve and depends on its mass and stiffness. The above results indicate that the frequency and magnitude of flutter depend strongly on the natural frequency of the valve. The natural frequency of a vibrating cantilever can be changed by changing the geometry and hinge point of the valve, in a way so as to minimize flutter. Figure 9 shows the measured valve dynamics for the existing baseline valve and a modification of that valve with a different stiffness and mass combination. It is clearly seen that the modified version of the valve has much lower flutter than the existing valve. It should be noted that in a compressor, any change in the valve dynamics will also affect the mass flow rate of the refrigerant through the valves, e.g. a lower valve lift entails reduced mass flow rate during the suction stroke. This can be compensated for by suitably modifying the suction port area and shape. The involved parameters can be isolated quickly using the existing 1D simulation models.

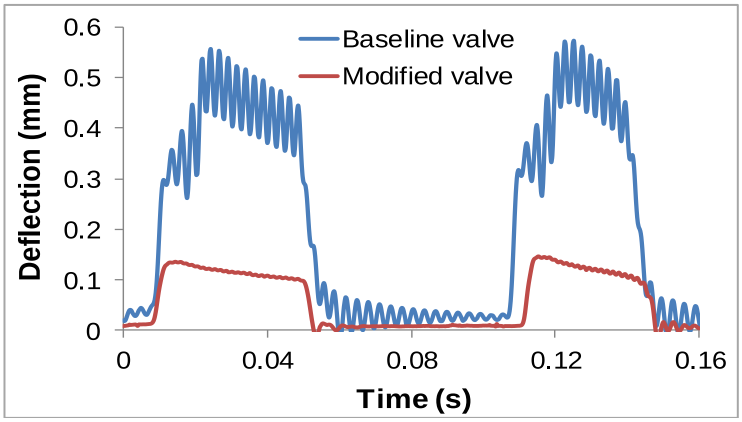

Figure 9: Differential pressure and valve lift of the baseline valve and a modified valve (different stiffness and mass combination. Reduced flutter and a smoother valve opening profile is observed (compared to baseline)

The above results show that valve flutter can be significantly reduced by tailoring the stiffness and mass of the valve. Another avenue for flutter elimination consists of the use of a valve stop. Soedel (2007) has shown that a valve stop which limits the valve lift reduces flutter significantly; this was directly verified using the pressure pulse setup. The valve stop in this case was the displacement probe itself; when the valve touches the probe (stop), it causes the probe to give an out of range response. The reconstructed valve lift profile in the presence of a valve stop is shown in Figure 10. The valve stays in contact with the probe (stop) without any flutter for the duration of the pressure pulse, confirming the utility of a valve stop in reducing valve flutter. However there are practical difficulties associated with putting a stop on the suction valve since the stop would need to rest inside the compressor cylinder. This experiment also shows the versatility of the present setup to test new valve development concepts in a quick and inexpensive manner (as compared to incorporating these changes and testing the valves under actual compressor conditions).

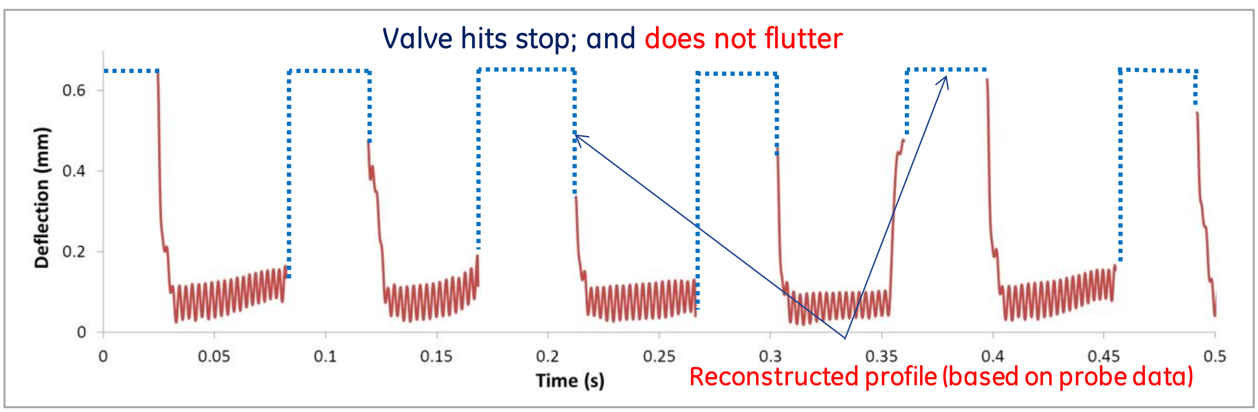

Figure 10: Valve dynamics in the presence of a valve stop for an existing suction valve. The valve hits the stop and stays in contact without any flutter for the duration of the suction pulse.

A significant finding emerging from the present work concerns the presence of oil on valves. In practice, the valve could be covered with an oil film, since the refrigerant vapor mixes with lubricating oil. Previous literature has not considered the effect of the presence of oil on valve dynamics beyond the effect of a delay in opening (Khalifa and Liu, 1998). To test the influence of oil, the surface of the valve and the space between the valve seat were brushed with machine oil (viscosity: 20 cSt) and the valve response to the pressure pulses was measured. Figure 11 shows the valve dynamics for the existing baseline valve and the same valve treated with oil respectively; the pressure pulse frequency was ~ 55 Hz which is very close to actual operating conditions. It is seen that the oil brushed valve flutters less as compared to the baseline dry valve. One of the possible explanations for this behavior is fluid damping. The oil film between the valve and the valve seat could be acting as a viscous damper to reduce vibrations when the valve opens. A layer of oil also means an increased moving mass. It is important to note that the viscosity of the oil will change at higher operating temperatures encountered during compressor operation. The present results indicate that the operation of valves in oil environments needs further study.

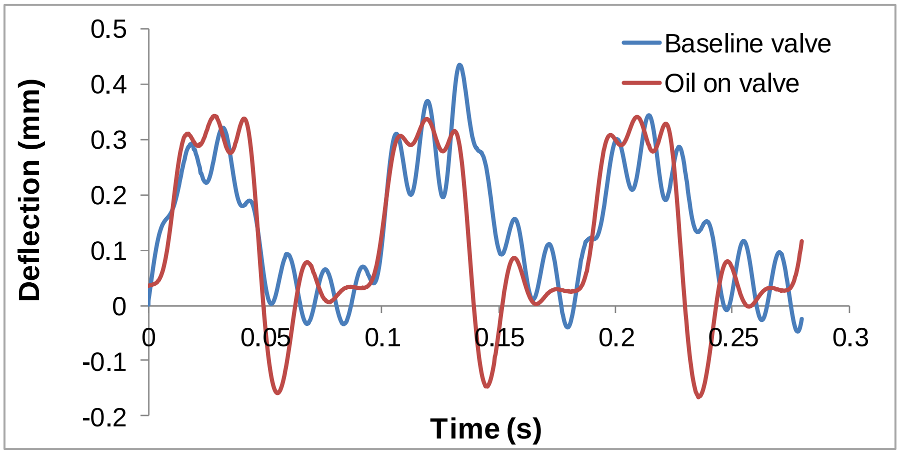

Figure 11: Valve dynamics of the dry baseline valve and the same valve brushed with machine oil, in response to 55 Hz pressure pulses. Reduced flutter is observed as compared to the dry valve.

5. DESIGN MODIFICATIONS/ OPTIMIZATION

Once a representative compressor 1-D model is ready, the sensitivity analysis of different parameters like the valve stiffness, valve mass, valve material, valve geometry on valve response can be easily undertaken. It is seen that a lighter valve opens and closes faster but also has higher flutter. Similarly, the influence of stiction can be quantified by estimating the valve response in presence of oils of various viscosities. Highly viscous oils will delay valve opening, but will result in a higher C_d because of higher valve lift; a higher valve lift will also increase the impact velocity on the valve seat and reduce the valve life. Figure 12 shows a case of a heavier suction valve and a stiffer discharge valve over a baseline case of typical compressor valves, which leads to a mass flow rate increase of 5.38% and an increased EER performance by approximately 1.34%. The increased performance can be attributed to the timely closure of the suction valve. The suction valve closes when the piston reaches the bottom dead centre and marks the start of the compression stroke leading to the elimination of back-flow through the suction port. The design problem at hand is definitely a multi-parameter optimization with nonlinear trends. An example of the % performance change due to the change in suction valve stiffness (baseline stiffness k0) can be seen in Figure 13. This is an estimation using the 1D simulation and provides a design change trend required for better performance.

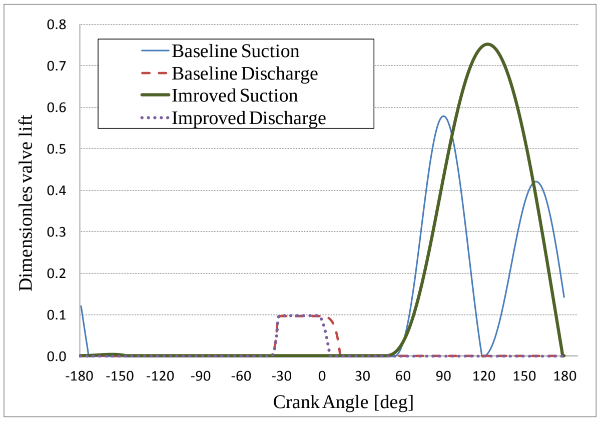

Figure 12: Valve lifts comparison for a design change of heavier suction valve and stiffer discharge valve.

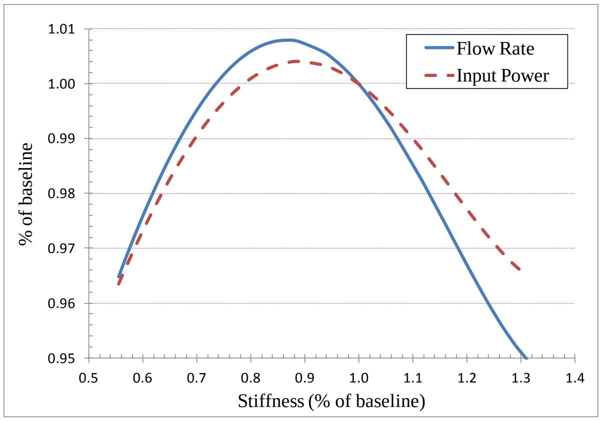

Figure 13: Compressor performance as a function of suction valve stiffness.

The 1-D model is thus a quick tool to determine trends towards better compressor performance. By estimating the parametric cloud of valve parameters for improved EER, various designs for the valve can be manufactured and tested on the rigs. The pressure-pulse setup provides for a quick validation of the design.

6. CONCLUSIONS

This study provides an understanding of compressor valve dynamics and its impact on system performance. The 1D model integrated with the experimental setups help estimate the inefficiencies associated with reed valves. It is clearly seen that elimination of valve flutter has energy saving benefits. Alongside the benefits of eliminating flutter, this study also develops a simplified valve characterization framework – the pressure pulse setup, to quantify valve dynamics. It is experimentally shown that valve flutter can be significantly reduced by optimum valve design and use of valve stops. This setup can be used for rapid testing of new valve concepts significantly reducing the cycle time for new valve development. The simulation and experimental tools presented in this study thus offer promising opportunities for the development of high performance compressor valves.

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