

Reed Valve Dynamics of Reciprocating Compressor – A Review

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Abstract - Reciprocating compressors are widely used in many industrial applications. One of the major influential component in deciding the performance of a compressor is reed valves. Reed valves are self actuating valves functioning due to differential pressure on either side of it. Reed valve dynamics is a complex study due to the various nonlinearities involved in it. An attempt is made to brief the various models developed over the years which helps to understand the behavior of reed valves and its interaction with working fluid in the larger purview of developing a global compressor simulation model. The necessary conditions involved in are discussed in keeping reed valve as a reference.

Keywords: Reciprocating Compressor, Reed Valves, Valve Dynamics, Indicator Diagram.

INTRODUCTION

Reed valves are the self-acting valves used in refrigeration and air-conditioning and air compressors. Compressor performance is controlled by the functioning of valves. Valve design is critical due to the interaction of flow of compressible gas and a dynamics of a valve. Both the non-linear thermodynamics and non-linear dynamics of flexible structures are involved in the study of reed valves [1]. The valves have sufficient stiffness to withstand the designated delivery/suction pressure. In the literature reviewed, the first work on reed valve dynamics was done by Costagliola in 1949 [2][9]. Spring mass damper SDOF model was used in his work and he concluded that the valve moves at its first natural frequency. Initial days, reed valves are modeled as one dimensional vibratory systems and the lift of the valve is assumed as amplitude of the valve motion. Computational techniques like finite element method, finite volume method and fluid structure interaction method were employed to critically analyze the behavior of reed valves. Simulation models were developed using these techniques and the performance of the compressors were analyzed. This paper classifies the various models and review the open literature presented for modeling valve dynamics. The paper also explores the possibilities of further research in valve dynamics by considering the larger purview of developing integrated computational model which includes cylinder kinematics, fluid flow, and heat transfer and valve dynamics.

Dynamic characteristics of reeds

Reed valves open due to the pressure difference between the gases and the frequency with which it vibrates is controlled partially by its natural frequency and the movement of the air. The valve motion is similar to the deflection of a cantilever up to the stop and deflection of a propped cantilever after touching the stop. Helmholtz, famous physician has classified reeds used in wind instruments as inward-striking reeds and outward striking reeds. Fletcher has extended the above to include the third type as sidewise striking reed. All the three are shown in the figure below. Figure a, explains the inward striking where the plenum chamber has excess pressure to open the wall (similar to the case of suction valve in compressor), outward striking where excess pressure is generated inside the cylinder (similar to the case of delivery valve) and sidewise striking where both the sides are having excess pressure (similar to the case of partial stagnant opening of valve).

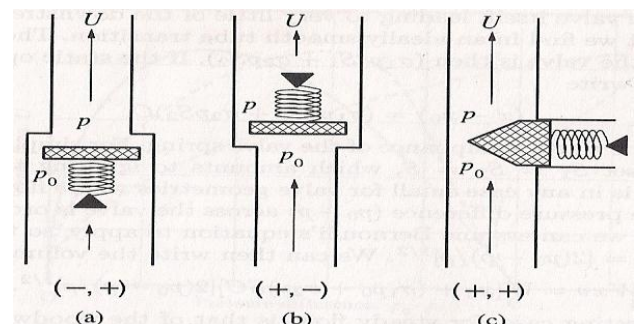


Figure 1. a. Inward striking b. Outward striking C.Sidewise striking

Motion of a reed is generalized as oscillating motion of a bar in its fundamental natural frequencies. The behavior of reed changes rapidly while oscillating at its higher natural frequencies. The condition changes from cantilever to propped cantilever and with more shapes as shown in figure. The example figure shows the first three natural frequencies of cantilever reeds.

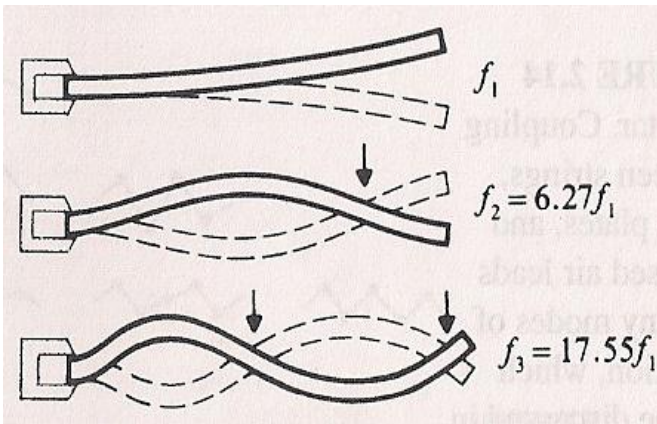


Figure 2 -First three natural frequencies of reed

Reed Valves used in compressors:

The typical reed used as a suction valve and delivery valve in a compressor of an air brake system used in automobiles is shown in the figure 3 below. Suction valve is made up of steel and weighs 20.2 grams. Delivery valve is made up of sheet steel and weighs 33.9 grams. The delivery reed assembly consists of the following parts:

- Valve seat (two pieces)
- Delivery reed
- Spring plate
- Support plate
- Curved back plate for reed deflection/stopper
- Hollow rivets to hold all together



Figure 3 – Inlet and delivery reed

The reed has a curved back plate and valve seat riveted together and separated with a spacer. The delivery reed assembly is screwed to the bottom half part of the cylinder head assembly. The plate spring-loaded reed increases the stiffness of the delivery reed and reduces back flow. The curved back plate controls the reed lift. The above reeds are made of stainless steel.

Reed Valve Design:

Self-acting valves have a significant influence on efficiency and reliability. Valve design is challenging due to serious bending and impact stresses. Design parameters such as valve lift, spring thickness, pressure ratio, and compressor speed were varied, and investigations were made to find the factors that greatly influence the valve dynamics [12]. Effective valve design is to use a set of valve parameters like

stiffness, material, root stress, impact velocity, and flow area to minimize losses associated with valves [11].

Reed Valve Dynamic Models Used:

According to the survey carried out in 1996, compressor valves are the primary reason for reciprocating compressor shut-downs with 36% relative frequency, followed by piston rod packing with 17.8%. [25]. Understanding valve dynamics is essential for improving the performance of the compressor. A lot of researchers have produced models useful in simulating the valve dynamics. The mathematical model for reciprocating compressor was first developed by R. Singh in 1974. The valve was modeled as a one-dimensional vibratory system [27]. To understand the valve behavior and its influence on compressor performance was discussed below through various models developed over the years.

Large Eddy Simulation Model:

A methodology was proposed to understand the discharge valve dynamics by considering compressible turbulent flow through the discharge valve using large eddy simulations [3] and predicted over-shooting pressure in the cylinder. The model is good to predict the instantaneous heat transfer and flow properties using TDMA (Tri-Diagonal Matrix Algorithm) algorithm.

Finite Element Model:

The finite element method was used to understand the simple geometry of the reed valve. Reed stop with constant height has caused a strong bending of the reed and reed oscillations, and it was concluded that the use of an oblique reed stop reduces forces and moments and thereby no reed oscillations [4][7]. A universal simulation algorithm was developed by considering the reed as a beam finite element model with up to 30 degrees of freedom to cover the natural frequencies of the reed valve [8]. Euler-Bernoulli's beam theory was used to model the reed valve as a beam, and the dynamic analysis of the reed was carried out using finite element techniques. [19-24].

Finite Volume Model:

Pressure pulsation in the suction chamber through modeling the suction muffler as a Helmholtz resonator analogy using the finite volume technique was used, and the governing equations developed were integrated over control volumes. The algebraic equations obtained were solved to simulate the dynamic behavior [10]. A one-degree-of-freedom model for valve motion and the finite volume method was employed, and a simulation model was developed using a moving coordinate system [18].

Fluid Structure Interaction Model:

ADINA, FSI (Advanced Dynamic Incremental Nonlinear Analysis, Fluid Structure Interaction) was used to solve the valve dynamics considering heat transfer and it was concluded that the fluid structure interaction can explain the realistic valve dynamic behavior and using sequential quadratic programming for optimum design of suction reed. [5]. An Immersed Boundary Method (IBM) with the Multi-Direct

Forcing Scheme was used to represent the valve geometry to solve the 3D unsteady flow for an imposed angular movement to the reed and an adaptive mesh was used to derive the governing equations. The governing equations were solved by semi-implicit second-order scheme for time integration and algebraic equations were solved by Multigrid-Multilevel technique and found that IBM is an alternative for solving the flow through reed valve with complex geometry [13]. Methodologies using FLUENT coupled with an embedded FSI tool based on suite of user defined functions was proposed and exchange of information between finite element structural model and computational fluid dynamic model [26]. These models require use of commercial computational tools using advanced matrix methods to solve and difficult to incorporate with global simulation models which predicts the pressure at crank angles instantaneously.

Experimental Models

Two main experimental methods are useful in finding the compressor performance. They are PV card and Enthalpy rise methods. Both the methods are beneficial depending upon the objective of the experimentations. For estimating the overall efficiency of the compressor, enthalpy rise method is preferred. For complete diagnostic of a compressor PV card method is used. To understand the valve dynamics, the variation of pressure above discharge and below suction pressures are useful.

5.5.1 PV Card Method:

In reciprocating performance testing, PV card method is used as most common method. This method measures the cylinder pressure along with the piston position measurement. Using these two, Pressure Volume curve is established. The area of the PV curve is used to find the work done during a cycle. All other performance parameters such as capacity, compressor efficiency, Indicated and brake powers and volumetric efficiencies at suction and discharge are calculated. GMRC (Gas Machinery Research Council) published the guidelines for field testing of reciprocating compressor performance on 2009 [15]. One can say PV diagram is like a ECG (Electro cardiograph) of a compressor and useful to study the effect of any associated parameters including valve dynamics.

5.5.2 Enthalpy Rise Method:

In this method, pressure and temperature of the suction and discharge processes are measured. Using equation of state relationships, the enthalpy is calculated at each position. The total power can be calculated based on the enthalpy difference [15].

5.5.3 Flow Visualization Method:

Experimental setup for simultaneous visualization of oil film rupture and measurement of the reed deformation and behavior was developed and found that reducing the reed/seat contact area to improve performance [6].

Non-linear model

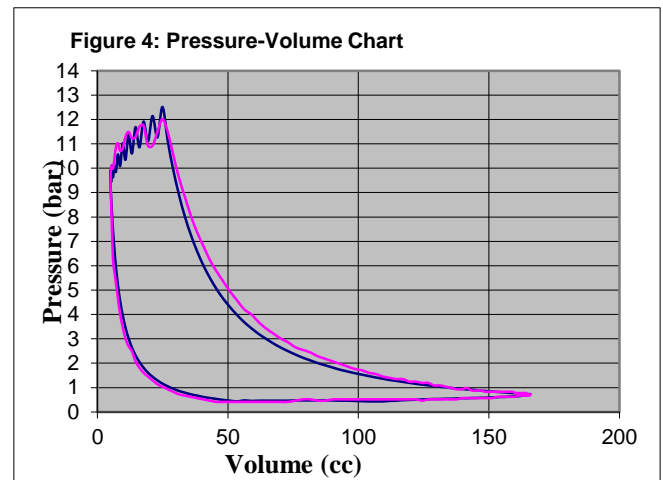
Non-linear valve modeling by incorporating the geometric nonlinearity through large deflection strain displacement relationship is presented. Assumed-modes method was used to simulate the valve behavior and simulation results are compared with linear valve model. Valve motion during various thicknesses were compared for suction processes and found that, for the small thickness valves, it was concluded that non-linear strain played greater role [14].

5.7 One Dimensional Quasi-static Model

One dimensional quasi static model was developed to integrate the fluid dynamics, heat transfer and valve dynamic models of compressor and a simulation was developed [16]. The models' capacity to capture the main characteristics of a compressor is proven. The model was extended further to 2 dimensional also and the results are compared. [17].

Discussion

In the literature reviewed, mathematical modeling and simulations were created for understanding compressor performance using simple valve dynamic model. The following figure 5 shows a comparison of predicted simulation model with actual one taken from PV card method. The blue line is a simulated one and the violet one is experimental model.



Venkatesan et.al., created a simulation model by considering reed as a cantilever beam vibrating at its first natural frequency till it hits the valve stop and second natural frequency after that. There is a greater degree acceptance on both the models as the model was able to predict the volumetric efficiency and peak pressure within 5% variation [28]. This proves that for creating overall simulation model for compressor performance, simple valve dynamics is sufficient enough to predict the parameters. For understanding the valve and modifying the valve geometry for providing better compressor operational efficiency, other models are used. Improvements made in computational fluid and solid mechanics ease the pressure on researchers to produce the new valve design using commercial CFD packages like STAR CD, ADINA, and Fluent. Few researchers are trying to use Fluid Structure

Interaction to predict the valve behavior. Though computational models help to integrate the fluid flow, heat transfer and valve dynamics, it is difficult for the researchers to create a standard model which predicts the compressor parameters using them. Conventional programming language like C or Fortran used by researchers for creating computer simulation of compressor performance are not having class libraries to solve such a type of higher order partial differential equations or solving simultaneous algebraic equations. Iterative nature of predicting the parameters for incremental crank angle by incorporating conventional equations are necessary for such a type of standard models.

7. conclusion

Close prediction of Pressure Volume data using modeling and simulation is essential for creating successful mathematical model. The valve dynamics of the compressor should be a part of the model. Pressure at incremental crank angle prediction is important for researchers while integrating valve dynamics. For creation of such type of models, simple valve dynamic equations which can be integrated with flow and heat transfer equations are needed. It also has to take the account of cylinder kinematics. Interpreting language (Ch language) developed by soft integration inc. can be used effectively for predicting compressor performance due to its built in classes of scientific numerical computing and 2D plotting [29].

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