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An approach towards reed valve geometry design

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ABSTRACT

Pressure-actuated reed valves play an important role in the compression process of a refrigerator compressor. The material properties and geometrical parameters of the valve and geometrical properties of valve port determine the flow coefficient which in turn impacts the compressor efficiency. Also, the moving mass of the valve and its stiffness governs the transient response (valve flutter) which impacts life and reliability of the valve in operation. Therefore, it is imperative to carefully design the reed valves to maximize compressor performance while meeting the above requirements. The design of reed valves involves determining the geometrical parameters (length, width and thickness) and material properties (type of steel etc.). These properties are chosen such that they correspond to the desired mass and stiffness of the valve. This work mainly focuses on determining the basic valve topology (geometrical parameters) with the desired mass and stiffness of the reed valve as design constraints. In order to obtain the optimum reed valve mass and stiffness values, an in-house system level performance simulation model is used. An analytical finite element based model has been built that searches for geometrical parameters which meets both target valve parameters and material limitations for reliability and life. This provides multiple valve designs with different geometrical parameters and gives the designer the flexibility to choose the most suitable valve design for a targeted application. Additionally, the basic valve topology will facilitate a more detailed performance analyses, viz. flow-thermal simulations and flow-structure interaction.

Keywords: reed valves, finite element method, geometrical properties

1. INTRODUCTION

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’. The efficiency of hermetic reciprocating compressors depends on the amount of pressure losses associated with the suction and discharge processes. Figure 1 shows the overpressure and under pressure which relate to valve operation.

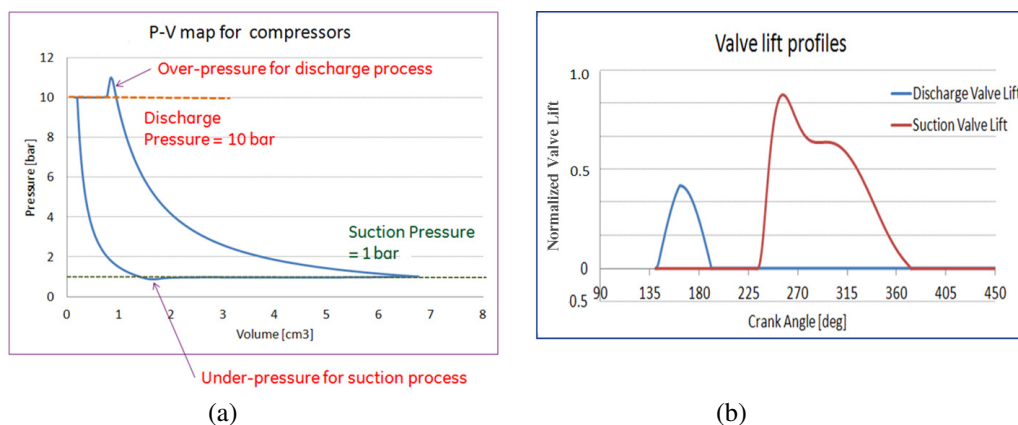


Figure 1. (a) P-V map for a compressor with valves (b) corresponding valve lifts (normalized)

Essentially, the design involves selection of valve materials, operating parameters that ensure optimal EER, geometrical and mechanical design. Typically, a valve needs to ensure sufficient build-up of in-cylinder pressure and must do so reliably for the operating life of a compressor. It may be noted that competitive prices in the compressor market entails for highly reliable valve design. Essentially that valve design is interplay between performance and reliability and both are ideally expected to be at respective optimum. For the sake of articulating the process, following main criteria have been identified for valve design.

1.1 Valve Response

For a given valve, response primarily depends on the pressure difference across the valve, the valve stiffness, preload and mass of the valve. During a typical compression cycle, gas is sucked into the cylinder at lower pressure, compressed to a higher pressure and discharged at higher pressure. Depending on in-flow or out-flow process, a valve may vary in its design, operation along with requirements on its mass and stiffness.

1.2 Valve Losses

From the performance point of view, losses play an important role in the design of a valve. These losses are classified based on loss of compressed refrigerant mass which is leakage, and pressure related losses. Leakage losses occur due to surface irregularities present on the valve and the valve gland sealing. Depending on the surface finish of the valve and the valve gland, leak severity varies. Pressure losses predominantly due to the presence of valves are overpressure and under pressure. An overpressure may be defined w.r.t. the ideal cycle as the amount of in-cylinder pressure beyond the rated discharge pressure due to the discharge valve. An under pressure in the similar sense may be defined as pressure below the rated suction pressure due to suction valve. The respective losses correspond to the duration of such events over one complete cycle. Due to limitations of flow area, there is a requirement of finite pressure difference (ΔP) to pump gas in and out of cylinder in a shorter period of time. From the simulations, it has been found that the valve parameters directly influence the loss magnitudes.

1.3 Valve Structural Requirements

Besides the performance, a valve should also last its designed lifetime which is indicated by root stress, fatigue strengths and impact velocity. Typically, reed valves are designed for fatigue as these valves undergo billions of stress cycles during their lifetime. Also, the design of hermetic compressor structure inhibits servicing these valves. Therefore, these valves are built out of materials with high endurance limit and one would like to have stress amplitudes that should lie below the endurance limit of the valve material. Typically, valve materials have high tensile strengths and endurance limits. Also, in a study conducted by Sandvik (Svenzon, 1976) it was shown that over the period of time, valve surface near the ports shows pitting. This type of damage compromises the structural integrity of the reed valve and leads to severe leakages around the valve. The same study correlates the damage on the valve to its impact acceleration and suggests a limiting value for this acceleration.

2. DESIGN GOAL

The valve design goal is to arrive at a set of valve parameters that help in minimizing losses associated with valves, maximize flow rate into and out of the compressor while retaining its performance and structural integrity for the life of a compressor. In order to evaluate the sensitivity of valve parameters, a system level model that includes mathematical representation of various subsystems of a compressor and their interactions has been developed. The model encompasses the piston and gas dynamics which provide a framework for finding the valve parameters that give the best EER. In the following section, valve parameters are listed that dictate the optimal design of the reed valves.

2.1 Valve Design Parameters

- **Stiffness:** For better performance from compressor, it has been evaluated through simulation studies that lower suction valve stiffness and higher discharge valve stiffness are favorable for compressor performance.

- **Material:** Sandvik 7C27Mo2 is reed valve steel that has the properties of high endurance limits and high tensile strength. This steel is widely used for fabrication of reed valves and hence chosen
- **Root stress:** For the Sandvik 7C27Mo2 steel, endurance limit for zero mean stress type of loading is 800 MPa and it reduces by 70% for unidirectional loading.
- **Impact velocity:** Sandvik conducted a study on impact velocity and found that it should be less than 9m/s for valve steel (Svenzon, 1976). The study results are shown in Figure 2.
- **Flow area:** Flow area may dictate the tip design of the valve and may require design from fluid flow perspective than structural design. One still has to check if the tip could be made safe for impact related damage, Figure 2.

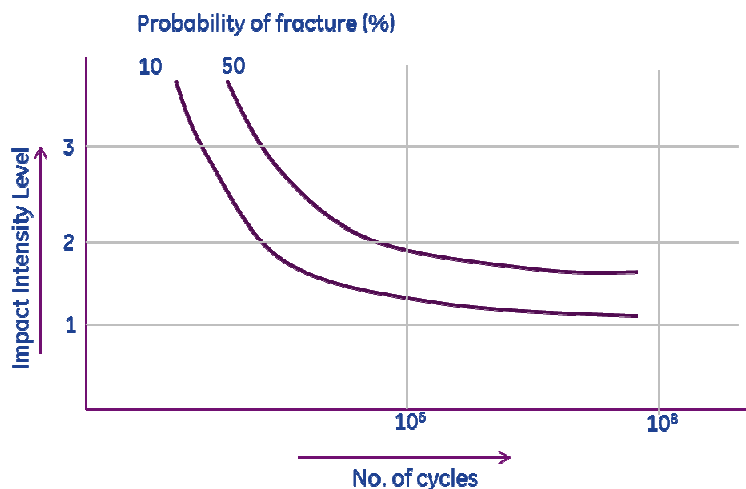


Figure 2: Impact acceleration curve for Sandvik 7C27Mo2 (Svenzon, 1976)

3. METHODOLOGY

Valve design can be assumed to be a two-step process wherein the first step corresponds to obtaining optimal valve parameters and second step uses the parameter values from step one to design the valve geometry. For the first step, in-house system level model has been used to obtain the optimal value for valve parameters. An integral part of the in-house model is the single degree of freedom valve model that has been developed from first principles and experimentally validated. A discussion on this model is given in the work by (Bhakta *et.al*, 2012). Based on the system level model, optimal stiffness and mass, required flow area and impact velocities were evaluated. In the subsequent process, an in-house valve geometry search algorithm has been developed and is the focus of current paper. In the following sections, an elaborate discussion is presented on development of this model.

3.1 Reed Geometry Search Algorithm (RGSA)

A lot of commercially available packages have shape optimization routines that can give optimal geometrical shapes based on listed constraints. However, including such packages as a part of design iterations that requires millions of runs may not be tractable. Under such circumstances, it may be sensible to develop an algorithm that can give minimum viable geometries which can be starting point for more elaborate shape design once valve parameters are fixed. This model can be included as a part of system level optimization routines with faster simulation. Therefore, the intent of developing the model is to give quick viable geometric starting points for the valve that meet the constraints on stiffness, mass and root stress.

The starting point to this approach is in understanding the geometrical features of commercially built reed valves. A reed valve may be assumed to be having three main geometrical features, the root, the gland and the tip, as shown in Figure 3.

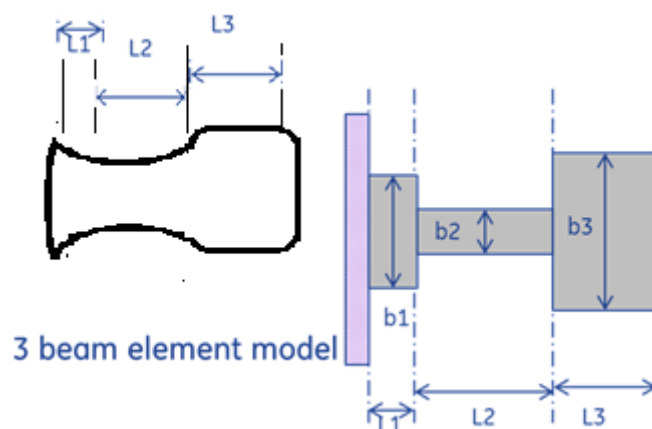


Figure 3: Geometrical correlation used in RGSA

From a designer's perspective, root takes most of the stress induced in the valve, gland may be associated with its flexibility and tip primarily covers the openings / ports. As shown in Figure 3, one can easily establish correspondence between the geometry on the left which is a typical valve and one on the right which is its representation as simple 3-beam system. Therefore, one can develop a simple 3-beam finite element model that can estimate the geometrical parameters (length, width and thickness) of the identified 3-beams of a reed valve. One such model has been developed and validate with results from commercially available FEA package. The comparison was made between the tip deflections by the in-house code and the FEA package and results are shown in Figure 4. A point load was applied at the port end of each of the three geometries and deflection along the valve is predicted. As shown in Figure 4, the 3-beam analytical model estimates tip deflections close to the simulations in ANSYS © and hence establishing the capability.

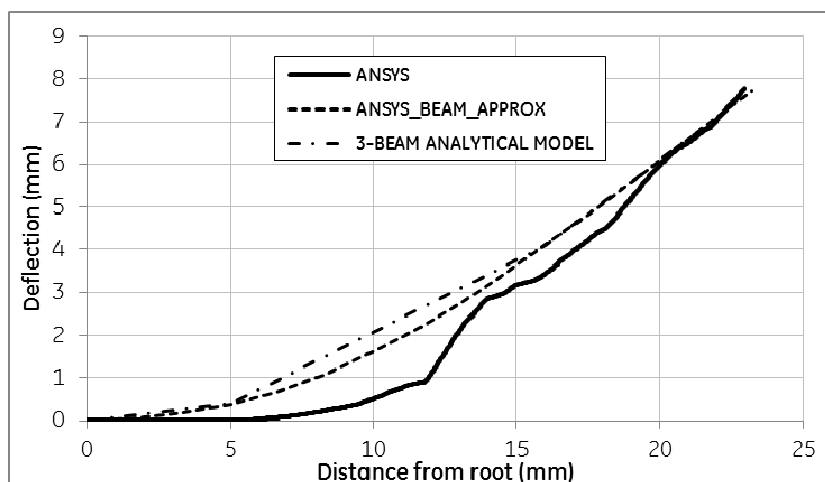


Figure 4: Analytical model corroboration with commercial package

The model was subsequently used to evaluate the size of the valve and meet the stiffness, mass and root stress criteria with in specified tolerance limits. To determine the favorable set of geometrical parameters, following constraints were identified.

- The tip area should be same as or greater than the port area
- The total length of the valve is constrained to be less than bore diameter

Once the constraints were set, following procedure was followed to compute the favorable geometrical parameter sets.

- Input limits on valve thickness, based on commercially available sheet thicknesses
 - Material properties of the valve, Young's Modulus
 - Pressure loading across the valve, ΔP
 - Target values of mass and stiffness from system level simulation and corresponding tolerances
 - Based on port area requirements choose the length L_3 and width b_3 of port section of valve
 - Build a DoE set as $DoE\ set = \{L_{1i}, b_{1j}, L_{2i}, b_{2j}, t_k, L_3, b_3, \Delta P\}$; $i, j, k = 1:5$ where i, j, k are the level of parameters for DoE.
 - Root length $L_{1i} = \{0.1 \times (Bore\ dia. - L_3) : 0.9 \times (Bore\ dia. - L_3)\}$
 - Neck length $L_{2i} = (Bore\ dia. - L_3) - L_{1i}$
 - Valve thickness $t_k = \{t_{min} : t_{max}\}$ $k = 1:5$
 - Root width $b_{1j} = \{0.5 \times b_3 : 1.5 \times b_3\}$ $j = 1:5$
 - Neck width $b_{2j} = \{0.5 \times b_3 : 1.5 \times b_3\}$ $j = 1:5$
 - Run 3-beam element model for each $i, j, k = 1:5$
 - Filter data that satisfies mass and stiffness criteria within $\pm 5\%$
 - Build a geometry based on favorable solution sets = $\{L_{1i}, b_{1j}, L_{2i}, b_{2j}, t_k, L_3, b_3, \}$
 - Use CFD simulations to further hone the geometry for better flow performance across the valve
- A typical result of this algorithm is as shown in Figure 5 which shows all the favorable $L_{1i}, L_{2i}, b_{1j}, b_{2j}, t_k$ sets along with respective root stress, computed mass and stiffness values.

4. RESULTS AND DISCUSSION

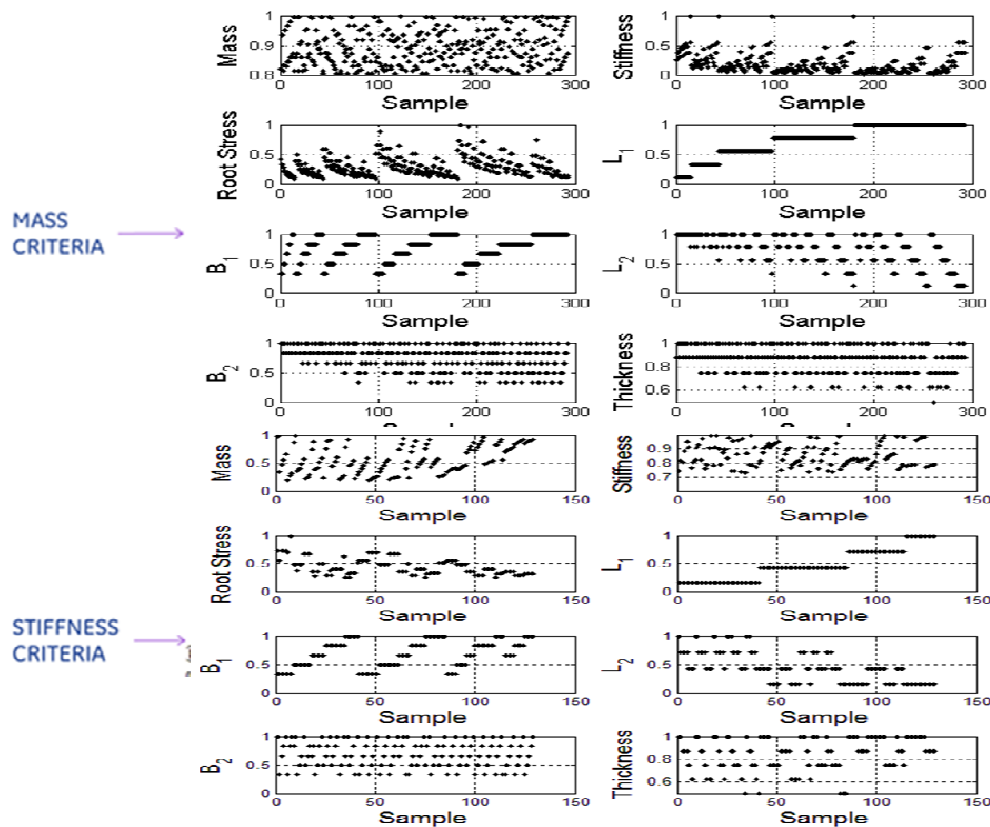


Figure 5: Normalized Mass and stiffness ranges satisfying a given constraint within $\pm 5\%$

The valve geometries corresponding to a few from the favorable sets are shown in Figure 6. The geometry (a) which was obtained as one of the geometric solution is close to the geometry which is commonly used and available. This validates the capability of the 3-beam analytical model to provide geometrical solution to valves.

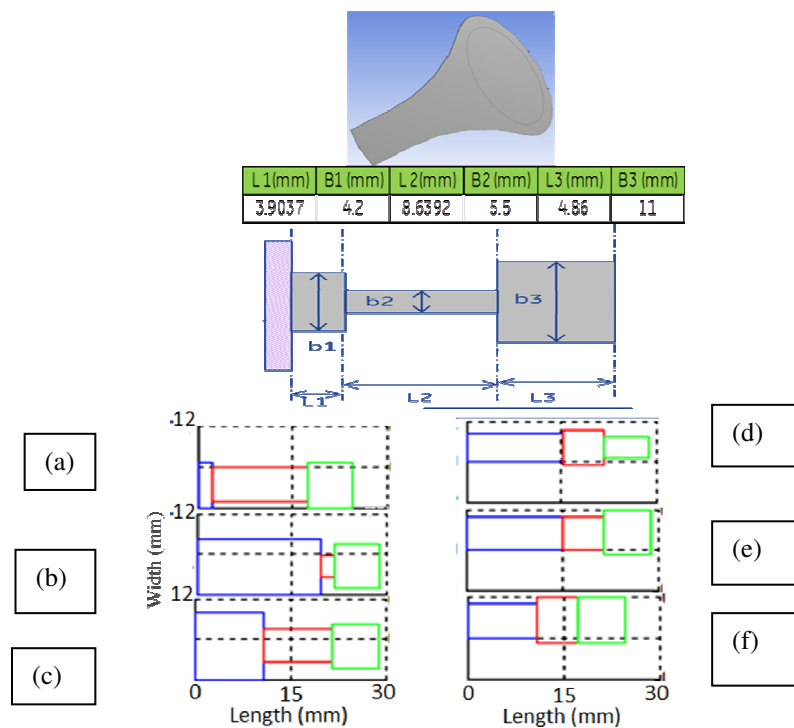


Figure 6: Results of RGSA for a typical valve geometry

From these results, one has multiple options of geometrical parameters that may satisfy stiffness and mass requirements and could be evaluated for structural toughness.

5. CONCLUSIONS

The 3-beam analytical model serves as the starting point in valve design and allows designer to choose from the list of geometrical parameters that satisfy the dynamics constraints on the valve viz. mass and stiffness. Additionally, the tool provides initial estimate on stresses that may be induce in order to achieve required valve deflection. Above all, the primitive shapes that the model gives may be refined through elaborate fluid dynamic analysis. Due to the the faster computation time of the model, it serves ideally for the purpose of system level optimizations through multiple iteration which often could run into several thousands.

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