Experimental analysis of reed valve movement for different reed valve designs tested in an impact fatigue test system

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Abstract. Impact fatigue is a phenomenon that is the main cause of failure of reed valves in compressor systems. This phenomenon occurs in compressors due to repeated opening and closing of reed valves during suction and exhaust cycles of compressors. When the valve opens it creates bending fatigue stresses in the body of reed valve; when the valve closes it strikes against the valve plate creating impact stresses. This reed valve movement and impact is repeated billions of times. This cyclic movement influences the impact fatigue life of the reed valve and, hence, the performance of a compressor. The valve movement can be defined in terms of valve frequency, valve lift, valve velocity and impact velocity. Inside a reciprocating compressor, a number of parameters including the valve design, valve material, compressor operating frequency and suction/exhaust pressure influence the reed valve movement.

In this paper, we studied the valve movement parameters for three different suction reed valve designs manufactured from Flap-X – a martensitic stainless steel grade developed for reed valves – tested in a custom-built impact fatigue test system. The valves were excited into movement using compressed air pulses varying in frequency up to 300 Hz and varying pulse width. The valve displacement and frequency was recorded by a laser sensor at 10 000 frames per second. Before starting each test, the operating conditions such as the operating frequency and the air pulse width were pre-set in the impact fatigue test system’s control software while the applied pressure was kept constant during the test. The valve response was measured to be different for the different valve designs tested in this study. The reed valve design influenced the important reed movement parameters such as the valve lift, valve velocity, impact velocity and the frequency of valve vibrations. The valves were not tested to failure as the focus of this study was to collect the dynamic data of valve movement. However, for a practical impact fatigue testing of the reed valves intended to achieve fracture of valves, the testing should be conducted at higher frequencies to reduce test times as well as for a stable amplitude of vibration and impact velocity as shown in this study. The information obtained from this study shows the applicability of the presented impact fatigue test system to study the reed valve movement as well as their impact fatigue characteristics.

1. Introduction
In compressor systems, the reed valve is a crucial component as its smooth operation allows the reliable operation of a compressor and, hence, the operation of any appliance that the compressor is installed in.
Such compressors are usually installed in the household or vehicle air conditioning systems, refrigeration systems and other cooling/ventilation systems.

Importance of the reed valve movement can be judged by its effect on the impact fatigue and bending fatigue life of the reed valve. Long impact fatigue and bending fatigue lives of the reed valves and, hence, their compressor systems are desired. The valve movement parameters, such as valve lift, affect the coefficient of performance (COP) of a compressor. Similarly, higher valve lift in a compressor would mean higher reed velocity due to valve’s elasticity and, hence, higher impact velocity when the valve shuts down and strikes against the valve seat. The higher impact velocity means higher impact fatigue stresses are established inside the reed valve body after the impact. Similarly, higher bending fatigue stresses arise in the reed valve body when the valve lift is higher.

The problem of impact of reed valves has been studied by several researchers using various experimental as well as numerical modelling techniques. Svenzon [1] and Futakawa et al. [2] conducted the impact fatigue experiments using their custom-built impact fatigue equipment and analysed the fractured valve surfaces. Altunlu et al. [3] have also studied the effect of different tumbling times as well as the different impact velocity levels on the life length of the tested reed valves in their own custom-built impact fatigue test system. Tofique et al. [4] have studied the impact fatigue phenomenon of reed valves when tested against impact plates of different materials. Their study focussed on understanding the influence of the material properties on the impact fatigue life of reed valves. Some other researchers have contributed towards understanding of the impact fatigue phenomenon using different numerical modelling techniques. For instance, Böswirth [5], Soedel [6] and Rigola [7] have proposed different numerical models to deepen the understanding of the reed valve movement behaviour incorporating both the fluid flow parameters as well as the structural properties of the reed valve. These modelling techniques have allowed researchers to study different geometrical aspects of the reed valve as well as to simulate the valve movement behaviour under compressors’ operating conditions. Other researchers have carried out validation of the numerical modelling techniques with their experiments. For instance, Mayer et al. [8] and Tao (2018) carried out a validation of Fluid-Structure Interaction (FSI) computational methods by reproducing experimental results of reed valves. There have also been numerous theoretical studies in the past such as by Böswirth [9], Pandeya et al. [10] and more recently by Yu et al. [11] that discussed the dynamic behavior of a generic geometry of reed valves and the impact fatigue stress state generated due to their impact against the impact seat during compressor operation.

Another important piece in solving this puzzle is the effect of the reed valve’s design. The design of the reed valves plays an important role in determining not only the magnitude of the valve movement parameters but also the life length of the reed valves. However, in the compressor market there are several types of valve designs that give varying amounts of advantages and disadvantages during the reed valve operation. Therefore, in this experimental study, different types of valve designs were selected to study their valve movement behavior.

The aim of this study was to analyze the influence of different valve designs on the reed valve movement parameters when tested in a custom-built impact fatigue test system. Based on this information, the valve parameters suitable for testing the impact fatigue life of reed valves were proposed.

2. Experimental
Reed valve movement experiments were conducted on a custom-built impact fatigue test rig that, in normal operation, uses air pulses to produce movement of the valves at a range of frequencies (Hz) and pulse widths (milliseconds). The frequency, and pulse-width, is provided as input to the control software on the connected computer.

A schematic sketch of this custom-built impact fatigue test rig is shown in Figure 1. A dedicated compressor provides compressed air at up to 13 bars pressure. This compressed air gets stored in a storage tank. The compressed air is transferred through tubes of 4 mm inner diameter and passes through a flow meter that measures the airflow rate in litres per minute. The air pressure regulator regulates the
magnitude of the compressed air pressure before it passes through a high frequency solenoid valve. There is a possibility to increase or decrease the magnitude of pressure supplied to the solenoid valve, and hence the airflow rate, through the pressure regulator. The compressed air pressure reported in this paper is measured at the solenoid valve opening.

The reed valve was made to strike the valve plate repeatedly inducing impact fatigue stresses in them, hence, mimicking the movement of a reed valve in an actual compressor. A laser sensor measures the reed valve’s displacement, and thus velocity, and its operating frequency at a sampling rate of 10000 per second. This data is displayed and stored on the control software.

Figure 1. Schematic drawing of the working of the custom-built impact fatigue test system available at voestalpine Precision Strip AB, Sweden that was used to test the reed valve (test specimen) movement in this study.

In the custom-built impact fatigue test system, one important component that influences the reed valve movement is the high frequency solenoid valve. It is a two-way, in-line valve that is electrically actuated with moulded-in cable. Installed in the impact fatigue test system, it receives compressed air after the pressure regulator and through its fast switching action converts it into pressurized air pulses of fixed frequency and pulse-width. These pressurized air pulses are then supplied to a reed valve/test specimen that moves in response. A schematic representation of the switching behavior of the solenoid valve for a trigger pulse-width of 5 milliseconds is shown in Figure 2. It shows that the solenoid valve takes about 1 millisecond to switch on as the electric current flows through the moulded-in wire and into the solenoid coil. As the solenoid valve opens the compressed air pushes through a small opening as the pressure starts to rise to reach its maximum value of 6 bars; the air pressure then stabilizes for approx. 3 milliseconds before the valve switches off; the valve switching off time delay is approx. 0.6 milliseconds; as the solenoid valve starts to close the pressure starts to reduce to its minimum value. This pulsing cycle is repeated a few thousand times as the reed valve movement data is recorded on the control software.

Figure 2. Schematic representation of the switching behavior of the high frequency solenoid valve provided by its manufacturer for compressed air pressure of 6 bars.
2.1. Test specimen designs & material
The geometry of the reed valves tested in this work is presented in Figure 3. The valve designs were chosen as typical examples of the suction valves found in the commercially available compressors. The suction valves, typically, are not limited by a valve stopper or space limiter in compressors. Therefore, only suction valve designs were chosen to be studied here. The reed valves were produced by photochemical etching process along the rolling direction of the 0.203 mm thick Flap-X material. The reed valves were subsequently tumbled as is common practice in the compressor industry.

The reed valve design 1 consists of a neck and head with a gradual curvature connecting these two components of the valve, see Figure 3a. The reed valve design 2 is like a cantilever beam with the head diameter equal to that of the valve design 1, see Figure 3b. The valve design 3 is a two-legged cantilever beam type with an empty groove in the middle separating the two legs, see Figure 3c.

In the impact fatigue test system, all the valve specimens tested in this study were mounted through two pins attached to a steel block passing through two holes in the valves. This steel block covered the bottom end of the valves over a length of 8.5 mm, thus, clamping the valve’s movement in any direction in that area, see Figure 4. The reed valves were tested against the tool steel valve plates. No valve limiter/stopper was used instead full free movement of the suction valve was allowed in the outward direction.

Figure 3. The geometry and dimensions of the suction valve specimens used in this study: a) reed valve design 1; b) reed valve design 2; c) reed valve design 3.
Figure 4. In the impact fatigue test system, the reed valve was mounted using a steel block that covered a part of its length. The measuring point of the laser detecting valve movement detecting valve movement data was 2.5 mm from the top edge of the valve head along the centerline.

The reed valves were manufactured from 0.203 mm thick strip of Flap-X steel grade. Flap-X is a martensitic stainless steel that is hardened and tempered to achieve a combination of high tensile strength, ductility and high cleanness that are vital for good impact fatigue and bending fatigue properties. The nominal chemical composition of Flap-X is shown in Table 1

Table 1. Nominal chemical composition (wt. %) of the Flap-X steel grade used for the reed valve specimens

| Steel grade | C  | Si  | Mn  | Cr  | Mo  | P   | S   |
|-------------|----|-----|-----|-----|-----|-----|-----|
| Flap-X      | 0.38 | 0.45 | 0.55 | 13.5 | 1.00 | ≤0.025 | ≤0.015 |

3. Results and Discussion

3.1. Reed valve frequency

The reed valve frequency data of the reed valve design 1 as recorded by the laser sensor is plotted in Figure 5. The frequencies plotted here are the response frequency of the reed valves when they are subjected to air pulses of certain frequencies and pulse-widths. The main feature of the plots in Figure 5a and 5b is that the response frequencies of the reed valves as indicated by the peaks are multiples (0.5, 1, 1.5, 2, 2.5, 3...) of the frequency of the input air pulse. The response plot in Figure 5c shows that although one of the peaks matches the input frequency of the applied air pulses of 305 Hz but there are a few other peaks that are not multiples of the input frequency. This could be due to the fact that the pulse width of 2.49 ms is 3/4th of the time period compared to ½ of the time period for lower frequencies of 50 Hz and 110 Hz. The longer pulse-width of 2.49 ms was applied because half of the time period of the input pulse of air would be too little time for the high frequency solenoid valve to be able to open and close to generate pulses (see Figure 2). In terms of the frequency data, the response of the other two valve designs was also similar with minute differences.
Figure 5. Reed valve displacement plotted as a function of time for the valve design 1 specified to the solenoid high frequency valve: a) test frequency = 50 Hz, pulse-width = 10 ms, airflow rate = 90 litres/minute; b) test frequency = 110 Hz, pulse-width = 4.54 ms, airflow rate = 76 litres/minute; c) test frequency = 305 Hz, pulse-width = 2.47 ms, airflow rate = 131 litres/minute.

3.2. Valve lift measurements
The valve lift measurements were done by the laser sensor installed in the impact fatigue test system. The plots in the following sections show the response displacement of the valve recorded at a sampling rate of 10 000 Hz by the laser sensor i.e. each data point on the curves shows position of the valve recorded after an interval of 0.0001 seconds.

3.2.1. Test frequency = 50 Hz, Pulse width = 10 ms: The reed displacement response is plotted for the three specimen designs at input frequency of 50 Hz and pulse-width of 10 ms in Figure 6. It can be observed that the reed valve opens with a slight delay after the trigger voltage is applied to the high frequency solenoid valve. After the valve is pushed open to the maximum amplitude, the valve flutters without striking against the valve plate that is positioned at approx. -4 mm. After the air pulse is finished – observe the trigger voltage pulse in Figure 6 – the reed valves strike against the valve plate. There are at least three bounces of the reed valve observed for all the valve designs before the reed valve is opened by another incoming air pulse. One can observe that the highest reed valve opening amplitude is the highest for reed valve design1 and the lowest for the design 3. Furthermore, some variations in the shapes of the response displacement curves can also be observed between the different reed valve designs. These differences are mainly due to the different designs of these valves as all the other input test conditions such as the air pressure (approx. 7 bars) and airflow rate (90 litres per minute) were kept the same.
3.2.2. Test frequency = 110 Hz, Pulse-width = 4.54 ms. The response displacement is plotted for three different valve designs for higher frequency of 110 Hz and smaller pulse-width of 4.54 ms in Figure 7. Here, it can be seen that the valves of design 1 bounced two times against the valve plates for each applied pulse of compressed air. However, no fluttering of the reed valves was observed for this valve design, see Figure 7a. On the other hand, the shape of reed valve’s response displacement curves for the design 2 varies from one applied pulse to another even though cyclic patterns can be observed, see Figure 7b. The maximum opening amplitude varies considerably for different cycles of movement. In addition, fluttering of reed inter-mixed with multiple bounces against the valve plate were observed. Similarly, for the valve design 3 the valve lift curve shows considerable variations in response to successive pulses of applied compressed air, see Figure 7c. The results from this testing shows that the valve design 1 is not only more efficient as it shows higher displacement amplitude for same input test conditions but it shows the most steady movement as well.
3.2.3. Test frequency = 300 Hz, Pulse-width = 2.49 ms: In this test condition, the valves were subjected to a much higher frequency of 300 Hz and pulse-width of 2.49 ms that makes 3/4th of the total time period of the applied frequency, see Figure 8 for the displacement response. Since, the pulse width is quite small there is very little variation in the applied pressure magnitude as shown by the almost flat line at the top. This is due to the switching behaviour of the high frequency solenoid valve, its inherent time delay and the limitation of its response time, see Figure 2. The small pulse-width also means that there is only one clean vibration of the reed valve per pulse-width without any valve fluttering or multiple bounces. Moreover, such a valve movement means more stable and constant amplitude of displacement over many cycles which allows more accurate evaluation of the average valve impact velocity as the loading parameter. It can also be seen that the valve lift or the highest opening amplitude of the reed valve is the highest for design 1 and the lowest for the design 3. Therefore, the valve design 1 has once again proven itself to be more efficient at higher frequency too.
3.3. Reed velocity measurements

The reed valve’s velocity is one of the most important parameters as it helps determine the intensity of its impact against the valve plate. The reed valve velocity was determined by subtracting the successive points of displacement, say $x_1$ and $x_2$, recorded by the laser sensor at successive time points, say $t_1$ and $t_2$, as shown in the following formula:

$$v_1 = \frac{x_2 - x_1}{t_2 - t_1}$$  \hspace{1cm} (1)

The intensity of the impact is determined by the kinetic energy transferred by the valve to the valve plate. This kinetic energy depends on the velocity of the valve, thus termed the impact velocity of the valve, just before it strikes against the impact plate.

3.3.1. Test frequency = 50 Hz, Pulse-width = 10 ms: The reed velocity of the different valve designs studied in this paper are shown in Figure 9 for test frequency of 50 Hz and pulse-width of 10 ms. The positive side of the scale showing reed velocity is for the valve opening phase whereas the negative for the closing. In this study, we are more interested when the valve is in the closing phase, i.e. the negative velocity values in Figure 9. For each pulse-width the highest negative are the ones when the valve is about to strike against the valve plate, thus, its impact velocity. It can be observed that the highest impact velocity was attained by the valves of design 1 and the lowest by the design 3.
3.3.2. Test frequency = 300 Hz, Pulse-width = 2.49 ms: Similarly, reed velocity data for the three different valve designs is shown in Figure 10 for a much higher test frequency of 300 Hz and smaller pulse pulse-width of 2.49 ms. Testing these valve designs at this frequency provides too advantages: 1) accelerated impact fatigue testing that reduces test times to practical limits, 2) the loading parameter of the impact fatigue tests i.e. impact velocity is much more stable in magnitude. It can be observed from Figure 10 that the impact velocity – the negative peaks of the reed velocity curve – is the highest for the valve design 1. The higher the impact velocity of a reed valve the higher the impact fatigue stresses generated in it. Thus, from this point of view, the highest impact fatigue stresses would be generated in the valve design 1 due to its higher valve lift and velocity. However, other design parameters of valves also dictate the concentration and magnitude of impact fatigue stresses in them [11].

Figure 10. Reed valve velocity plotted as a function of time for input frequency of 300 Hz and pulse-width of 2.49 milliseconds specified to the solenoid high frequency valve: a) specimen design 1; b) specimen design 2; c) specimen design 3.

In order to conduct the fatigue testing of a material, at least 15 specimens should be tested for indicative testing of the fatigue strength [12]. Following the same standard and applying it to the impact
fatigue testing would mean that the test times could be very long at the lower frequencies such as 50 Hz or 110 Hz. Testing at higher frequencies, such as 300 Hz for the valve designs tested in this study, would mean reducing the testing times to more practical times since the reed valves undergo several hundred millions of cycles during their operation. Moreover, the compressor manufacturers are interested in knowing the critical impact velocity values at which the reed valves suffer impact failure. Therefore, it is advisable to test the reed valves at frequencies where there is only one impact per pulse-width of compressed air and the scatter of impact velocities is as low as possible. Depending on the valve design, this optimal frequency could be different for different reed valves. Hence, an initial testing of a specific reed valve is suggested to determine the frequency and pulse-width at which the scatter reed valve displacement and velocity is minimum. This study further provides a template to test the bending fatigue and impact fatigue characteristics using the custom-built impact fatigue test system used here.

4. Conclusions
Following are the conclusions drawn from the suction valve movement experiments conducted using the impact fatigue test system in this study:

1. The reed valve design influences the important reed movement parameters such as the valve lift, valve velocity, impact velocity and the frequency of valve vibrations.
2. The valve design 1 was found to be more efficient as it produced higher valve lift while all the input parameters were kept the same.
3. The impact velocity of the valve design 1 was also found to be the highest, thereby, exposing the valve to possibility of higher impact fatigue stresses.
4. For a practical impact fatigue testing of the reed valves, the testing should be conducted at higher frequencies to reduce test times as well as for a stable amplitude of vibration and impact velocity.
5. The custom-built impact fatigue system used in this study shows prospects to conduct further research on the reed valves.

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