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HERMETIC COMPRESSOR VALVE ROBUST DESIGN ASSESSMENT

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ABSTRACT

Improving the performance or reducing the noise levels of a hermetic compressor often entails optimizing its discharge or suction reed valve design. However, such endeavors frequently involve conflicting objectives, necessitating a trade-off solution. Amidst switching designs, adherence to a crucial constraint is imperative: reliability. This work aims to utilize the staircase method to experimentally determine the bending fatigue strength of different valve materials while minimizing the number of tests and samples required. A shaker was employed to dynamically excite the valve at its resonance, with valve displacement continuously measured using a laser sensor. A software was developed to actively regulate the shaker power and frequency, ensuring precise control of displacement within the desired tolerance for each test. The load on the valve undergoes complete reversal with a mean stress of zero, subsequently adjusted to a zero-based approach using Goodman criteria. Testing proceeds until reaching 2 million cycles or valve failure. Since a real valve is used as specimen, not only the material properties are measured, but also the effect of manufacturing process for this specific design, like the tumbling edge radius. Later, this information is crossed with a specific valve design. To achieve this, FEA is employed to calculate stress and its variability. Material properties, shape, valve fixation position, valve opening, among others are included as variable parameters. A robust design is deemed achieved when the stress distribution is far away from the material strength distribution.

Keywords: Staircase, Fatigue, Valve, Bending, Stress

1. INTRODUCTION

Compressors play a vital role in various industrial and domestic applications in refrigeration systems. The efficiency and reliability of these compressors rely on the internal components like suction and discharge reed valves (Glaeser, 1999). These valves control the flow of the refrigerant in the compressor through a compression and expansion processes. To enhance the compressor performance or to reduce the noise levels, design optimization of the reed valves is necessary. However, this optimization often involves a complex variation in design parameters, while improving one may unknowingly compromise another. Employing modeling and simulation techniques can aid in understanding the potential trade-offs between compressor efficiency, noise levels, and valve reliability, thereby guiding the search for optimal design configurations.

The reliability of the compressors is crucial, as failure can lead to energy inefficiency, high costs and potential safety hazards. Reed valves in general are often subjected to cyclic loading during operation. Due to which these valves are susceptible to fatigue failure. Hence, ensuring the robustness of reed valve designs is crucial to mitigate the risk of premature failure and increase the operational lifespan of compressors.

In this paper, we present a comprehensive investigation aimed at achieving a robust design for reed valves in hermetic compressors. By integrating experimental testing and Finite Element Analysis (FEA), our aim is to uncover the complex relationships among material characteristics, manufacturing techniques, and design variables. We employ the staircase method as a systematic approach to ascertain the bending fatigue strength of diverse valve materials, all while maintaining strict adherence to reliability standards.

2. DESIGN AND METHODS

2.1. Staircase Method to compute the lower limit of the fatigue strength

The staircase method, as described by technique (Müller, Wächter, Masendorf , & Esderts, 2017) offers a robust and efficient approach for estimating the lower limit of fatigue strength in material testing. This method employs a sequential testing procedure wherein the stress level is iteratively adjusted based on the outcomes of previous tests. Specimens undergo cyclic loading at a predetermined stress level for a specified number of cycles, known as the "survival threshold" (e.g., 2 million cycles in this study). If a specimen survives this threshold, it is considered to have withstood the fatigue load, and the stress level is increased for the subsequent specimen. Conversely, if failure occurs before reaching the threshold, the specimen is deemed to have succumbed to fatigue damage, and the stress level is decreased for the next test. This iterative adjustment, based on binary outcomes (survival or failure), gradually converges towards the fatigue strength, with a systematic step size for stress increments typically set at 20 MPa.

The initial stress for the test is determined through simulation and prediction, aiming to locate the true fatigue strength just below the stress level where failure becomes increasingly probable, usually slightly beneath the established 2 million cycle threshold. By concentrating data points around the true fatigue strength, the staircase method achieves a more accurate estimation with a statistically determined lower limit, while utilizing fewer specimens. The test is concluded based on reaching a predetermined number of failure and survival events, such as 20 each, upon which statistical analysis is performed. Through systematic stress control and continuous monitoring of specimen response, the staircase method offers valuable insights into material fatigue characteristics, optimizing resource utilization and testing efficiency in engineering analyses. Further elaboration on this methodology can be found in the (ISO 12107, 2003), and the implementation of this test method involved the development of an in-house fatigue test rig.

2.2. Fatigue Test Setup and Software

The valve fatigue analysis is conducted using a comprehensive measurement system comprising several key components as shown in Fig. 1. A NVH permanent magnet shaker (PM-20) generates small cyclic vibrations to excite the valve clamped end, allowing it to oscillate at its resonance frequency at the port of the valve. This shaker, with a frequency range of 0-12 kHz and peak-to-peak displacement of 5mm, can withstand a maximum payload of 0.8 kg, facilitating precise testing conditions. Displacement measurements during testing are captured using a high-speed laser system (Opto NCDT 2300 and 1900), with a measuring range of 2 – 500 mm and accuracy of 0.03 µm – 0.1 µm, enabling the detection of crack initiation and amplitude decrease. Additionally, a small mass (~1 gm) affixed at the port of the valve ensures testing at the mode 1 natural frequency.

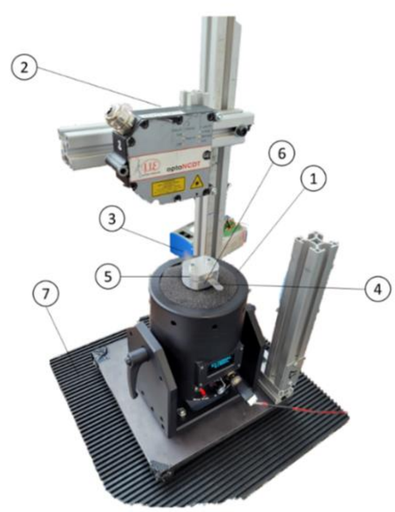

Figure 1: Test setup to measure the bending fatigue of Reed Valves

The fatigue test bench is automated using LabView Scripts, featuring a user-friendly graphical user interface (GUI) for input parameters such as cycle target, target amplitude, resonance frequency, and maximum deviation. The software controls and monitors the test parameters, including resonance frequency analysis, amplitude control using a PID controller and Laser system, and the determination of the number of cycles to failure, offering an integrated solution for precise and efficient fatigue testing of valves.

The automated fatigue test system is programmed to deliver a controlled amplitude with tolerance of ± 0.1 mm. An inbuilt PID controller is used to control the amplitude and deliver the required peak to peak amplitude. Additionally, the amplitude "deviation limit" plays a vital role during the valve testing. An amplitude deviation below the limit specified indicates that a crack has been initiated in the valve. The measurement stops and the number of cycles to failure is noted. The moment of failure is shown in Fig. 2.

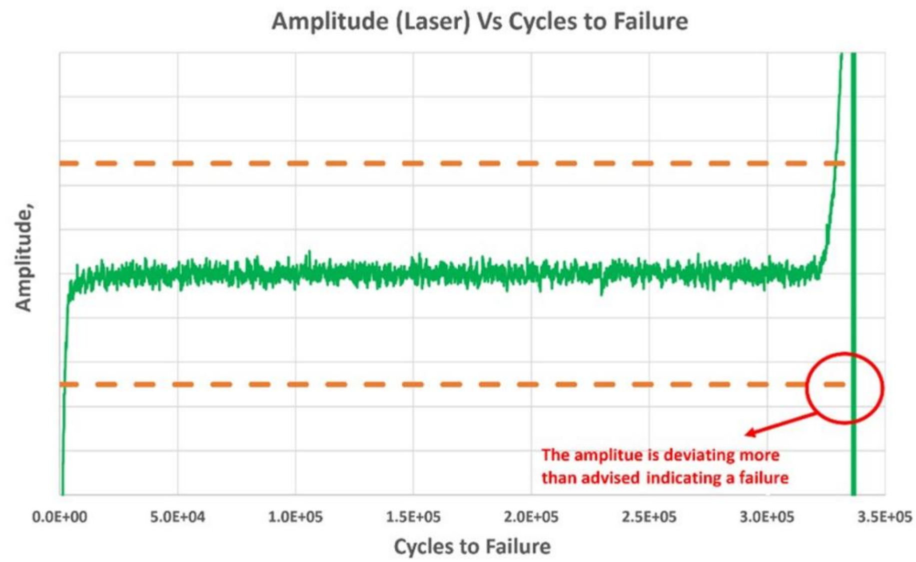

Figure 2: Amplitude Control in Software and detection of crack in Valve Reed

2.3. Experimental setup

In this investigation, the emphasis was on subjecting a commonly employed compressor suction reed valve to fatigue testing. The valves were carefully selected ensuring an edge radius representative of tumbling process. Utilizing the staircase method, renowned for its effectiveness in fatigue testing, the study explored the fatigue behavior of this valve across four different materials. These materials, as detailed in Table 1, vary in their compositions, thereby presenting a diverse spectrum of properties for analysis and comparison.

Table 1. Materials used for Staircase method of fatigue testing.

Material	Type
A	Carbon Steel
B	Stainless Steel
C	Improved materials for bending and impact fatigue strength
D	

Each specimen is carefully placed in the test device using a gauge to ensure low variability in the clamping location. A sensitivity analysis was done both numerically and experimentally, and this factor can significantly affect the conclusions of the investigation.

The laser position needs to be placed consistently between all tests, for that, the laser position was fixed vs the shaker for the same valve model.

The software controls the amplitude of the valve motion very precisely. Nevertheless, the shaker power and displacement amplitudes are limitants to the maximum valve displacement achieved. Due to that, a small mass must be added to the valve tip in order to maximize the displacements achieved, but just for the amount needed. The target is to use the smallest possible mass that can achieve enough displacement to obtain failures because the higher the mass, the lower the 1st mode natural frequency, and the longer the test execution time.

2.4. Numerical model FEA

For the valve design stress distribution, FEA was employed to evaluate the effect of different parameters variation (inputs) on the bending stress (output). The main contributing parameters are Young modulus, clamping length, cross section widths, shape radius, clamping position, valve opening, among others. Those are varied withing their tolerance ranges. A similar approach was used by Castro et al., (2021) to obtain the sensitivity of a ceirtan output to variations of design parameters.

Monte-Carlo Simulation was used to combine all those different designs with small variations. The result is a normal distribution of stress values which is then crossed with the experimentally obtained fatigue strength (Fig. 4 bending stress black curve).

3. RESULTS

The results from the staircase tests for all the material types is depicted in Fig. 3. Using statistics, the staircase results are converted into average and standard deviation for fatigue strength, for a defined confidence level. The lower limit can be selected for the desired failure probability. This is combined with the valve design stress in Fig. 4. Note that the FEA results are using the valve opening amount, and the minimum stress is zero (R=0). To compare this to the experimental results in the same basis, one must convert the fully reversed stress (R=-1) from the experiment into zero base (mean stress not zero) using Goodman.

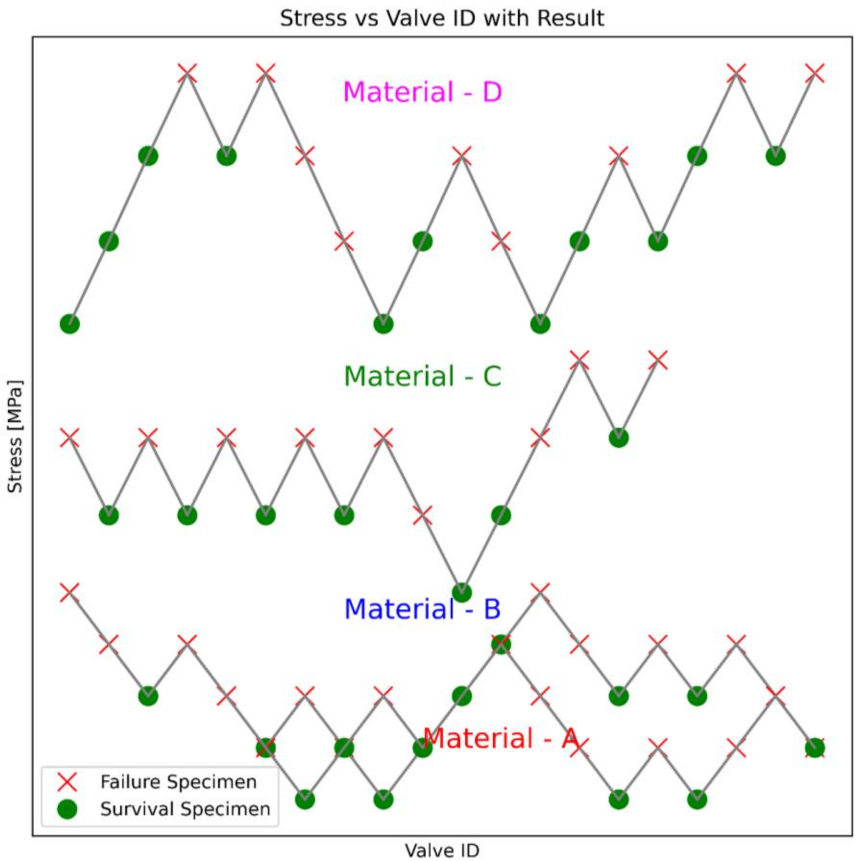

Figure 3: Staircase results

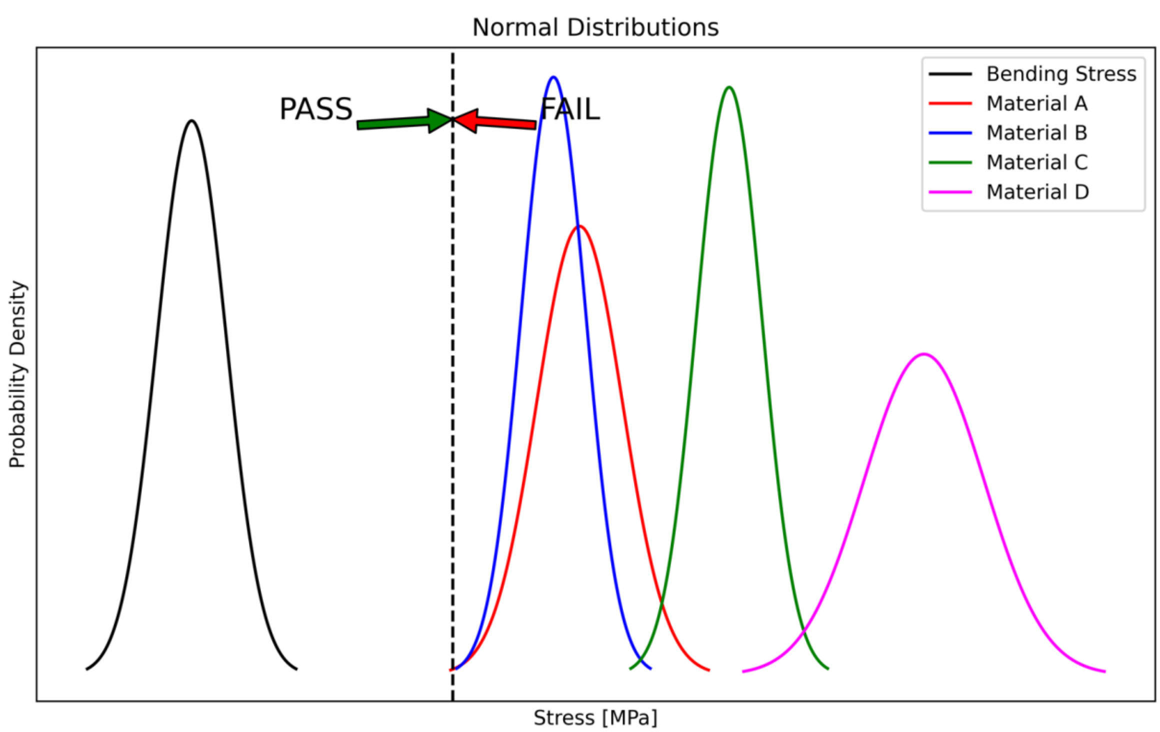

Figure 4: Stress vs strength distributions

Figure 5 shows the crack location corresponding to the maximum stress region on this valve. All failures happened in the same location. It is important to keep the test running for some seconds when a deviation happens to ensure it is a real failure, this also allows the crack to grow and be visible. If the test is stopped too fast at the minimum value of deviation, many times the crack can't be seen, but once the test is restarted for some seconds, it is visible.

Another detail to take into account that affects significantly the results is that since the laser measures the linear distance below it, for high openings (more than 10mm) it is not correct to use a node displacement in the FEA model. The workaround was to create a gap sensor where the laser is located, and the distance to the valve was always checked, so the bigger the opening, the distance point on the valve moves accordingly.

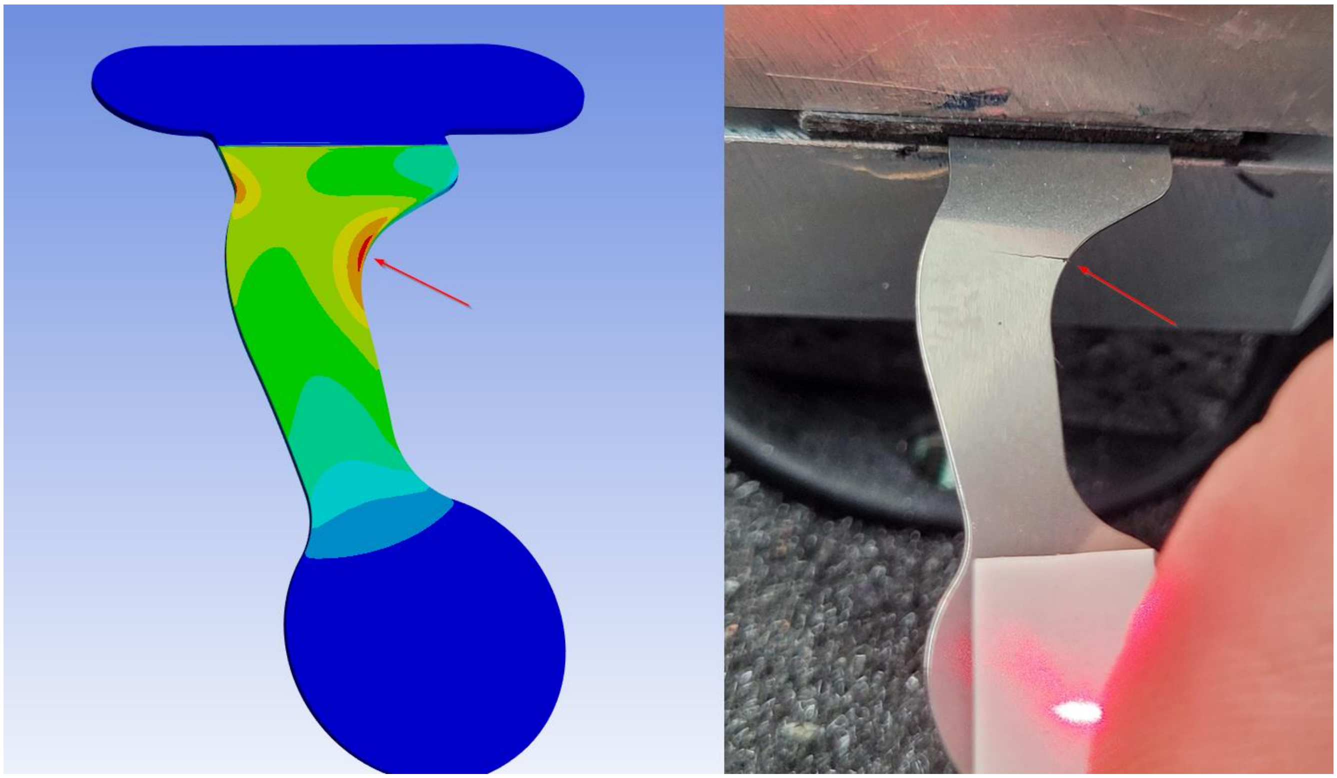

Figure 5: Stress from FEA and crack location from test failure

4. CONCLUSIONS

Results show that for this valve design and boundary conditions, any material can be used regarding bending fatigue. Some with larger safety factor than others. Finally, the correct material is selected based in other characteristics that affect reliability as well. As an example, impact velocity is a possible failure mode, and higher grade materials are normally better suited for this.

Materials A and B did not show relevant difference regarding bending stress for this valve design and thickness, which does not mean they are not different regarding other characteristics.

NOMENCLATURE

FEA	Finite element analysis
MPa	Unit of pressure
GUI	Graphical user interface
NVH	Noise, vibration, and harshness
PID	Proportional – Integral – Derivative

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