Testing and calculation of impact fatigue strength of Flap-X and SS 716 flapper valve steel grades

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Abstract. During the operation of reciprocating compressors, the flapper valve opens and closes under fluid pressure and flow. As it closes, it strikes against the valve seat, generating stresses and noise. This cycle of loading produces bending and impact fatigue stresses in the reed. This load pattern is repeated billions of times during the service life of a compressor and it defines the service life and reliability. The goal of this study was to calculate the impact fatigue strength of the Flap-X and the SS 716 grades and, to provide the compressor manufacturers with the information they can use to specify a steel grade to be used in their compressors, for reliable service. Impact fatigue tests were conducted on a custom-built impact fatigue test rig that used air pulses to produce movement of the reed valves manufactured by a major European compressor manufacturer Nidec Global appliance GmbH, at a frequency of 315 Hz and pulse width of 2.2 milliseconds. The testing was conducted according to the staircase test method detailed in the International Standard SS-ISO 12107:2012. The impact fatigue strength of the Flap-X and SS 716 steel valves was calculated in terms of the impact velocity according to the modified staircase test method in the standard. The test results and their statistical analysis showed that the impact fatigue strength of the Flap-X grade was higher compared to the SS 716 grade. The calculation and testing of the impact fatigue strength of the flapper valve steel grades could help the compressor designers to select the optimum material for their compressor designs, to provide reliable service. The higher impact fatigue strength of the Flap-X grade, lower failure rate and longer impact fatigue life will allow the compressor manufacturers to design thinner valves, as Flap-X can sustain higher impact fatigue stresses reliably for longer time and, at the same time help reduce noise, as thinner valves produce less noise for a given pressure and frequency.

1. Introduction
Reed valves are one of the vulnerable components of reciprocating compressors. The efficiency and reliability of compressors depends a lot on the valve’s performance. For example, higher valve lift can improve the efficiency of compressors. But, higher valve lift tends to increase impact velocities and impact fatigue stresses in valves. Increased impact fatigue stresses in the reed valves are detrimental to their impact fatigue life. In the past, several experimental studies have been conducted on the impact fatigue testing of different valve materials and their beneficial characteristics for improving the impact fatigue life and the impact fatigue strength such as Svenzon [1], Dusil and Johansson [2], and Chai et al. [3]. In addition, numerous theoretical studies such as by Pandeya and Soedel [4] and Böswirth [5]...
have discussed the dynamic behavior of the reed valves. Also, the impact fatigue stress state generated due to their impact against the impact seat during compressor operation was discussed. A previous study by Löf et al. [6] has reported that the reed valves of the Flap-X grade have significantly increased impact fatigue life.

This study aims to calculate and test the impact fatigue strength of the Flap-X and the SS 716 grades and, to provide the compressor manufacturers with the information they can use to specify a steel grade to be used in their compressors, for reliable service.

Materials

In this specific study, two flapper valve steel grades were investigated for their impact fatigue properties. Flap-X and SS 716 steel grades are upgrades of the standard martensitic stainless steel AISI 420, see their chemical composition in Table 1. The “SS 716” grade is a well-established valve steel which has been used for many years while “Flap-X” is the latest upgraded version developed and produced by voestalpine Precision Strip AB.

### Table 1: Nominal chemical composition of the tested steel grades (wt. %)

| Steel grade | C   | Si  | Mn  | Cr  | Mo  | N   | V   | P   | S   |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| SS 716      | 0.38| 0.45| 0.55| 13.5| 1.00| ≤0.025| ≤0.015|
| Flap-X      | 0.38| 0.45| 0.56| 13.5| 1.00| +   | +   | ≤0.025| ≤0.015|

The tested valve steel grades are high strength hardened and tempered strip grades that exhibit primarily martensitic microstructures. They are hardened and tempered at suitable temperatures and times in order to obtain a good blend of mechanical strength and toughness. The mechanical and physical properties of all the tested steel grades are shown in Table 2.

### Table 2: Mechanical and physical properties of the tested steel grades

| Steel grade | Thickness (mm) | Elastic modulus (GPa) | Density (kg/m³) | Tensile strength (MPa) |
|-------------|----------------|-----------------------|----------------|------------------------|
| SS 716      | 0.203          | 210 - 220             | 7700            | 1810±80                |
| Flap-X      | 0.203          | 210 - 220             | 7700            | 2100±60                |

### 2. Experimental testing

**Impact fatigue tests by voestalpine Precision Strip AB**

Impact fatigue tests were conducted on a custom-built impact fatigue test rig that uses air pulses to produce movement of the reed valves. The testing equipment is connected to a dedicated compressor. The operating conditions of test such as the operating frequency (valve reed’s natural frequency) and pulse width, can be varied. However, it is preferred to run the testing at or close to the natural frequency of the valves in order to ensure high values of impact velocity and valve lift of the reeds at the applied pressure.

The suction valves in the as-received condition were already spot welded to the valve plate. The valves were mounted by covering the root area by a steel strip to support and prevent the spot welds from fracturing during the impact fatigue tests, see Figure 1. A pink paint marker was used to create a spot at the tip of the reed valves to facilitate better detection of their movement by the laser sensor.
Figure 1. Nidec’s suction reed valves mounted in the impact fatigue test rig at voestalpine Precision Strip AB. The pink paint was placed on the tip of the reed valve for efficient reflection of the laser from the reed surface.

During the testing, the valve reeds were repeatedly pushed away from the valve plate using air pressure pulses and then allowed to strike the impact plate due to the elastic restoring force, after the pressure pulse was removed. The laser sensor recorded the displacement of reed and its frequency while the piezoelectric sensor recorded the amplitude of the induced vibrations, and their frequency, in the impact plate. The control software was used to control the operating conditions. The software also recorded the displacement amplitude, impact velocity and the frequency of reed movement data onto a dedicated PC. However, the recorded impact velocity data cannot be directly used. Therefore, this recorded data is used to calculate the reed velocity and is plotted against the reed displacement in Figure 2. From this data the average impact velocity of about 126 cycles is calculated at the instance when the valve is about to strike the impact plate as shown by the interval indicated by parallel lines on the right half of the plot. As explained before the staircase impact fatigue testing of the suction reed valves was conducted at the frequency of 315 Hz and pulse width of 2.2 ms.
Figure 2. With frequency of 315 Hz and pulse width of 2.2 ms, the reed velocity of the tested valves is plotted against the reed displacement by the data points registered after every 0.1 ms for 400 ms (~126 cycles).

The impact fatigue strength of the Flap-X and SS 716 reed valves was calculated in terms of their impact velocity at 50 million cycles as the runout limit using the International Standard SS-ISO 12107:2012 [7]. In the staircase test method 15 samples of reed valves of Flap-X and SS 716 were tested, see Table 3. In addition to the staircase testing, to estimate the average impact fatigue life of the Flap-X grade five samples of reed valves were tested at the highest achievable normalized impact velocity of 1. The normalized velocity is calculated by dividing the test impact velocity by the observed highest achievable velocity (v/v$_{max}$) for Nidec’s design of valves.

Table 3. Test matrix showing the types of tests and the number of samples

| Steel grade | Staircase testing | Impact fatigue life tests |
|-------------|-------------------|----------------------------|
| Flap-X      | 15                | 5                          |
| SS 716      | 15                | -                          |

There are two methods described for calculating the fatigue strength in the standard SS-ISO 12107:2012 [7]. The standard staircase test method for data analysis (referred, hereafter, as “method 1”) counts the frequencies of failure and non-failure (or runout) of the specimens tested at different stress (normalized impact velocity) levels. The method 1 is used for the group of samples (failure or non-failure) with the least number of observations. The modified staircase method (referred, hereafter, as “method 2”) determines the mean fatigue strength by averaging the test stresses (normalized impact velocities) of the samples from and beyond the last non-failure from the beginning. The method 2 takes into account all the test sample without regard to failure or non-failure.

_Compressor tests by Nidec Appliances GmbH_
These tests were conducted in an actual compressor with Flap-X and SS 716 valves being tested using the staircase test method. However, in these tests the compressor operating frequency was varied with a step length of 5 Hz instead of the impact velocity. The runout limit was chosen to be 5 million cycles. The number of cycles endured by the valves could be calculated from the following formula:

\[ L(f, t) = 60 \times f \times t \times 2 \]  

\( L \) = Number of load cycles  
\( f \) = compressor operating frequency (Hz)  
\( t \) = test time (min)

The compressor was operated at exhaust pressure of 10.9 bar and the suction pressure was kept to 1.087 bar. The temperature conditions inside the compressor were -10 °C and 70 °C. The impact velocities and the valve lift of the tested valves could not be measured in these tests.

3. Results

Impact fatigue test results from voestalpine Precision Strip AB

The staircase impact fatigue testing was conducted by testing the test sample at four different levels. It was intended to choose step length of 18% between the successive impact velocity levels. However, the highest impact velocity level that could be achieved for these Secop Nidec valves with our impact fatigue test equipment was limited by the equipment’s loading capability. Therefore, the final step between the highest and second highest stress level was 9%, see Tables 4, 5. The runout limit was selected to be 50 million cycles based on previous experience and also due to test equipment availability. If a test sample did not fail before 50 million cycles then the impact velocity level was increased for the subsequent test sample, otherwise if it failed, then the impact velocity level was decreased for the next sample.

For the Flap-X reed valves only two samples failed at the highest impact velocity level. However, the impact velocity levels could not be raised beyond a certain level (normalized stress value 1) even by increasing the magnitude of the applied pressure. The samples following the non-failures were also tested at normalized stress value of 1 as the limitations of the test equipment did not allow velocities beyond this for Nidec’s valve design, limiting the opportunity to evaluate the true performance of Flap-X.

Further impact fatigue tests were conducted to attempt to calculate the average impact fatigue life of the Flap-X valves at normalized impact velocity level of 1, see samples 16-20 in Table 4. However, this did not help as none of the five tested samples failed after 100 million cycles, and the tests were aborted without failure being achieved.

Table 4. Test matrix showing the normalized stress levels for the staircase impact fatigue testing of the Flap-X reed valves (Samples 1 - 15) and the impact fatigue testing to calculate the average impact fatigue life (samples 16 - 20). 0 = runout test sample, x = failed test sample

| Test sequence | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Normalized stress (v/v_{max}) | 1  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
|               | 0.91| 0  | 0  | x  | x  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
|               | 0.73| 0* | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
|               | 0.545| 0* | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |

None of the SS 716 reed valves survived 50 million cycles without failure when tested at the highest normalized stress value of 1, see Table 5. The test sample 11 failed at the intended normalized stress value of 0.91.

Table 5. Test matrix showing the normalized stress levels for the staircase impact fatigue testing of the SS 716 reed valves. 0 = runout test sample, x = failed test sample
The fatigue test plot in Figure 3 shows the values of the actual impact velocity of the reed valves of the Flap-X and SS 716 steel grades. This plot shows the normalized impact velocity values calculated from the reed valve’s movement data from the laser sensor, as explained in the description of Figure 2. It can be seen that the control of the impact velocity of the reed valve is not exact as the plotted values deviate slightly from the intended values in Tables 4, 5. The normalized impact velocity can be higher than 1 as, in some cases, the observed test impact velocity might be slightly higher than the assumed “highest” impact velocity level. For Flap-X the average impact fatigue life tests conducted at normalized impact velocity of 1 are shown by the samples 16 – 20 in Figure 3. For the SS 716 test sample 11 the actual impact velocity was slightly higher than the intended normalized impact velocity 0.91 and the sample suffered failure.

The table below illustrates the test sequence and normalized stress levels for Flap-X and SS 716:

| Test sequence | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|
| Normalized stress (v/v_{max}) | x | x | x | x | x | x | 0,91 | 0 | 0 | 0 | x | 0 | 0 | x | 0 |
| 0,73 | 0* | 0 |
| 0,545 | 0* |

![Graph](image)

**Figure 3.** Impact fatigue testing of the Flap-X and the SS 716 reed valves conducted according to the staircase test method (samples 1 – 15). The average impact fatigue life tests are shown by the samples 16 – 20.

Only two failures were observed among the tested Flap-X reed valves at the normalized impact velocity of ~1 after 21 077 463 and 8 369 089 cycles, respectively as shown in Figure 4. The remaining test samples did not fail within the 50 million cycles. The test data shows that among the runout test samples there are 13 samples that did not fail at and above normalized impact velocity of 1. The tests conducted to calculate the average impact fatigue life did not reveal much as none of the Flap-X samples failed up to 100 million cycles and beyond at the highest load level achievable.
Figure 4. Impact fatigue test data of the tested Flap-X reed valves with 50 million cycles as the runout limit.

All six of the SS 716 reed valves that were tested at the normalized impact velocities of 0.98 and above fractured before 50 million cycles, see Figure 5. The samples that were tested at the normalized impact velocities below 0.98 did not fail up to 50 million cycles.

Figure 5. Impact fatigue test data of the tested SS 716 reed valves with 50 million cycles as the runout limit.

Figure 6 compares the number of failures of the Flap-X and SS 716 valves at the highest achievable normalized impact velocity of 1. It can be seen that the failure rate of the Flap-X valves was half of that for the SS 716 grade. It can be seen that 15 Flap-X samples did not fail at this impact velocity level. On the other hand, none of the SS 716 valve samples survived at this velocity level.
Figure 6. Number of failed and runout values of Flap-X and SS 716 grades at the highest achievable normalized impact velocity of approx. 1.

Table 6 shows the calculated impact fatigue strength for the Flap-X and SS 716 grades at 50% and 95% probability of survival using the modified staircase method (method 2). The calculations of impact fatigue strength shown in Table 6 are based on the actual impact velocity values of the tested reed valves. The number of failures for the Flap-X grade (only 2) were not enough to apply the method 1 which took into account only the less frequent event (failures in this case). For the SS 716 grade there were enough failures (less frequent event) to enable a reliable estimate the impact fatigue strength at 50% and 95% probability of survival. According to the method 2, which took all the test samples into account regardless of them being failures or non-failures, the calculated impact fatigue strength of Flap-X was nominally higher than SS 716. The impact fatigue strength of the SS 716 grade calculated according to the method 1 was significantly lower than that estimated according to the method 2.

| Grade   | Probability of survival | Method 1 (v/v\_max) | Method 2 (v/v\_max) |
|---------|--------------------------|----------------------|---------------------|
| Flap-X  | 50%                      | N.A.                 | 1.06                |
|         | 95%                      | N.A.                 | 0.93                |
| SS 716  | 50%                      | 0.94                 | 1                   |
|         | 95%                      | 0.69                 | 0.87                |

An approximately linear relationship was seen when the valve lift of the tested reed valves was plotted against their impact velocities, see Figure 7. The higher the valve lift the higher the corresponding impact velocities of the tested reed valves. The valve lift of the SS 716 reed valves is approximately same or marginally lower than that for those of the Flap-X reed valves while their highest impact velocities are slightly higher.
Figure 7. Linear relationship between the valve lift of the tested samples of the reed valves when plotted against the corresponding normalized impact velocities.

Compressor test results by Nidec Global Appliance GmbH

The compressor test results are shown in Table 7. The number of samples and the average, minimum and maximum number of cycles endured by the SS 716 and Flap-X valves are shown against the compressor operating frequencies. The runout limit was set to 5 million cycles. At 105 Hz one SS 716 valve failed but the other survived while the only Flap-X valve that was tested survived up to 5 million cycles. At 110 Hz six valves of each Flap-X and SS 716 grades were tested but none of them failed up to the runout limit. It can be seen that the failures were more frequent at 115 Hz frequency and a comparison in the average impact fatigue life of the Flap-X and SS 716 valves can be made.

Table 7. Compressor test data for the Flap-X and SS 716 valve series showing average, minimum and maximum number of load cycles endured at each frequency.

| Frequency (Hz) | 100 Hz | 105 Hz |
|---------------|--------|--------|
| Runout limit = 5 × 10⁶ load cycles |        |        |
| No. Of samples tested | No. Of runouts | No. Of failures | No. Of samples tested | No. Of runouts | No. Of failures |
| SS 716 | 1 | 1 | 0 | 2 | 1 | 1 |
| Average no. of load cycles | - | 5,00E+06 | - | - | 5,00E+06 | 3,28E+06 |
| No. Of load cycles to failure | Min | - | - | - | - | - |
| Max | - | - | - | - | - | - |
| Flap-X | 0 | 0 | 0 | 1 | 1 | 0 |
| Average no. of load cycles | - | - | - | - | 5,00E+06 | - |
| No. Of load cycles to failure | Min | - | - | - | - | - |
| Max | - | - | - | - | - | - |
At 115 Hz compressor operating frequency, the average number of load cycles endured by the Flap-X valves was found to be about 20% higher than the SS716 valves as shown in Figure 8.

| Frequency (Hz) | 110 Hz | 115 Hz | 120 Hz |
|---------------|--------|--------|--------|
|               | No. Of samples tested | No. Of runouts | No. Of failures | No. Of samples tested | No. Of runouts | No. Of failures | No. Of samples tested | No. Of runouts | No. Of failures |
| SS 716        | 5      | 5      | 0      | 5      | 0      | 5      | 0      | 0      | 0      |
| Average no. of load cycles | 1,44E+06 | - | - | 3,38E+06 | - | - | | 4,14E+06 | - | - |
| No. of load cycles to failure | Min | - | - | - | - | - | - | - | - |
|                      | Max | - | - | - | - | - | - | - | - |
| Flap-X            | 6      | 6      | 0      | 6      | 1      | 5      | 1      | 0      | 1      |
| Average no. of load cycles | 3,38E+06 | - | - | 4,32E+05 | - | - | - | - | - |
| No. of load cycles to failure | Min | - | - | - | - | - | - | - | - |
|                      | Max | - | - | - | - | - | - | - | - |

**Discussion**

The standard staircase test according to the International Standard (SS-ISO 12107:2012) [7] requires at least 15 specimens to be tested for exploratory studies and at least 30 specimens for reliability purposes. In the current study, due to the constraints of the required testing time and available machine capacity, an exploratory study was conducted at voestalpine by testing 15 test samples of reed valves made of the Flap-X and the SS 716 steel grades. The test results obtained in this study are specific to Nidec’s design of reed valves. The failure rate of the reed valves of the Flap-X and SS 716 grades was compared. Estimation of the impact fatigue strength in terms of the impact velocity of the reed valves was done from the obtained impact fatigue test data. From the compressor tests conducted at Nidec the failure rate of the two grades was compared at varying frequencies.

The lower failure rate of the Flap-X reed valves as well as their higher impact fatigue strength, as the presented impact fatigue test and compressor test results have shown, is attributed to the higher impact fatigue resistance of the Flap-X material. The higher tensile strength, ductility and bending fatigue strength of Flap-X and the greater amount of retained austenite in its martensitic microstructure lead to greater impact fatigue resistance in the reed valves [6]. The fact that some of the test samples of the
Flap-X grade when tested at the normalized impact velocities of 1 (see Figure 4) or at 115 Hz frequency (see Figure 8) in compressor tests and survived up to the runout limits without fracture indicates that the survival probability of the Flap-X reeds at high impact velocities and frequencies is higher. On the other hand, none of the samples of the SS 716 grade survived when tested at and above normalized impact velocity of 0.98 (see Figure 5), which indicates their lower impact fatigue resistance at higher impact velocities. Therefore, the Flap-X reed valves are much more reliable from the impact fatigue perspective especially when subjected to higher impact velocities.

The calculation of the impact fatigue strengths stated in Table 6 at 50% and 95% probability of survival according to the methods described in the International Standard (SS-ISO 12107:2012) are handicapped by the lack of statistical data obtained from this testing. The testing was conducted according to the standard staircase test method (method 1). However, for the Flap-X grade the calculation of impact fatigue strength according to the method 1 could not be done because only 2 samples failed in our tests. The impact velocity levels could not be raised high enough to generate more failures of the Flap-X reed valves. On the other hand, the calculation of impact fatigue strength for the SS 716 grade was statistically reliable, as enough failures (7 failed samples) were observed. The calculation of the impact fatigue strength using method 2 was statistically reliable for both grades as it took all the test samples into account (failure and non-failure), although providing a conservative value for Flap-X due to the proportion of runouts. The impact fatigue strength for the Flap-X grade by this method was found to be approximately 6% higher than the SS 716 valves even though their failure rate was much higher. This is due to the limitation of not being able to test at the higher impact velocities required to fracture the Flap-X valves.

The control of the impact velocities was not exact, as the velocities varied slightly from the intended values. The deviation of the impact velocities from the intended values might be due to imprecise applied pressure regulation, uncontrolled variation of pressure from the dedicated compressor or possibly also due to the small differences in manufacturing or material of the reed valves. Some of the test samples when tested at the same applied pressures did not have the same impact velocity and valve lift values.

The higher impact velocities of the SS 716 did not mean higher valve lift for them, as shown in Figure 7. At roughly the same pressure, the impact velocities of the SS 716 reed valves were marginally higher but their valve lift was slightly lower. The lower impact velocities and the higher valve lift of the Flap-X reed valves is beneficial from the perspectives of reliability and efficiency of the compressors. The lower impact velocities mean that the Flap-X reed valves experience lower impact fatigue stresses and that, in turn, can translate into longer impact fatigue life of these valves.

**Conclusion**

1. The failure rate of the SS 716 reed valves in the impact fatigue tests is significantly higher compared to the Flap-X reed valves.
2. The conservative estimate of the mean impact fatigue strength (impact velocity) for the Flap-X reed valves was 6% higher than that for the SS 716 reed valves.
3. The compressor tests showed that Flap-X endured greater number of cycles compared to SS 716 at the compressor operating frequency of 115 Hz.
4. The limitations in the maximum applied stress of the existing impact fatigue testing apparatus reduced the number of failures in the Flap-X valves and therefore reduced the measured difference in impact fatigue strength between Flap-X and SS716.
5. The test results obtained in this study are specific to Nidec’s design and manufacturing process for reed valves.

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