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EXPERIMENTAL ANALYSIS OF THE PRECHARGING EFFECT AT THE DYNAMIC BEHAVIOR OF A REED VALVE USED IN REFRIGERATION COMPRESSORS

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Abstract. Hermetic reciprocating compressors are widely used in vapor compression refrigeration systems. An important component of this type of compressor is the automatic valve system, which controls the suction and discharge processes. The experimental or analytical/numerical study of this system is complex due to the fluid-structure interaction between the valves and the refrigerant flow, the geometric complexity of the system and also due to the non-linearity caused by the impact between the valve and its seat. A literature review suggests that this theme still deserves attention from the researchers, mainly for those who need accurate experimental data to validate numerical methodologies. Here, we experimentally evaluate the influence of precharging forces ranging from 95 to 360 mN on the dynamics of a large scale valve model used in refrigeration compressors. We measured the amplitude of the valve movement using optical sensor for Reynolds number ranging from $1,500$ to $20,000$ and calculated its frequency. In general, the effect of the precharging force is larger for lower Reynolds numbers - $1,500 < Re < 12,000$ -, and it decreases for higher Reynolds numbers. In addition, transition regions with unexpected abrupt reduction on the amplitude and frequency occur for precharging force ranging from 95 to 290 mN.

Keywords: compressor, fluid-structure interaction, valve dynamics, refrigeration.

1. INTRODUCTION

Energy saving became an important issue nowadays due to a future lack of resources and an environmental concern caused by burning fossil fuels. Solutions for this problem consist on finding alternative energy sources or improving machine efficiency. According to a ELETROBRAS report from 2007 freezers, refrigerators and air conditioners represent a large amount of domestic energy use in Brazil (47%). Therefore, any efficiency improvement at this kind of system could reduce substancially the energy usage.

One of the most important parts of refrigeration systems is the compressor, which converts electrical energy into energy stored in the form of pressure of the evaporated refrigerant. Besides its importance on the whole system, increasing efficiency increasing is desirable because compressors consume the large amount of electrical energy of the refrigeration system (She *et al.*, 2014).

Among the several types of compressor, the hermetic reciprocating compressors are the most commonly used in vapor domestic refrigeration systems (Yesilaydin and Erbay, 2015). According to Possamai and Todescat (2004), in this type of compressor, the losses can be subdivided into mechanical, electrical, thermodynamic and cycle losses. Disregarding the cycle losses because of its dependency on machine design and refrigerant properties, the thermal efficiency plays a critical role, because of its low value - about 83% - in relation to the others. According to Ribas *et al.* (2008), flow losses in the sucction and discharge valves can represent about 47% of the thermodynamics losses.

Due to manufacturing feature and based on low cost, reed valves are used in this type of compressor (Wang *et al.*, 2016). Its operation is based on the pressure difference between two chambers separated by the reed valve (Yoshizumi *et al.*, 2014). A good performance of the compressor requires: a quick response of the valve under pressure variation, a high refrigerant flow through valves, low pressure drops at the valve, no return of refrigerant and high mechanical resistance (Wang *et al.*, 2016). Therefore, the dynamics of this type of valve strongly interferes with compressor efficiency (Bhakta *et al.*, 2012).

Despite of their manufacturing and operation simplicity, the fluid-structure interaction between the valve and the refrigerant flow is very complex and can produce undesired effects on the dynamics of reed type valves. For example,

valve flutter can occur in suction valves, which can decrease the efficiency of the system (Burgstaller *et al.*, 2008; Hareland *et al.*, 2014; Wang *et al.*, 2015a).

In order to understand the dynamics of reed type valves, several authors investigated the influence of parameters such as valve stiffness (Wang *et al.*, 2015a; Gonzalez *et al.*, 2016; Wu *et al.*, 2016), valve damping (Lohn *et al.*, 2016), suction/discharge port diameter and valve stop (Rigola *et al.*, 2005), operating conditions (Rigola *et al.*, 2005; Lemke *et al.*, 2016) and representative valve models (Bukac, 2002). With the exception of valve damping, these studies suggested that the dynamics of the valve is sensitive by stiffness (Wang *et al.*, 2015a), suction/discharge port diameter, valve stop and operating conditions (Rigola *et al.*, 2005).

The precharging force is another parameter that affects considerably the dynamics of reed valves (Bukac, 2002; Lang *et al.*, 2016)and should be considered to better model the system (Lemke *et al.*, 2016; Wang *et al.*, 2015b), once it affects the gas leakage through the valves (Silva and Deschamps, 2015).

The objective of this work is to investigate experimentally the influence of the precharging force on the dynamics of a large scale reed valve model installed in an experimental bench specifically designed to study reed type valves, in which the parameters that influence the problem are well controlled and accurate measured.

2. EXPERIMENTAL PROCEDURE

Figure 1 shows the experimental set up used to study the valve dynamics. his set up is composed by two 500 liters air tanks connected in parallel, a mass flow rate control valve, a Coriolis mass flowmeter, a flexible tube, an aluminum tube containing two fine nets at the inlet and the test section (Figure 2), which is installed on a concrete base to attenuate vibration transmitted by the external environment.

A two-stage compressor fills the tanks with air at 10 to 12 bar. A constant mass flow rate - thus, the Reynolds number of the flow - is set by adjusting the pressure in the flow and pressure control valve, which maintains the mass flow rate constant while the upstream pressure is higher than the adjusted pressure. Then, the air flows through the Coriolis mass flow meter, flexible tube and through a 2 m long and 34.9 mm inner diameter aluminum tube until reaching the test section, where the valve model is installed. Two fine nets were installed at the inlet of the aluminum tube to regularize the velocity profile of the flow, which also help to guarantee a completely developed flow at the inlet of the valve model.
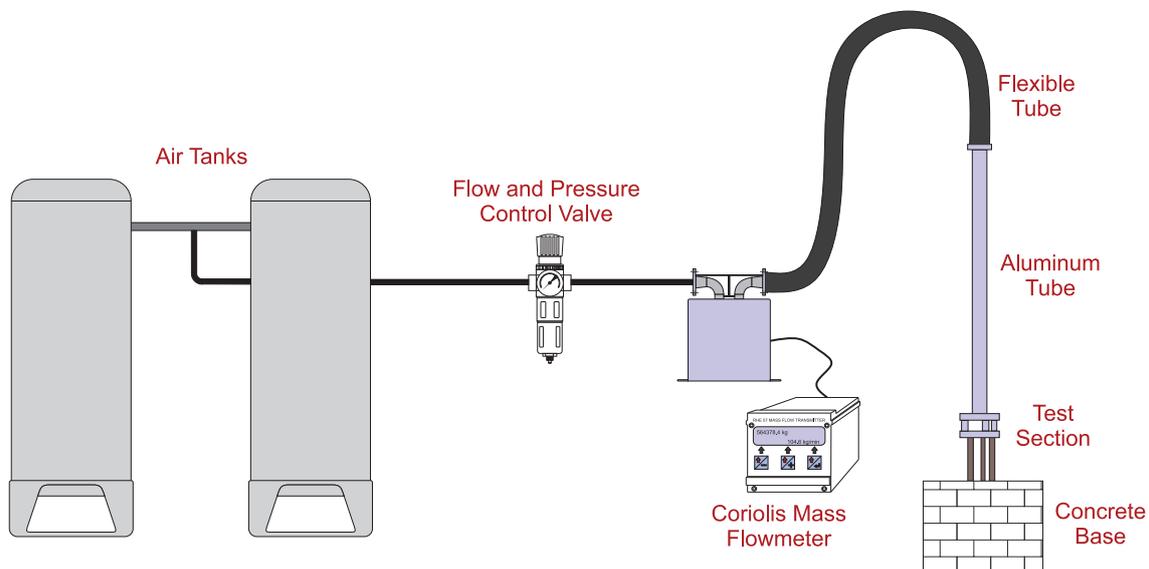

Figure 1. Experimental set up

The tests section consists of two circular steel disks (30 mm thick): the bottom plate and the valve seat. The bottom plate is fixed on the concrete base by three columns. The valve seat is assembled on the bottom plate through three similar columns displaced $120°$ from each other in order to guarantee the parallelism between the plates. In the bottom plate was installed the optical sensor used to measure the instantaneous position of the reed valve. The aluminum tube is installed in hole milled in the top of the valve seat. The inner diameter of the hole matches with the external diameter of the aluminum tube in order to avoid perturbations of the flow. The large scale model of a reed valve - 0.5 mm thick, made of stainless steel $AISI304$ - is fixed on the lower side of the valve seat through six bolts (Figure 3). This assembly was used to mimic the actual fixing procedure of the valve in reciprocating compressors.

The precharging effect was achieved by manufacturing the valve with a gap between the valve and the seat, δ, when the side 1 of the valve is faced up (Figure 4). In order to obtain the precharging effect, the valve is installed with side 1 faced down (Figure 4) - thus, the valve remains forced against the seat. The parameter δ was measured by the same optical
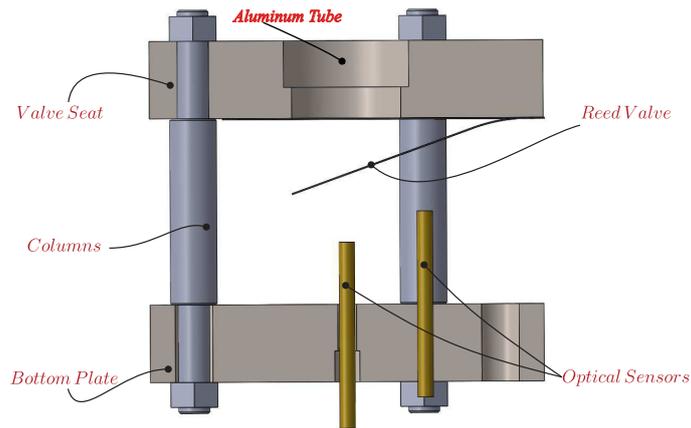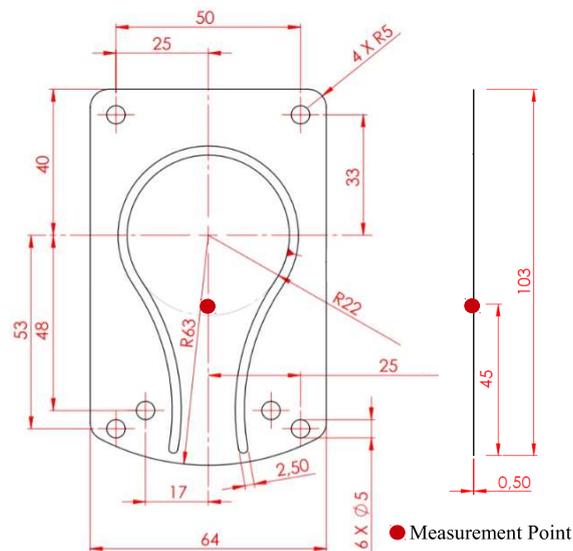
Figure 2. Test section

Figure 3. Reed valve model

sensor used for measuring the instantaneous position of the valve and in the same position - measuring point in Figure 4. The calibration curve provided by the manufacture states an uncertainty of $\pm 1\mu$m for the optical sensor.
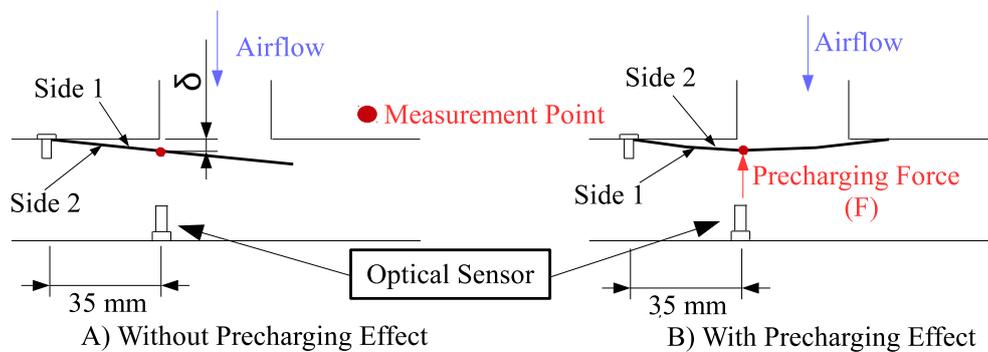

Figure 4. Precharging effect and measurement point of the instantaneous position of the valve

The precharging force was calculated using the software Ansys®. After implementing the geometry of the valve with the gap (Figure 4A) in the software Ansys, we numerically inverted the side of the valve - side 1 faced down - and calculated the force needed to place side by side the valve and the seat, that is, to turn the initial gap δ into zero. The precharging force corresponding to each δ is shown in Table 1.

Table 1. Precharging force (F) corresponding to each inicital gap δ.

Without precharging	With precharging
δ (mm)[1]	Force (mN)
0.10	95
0.14	126
0.30	280
0.31	290
0.38	360

[1] uncentainty of $\pm 0.002 mm$

3. RESULTS AND DISCUSSION

We performed 5 tests for each δ with side 1 faced up - tests without precharging - and 5 tests for each δ with side 1 faced down - tests with precharging -, for Reynolds numbers varying from $1,500$ to $20,000$. Although the objective of the work is studying the precharging effect, the results for the tests without precharging force were also provided for comparison reasons (Figure 5). We can see that the initial gap δ affects the amplitude and frequency of the valve movement when the valve is installed without precharging force (Figure 5). Even for these tests, we observe the impact of the valve on the seat - valve closed, which is indicated as zero displacement in the graph. The standard deviations of the Reynolds numbers varied between 0.4% and 0.9% for all tests. The difference between the maximum displacements were calculated, as the following equation demonstrates:

$$\Delta D_{max} = \frac{max(D_{max}) - min(D_{max})}{D_{max}} * 100\% \tag{1}$$

where, ΔD_{max} corresponds to the dimensionless maximum displacement difference and D_{max} to average of the maximum displacement for the 5 tests, for each δ.

Considering the tests without precharging (Figure 5), we observe that tests with similar gaps result in similar displacements and movement frequencies, except for Reynolds numbers equal to $4,000$ and $\delta = 0.1$, in which we notice higher frequency and amplitude. In general, the amplitude of the movement increases for increasing Reynolds numbers, except for the test with $\delta = 0.1$ mm, in which we observe a transition region with an abrupt reduction of the amplitude for Reynolds number of about $8,000$ (Figure 6). The amplitude behavior is reflected on the frequency behavior (Figure 7), in which we notice an abrupt reduction of the frequency from about 60 to 40 Hz for Reynolds numbers of about $8,000$. The physical mechanisms responsible for these behaviors still need to be investigated.

The presence of the same higher frequency (around 59Hz) is observed for all tests with precharging (Figure 8), which indicates again the increasing of system stiffness due the counter force caused by the precharging. As well as for the non precharging side, the movement frequency becomes similar for all tests as the Reynolds Number increases. Although, the presence of precharging increases the barrier for the valve movement, that makes higher flows (higher Reynolds Numbers) to overcome this barrier. Thus, the movement frequencies and the dynamics of the valves becomes similar only for higher Reynolds Number (around $12,000$).

For the tests with precharging effect (Figure 8), we observe that the influence of the precharging force is larger for Reynolds numbers lower than about $12,000$, in which we notice different amplitudes and frequencies for different precharging forces. This behavior can be better seen in Figures 9 and 10, where transitions regions presenting abrupt reduction of amplitude and frequency occur, except for the highest value of the precharging force - $F = 360$ mN. For this force, the amplitude increases monotonically for increasing Reynolds numbers, that is, there is no transition region. In addition, we can see that the transitions regions occur for different Reynolds numbers, depending on the value of the precharging force, and without a predictable tendency. For the most precharging forces - 95, 280, and 290 mN - the transition region occurs for Reynolds numbers ranging from about $9,000$ to $12,000$, while for the precharging force equal do 126 mN, the transition region occurs for Reynolds number of about $4,000$. The data also suggest that for precharging forces equal to 280 and 290 mN there is another transition region for Reynolds numbers of about $4,000$; however with the opposite tendency, that is, presenting a small increase of the amplitude during the transition. The behavior of the amplitude is passed on to the frequency behavior (Figure 10). However, we notice almost the same reduction of the frequency - from about 60 to 40 Hz - as observed for the valve without precharging effect, independently of the Reynolds number of the flow in which the transition region occurs. The physical mechanisms responsible for these transitions regions must be still investigated through other tests in the future.
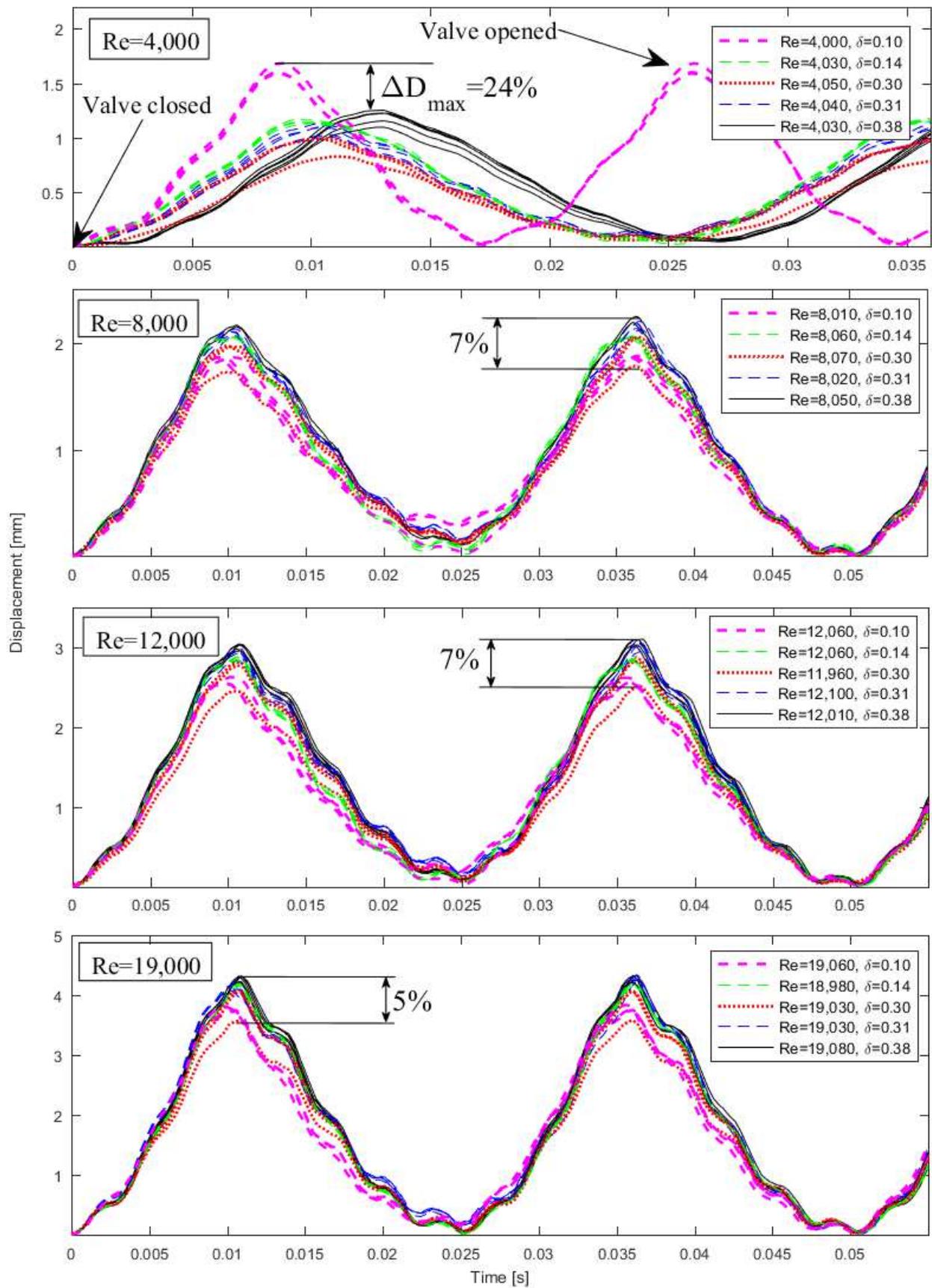
Figure 5. Instantaneous position of the valve for 5 tests without precharging effect
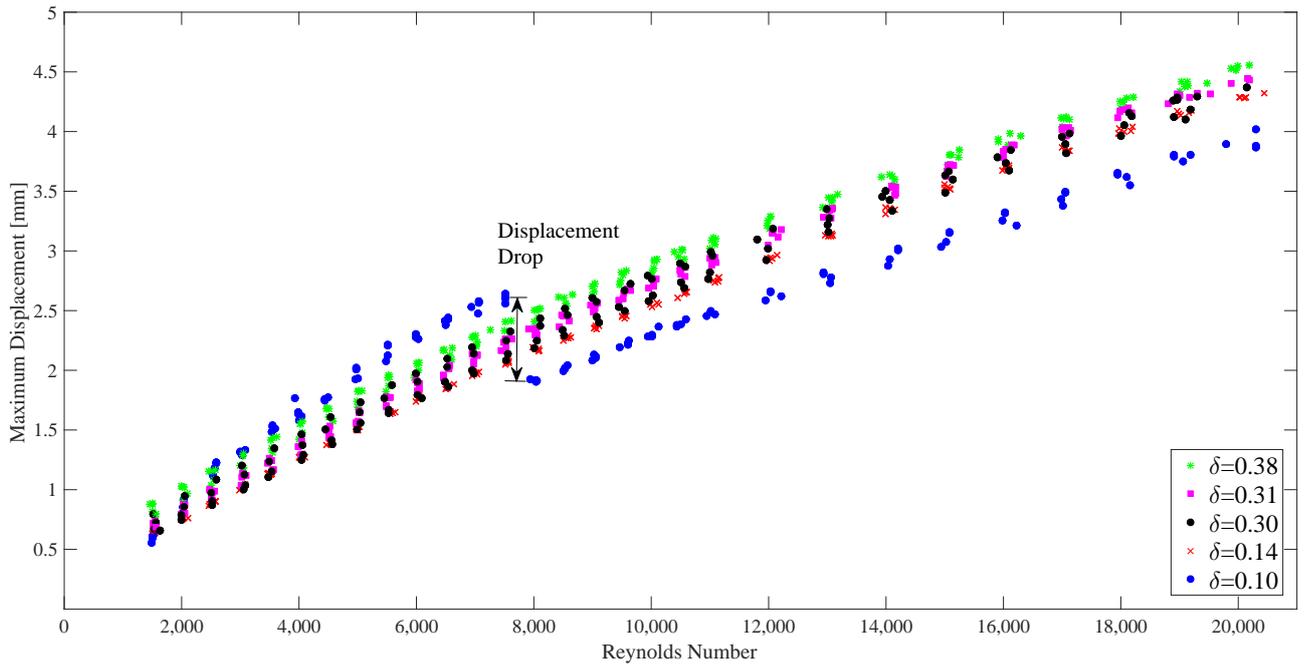
Figure 6. Amplitude of the valve movement as a function of the Reynolds numbers for all tests without precharging effect
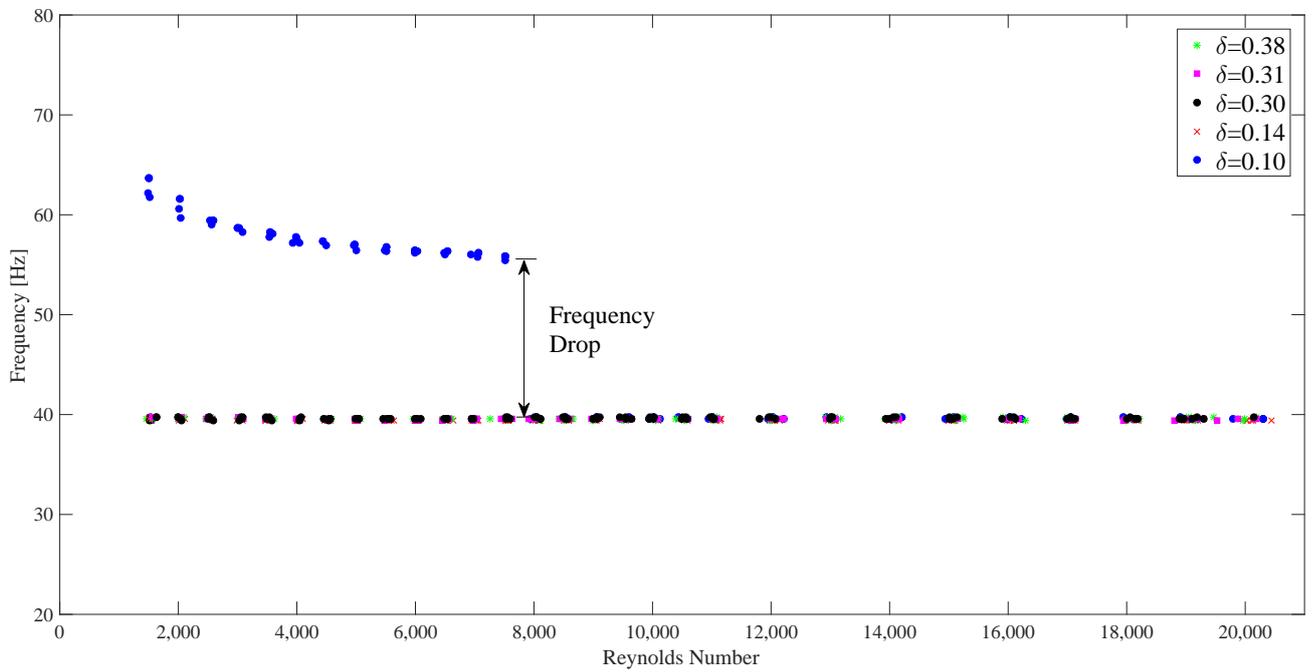

Figure 7. Frequency of the valve movement as a function of the Reynolds number for all tests without precharging
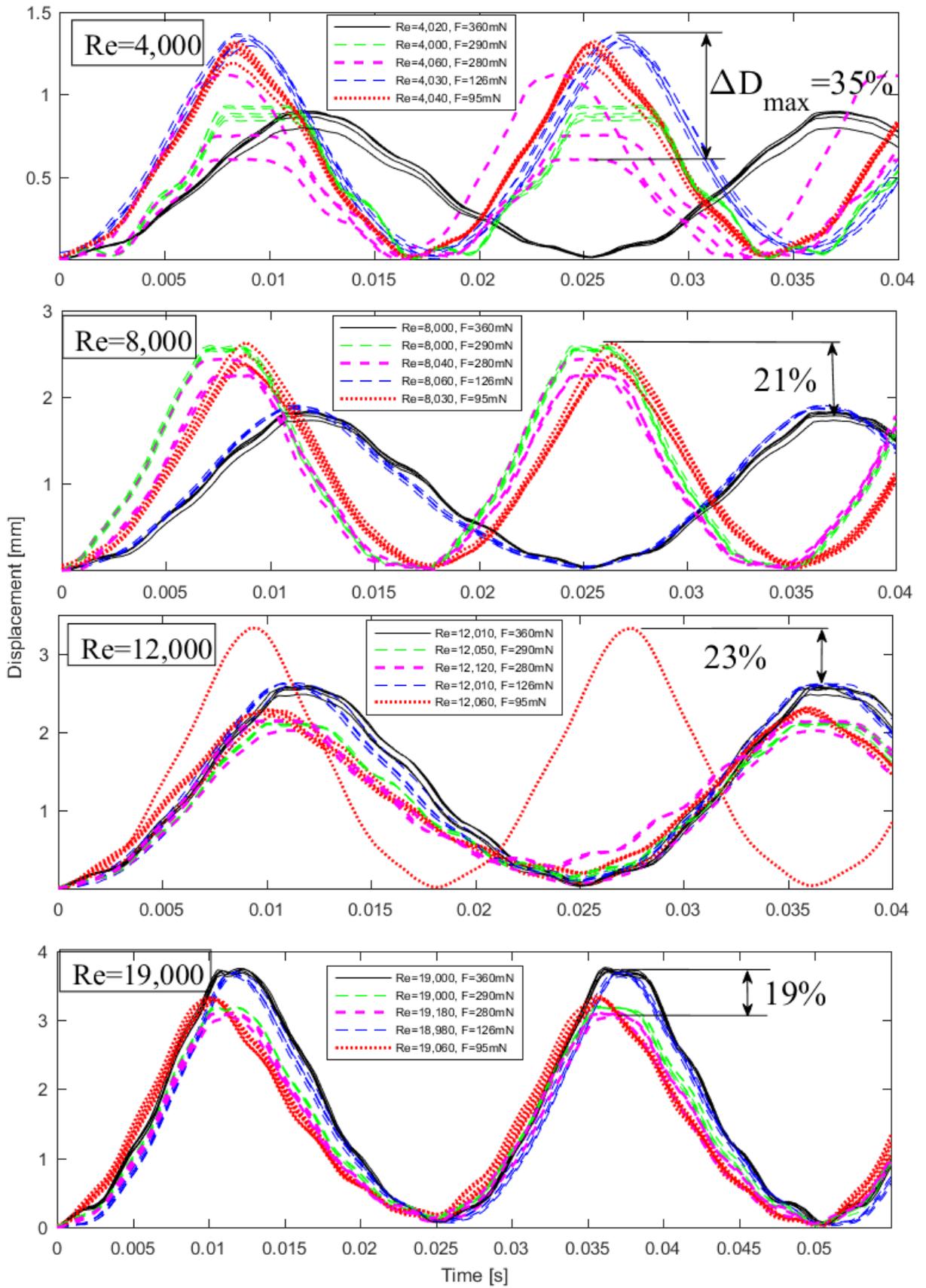
Figure 8. Instantaneous position of the valve for 5 tests with precharging effect
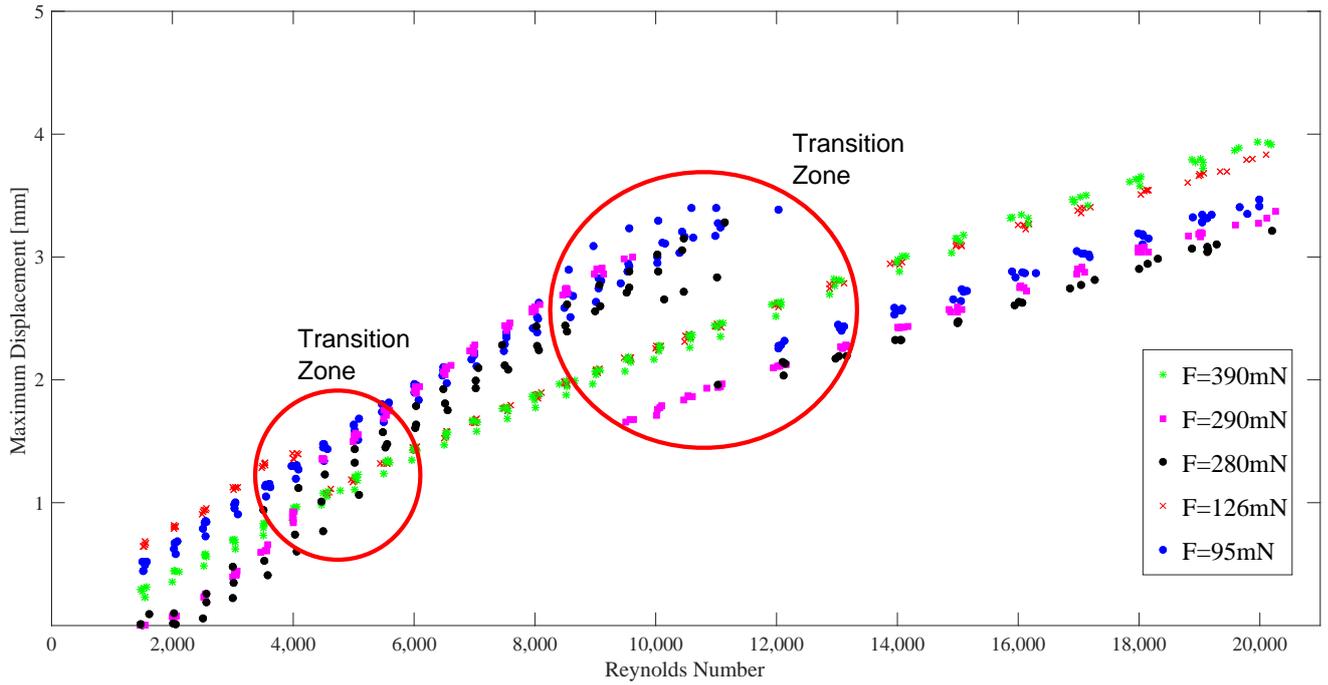
Figure 9. Amplitude of the valve movement as a function of the Reynolds numbers for all tests with precharging effect
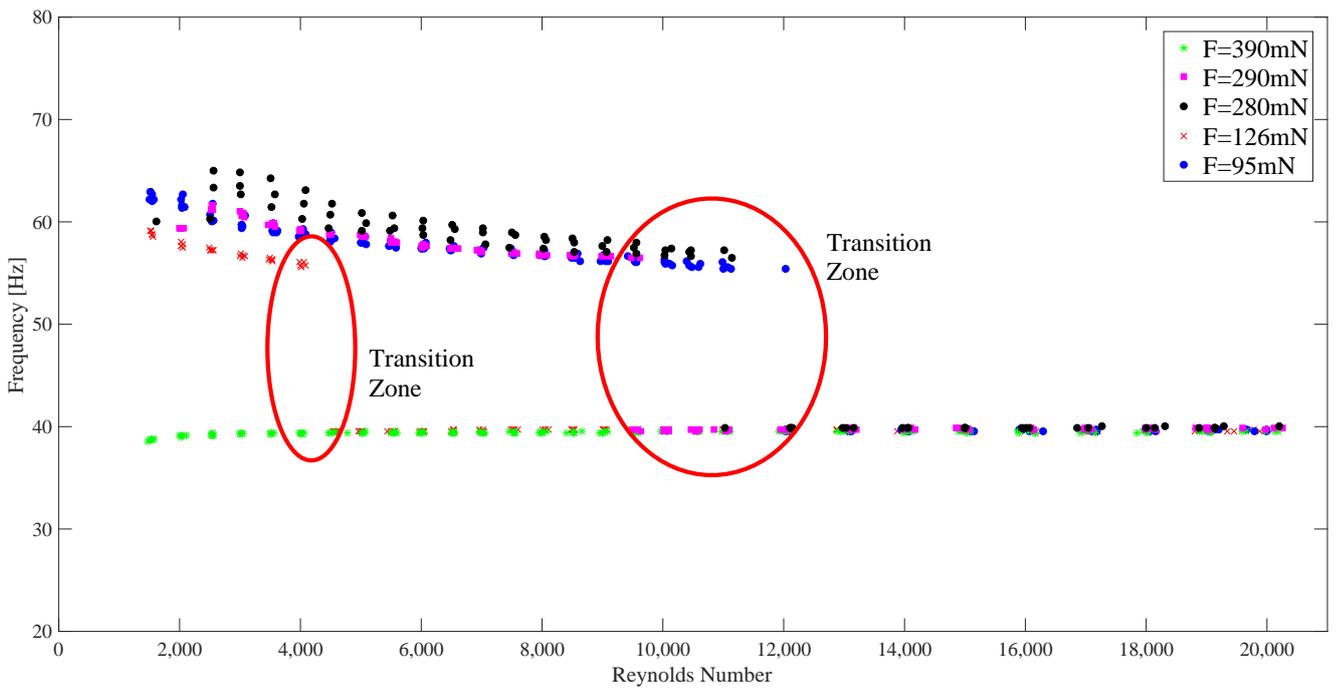

Figure 10. Frequency of the valve movement as a function of the Reynolds number for all tests with precharging effect

4. CONCLUSIONS

The effect of precharging forces varying from 95 to 360 mN on the dynamics of a large scale reed type valve was studied experimentally for Reynolds numbers varying from $1,500$ to $20,000$. For the highest precharging force - 360 mN -, the amplitude of the valve movement increases for increasing Reynolds numbers but its frequency is almost constant. However, transition regions with unexpected abrupt reduction on the amplitude and frequency occur for precharging force ranging from 95 to 290 mN. In addition, the transition regions depend on the precharging force: for most precharging forces - 95, 280, and 290 mN -, the transition region occurs for Reynolds numbers varying from about $9,000$ to $12,000$, whereas for the precharging force equal to 126 mN, the transition region occurs for Reynolds number at about $4,000$. In general, the effect of the precharging force is larger for lower Reynolds numbers - $1,500 < Re < 12,000$ -, and it decreases for higher Reynolds numbers.

5. ACKNOWLEDGEMENTS

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