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EXPERIMENTAL ANALYSIS OF THE FLUID-STRUCTURE INTERACTION IN A MODEL OF REFRIGERATION COMPRESSOR VALVE

Danilo Martins Arantes
Thiago Andreotti
José Luiz Gasche
Unesp-Faculdade de Engenharia de Ilha Solteira, Av. Brasil Centro, 56, Ilha Solteira-SP
arantes.danilo@yahoo.com.br
aga5thi@hotmail.com
gasche@dem.feis.unep.br

Abstract. *Hermetic reciprocating compressors are widely used in small and medium size vapor compression refrigeration systems. One of the main parts of this type of compressor is the automatic valve system used to control the suction and discharge processes. The experimental study of these processes in the compressor itself is very complex, mainly because the small size of the compressor. Thus, experimental analysis in laboratory valve models can be useful for improving the understanding of the flow characteristics. This work consists in an experimental investigation of the fluid-structure interaction problem in a model of reed suction valve with diameter ratio equal to 1.3. The fluid-structure interaction problem was studied by measuring the instantaneous position of the reed for Reynolds number varying from 2,000 and 10,000. Due to hydrodynamic instabilities of the flow, the reed does not reach an equilibrium position. The results show that there is a well-defined frequency for the reed movement for a given Reynolds number, which reduces slightly for increasing Reynolds numbers. The results are also important for validating computational codes used for the solution of general fluid-structure interaction problems, and specifically for simulation of flows in reed type valves.*

Keywords: *Refrigeration, Compressor, Reed valve, Fluid-Structure Interaction*

1. INTRODUCTION

Hermetic reciprocating compressors are widely used in small and medium size refrigeration cycles based on the vapor compression process. Ribas *et al.* (2010) stated that the thermodynamic efficiency in a high efficiency refrigeration compressor operating with refrigerant R134a is about 80 to 83%. They divided the thermodynamic losses in leakage losses (4%), superheating losses (49%), and suction and discharges losses (47%). As the suction and discharge losses represent a large amount of the total thermodynamic losses, small improvement in the suction and discharge processes can produce expressive increase in the thermodynamic efficiency.

In order to improve the suction and discharge processes, it is necessary to study the flow through the suction and discharge valves. In this type of compressor, the valves must be as simple as possible to reduce manufacture cost. Thus, the valve system is usually designed to operate without any device to control the movement of the valve. Therefore, valves are usually just thin beans (reeds) fixed on one edge. The movement of the reed depends just on the forces of the flow acting on its surfaces, and on the structural response of the reed defined by its physical parameters (mass and stiffness). This is a typical problem of fluid structure interaction, which results in a very complex flow.

The fluid structure interaction problem in refrigeration compressor valves has been extensively investigated in the last decade. Numerical works were performed in order to determine the dynamic behavior of the valves for several applications, highlighting the works of Machu *et al.* (2004), Kim *et al*. (2008), Kinjo *et al*. (2010), Mistry *et al*. (2012), and Pereira *et al*. (2012). Several experimental works were also developed in the same subject (Prater and Hnat, 2003; Habing and Peters, 2006; Burgstalller *et al*. 2008; Lens, 2010; Nagata *et al*. 2010; Bhakta *et al*. 2012; Ma *et al.* 2012). There has been detected from these works that there is no experimental data that could be used to validate numerical procedures developed to solve fluid structure interaction problems in reed type valves.

The main purpose of this work is to present an experimental methodology to study the fluid structure interaction problem in reed type valves in order to provide reliable data that could be used to validate numerical procedures developed to simulate the flow. In order to accomplish this task, an experimental setup was built to study the flow through a model of a reed valve frequently used as suction valve in refrigeration compressor. An optical system was used to measure the instantaneous position of the valve for Reynolds numbers of the flow varying in the range of 2,000 to 10,000.

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2. METHODOLOGY

Figure 1 shows a schematic diagram of the experimental setup, which is composed by two 500 liters reservoirs connected in parallel, a filter, a pressure control valve, a mass flow rate control valve, a Coriolis mass flow meter, a flexible tube, an aluminum tube containing two fine netting at the inlet, and the test section, which is installed on a concrete block (40x40x50 cm) through three spacer bars displaced 120° from each other. The concrete block is used to isolate the test section from vibration transmitted by the external environment.

Before running a test, the reservoirs are filled with air at 12 bar by a two-stage compressor. During the test, the air flows to the filter, where it is cleaned and dehumidified, and to the pressure control valve, which has the purpose of maintaining the downstream pressure always constant despite the reduction of the pressure in the reservoirs. Thus, the mass flow rate at the test section can be maintained constant at the desired value. The desired mass flow rate is adjusted in the mass flow rate control valve installed downstream the pressure control valve. Then, the air flows through the Coriolis mass flow meter, flexible tube, and through a 2 m long, 34.9 mm inner diameter aluminum tube before reaching the test section. Two fine netting were installed at the inlet of the aluminum tube in order to initiate the regularization of the velocity profile of the flow. The length of the aluminum tube was chosen to guarantee a completely developed flow at the inlet of the test section.

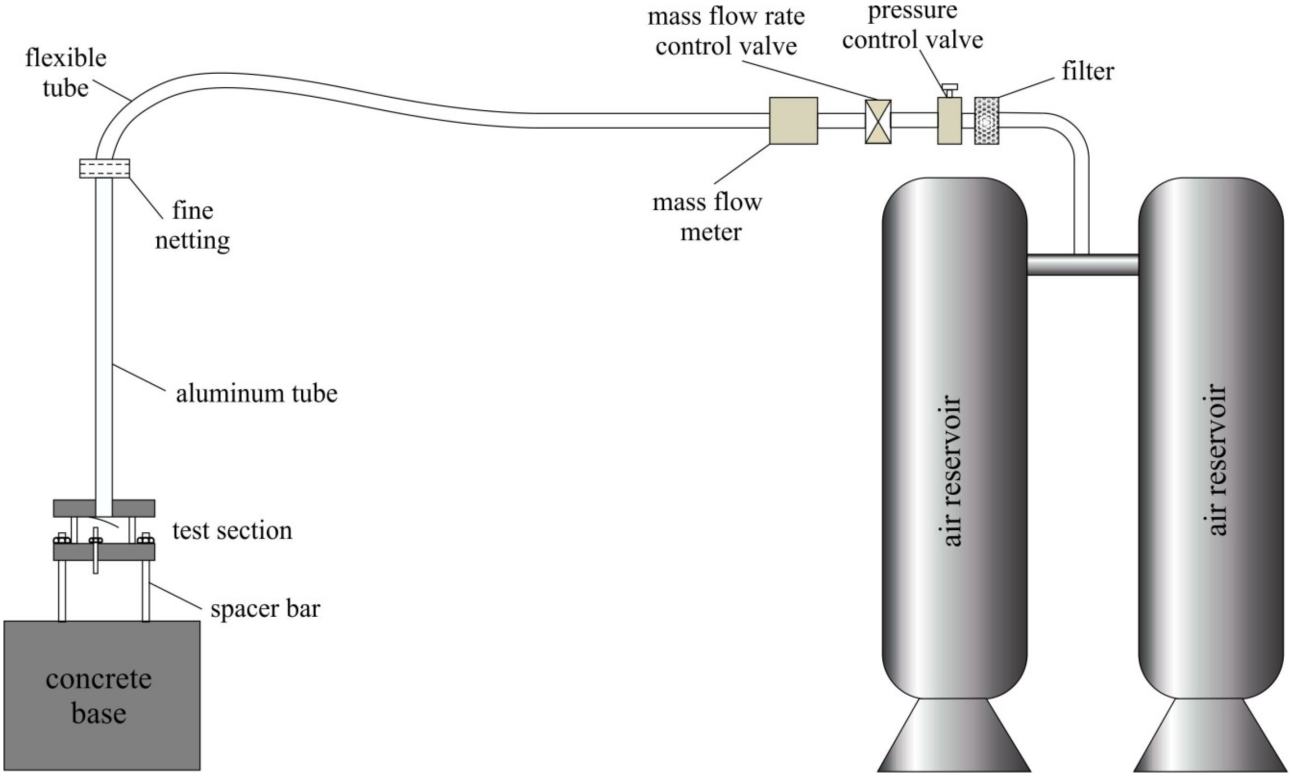

Figure 1 – Experimental setup

A schematic diagram of the test section is shown in details in Figure 2. The test section is basically built by two very rigid circular steel plates (30 mm tick). The bottom plate is fixed in the concrete block by the spacer bars. The upper plate is installed in the bottom plate through three similar spacer bars displaced 120° from each other. The aluminum tube is installed in the upper side of this plate. The inner diameter of the hole made in the upper plate matches the inner diameter of the aluminum tube in order to avoid perturbations of the flow. The model of the reed valve is fixed on the bottom surface of the upper plate through two small screws in such a way to guarantee that the surface of the reed is in perfect contact with the surface of the plate. An optical sensor used to measure the instantaneous position of the reed is installed in the bottom plate. All these parts are rigidly connected to each other in order to avoid relative displacement during the tests.

The reed valve dimensions are shown in Figure 3. The diameter ratio and thickness of the reed are D/=1.3 and 0.4 mm, respectively. Two parameters that play an important role on the dynamic of the reed are the stiffness, k, and the natural frequency, f_n. These two parameters were obtained numerically by using the commercial code Ansys, resulting in k=214.7 N/m and f_n=31.4 Hz,

The following parameters are measured during the tests: temperature of the flow, pressure at the inlet of the test section (upstream pressure), mass flow rate of the flow, atmospheric pressure, and instantaneous position of the reed.

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The atmospheric pressure is measured by a Barometer with 0.05 kPa resolution. The upstream pressure is measured by an inductive pressure transducer with 1 bar operating range and uncertainty of ±0,001 bar. The mass flow rate is measured by using a Coriolis mass flow meter with operating range of 5.0 kg/min and uncertainty equal to ±0.2% of the reading of the mass flow rate. The temperature of the flow is also measured by the Coriolis mass flow meter with an estimate uncertainty equal to ±0.5°C. The instantaneous position of the reed is measured by a fiber optic sensor. The manufacture calibration curve for a standard reflexive surface (retro tape), providing an uncertainty of ±1 μm, was used to convert the signals. The retro tape surface was glued on the bottom surface of the reed in order to reflect the light emitted by the optical sensor.

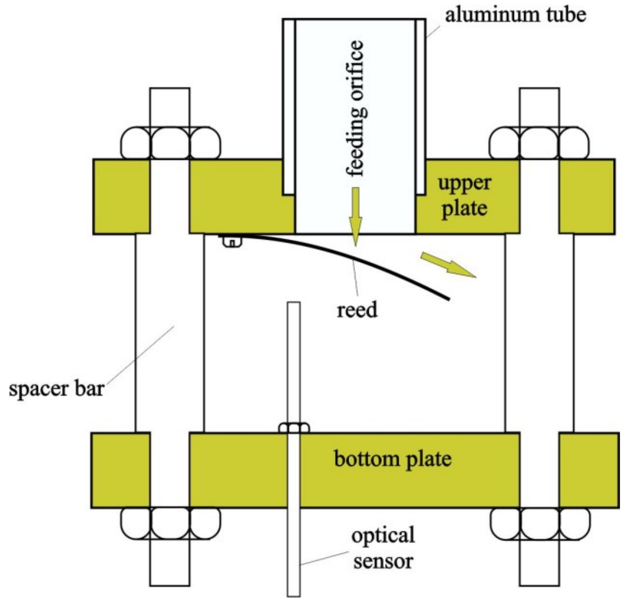

Figure 2 – Test section

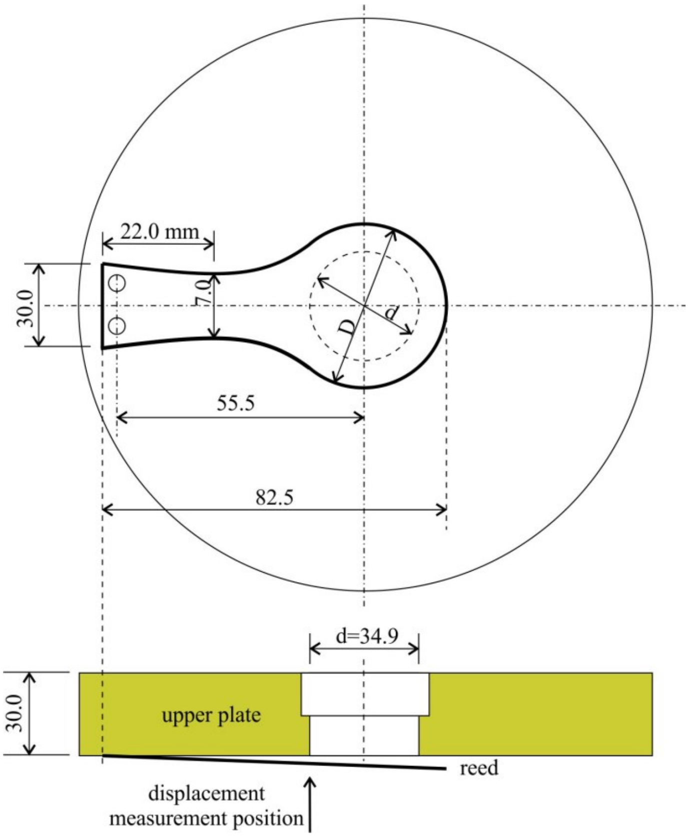

Figure 3 – Reed dimensions

All analog signals were converted to digital signals and wired to a computer where they were treated by a LabView program.

3. RESULTS

In order to analyze the fluid structure interaction phenomenon in the flow through the reed, the instantaneous displacement of the reed was measured in one position on the surface of the reed, as shown in Figure 2. The tests were performed for Reynolds numbers, defined by Equation (1), varying from 2,000 to 10,000,

$$\mathrm{Re} = \frac{\rho V d}{\mu} \tag{1}$$

where ρ and μ are the specific mass and dynamic viscosity of the air, respectively, V is the average velocity of the flow at the feeding orifice, and d is the inner diameter of the feeding orifice. The specific mass of the air was calculated by using the equation of state for ideal gas, considering the measured values of the upstream pressure and temperature of the air. The dynamic viscosity of the air was calculated by using the equation adapted from Possamai (1994),

$$\mu = (0.872 + 7.029\text{x}10^{-2}\ T - 3.81\text{x}10^{-5}\ T^2)\ \text{x}\ 10^{-6} \tag{2}$$

where T and μ are given in Kelvin and Pa.s, respectively.

Considering the standard uncertainty for the upstream temperature T and upstream pressure as uncertainty type B with rectangular distribution, the combined uncertainty for the specific mass and dynamic viscosity resulted both in ±0.1% (ABNT and INMETRO, 2003).

Applying the same procedure for estimating the uncertainty for the Reynolds number, the combined uncertainty resulted seven times smaller than the typical standard deviation of the data during the tests, which was of the order of 1% of the reading. Therefore, the uncertainty of the Reynolds number was estimated in ±1% of its value.

Figure 4 depicts a typical result for the instantaneous displacement of the reed as a function of the time for Re=10,000. In this figure it is plotted the results for three tests run in similar flow configurations. The results were displayed with a time delay in order to provide a better analysis. It can be seen that the experimental setup provides very good repeatability of the data. First of all, it is observed qualitatively that the movement of the reed is periodical. Figure 5 shows the Fast Fourier Transform result for one signal to confirm the periodicity of the movement. A very definite frequency of 115.9 Hz characterizes the movement of the reed.

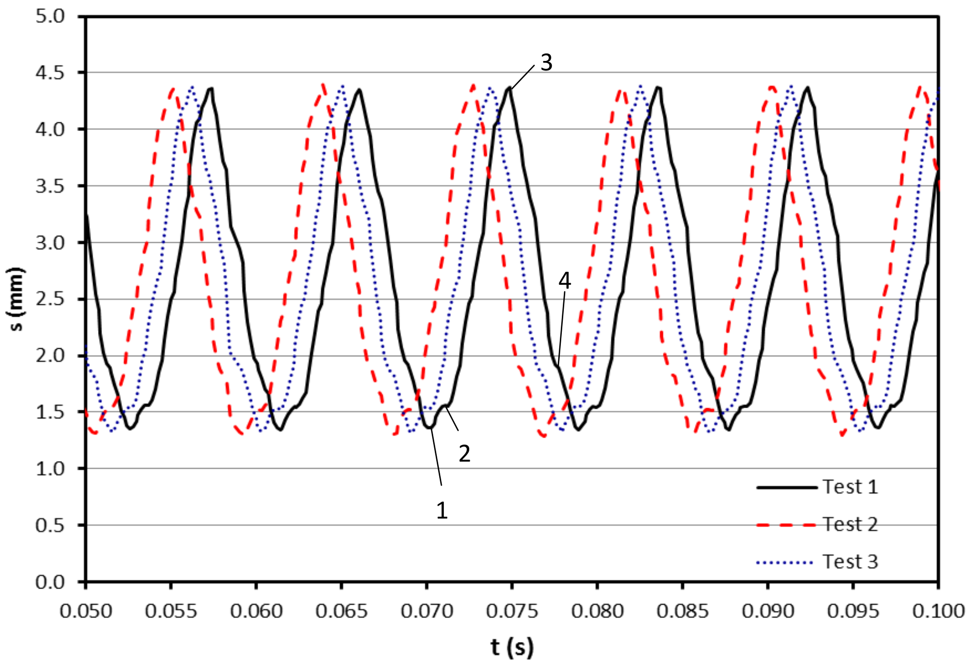

Figure 4 – Instantaneous displacement of the reed, s

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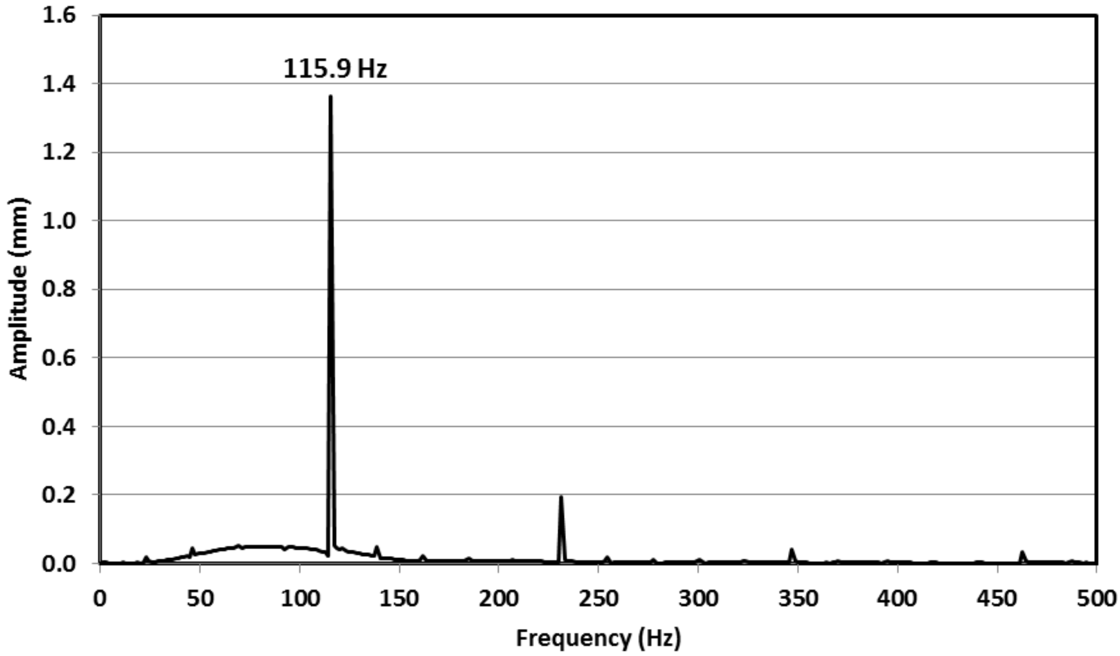

Figure 5 – Fast Fourier Transform of the instantaneous displacement signal

Analyzing the behavior of the displacement of the reed, one can withdraw several information. Starting at point 1 (Figure 4), where the reed is completely open, one can see that after the initial acceleration, the reed stops momentarily at point 2 and, then, starts another period of acceleration. When the reed is about to close (point 3), one can observe that there is a reduction of the reed velocity, probably due to the increase of the pressure force of the flow as a consequence of the reduction of the gap between the reed and the upper plate. The reduction of the gap fosters an increase of the friction force of the flow, which increases the upstream pressure, and consequently, the flow force, decelerating the reed. Then, the reed hits the upper plate and starts opening. Near the end of the opening process, one can observe a small and momentarily deceleration of the reed at point 4. Finally, one can see the deceleration of the reed before reaching the end of the opening process at point 1. This deceleration is due to the increase of the reaction force of the reed. This cycle is repeated almost identically for every movement of the reed.

From the point of view of the compressor efficiency, this type of movement of the valve is unfavorable because it reduces the refrigerant mass being sucked (for the suction valve) or discharged (for the discharge valve) by the compressor. The mass flow rate is still momentarily zero as the reed hits the upper plate. In an ideal situation, that is, to foster the largest mass flow rate, the reed should remain always opened for a prescribed constant mass flow rate (or Reynolds number). Another disadvantage of this type of movement is the impact of the reed against the upper plate, which can produce structural damage to the valve.

An important application for this type of data is the validation of numerical codes developed to study general fluid structure interaction problems, and specifically for validating numerical procedures dedicated to simulate the flow through reed type valves. The experimental results found in the literature have been obtained for actual valves running within the compressor environment. In this situation, the parameters are difficult to measure due to the small size of the system (which implies in special instrumentation), access problems to install the sensors, and disturbance of the system due to the measurement itself. In addition, undesirable effects as the presence of lubricant oil are impossible to eliminate. In a more controlled environment like an experimental bench, these problems are minimized and undesirable effects are absents with suitable design.

Similar displacement results were obtained for Reynolds numbers varying from 2,000 to 9,000. The frequencies of the movement of the reed for all tests are presented in Table 1. The uncertainty of the frequency was estimated considering that the data are represented by a rectangular distribution (ABNT and INMETRO, 2003). Figure 5 depicts the same results in the graphical form. In this figure, one can observe that the frequency decreases about 7% for increasing Reynolds numbers until Re=9,000, and then remains constant.

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Table 1 - Frequency of the reed movement for Reynolds number ranging from 2,000 to 10,000.

Reynolds	Test 1	Test 2	Test 3	Average
2,000	126.0	124.6	124.6	125.0±0.4
3,000	121.7	120.2	120.2	120.7±0.4
4,000	120.2	120.2	120.2	120.2±0.0
5,000	118.8	118.8	118.8	118.8±0.0
6,000	118.8	117.3	117.3	117.8±0.4
7,000	117.3	117.3	117.3	117.3±0.0
8,000	117.3	115.9	115.9	116.4±0.4
9,000	115.9	115.9	115.9	115.9±0.0
10,000	115.9	115.9	115.9	115.9±0.0

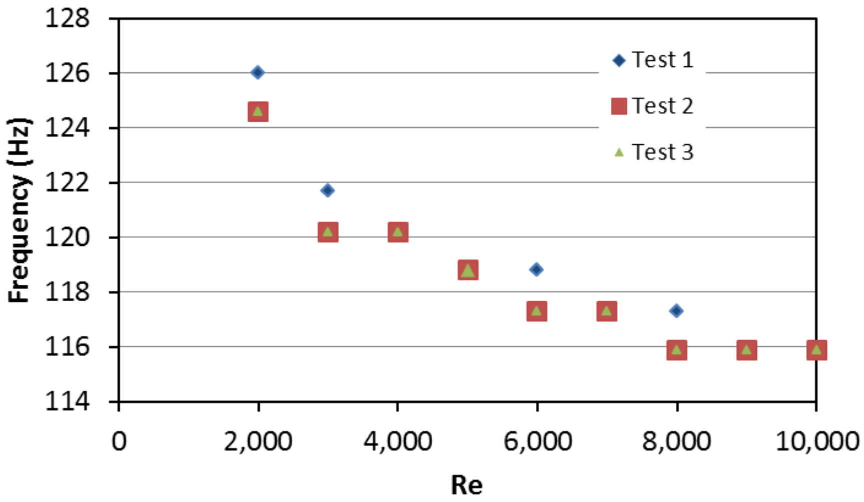

Figure 5 – Frequency of the reed movement as a function of the reynolds number

Table 2 presents the maximum displacement (s_{max}) of the reed for all Reynolds numbers and all tests. The uncertainty of the maximum displacement was also estimated considering that the data are represented by a rectangular distribution (ABNT and INMETRO, 2003). Figure 6 presents the same data in the graphical form, where one can observe that the maximum reed displacement increases almost linearly with the Reynolds number. The rate of the increase, however, diminishes slightly for increasing Reynolds. This behavior can explain why the frequency decreases for increasing Reynolds numbers. Assuming that the velocity of the reed remains practically constant, the opening time interval increases for higher reed displacement, which means that the frequency of the movement decreases. For the highest Reynolds numbers the decrease of the frequency is not noticed.

Table 2 – Maximum displacement of the reed, s_{max}, for Reynolds number ranging from 2,000 to 10,000.

Reynolds	s_{max} (mm) Test 1	s_{max} (mm) Test 2	s_{max} (mm) Test 3	s_{max} (mm) Average
2,000	0.703	0.737	0.719	0.72±0.01
3,000	1.015	1.073	1.073	1.05±0.02
4,000	1.320	1.361	1.361	1.35±0.01
5,000	1.596	1.666	1.657	1.64±0.02
6,000	1.936	1.985	1.960	1.96±0.01
7,000	2.239	2.287	2.297	2.27±0.02
8,000	2.542	2.615	2.573	2.58±0.02
9,000	2.814	2.862	2.841	2.84±0.01
10,000	3.036	3.099	3.069	3.07±0.02

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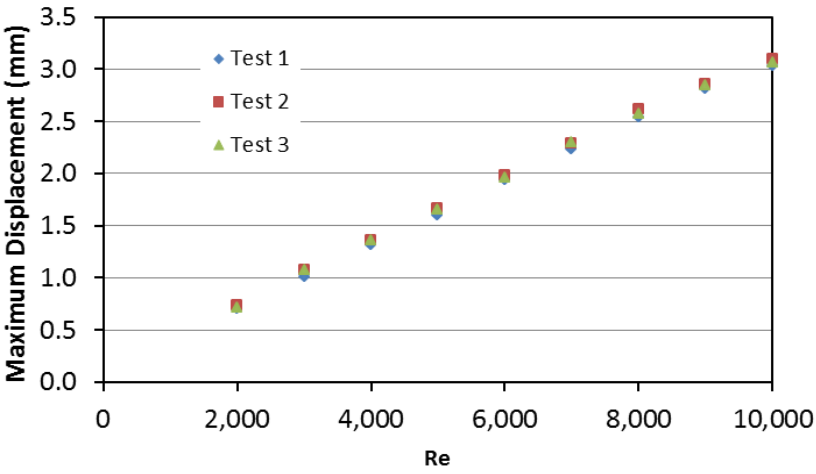

Figure 6 – Maximum displacement (s) of the reed as a function of the Reynolds number

4. CONCLUSION

This work consists in an experimental investigation of the fluid-structure interaction problem in a model of reed suction valve with diameter ratio (D/d) equal to 1.3. The fluid-structure interaction problem was investigated by measuring the instantaneous position of the reed for Reynolds number varying from 2,000 to 10,000.

Due to hydrodynamic instabilities of the flow, which are probably generated by vortex detachment at the exit of the flow, the reed does not reach an equilibrium position. The results show that the reed takes a periodical movement with a well-defined frequency, even for a constant Reynolds number. The reed still hits the upper plate, closing completely the fluid passage, with the same frequency of the reed movement. From the point of view of the compressor efficiency, this type of movement is to be avoided. In addition, it was observed that the frequency of the movement reduces 7% for increasing Reynolds numbers, as the entire Reynolds number range is considered. Despite the simplifications added to the valve model, the results are useful to improve the understanding of the actual problem of valve motion.

The dynamic behavior of the reed represented by its displacement in time is also an important result for validating computational codes used for the solution of general fluid-structure interaction problems, specifically in the case of numerical simulation of reed type valves.

5. ACKNOWLEDGEMENTS

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