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Reed Valves‘ Impact Velocity Measurements on Working Compressors

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ABSTRACT

This work proposes a suitable way for measuring the impact velocity of reed valves used in suction ports of reciprocating compressors. We introduce a simple handcrafted inductive sensor, made by a permanent magnet, a metallic stem of circular cross-section and copper wire. Then, the procedure for compressor's instrumentation is detailed, and a method to calibrate the recorded signal from the sensor is presented. Due to some complexity on its calibration, a special attention was given to this regard. The calibration process was analyzed statistically, and results are presented. In the calibration process we recorded 1.25 seconds, which properly detected around 62 cycles for a compressor operating at 3000 RPM. The same parameters were used for 3 different valve plates. Then, the signal was postprocessed and calibration values were compared. Finally, actual measurements were performed with the compressor connected to a refrigerant system, running under a given condition. Data from its valve velocities are presented and discussed.

1. INTRODUCTION

This paper proposes a method to obtain suction valve impact velocity of compressors running under working conditions. The impact velocity of valves is a critical topic for compressors' reliability, since its directly connected to the valve stresses and fatigue problems.
Although is quite difficult to find a proper guideline in the literature, past experiences showed the valve impact velocity should not exceed 5 m/s. But of course, this value can vary due to compressor's size and running speed.
Therefore, this work is divided into:

1. Presentation of measurement methodology: Where the technical discussion regarding signal acquisition, instrumentation and actual measurement will take place.
2. Results from calibration and measurement will be presented.
3. Finalizing statements about proposed method and suggestions of future research.

2. METHODOLOGY

A custom-made induction sensor was introduced to avoid significantly changing the gas-line geometry, while still suitable for acquiring the dynamic behavior of suction valves. The following section describes the construction of this special sensor as well as the instrumentation of a suction muffler. Hence, how the signal is recorded and postprocessed. Finally, how the instrumentation is calibrated and how the actual measurement is performed.

2.1 Sensor Construction

The sensor consists of a small metallic (magnetic) rod of circular cross-section with circa 1mm diameter and 14mm length, winding wire of 0.28mm and a permanent magnet. The small metallic rod is called needle and its purpose is to focus the magnet's magnetic flux. The winding wire is coiled around the metallic rod, while the magnet is placed aligned with rod's axis (Fig. 1).

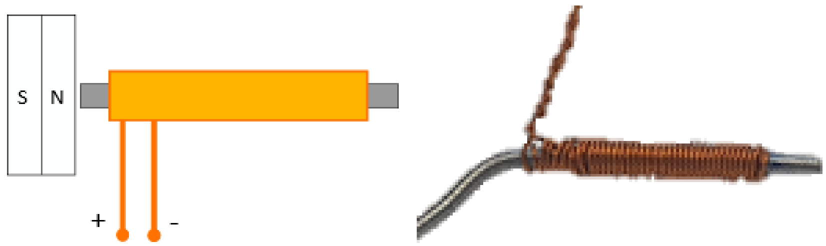

Figure 1: Schema of handcrafted inductive sensor (left) and sensor being made (without magnet, right)

The sensor should be positioned in the suction port's center, so whenever the valve moves, it changes the magnetic flux coming out from the needle. This change on the magnetic flux, considering a magnet that is strong enough, is sufficient to create a small current/voltage variation between the windings' ends.
The windings' ends can be directly connected to a signal acquisition platform, such as an oscilloscope or an ADC for digital postprocessing.

2.2 Compressor Instrumentation

The sensor needs to be placed as near the valve as possible, in the suction port's center. Circular suction ports are even better since they maintain a more uniform magnetic flux throughout the sensor's body. Also, it is recommended to position the needle as perpendicular as possible to the valve for the same reason (Fig. 2).
It is also recommended the usage of microdot interfaces for better cable management (Fig. 3).

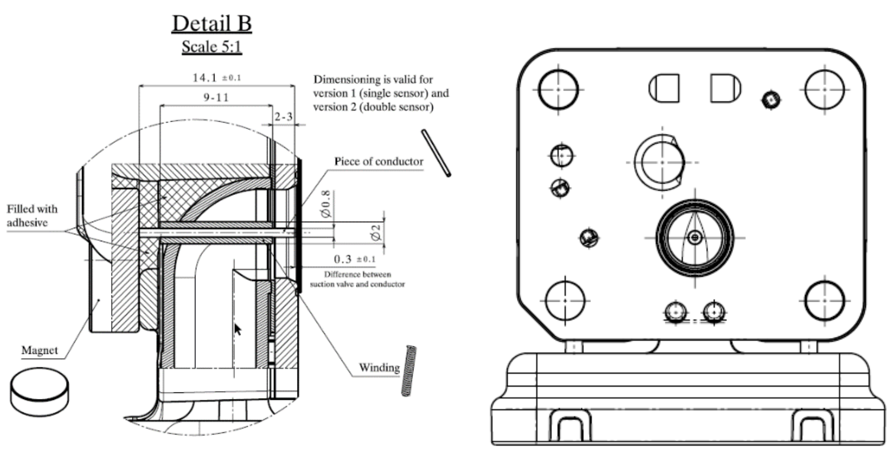

Figure 2: Example of instrumentation of a typical compressor's headgroup

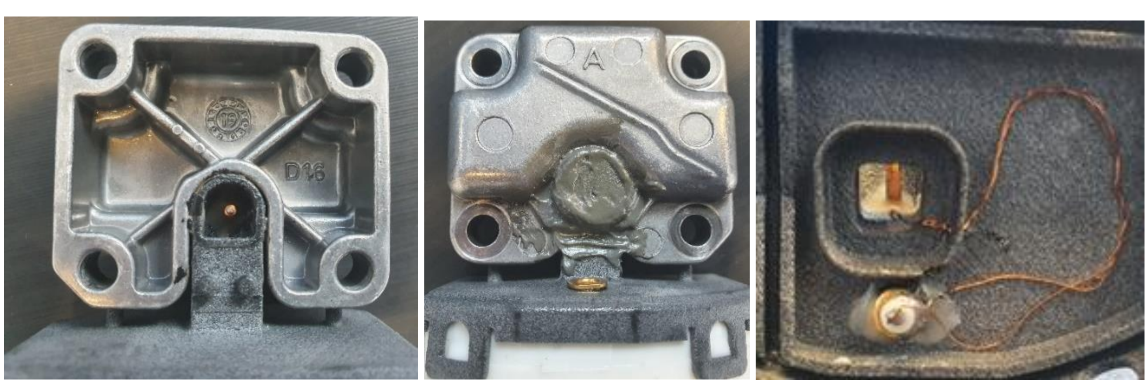

Figure 3: Example of headgroup instrumentation of a typical compressor (microdot interface in middle and right pictures)

2.3 Signal Acquisition

We used Brüel & Kjaer hardware and software for signal acquisition and measurement recording, but any signal recorder would suffice. When any change occurs on the magnetic flux, *i.e.*, when a moving object disturbs this flux, the input signal will trace a variation on the voltage (example of a typical signal is shown in Fig. 4).

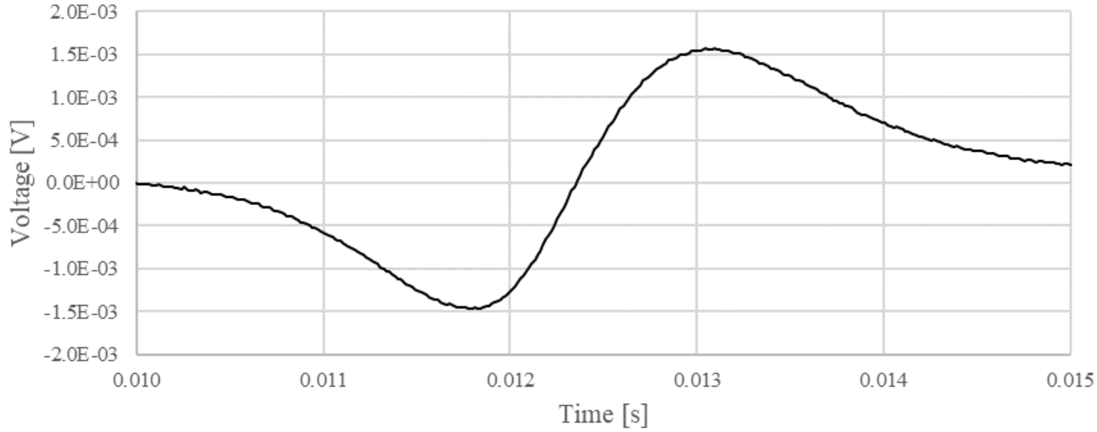

Figure 4: Example of voltage signal acquisition vs. time.

2.4 Calibration Theory

Our goal is to determine how much the voltage varies for a moving object with a known velocity. Thus, our calibration rig uses the same compressor's mechanism running unloaded (open circuit, with air, Fig. 5 shows an example signal). This is a simple solution for calibration, since we can calculate the piston's position and velocity by using the mechanism properties (eccentricity, conrod length and piston offset).

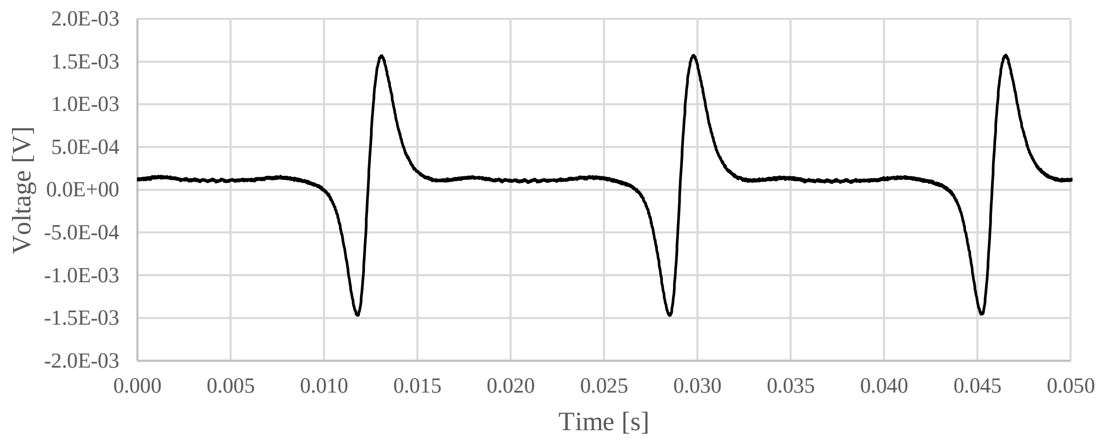

Figure 5: Example of a signal acquire from a moving mechanism of a typical compressor.

It is known the handmade sensor has a very short distance range, due to magnet's size. Therefore, the signal strength (amplitude) will depend on both velocity and distance from the piston.

With our setup, the sensor was able to detect the piston movement up to 0.7mm away from its top dead center. Inside this range, we can assume the amplitude varies linearly with the velocity and exponentially with the distance, so the calibration factor *K* is like:

$$K = Ae^{Bd}, \tag{1}$$

which, *A* and *B* are constants obtained from comparing the measured signal with piston movement, and *d* is the distance

between sensor and piston, and will be explained in the following.
Firstly, one calculates the respective position and velocity of the piston by using:

$$u_x = \epsilon \sin(\theta),$$
$$u_y = \epsilon \cos(\theta) - r, \tag{2}$$
$$u_p = u_x + \sqrt{L^2 - u_y^2} - L,$$

being ϵ the eccentricity, Θ the crank angle, r the piston offset, L the connecting rod length, finally u_p is the piston displacement.
The piston velocity is obtained by a simple gradient:

$$v_p = \frac{u_p(t_2) - u_p(t_1)}{t_2 - t_1}, \tag{3}$$

which t_1 and t_2 are different times sufficiently close so the velocity still has a linear behavior.
To acquire the signal as fair as possible in the calibration phase, a suction valve is glued at the piston recess to ensure similar magnetic properties and reduce the distance from the sensor (example in Fig. 6). Thus, the distance between piston and sensor is a function of the piston's maximum displacement (top dead center, TDC), which is easily given by:

$$d(u_p) = d_s + TDC - t_v - u_p, \tag{4}$$

being d_s, the distance between sensor and cylinder head, and t_v the valve thickness glued on the piston. The distance between sensor and piston's TDC can be measured manually.

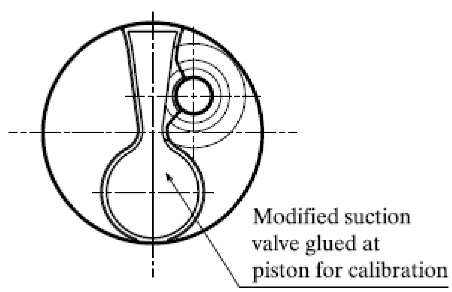

Figure 6: Example of position which suction valve should be placed in the piston recess for calibration.

The calibration consists in selecting the portion of measured signal *s* that corresponds to $d(u_p)$ when u_p is circa 0.7mm away from TDC (when the sensor is active). Since we assumed the calibration coefficient *K* having 2 unknowns (Eq. 1), we can infer a linear polynomial $p(x) = Cx + D$, which parameters *C* and *D* can be obtained by minimizing the squared error of:

$$E = \sum_{j=0}^{k} \left| p(x_j) - y_j \right|^2, \tag{5}$$

where x_j are the discrete values of $d(u_p)$ and y_j, discrete values of $\ln\left(\frac{v_p}{s}\right)$. So, the relationship of *A*, *B*, *C* and *D* is given by:

$$A = e^C, \qquad B = \ln\left(\frac{e^D}{A}\right). \tag{6}$$

This way, the calibration factor *K* can be fully determined by Eq. 1 and relationships of Eq. 6. The only remaining

unknown of calibration is to correct the distance from the valve, which is given by the difference of $d(TDC)$ from Eq. 4 and the distance between sensor and top surface of valve plate (let us call this as d_v), which can also be measured manually, and is extremely important to avoid unwanted variation of calibration factor K.
Figure 7 shows how the signal behaves while the piston approaches its top dead center, and how the piston velocity signal is like the acquired signal, and Figure 8 shows how the ratio between piston velocity v_p and signal s varies exponentially with piston distance $d(u_p)$.

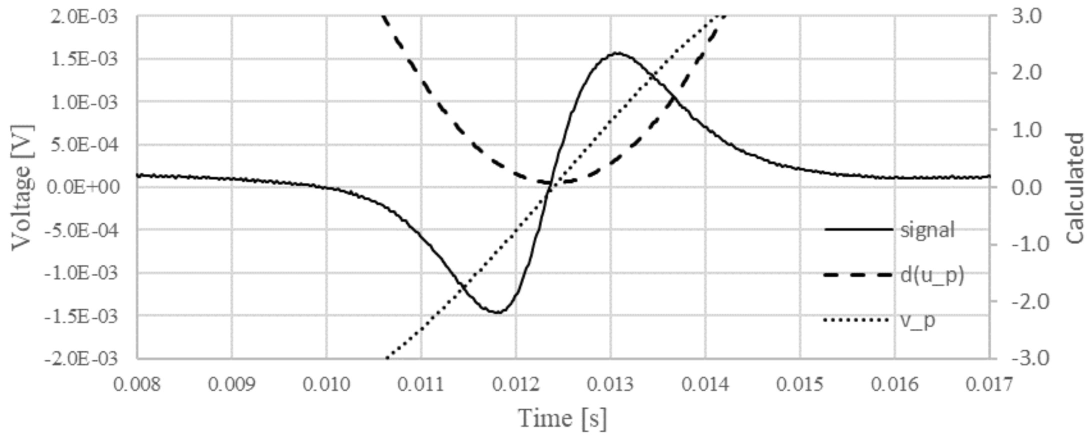

Figure 7: Example of measured signal, distance variation between sensor/piston and piston velocity.

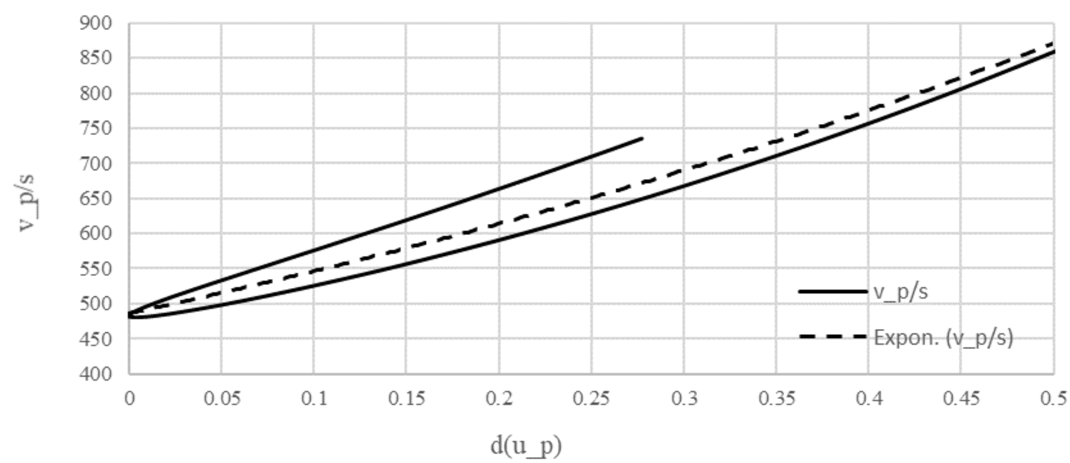

Figure 8: Piston velocity/Signal ratio vs. piston displacement when sensor detects movement.

By doing so, one can determine the corrected factor K (here called as K_c, due to distances correction) as:

$$K_c = Ae^{Bd_v}, \tag{7}$$

which will be used to transform the signal s from valve impact velocity measurements into actual values of velocity v_v by $v_v = K_c s$.

2.5 Application of Calibration Procedure and Discussion

We attempted to calibrate the sensor using one instrumented muffler, same compressor pump and cylinder cover, but 3 different valve plates. The assumption was the results should give the same calibration factor K_c, since valve plate differences were negligible.
We ran the calibration procedure 5 times (which we called "waves") for each valve plate assembly, in a total of 15 measurements. The results are shown in Table 1.

The issue was K_c values were not as similar as expected, which resulted in 30% differences between the 3 valve plates in wave 3. Since the valve velocity is just a multiplication of K_c by s, 30% difference in factor will be carried for actual valve velocity values.
Further investigation also pointed out a high deviation with a single valve plate, as in valve plate number 8, which only by between assemblies had given 25% variability in results.
This statistical analysis shows the calibration process still needs improvement. Nonetheless, measurements from a running compressor were conducted and results are presented in the next section.

Table 1: Calibration factors for a single coil sensor with different headgroup assemblies.

K_c	VP7	VP8	VP9	Avg.	Min.	Max.	(max-min)/avg
Wave 1	214.1	209.2	185.9	203.1	185.9	214.1	14%
Wave 2	220.0	197.0	171.9	196.3	171.9	220.0	25%
Wave 3	211.5	161.1	158.4	177.0	158.4	211.5	30%
Wave 4	238.9	203.0	178.0	206.7	178.0	238.9	29%
Wave 5	239.6	199.2	188.8	209.2	188.8	239.6	24%
Avg.	224.84	193.90	176.62				
Min.	211.54	161.06	158.43				
Max.	239.6	209.2	188.8				
(max-min)/avg	12%	25%	17%				

2.6 Application of Measurement Procedure

As previously described, the actual measurement of valve velocity uses the standard valve plate, with suction valve in place, and compressor in a closed shell. Then, the compressor runs in a closed refrigerant circuit, which pressures on the discharge and suction sides are controlled by valves, simulating actual conditions on an appliance.
The signal s is acquired the exact same way as in calibration phase, only the factor K_c (Eq. 7) is applied to transform signal values into actual velocities.
Since the calibration phase still shows a high variability, we used an average value of K_c from all waves, which resulted in valve velocities shown in Fig. 9. The valve displacement was calculated considering a zeroed starting position (valve resting on its seat) and them using the velocity to obtain the displacement values.
Since the shape of velocity plot is close enough to expected, with valve fluttering and returning to its seat, this measurement was considered successful. This was reproduced also for other compressors and other running speeds.

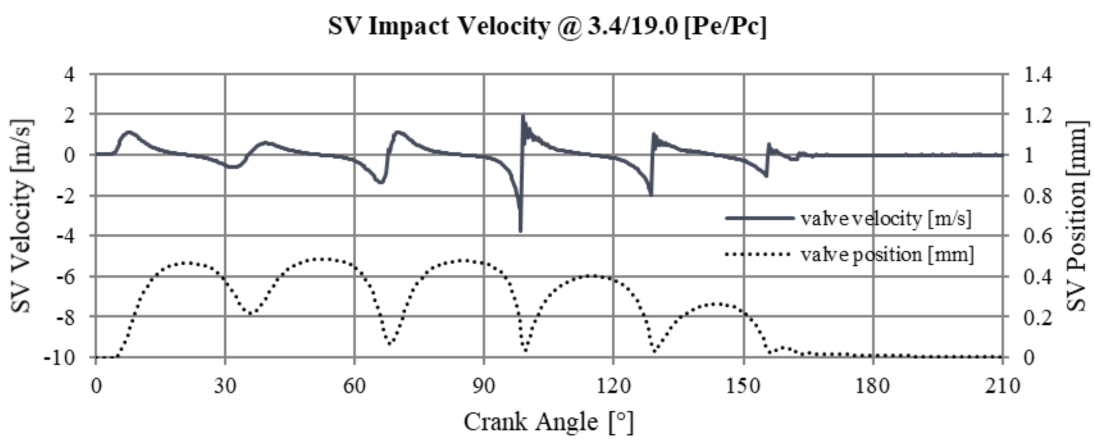

Figure 9: Measurement of suction valve impact velocity with 3.4bar pressure on evaporator and 19.0bar pressure on condenser, operating at 3000rpm, using an average K_c value.

3. FINAL REMARKS

A novel attempt at acquiring suction valve velocity values, with compressor running under appliance conditions was presented.
Unfortunately, calibration procedure shows a high deviation of values K_c.
Some assumptions were drawn as slight differences on assembly, such as thickness of gaskets used, or press fit of screws. One needs to conduct further investigations to mitigate these doubts and improve the calibration methodology.
Nonetheless, the signal from valve impact velocity was successfully acquired, and it could draw some understanding of valve dynamics from the pump running under working conditions.
Different evaporator and condensing pressures were also tested giving similar results, which confirmed the handcrafted sensor was working as intended.
Future studies will focus on improving the calibration procedure, as well as acquiring the actual distances from the sensor to the moving objects. A cross-comparison with different sensors and controlling the number of sensor coils are recommended.

NOMENCLATURE

A,B,C,D	calibration unknowns	(–)
d	distance	(mm)
ϵ	eccentricity	(mm)
E	squared error	(–)
K	calibration factor	(mm.s^{-1}/V)
L	connecting rod length	(mm)
r	piston offset	(mm)
s	signal	(V)
t	thickness	(mm)
TDC	top dead center	(–)
θ	crank angle	(rad)
u	displacement	(mm)
v	velocity	(mm/s)
x	discrete values of $d(u_p)$	(mm)
y	discrete values of $\ln\left(\frac{v_p}{s}\right)$	(mm.s^{-1}/V)

Subscript

j	discrete index
p	piston
x, y	axis direction
v	valve

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