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VALVE LIFT MEASUREMENT BY OPTICAL TECHNIQUES IN COMPRESSORS

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ABSTRACT

The paper addresses the development of a non-invasive measurement method for valve motion in hermetic compressors for domestic refrigerators; the main aim is vibro-acoustic comfort improvement. The methodology developed is based on a single point laser Doppler vibrometer. These tests required a special compressor case equipped with transparent windows for optical access to the valves.

Main metrological problems are related to optical access: the paper discusses the effects on optical signals of a variety of disturbing inputs and environmental effects, which affect signal quality and measurement uncertainty. Effects of beam incidence angle, valve surface roughness, depth of field and oil used for lubrication are analyzed and minimized.

NOMENCLATURE

n: refraction index
ψ,ϑ: incidence angles
f_a: Doppler frequency shift
LDV: Laser Doppler Vibrometer

T: temperature
λ: laser wavelength
v: valve velocity
DOF: Depth Of Field

INTRODUCTION

Compressor valve design has an effect on the following compressor performances:

1. *Thermodynamic efficiency*. Both static and dynamic mechanical properties of a reed valve affect the lift function under given fluid-dynamic forces, hence the gas flow at opening phase and finally cylinder filling and COP.
2. *Reliability*. No part inside a sealed shell is accessible; therefore any failure causes the whole compressor replacement. Valves are strongly stressed to fatigue and must be designed to last for the whole compressor life. Reed valves life is related to the number of fatigue cycles done for each thermodynamic cycle. The number of fatigue cycles per thermodynamic cycle is given from the opening and closing motion of the valve and the other superimposed vibrations.
3. *Noise level.* Vibrations arisen from valve interaction with valve-seat, lift-stop, refrigerant and oil-layer are transmitted via solid structure or gas and contribute to noise generation.

Numerical modeling is used to evaluate the correlation between valve design and compressor performances. In order to validate and tune a model of the valve motion and valve vibration under given fluid-dynamic forces, valve motion at working conditions should be measured.

At present no straightforward measurement technique has been proposed for compressor valve lift motion. The ideal method should be non-invasive, reliable and flexible. Main problems are:

- Valves are small and light parts: no contact transducers can be attached to them without changing their behavior;
- Valves are not directly accessible;
- The space available for transducers - without modifying head or compression chamber volumes and thus operating conditions - is small;
- The environment is harsh, due to temperature and oil droplets moving with the flow;
- The duration of valve opening and closing is a fraction of a cycle, i.e. a fraction of about 20 ms: too much a short time for many transducers, due to their frequency range;

- Measurements must be accurate over the whole valve lift, typically from 0 to some mm's, with the capability of resolving small bounces of the order of 50 µm;

In literature some works can be found for measurement of poppet valve kinematics, by eddy current proximity sensors. The disadvantages are: non-linearity, decreasing sensitivity with distance, calibration curve influenced by temperature, possibility to measure only the base of the valve (to locate the transducer away from the flux), low spatial resolution.

In [2] fiber-optic displacement sensors were used to measure valve motion in a VIP (Valve in Piston) compressor. The installation of the fiber bundle needs small seat holes on the cylinder head.

Video cameras - with the aid of stroboscopic light - were also recently proposed in [3] and tested successfully. In this case two endoscopes were installed inside the compressor. The main limiting factors are the complex experimental set-up, the introduction of additional dead volumes caused by the endoscope seats, the need of steady-state operating conditions, the low sampling frequency and the need of large memory usage and intensive image processing.

The advantage of using an optical instrument such as a Laser Doppler Vibrometer (LDV) is extensively documented in [1]. Based on the available experience reported in [1], an approach based on a single-point LDV has been developed in this work.

A LDV is an instrument which can measure independently one component of velocity and displacement of a moving solid surface by means of the Doppler effect on a scattered light wave [4,5]. Velocity and displacement are measured along the optical axis of the system with no contact. A major characteristic of these sensors is that they do not require calibration and their output does not strongly depend on target material and on surface conditions. Their use for measuring valve kinematics is well justified by several reasons like dynamic range and bandwidth. Resolution and accuracy are superior to any other available sensor and allow the use of only one instrument to measure the maximum valve lift and bounces. Measurements are taken keeping the laser head away from the object: the only need is optical access to the point.

TEST BENCH

The ZEM GQY 75 AA model – chosen for tests – is a part of the high efficiency compressor family for R134a refrigerant. It is a hermetic single-cylinder, alternative compressor for low back pressure household refrigerators driven by an induction motor at a nominal speed of 2915 rpm. Bore x stroke measures are 24.28 x 17.45 mm.

The compressor housing was modified by inserting quartz windows, allowing an optical access for the laser beam to the valves surface. Two windows are needed to provide optical access in a hermetic compressor: the first one lets the beam enter the external case of the compressor, while the second one is needed to cross the compressor head. Such windows do not alter significantly the geometry of the machine; therefore invasion is kept to a minimum. This was verified measuring compressor thermodynamic performances and comparing them to those of a standard compressor.

DISTURBING INPUTS DUE TO OPTICAL ACCESS

The main problems concerning optical access are due to:

1. Light scattering and reflections by optical windows;
2. Light scattering by lubrication oil.

The first question is related to the fact that each optical interface scatters light back to the laser vibrometer: the vibrometer will then measure the interfaces motion and not the valve motion, as the signal intensity scattered by the valve is too low if compared to the flat windows one.

Two strategies must then be adopted: the scattering efficiency of valve surface must be maximized and a proper optical alignment must be obtained.

Figure 2 highlights the different optical characteristics of smooth versus rough surfaces, when hit by a collimated laser beam. When surface roughness is increased, a transition from specular reflection to diffused scatter is observed [9]. The two flat optical windows have two reflecting surfaces each, which reflect about 4% of incoming power in the visible range. Also the valve's surface, being a thin metal foil, shows a reflective character. However, it can be treated to increase its surface roughness, thus changing its behavior into a diffusive surface. This does not modify its functionalities, but allows the solution of the first over mentioned problem: in fact, as the valve scatters the light in a solid angle, the measurement can be performed without a perfect ortogonality between surface and beam.

This immediately produces two advantages:

a. The laser beam can be put at an angle so that light reflected by the flat windows does not reach any more the vibrometer head;

b. The light scattered from the valve always reaches the vibrometer, even when valve rotates during lift.

Figure 3 shows the test bench developed to assess the effectiveness of such an approach. A compressor valve is put on an optical table and aligned to the laser vibrometer; the two optical windows are inserted in front of the valve to reproduce the optical access configuration. Each component can be tilted at an angle. The valve was moved by a stinger put on an electro-dynamic shaker, excited with a step signal. The velocity measured by the vibrometer was acquired.

With the aid of the above described test bench the optimal angles were found. In such conditions the valve motion is measured correctly, as if the windows were not present.

Oil particles in the gas and oil films on the windows – the second problem – can compromise the optical access to the valve and the increased light scattering from the windows will again compromise the signal to noise ratio. A way to overcome this problem was to create a protection screen for the laser beam path inside the compressor shell. Such a screen consists of two coaxial little copper cylinders, mounted as shown in Figure 4 and does not modify the compressor fluid-dynamics. It only prevents oil droplets to interact with the laser light and to form a film on the windows.

Finally another question to point out concerns depth of field (DOF). All optical systems have a range around the focal distance in which objects are still in focus. DOF depends on the focal length *f* and the diaphragm aperture *D*. In our case the DOF has to be minimized in order to “isolate” the valve respect to the near windows. This can be obtained by increasing the diaphragm aperture or decreasing the focal length, avoiding the reception of scattered light which increases noise. DOF should in any case be larger than valve lift.

EFFECTS OF THE WORKING FLUID ON LDV SENSITIVITY

The compressor working fluid has a different refraction index (nÑF respect to air (n~F: it affects LDV sensitivity, so that velocity data need to be corrected. The model shown in Figure 4 is considered. Snell’s law describes the optical path of the LDV beam:

$$n_a \cdot \sin\theta_a = n_f \cdot \sin\psi \qquad (1)$$

nÑ should be evaluated at the working conditions in the compressor housing, because:

$$n_f\,(T) = 1 + \left[n_f\,(T_0) - 1 \right] \cdot \frac{T_0}{T} \qquad (2)$$

where *T* is the gas temperature and T_0 is a reference temperature. LDV sensitivity depends on nÑ [10]. In fact, laser wavelength in the fluid is:

$$\lambda_f = \frac{n_f}{n_a} \lambda_a \qquad (3).$$

LDV sensitivity in air is:

$$k' = \frac{f_D}{v} = \frac{2}{\lambda_a} \qquad (4),$$

being f_a the measured Doppler shift and v the target velocity. Inside a different fluid it becomes:

$$k'' = \frac{f_D}{v} = \frac{2}{\lambda_f} = \frac{2}{\lambda_a} \frac{n_a}{n_f} = k' \frac{n_a}{n_f} \qquad (5).$$

Therefore, in a fluid different than air, LDV measures with a different sensitivity k”. Using sensitivity k’ all the same, it will be observed that:

$$v_{measured} = k'\, f_D = \frac{n_f}{n_a} k''\, f_D = \frac{n_f}{n_a} v_{real} \qquad (6).$$

Therefore measured velocity has to be corrected; the final correction is in eq.7, taking into account also the angle of incidence ψ:

$$v_{real}(t) = \frac{v(t)_{measured}}{\cos\psi} \cdot \frac{n_a}{n_f} \qquad (7).$$

SIGNAL ACQUISITION AND PROCESSING

The analog displacement signal is digitalized by an 8 bit AD converter at a sampling frequency always larger than 100 kHz. Figure 5 and Figure 6 show some resulting measurements.

Valve lift traces show a fast valve opening, followed by damped oscillations around maximum valve lift, and then the valve closes.

This procedure has been applied successfully both to the intake valve and to the discharge valve (see Figure 8); measurements have been taken in different working conditions of the compressor (see Figure 7); moreover it was possible to measure valve motion during transient (see Figure 10).

Compressor was also equipped with conventional seismic accelerometers (see Figure 9).

In order to assure realistic conditions, gas temperature at suction and oil temperature were controlled and refrigerant pressure at noticeable positions was monitored.

CONCLUSION

A measurement method for compressor valve lift based on a single-point laser Doppler technique has been developed.

The paper has discussed the effects of optical disturbances on the LDV signal; signal to noise ratio in operating conditions has been maximized by proper alignment of the laser head and by protecting the laser beam path from oil. In such condition the valve motion is measured correctly, as if windows and oil droplets were not present.

The measurement method provides information without relevant modifications to compressor's geometry and to its characteristic volumes; therefore it is far less invasive than any other measurement method proposed up to now.

Measurements have been taken in various operating conditions including transient.

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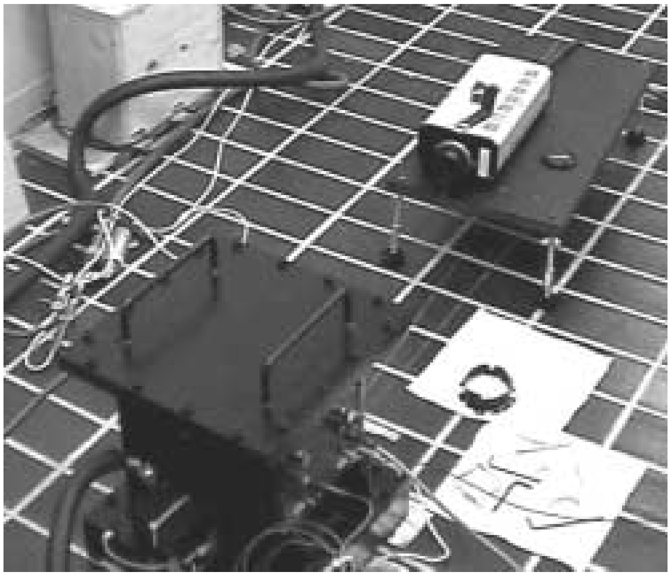

Figure 1 Experimental setup.

Figure 2 Scattering efficiency of surfaces: a) reflective surface, b) real rough surfaces.

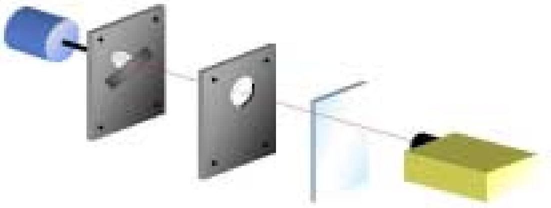

Figure 3 The optical test bench.

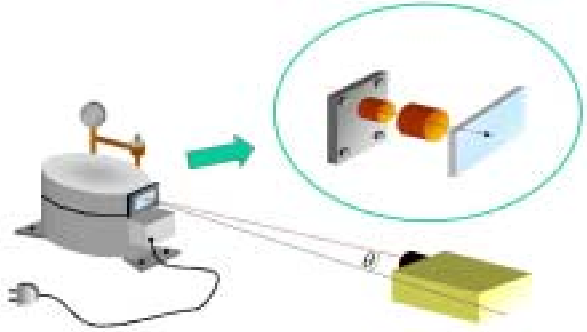

Figure 4 Final configuration with tilted optical axis and laser beam protection from oil spray.

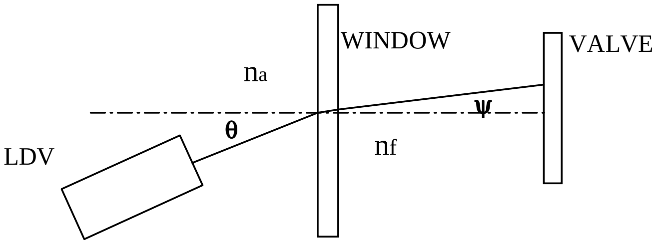

Figure 4 Optical path through a window and 2 different fluids.

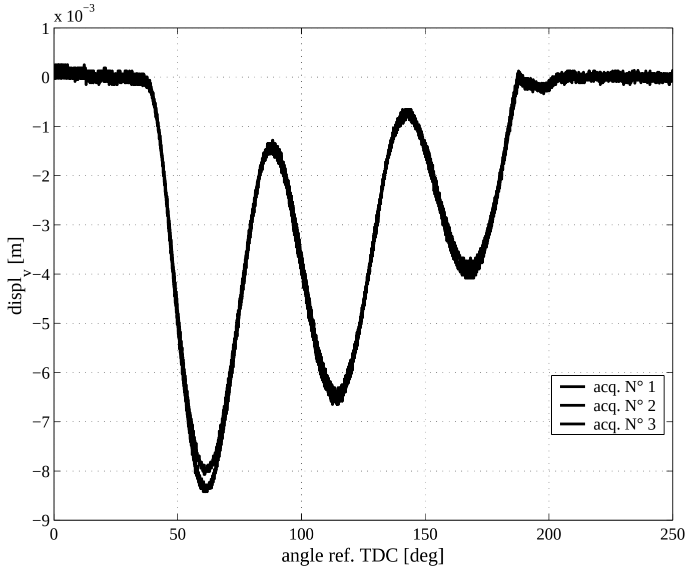

Figure 5 Three measurements done at different times, with same operating conditions, on suction valve.

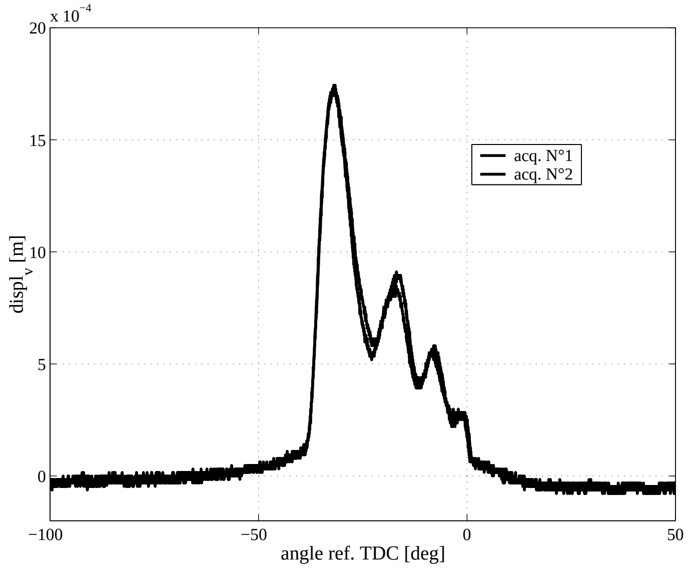

Figure 6 Two measurements done at different times, with same operating conditions, on discharge valve.

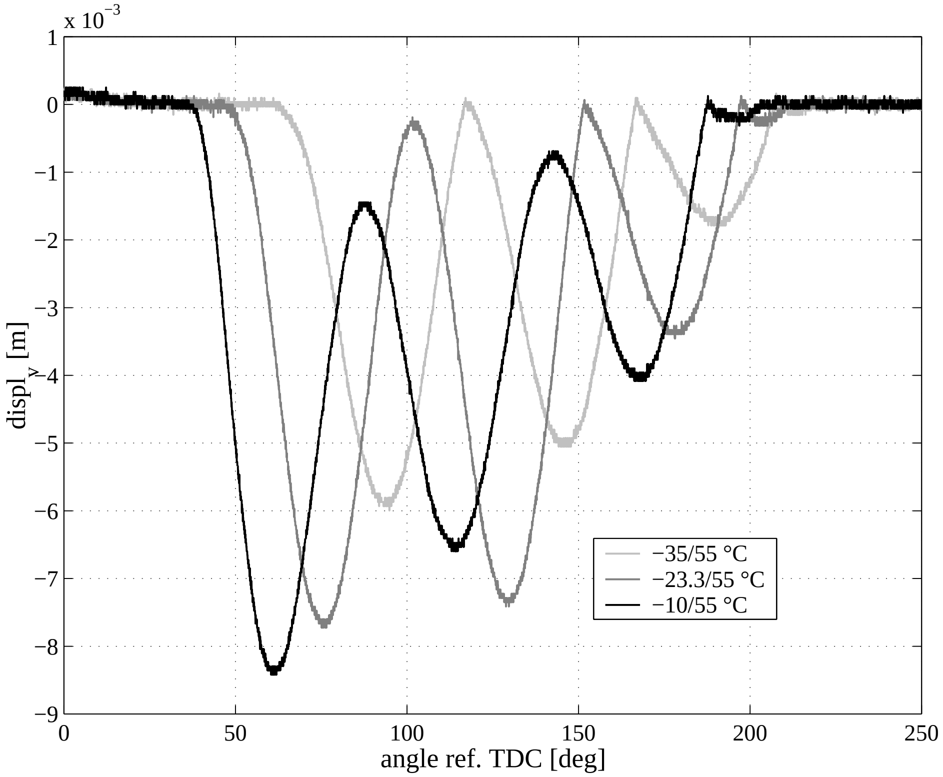

Figure 7 Suction valve displacement at different evaporating/condensing temperatures.

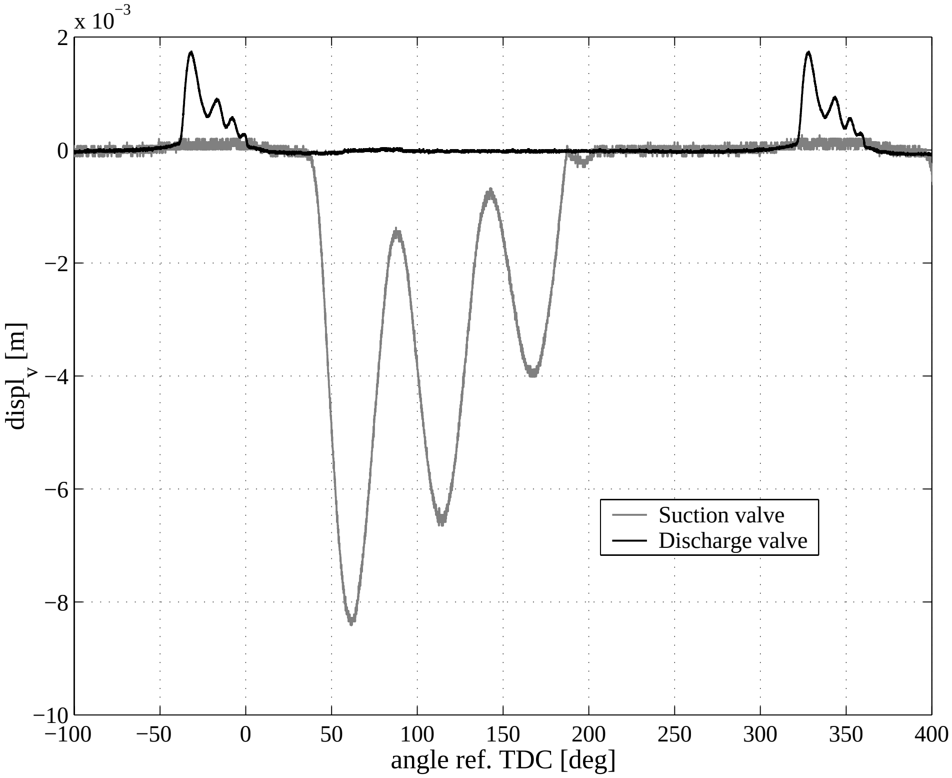

Figure 8 Suction and discharge valve displacement superimposed on the same graph.

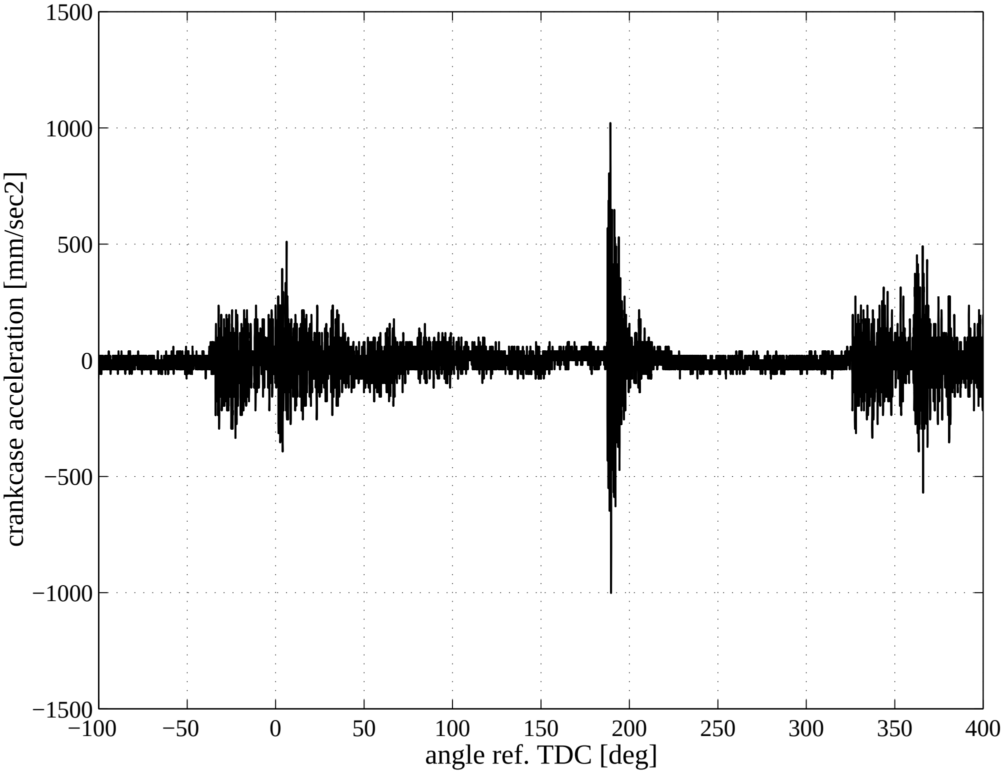

Figure 9 Acceleration simultaneously measured on the compressor crankcase by a conventional piezoelectric transducer.

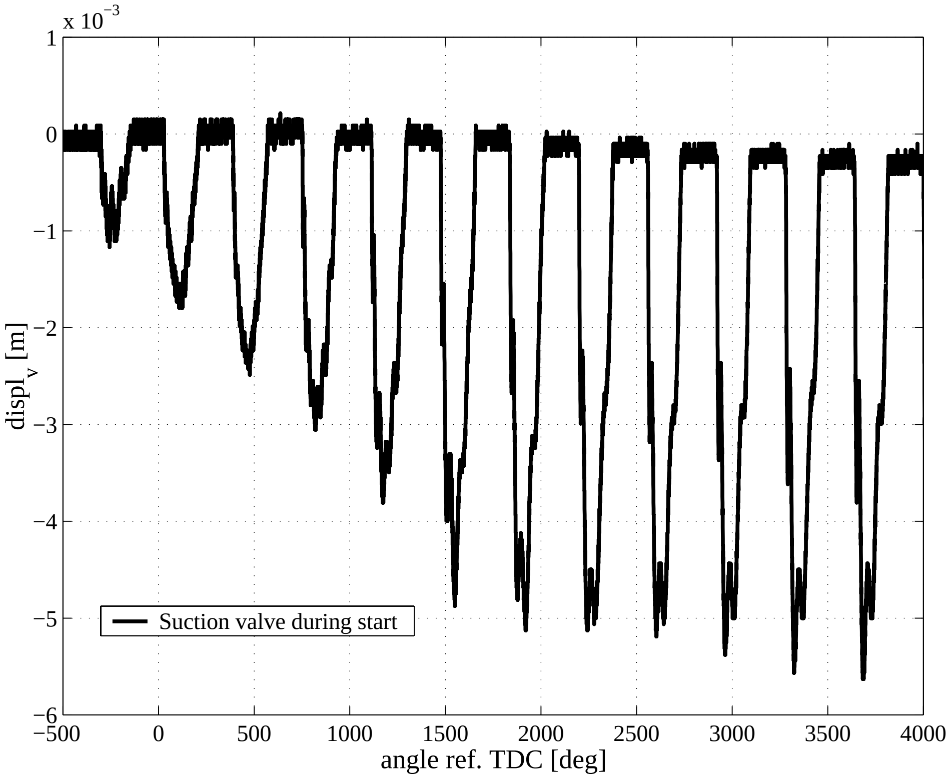

Figure 10 Suction valve motion during start.