Purdue University
Purdue e-Pubs

International Compressor Engineering Conference | School of Mechanical Engineering

2008

# Improvements in the Instantaneous Swept Volume Measuring Device

Kesavan Selvam Pannir
*National Institute of Technology*

Meivelu Udayakumar
*National Institute of Technology*

T. Suthakar
*National Institute of Technology*

# IMPROVEMENTS IN THE INSTANTANEOUS SWEPT VOLUME MEASURING DEVICE

PANNIR SELVAM,K.[1], UDAYAKUMAR,M.[2], SUTHAKAR,T.[3]

[1,2,3] National Institute of Technology, Mechanical Engineering Department,
Tiruchirappalli, Tamil Nadu, India
[1](Phone: 91-431-2503412 Fax: 91-431-2500133 e-mail: pannir_mech@yahoo.com)

## ABSTRACT

In this paper improvements in the device used for measuring instantaneous swept volume of reciprocating compressors is discussed. The instantaneous swept volume device is suitable for measuring instantaneous swept volume of reciprocating compressors in offline method. The instantaneous swept volume measuring device consists of a cam and a non contact laser displacement sensor. A cam, whose profile simulates, swept volume as a function of crank angle is fabricated and fitted on the crankshaft of the reciprocating compressor. The swept volume is calculated by measuring the profile of the cam, which rotates in unison with the crankshaft, using a dynamic non-contact type laser displacement sensor. The laser displacement sensor provides voltage output proportional to the cam profile, which in turn is proportional to the instantaneous swept volume. This voltage output can be given to any analyzer or an oscilloscope as swept volume signal for plotting p-V diagram. This paper discusses the improvement made in the device since it was presented in International Compressor Engineering Conference in year 2004 by the lead author. The maximum operating speed of the device is improved by using high speed laser sensor and the Cam is designed with AUTOCAD software and made out of steel plate using EDM. The device is validated by comparing it's measurements with a crank angle encoder. Uncertainty of the device is estimated.

## 1. INTRODUCTION

Measuring in-cylinder pressure and instantaneous swept volume are required to plot p-V diagram of reciprocating compressors. Soedel (1984) discussed in detail the importance of p-V diagrams. The p-V diagrams are useful in two ways; one for calculation of indicated work and other for diagnosing problems like valve losses and leakages. Area enclosed by a p-V diagram indicates the work performed by the piston as the gas is compressed, which is useful for calculating indicated power of compression. Comparing the experimentally obtained p-V diagram of compressors with theoretically constructed p-V diagrams assuming ideal conditions helps to identify the losses and the problem areas.

In large capacity industrial reciprocating compressors used in process industries, online performance monitoring gadgets are permanently installed to monitor its performance continuously. These online monitoring systems have built in facility to acquire in-cylinder pressure of the compressor and instantaneous swept volume. However in industrial compressors of medium capacity range, installation of online monitoring system is not justified considering the capital cost involved. In-cylinder pressure and instantaneous swept volume of medium capacity range reciprocating compressors need to be measured periodically offline. However permanent installation of measuring instruments is not needed for offline monitoring. The offline measuring instruments are such that they can be fitted to the compressor only when measurement is performed. The measuring instruments used for offline measurements should thus felicitate easy fitting and removal on the compressor.

Crank angle encoders are used presently for instantaneous swept volume measurement. Crank angle encoders fitted to the crankshaft of the reciprocating machines, generate an electrical pulse for every degree of crank rotation. The crank angle encoders also produce one electrical pulse per revolution corresponding to TDC position. These electrical pulses are fed to an auxiliary electronic module. The auxiliary electronic module uses the kinematic relationship of the slider crank mechanism of the reciprocating compressor and converts the crank angle pulses to an analog voltage proportional to the instantaneous swept volume. The crank angle measuring devices are delicate equipment and need precise alignment with the crankshaft. The fitting of the crank angle measuring device to the reciprocating machine often requires a fixture or modification of the existing machine. Moreover an auxiliary electronic module is necessary for converting crank angle to swept volume. Therefore the crank angle encoders are not quite suitable for performing offline measurements. The instantaneous swept volume measuring device developed by authors (Pannir Selvam *et al.,* 2004) is suitable for offline measurements.

## 2 INSTANTANEOUS SWEPT VOLUME MEASURING DEVICE

The instantaneous swept volume device consists of a cam and laser displacement sensor. The cam is a device made out of a plate, having a profile geometry cut according to the relationship between the crank angle and instantaneous volume superimposed on a suitable base circle. The laser displacement sensor is a device available commercially, which is capable of measuring displacement of objects by targeting the laser beam on it. The displacement is measured in non-contact method at high sampling rates. The cam is fitted to the crankshaft or flywheel. The laser displacement sensor is fixed on a rigid reference frame using a stand or a fixture. The laser beam is targeted on the cam profile, to measure the profile of the cam. When the compressor is operating, the cam rotates in unison with the crankshaft. The non-contact type laser displacement sensor measures the profile of the cam dynamically and produces a voltage signal proportional to the distance between the cam and the sensor. Since the profile of the cam is manufactured to indicate instantaneous swept volume, the voltage output of the laser displacement sensor is the measure of instantaneous swept volume. This voltage signal can be connected to an oscilloscope directly to read instantaneous swept volume of the reciprocating compressor.

### 2.1 Advantage of the proposed device

Using the proposed device, the p-V diagram can be obtained on an oscilloscope by operating it on X-Y mode. p-V diagrams can be displayed in the oscilloscope in real time. In industrial facilities involving multiple installations, the cam could be fixed permanently to each machine, and the portable laser displacement sensor can be carried to each machine whenever the measurements are to be performed. The installation time required for fixing the laser displacement sensor is minimal.

## 3. CAM

Pannir Selvam *et al.,* (2004) explained in detail the procedure for the design of the Cam. The cam is the most important part of the proposed device. The instantaneous swept volume of a reciprocating machine is given by the kinematic relation as a function of crank angle.

$$V(\theta)=\frac{\pi D^2}{4}[l+a-(a\cos\theta+\sqrt{l^2-a^2\sin\theta})] \tag{1}$$

The cam profile is made according to the relationship given by,

$$r(\theta)=R_b+kV(\theta) \tag{2}$$

The scale factor 'k' is chosen in such a way that the maximum variation of cam radius 'r' over its entire profile is within the measuring range of laser displacement sensor. To enable the fixing of the cam at its center, the profile is super imposed on a base circle of radius, '$R_b$'.

## 4. LASER DISPLACEMENT SENSOR

The non-contact laser displacement used in the device works on optical triangulation principle. Doebelin (1990) explains the principle of operation of optical triangulation. A commercial, ready-to-use laser displacement sensor, based on a lateral- effect detector uses the "triangulation" principle is shown in Figure 1 . An IR laser diode at 850 nm, modulated at 16 kHz, is the light source, projecting a spot onto the surface to be measured, which need not be highly reflective. As the surface moves within the measuring range on either side of the standoff distance, the image of the spot (formed by a suitable lens system) moves laterally over a single-axis detector, producing an output voltage linear with target displacement. The modulated, rather than steady, light source extends life and allows use of high-gain ac-coupled electronics, reducing drift due to background lighting and a temperature-sensitive detector offset voltage.

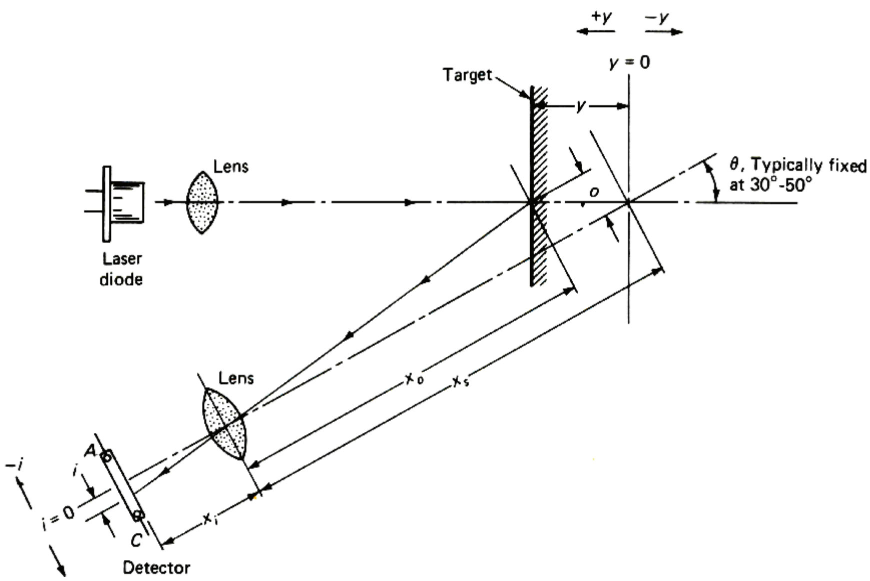


**Figure 1 Working principle of optical triangulation sensors**

### 4.1 Description of the laser sensor

The laser sensor used in the device is manufactured by M/s Microepsilon, Germany. The specifications of the sensor is given in Table 1

**Table 1 Laser Displacement Sensor Specifications**

| | |
|---|---|
| Sensor type | Laser Sensors |
| Model | LD 1605 |
| Type | 100 |
| Measuring range (mm): | ±50mm |
| Linearity | 300μm |
| Resolution Static (μm) | 30 |
| Spot Diameter | 1.5 mm |
| Laser Sampling Frequency | 25 kHz |
| Light source wave length | 675nm, red |
| Max vibration | 10g up to 1 kHz |
| Supply voltage | 24V DC/200mA |
| Voltage output | ±l0v dc |

## 5. LIMITATIONS OF PREVIOUS DESIGN AND IMPROVEMENTS MADE

Earlier Cam was manufactured using an acrylic sheet and it was not dynamically balanced. Now the cam shown in Figure 2 is made of steel plate and it is dynamically balanced. A computer code using AutoCAD software is used to model the cam. The cam is dynamically balanced by choosing a proper geometry. An AutoCAD command is used to check the alignment of center of gravity of the cam with the center of the 70mm bore. The machining of the cam was performed using EDM.

The sampling rate of laser displacement sensor used in the earlier design is 1kHz. This limits the number of readings to 1000 per second. With this laser displacement sensor, to acquire at least one reading per degree of crank rotation, ie.360 readings per revolution, the speed of the compressor should not exceed 166 r/min. This speed limitation makes it not suitable for compressor application. The sampling rate of laser sensor presently used is 25kHz. Therefore the maximum speed of operation is increased to 4166r/min.

**Figure 2 Cam**

# 6. VALIDATION OF INSTANTANEOUS SWEPT VOLUME MEASURING DEVICE

The instantaneous swept volume measuring device is validated by comparing the output of the device with the output obtained using a standard device. In this research work, a crank angle encoder Make: M/s Kistler Instrumetns, Switzerland Model:2613B1, is used as reference for the validation. To make the validation appropriate, it is performed on a reciprocating compressor at actual working conditions.

## 6.1 Experimental Setup

An experimental facility shown in Figure 3 was established to validate the performance of the swept volume measuring device. The cam and crank angle encoder are mounted on the crankshaft of M/s Ingersoll Rand make compressor model IR7X5 Lub. It is a single cylinder double acting compressor. The rated speed of the compressor is 750 r/min. The compressor is driven by a 22 kW three phase induction motor. A variable speed drive is used to control the speed of the motor, which facilitates performing experiments at different speeds.

The installation of instantaneous swept volume measuring device on the reciprocating compressor is shown in Figure 4. The cam is mounted on the flywheel of the compressor. The non-contact laser displacement sensor is fixed on a sturdy tripod. The laser beam of the laser displacement sensor is focused on the cam and the tripod is positioned such that the laser beam is targeted on the cam profile throughout the rotation of the flywheel, and the profile of the cam is within the measuring range of the laser displacement sensor. The voltage outputs of the laser sensor and crank angle encoder are connected to a four channel digital storage oscilloscope. The data acquired in the oscilloscope is transferred to a personal computer for converting the crank angle encoder output into instantaneous swept volume.

## 6.2 Experimental Procedure

The compressor is operated at different speeds using a variable speed drive. For each speed, the output of crank angle encoder and the output of laser displacement sensor are recorded simultaneously using a DSO. The data acquired in DSO is downloaded to a PC.

In the DSO, the data acquired in a single sweep, contains data lasting more than one cycle. To perform calculations for one cycle, the recorded data is trimmed to one cycle. For this the data points acquired between two consecutive TDC pulses are taken. The crank angle encoder pulses acquired in time domain are converted to crank angles and subsequently to swept volume, by using the kinematic relation (1), by a computer programme. The swept volume indicated by the device is calculated by multiplying the voltage output of the laser displacement sensor with voltage to displacement conversion factor and scale factor ‘k’. The swept volume measurements indicated by the device are compared with crank angle encoder measurements.

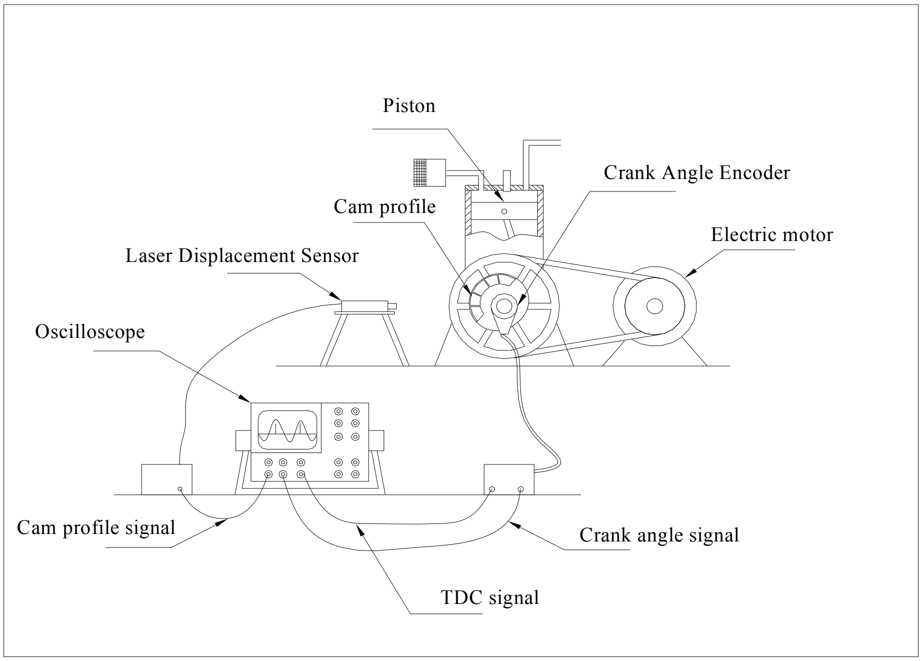


**Figure 3 Experimental setup for validation of Instantaneous swept volume device**

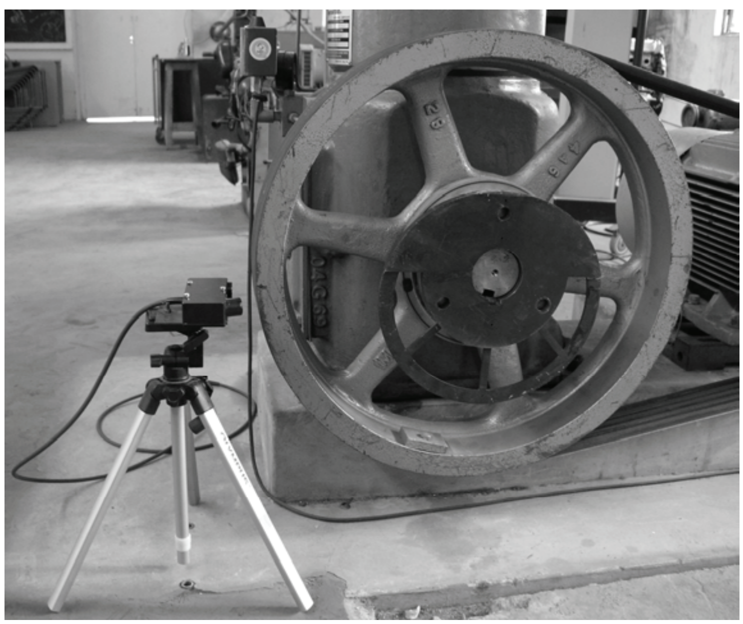

**Figure 4 Instantaneous swept volume device installation**

## 6. 3 Results and Discussion

Table 2 gives the error of the instantaneous swept volume measuring device in comparison with the crank angle encoder measurements by running the compressor at different speeds. Figure 5 shows the comparison of instantaneous swept volume measurements made with the device and crank angle encoder. Figure 6 shows the error of the device in percentage FSR in comparison with crank angle encoder.

**Table 2 Error of instantaneous Swept Volume Measuring Device**

| Compressor Speed (r/min) | Error (percentage of FSR) | |
|---|---|---|
| | maximum | minimum |
| 750 | 1.059 | -0.949 |
| 675 | 0.865 | -0.934 |
| 600 | 0.740 | -0.828 |
| 525 | 0.628 | -0.966 |
| 450 | 0.685 | -0.917 |
| 425 | 0.860 | -0.6489 |

The uncertainty in measurement of swept volume of the device when measuring at rated speed of the compressor at rated speed of 750r/min is within ±1.05% with respect to the crank angle encoder measurement.

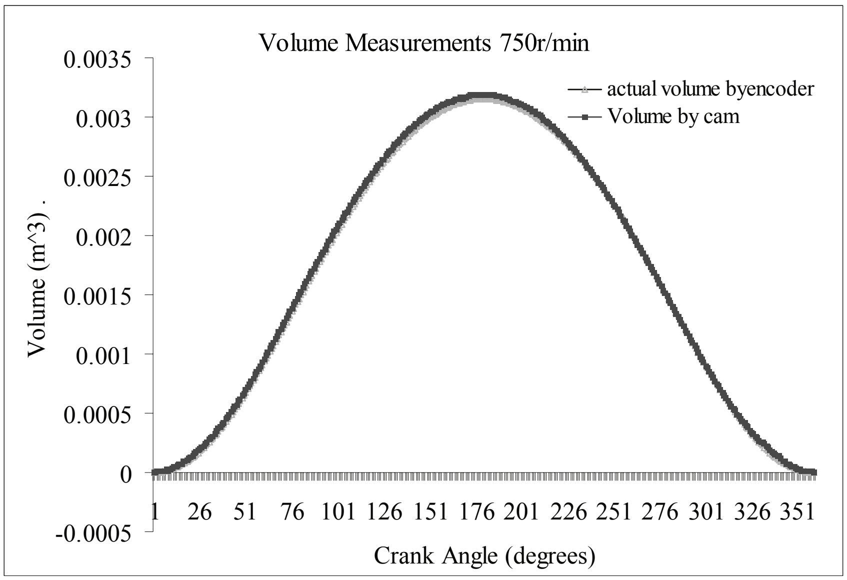


**Figure 5 Comparison of Instantaneous Volume Measurements 750 r/min**

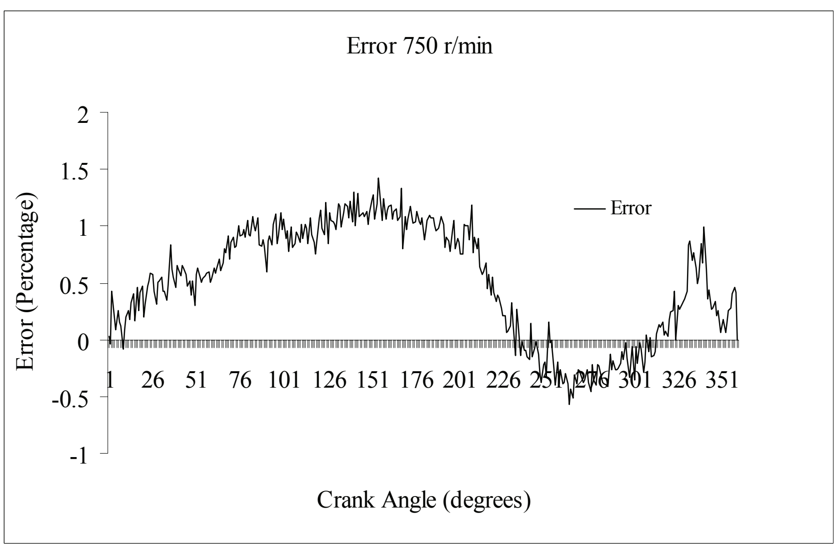


**Figure 6 Error in comparison with Crank Angle Encoder Measurements**

## 7. UNCERTAINTY IN MEASUREMENT OF INSTANTANEOUS SWEPT VOLUME

The instantaneous swept volume measuring device is validated using a crank angle encoder. The total uncertainty of the instantaneous swept volume device is estimated by adding uncertainty of the encoder and uncertainty of the swept volume device with respect to the crank angle encoder. The crank angle encoder measures the crank angle with uncertainty of ±0.02°. The Uncertainty of instantaneous swept volume measurement using encoder is measured by computing propagation of measurement uncertainty. The swept volume of a slider crank mechanism is given by the kinematic equation (1).The dimensions and corresponding uncertainties of slider crank mechanism of the compressor used are given in Table 3

**Table 3 Dimensions and Uncertainty of Slider Crank Mechanism components**

| Parameter | description | Value | Uncertainty |
|---|---|---|---|
| $a$ | Crank Radius | 63.5 mm | ±0.01 mm |
| D | Bore diameter | 177.8 mm | ±0.02 mm |
| l | Connecting Rod Length | 260.5mm | ±0.03 mm |
| θ | Instantaneous Angle | 1 to 360° with 1° increments | ±0.02° |

The influence coefficients of each parameter are derived as follows
Equation (3) gives the influence coefficient of Bore diameter

$$\frac{\partial V}{\partial D} = \frac{\pi D}{2} \times \left( l + a - a \text{ Cos } \theta - \sqrt{l^2 - a^2 \text{ Sin }^2 \theta} \right) \tag{3}$$

Equation (4) gives the influence coefficient of crank angle

$$\frac{\partial V}{\partial \theta} = \frac{\pi D^2}{4} \times \left( a \text{ Sin } \theta + \frac{a^2 \text{ Sin } \theta \text{ Cos } \theta}{\sqrt{l^2 - a^2 \text{ Sin }^2 \theta}} \right) \tag{4}$$

Equation (5) gives the influence coefficient of crank radius

$$\frac{\partial V}{\partial a} = \frac{\pi D^2}{4} \times \left( 1 - \text{Cos } \theta + \frac{a^2 \text{ Sin }^2 \theta}{\sqrt{l^2 - a^2 \text{ Sin }^2 \theta}} \right) \tag{5}$$

Equation (6) gives the influence coefficient of connecting rod length

$$\frac{\partial V}{\partial l} = \frac{\pi D^2}{4} \times \left( 1 - \frac{1}{\sqrt{l^2 - a^2 \text{ Sin }^2 \theta}} \right) \tag{6}$$

The sum of error due to all contributing factors is computed numerically and plotted with respect the crank angle θ as shown in Figure 7. Uncertainty in swept volume measurement using crank angle encoder is with in ± 1.046%
Uncertainty of instantaneous swept volume device = ± (1.046% + 1.05%) = ±2.096% of FSR.

## 6. CONCLUSIONS

It may be concluded from the above discussion that improvements in instantaneous swept volume device is achieved. The cam is dynamically balanced and made out of steel. The maximum speed range of the instantaneous swept volume device is increased from 166r/min to 4166r/min. The performance of the device is validated using a crank angle encoder. The uncertainty of the device is estimated to be 2.09% FSR.

.

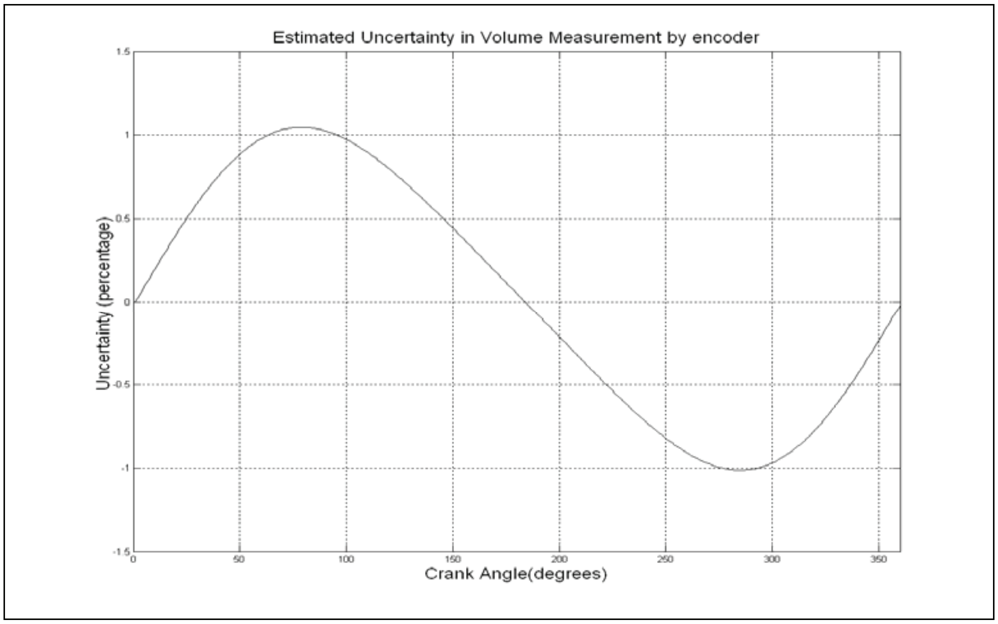


**Figure 7 Estimated Uncertainty in swept volume measurement**

## NOMENCLATURE

| | | |
|---|---|---|
| $a$ | Crank Radius | (m) |
| D | Cylinder diameter | (m) |
| BDC | Bottom Dead Centre | |
| EDM | Electrical Discharge Machining | |
| $R_b$ | Base Radius | (m) |
| DSO | Digital Storage Oscilloscope | |
| FSR | Full Scale Reading | |
| l | Connecting Rod Length | (m) |
| S | Stroke | (m) |
| TDC | Top Dead Centre | |
| V | Instantaneous Volume | ($m^3$) |
| θ | Instantaneous Angle | (degree) |
| r | radius of the cam at angle θ | (m) |
| k | scale factor | |

## REFERENCES

Pannir Selvam, K, Udayakumar, M, Nageswawara Rao,C,2004,C011 A New device to measure instantaneous swept volume of reciprocating machines/compressors *Proceedings of Compressor Technology conference July 2004*, Purdue University, USA

Doeblin,O, 1990, *Measurement Systems Application and Design*, McGraw-Hill Publishing Company, singapore,960

Soedel, W, 1984, *Design and Mechanics of Compressor Valves*, Purdue University Publication , West Lafayette, pp 47-54.

## ACKNOWLEDGEMENT

The authors gratefully acknowledge the support rendered by, Mr. Rishi Chaitanya.N., M.Tech student and Mr. Rayer Kennedy and Mr. Baskar , the staff of Mechanical Department, National Institute of Technology, Tiruchirappalli -15 in this work