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A NEW DEVICE TO MEASURE INSTANTANEOUS SWEPT VOLUME OF RECIPROCATING MACHINES /COMPRESSORS

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ABSTRACT

In this paper a new method of measuring instantaneous swept volume of reciprocating machines/compressors is discussed. The device proposed is suitable for industrial facilities involving multiple reciprocating machines/compressors. A cam, whose profile simulates, swept volume as a function of crank angle is fabricated and fitted on the crankshaft of the reciprocating machine/compressor. The swept volume is calculated by measuring the profile of the cam, which rotates in unison with the crankshaft, using a dynamic noncontact type laser displacement sensor. The laser displacement sensor provides voltage output proportional to the cam profile, which in turn is proportional to the swept volume. This voltage output can be given to any analyzer as swept volume signal for further processing. An experimental setup is created to validate the measurements obtained by this method by comparing with measurements performed with a crank angle encoder. Error sources that arise in the cam device are identified and discussed.

1. INTRODUCTION

Measuring instantaneous swept volume of the piston cylinder arrangement is required to plot p-V diagram of reciprocating machines like IC engines and compressors. Soedel (1984) discussed in detail the importance of p-V diagrams. The enclosed area of the p-V diagram indicates the mechanical work available to the piston in IC engines. In compressors the area enclosed by the p-V diagram indicates the work performed by the piston as the gas is compressed. 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. The methods that are used to measure the instantaneous swept volume of reciprocating compressors and their merits and demerits are briefly discussed in the following sections.

1.1 Crank Angle Measuring Devices

Crank angle measuring devices like encoders fitted to the crankshaft of the reciprocating machines, generate an electrical pulse for every degree of crank rotation. These electrical pulses are fed to an auxiliary electronic module to convert them into the electrical voltage proportional to instantaneous swept volume. The kinematic relationship of the slider crank mechanism employed in the reciprocating machine should be keyed in to the auxiliary electronic module. The crank angle encoders also produce an additional electrical pulse per revolution, which is used as TDC reference.

The crank angle measuring devices are used widely for measurement of swept volume. It is a proven method. The TDC reference pulse is useful to locate the position of TDC in p-V diagrams, which is critical for thermodynamic calculations.

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.

1.2 Installation of Proximity Probe

Richardson *et al.* (1980) used a proximity probe installed in the cylinder as shown in Fig.1. A slot with tapered flat surface is cut in the piston. The proximity probe provides output proportional to the position of piston and therefore is proportional to instantaneous swept volume.

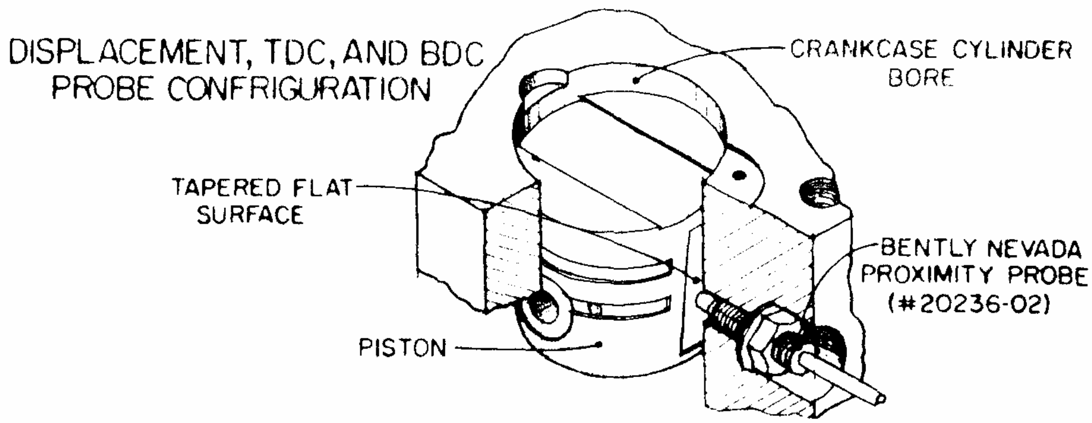

Figure 1: Installation of Proximity Probe to Measure Piston Displacement

This method gives direct measurement of swept volume without the need of an auxiliary electronic module. The error due to mismatch of TDC is eliminated. However this method needs modification in the cylinder and piston. Therefore this method is not suitable for industrial compressors.

1.3 **The Proposed Device**

The methods discussed in sections 1.1 and 1.2 are suitable for laboratory applications. However when p-V diagrams are to be acquired for multiple compressor installations, the methods discussed above require a dedicated instantaneous swept volume measuring device in each machine. In industrial facilities involving multiple reciprocating machines, for getting p-V diagram of each machine, the procedure is to be replicated and it is an expensive one.

The proposed device consists of a cam and laser displacement sensor. The cam is fitted to the crankshaft and a laser displacement sensor is used to measure the profile of the cam. The cam rotates in unison with the crankshaft. The non-contact type laser displacement sensor is used to sense the profile of the cam dynamically and produces a voltage signal proportional to the distance between the cam and the sensor and hence is the measure of instantaneous swept volume.

2. 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 (1), which is a function of crank angle.

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

The cam profile is made according to the relationship given by (2).

$$r(\theta) = R_b + k * V(\theta) \quad (2)$$

The scale factor k is chosen in such a way that the maximum variation of cam radius ‘r’ throughout its profile is within the measuring range of laser displacement sensor. Fig.2. shows the plot of V(θ) in the polar coordinates. The cam profile is shown in the Fig.3.

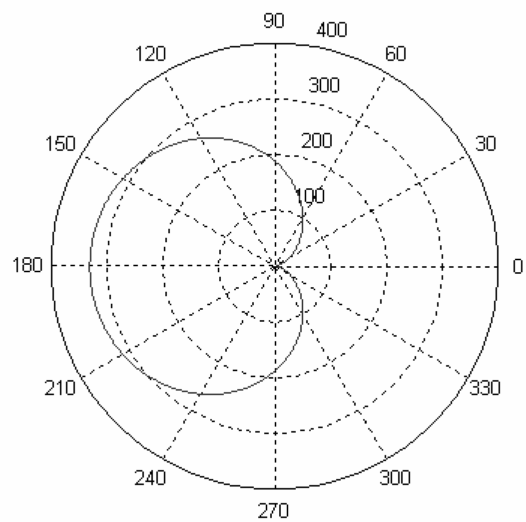

Figure 2: Plot of V(θ)

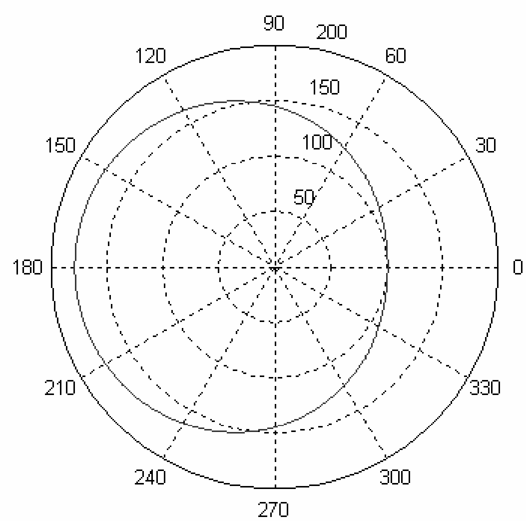

Figure 3: Cam profile

The cam is manufactured with acrylic sheet material using a CNC machining center. The TDC point, which corresponds to the extreme point on the profile, has been marked on the cam. The cam is fixed to the center of the crankshaft, by making a hole passing through the geometric center of the cam.

3. LASER DISPLACEMENT SENSOR

To measure the instantaneous swept volume, the radius of the cam should be measured instantaneously. For this purpose, a non-contact type sensor, which is capable of measuring the profile of the cam dynamically, is required. In this work a non-contact laser displacement sensor is used. The non-contact laser displacement sensor works on optical triangulation principle.

The specification of the laser displacement sensor used is given below

Range: 0-100 mm
Resolution: 20 µm
Frequency Response: 1 kHz
Linearity: ± 0.2 %

The laser displacement sensor is positioned firmly in such a way that laser beam continuously traces the profile of the rotating cam.

3.1 Calibration of Laser Displacement Sensor

The laser displacement sensor is calibrated using Grade '0'ceramic slip gage set as length standard. The laser displacement sensor is mounted firmly on a mounting stand. The slip gages are built to various discrete sizes between 1mm to 100 mm and the same is measured with the laser displacement sensor. The voltage output of the laser displacement sensor is measured using a calibrated 6 $^{1}/_{2}$ digit multimeter. The calibration curve obtained is shown in Fig.4. From this curve, it is inferred that the laser displacement sensor is less accurate at both the extremes of its measuring range.

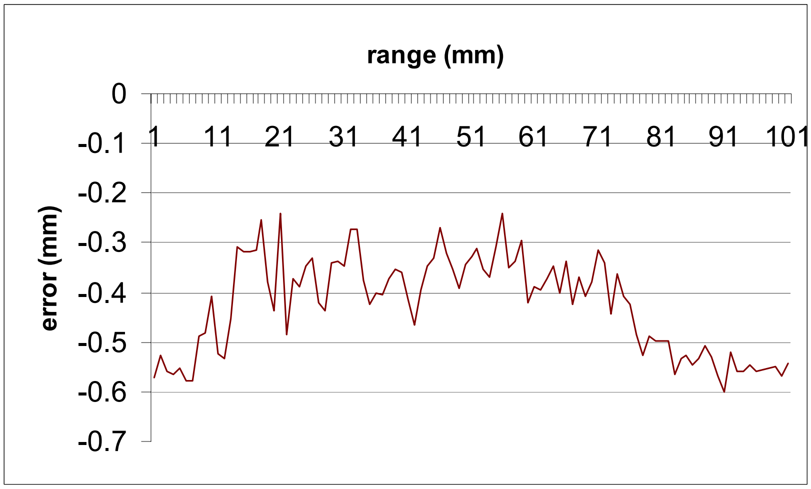

Figure 4: Calibration curve of laser displacement sensor

4. EXPERIMENTAL SET UP

An experimental set up has been established to validate the performance of the swept volume measuring device, using a single cylinder reciprocating compressor. The bore D and stroke S of the compressor used are 7.5cm and 8.5 cm respectively. The rated speed of the compressor is 550 r/min. The compressor is driven by a 2.2kW 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 head of the compressor is removed to enable the measurement of the piston displacement directly using laser displacement sensor. The instantaneous swept volume is calculated by multiplying the piston displacement with the area of the cylinder. The Fig.5 shows the experimental facility created for this research work.

The cam is fitted on the crankshaft on the flywheel side of the compressor. A hole drilled at the geometric center of the cam profile is used to fix the cam at the center of the crankshaft. The laser displacement sensor is fixed firmly to read the profile of the cam.

A crank angle encoder is fitted on the other side of the crankshaft. The crank angle encoder provides an electrical pulse for every degree of crank angle rotation and a single TDC reference pulse for every revolution. The shaft of the encoder is press fitted to the crank shaft of the compressor. To match the TDC position of the piston and TDC pulse of the encoder, the following procedure is adopted. The piston is positioned at TDC within ±1 µm accuracy using an electronic comparator. Then the body of the encoder is turned with reference to its shaft till corresponding TDC slot of the encoder matches the photodiode position and thus produces an electrical pulse.

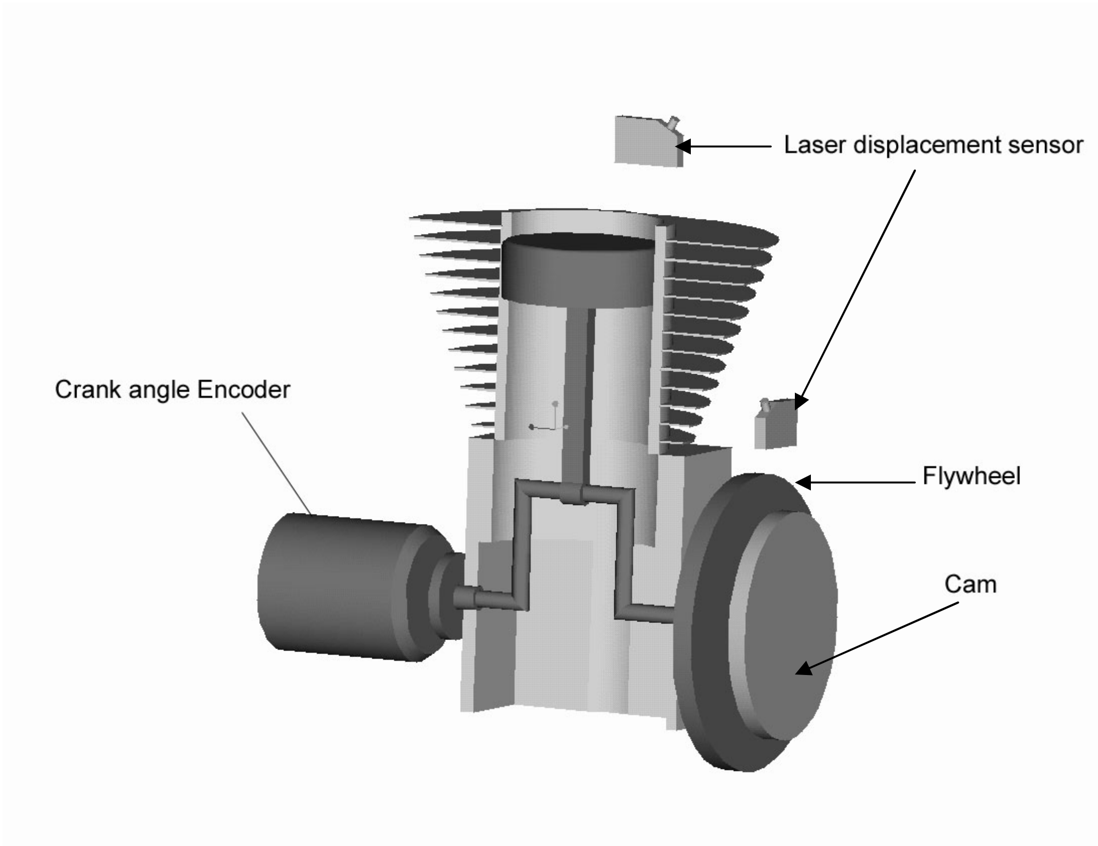

Figure5: Experimental Set Up

The voltage outputs from the laser displacement sensor and crank angle encoder are given to a 4-channel digital storage oscilloscope (DSO). The data acquired in DSO is transferred to a PC through RS-232 Serial Interface. The data transferred to the PC are analysed using programmes written in MATLAB software.

4.1 Experimental Procedure

The compressor is operated at different speeds using the variable speed drive. For each speed, the output of crank angle encoder and the output of laser displacement sensor, positioned to measure the radius of the cam, are recorded simultaneously using the DSO. Also, for each speed, the piston displacement data is acquired. 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 (2), 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 indicated by the piston displacement is calculated by taking the product of laser displacement sensor voltage output, voltage to displacement conversion factor and area of the cylinder.

The swept volume measurements indicated by the device are compared with crank angle encoder measurements and swept volume indicated by piston displacement is used as cross-reference.

4.2 Limitations of Laser Displacement Sensor

The sampling rate of laser displacement sensor used in this experiment 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. Therefore the experiments are performed below this limiting speed. However this limitation could be easily overcome by using laser displacement sensors of higher sampling speed.

4.3 Results and Discussion

The results of swept volume measurements obtained, at 160r/min, by the crank angle encoder and the device are shown in the Fig.6. The swept volume curves obtained by both methods are closely matching. The Fig.7 shows the error between the swept volume measurements obtained by the device in comparison with the crank angle encoder measurements. The maximum error, as seen in the Fig.7, is within limits $\pm 4\ cm^3$ and in percentage it is $\pm$ 1.22. The measurements are performed at different speeds and it is observed that at lower speeds the errors tend to decrease, whereas at higher speeds, the errors tend to increase, due to the frequency response limitation of the laser displacement sensor.

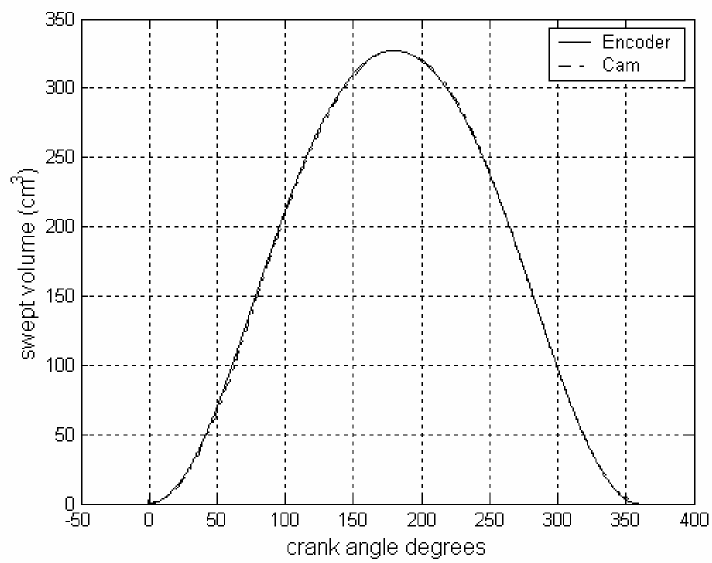

Figure 6: comparison of device measurement with crank angle encoder measurement

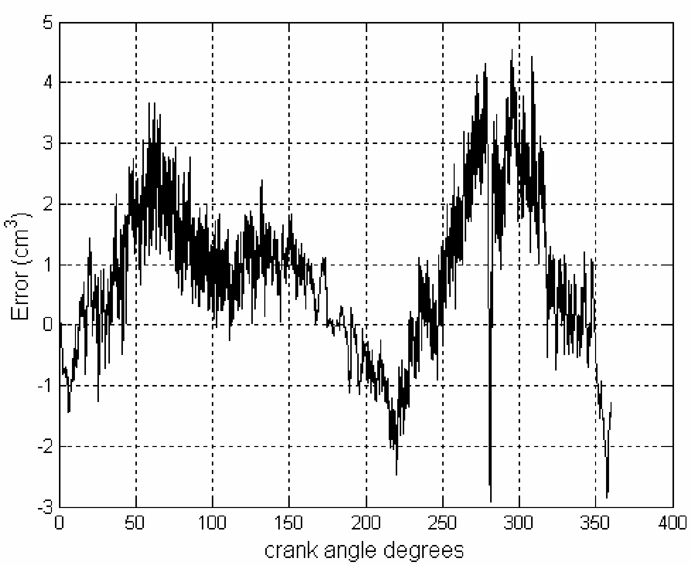

Figure 7: Error in the device measurement.

The results of the swept volume measurements obtained, at 160 r/min, using piston displacement measurement and crank angle encoder is shown in the Fig.8. The swept volume curves match closely with each other. The error in this measurement, as seen in Fig.9, is within the limits of $\pm 4\ cm^3$ and in percentage it is $\pm$ 1.22.

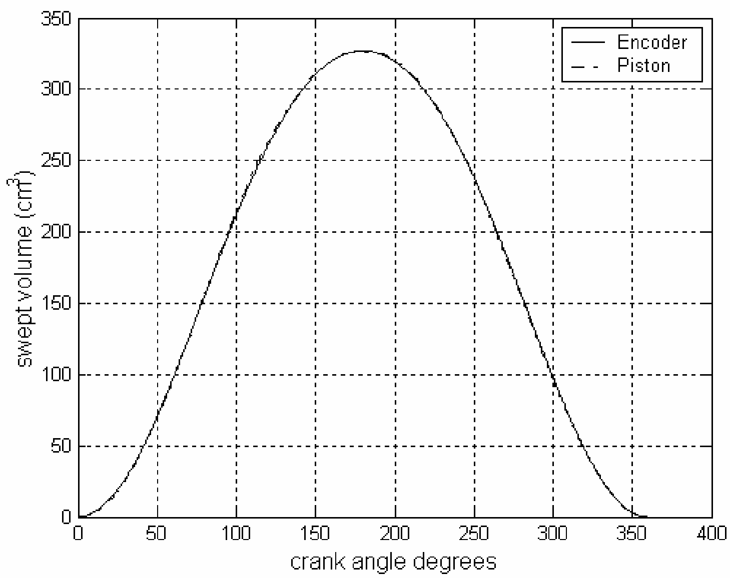

Figure 8: comparison of piston measurement with crank angle encoder measurement

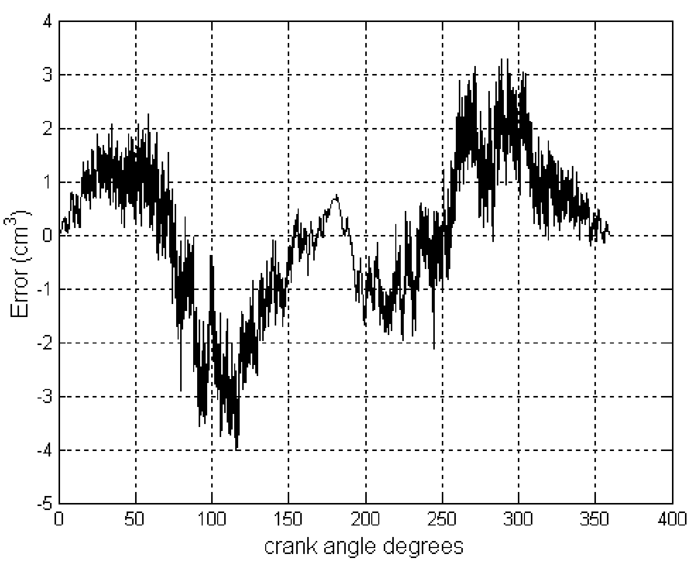

Figure 9: error in the piston measurement

5. ERROR SOURCES

The error sources of the proposed instantaneous swept volume measuring device are briefly discussed below

5.1 Cam Profile Error

The cam profile error is the deviation of the cam profile from the relation (2). It arises due to the imperfections in manufacture of the cam. The accuracy of the profile could be increased by employing CNC profile making machines.

5.2. Laser Displacement Sensor Error

The error due to laser displacement sensor can be classified into two types. First type of error is inherent error of the laser displacement sensor, which is referred to as linearity by the sensor manufacturers. The linearity of laser displacement sensor is poor at both extremes of the measurement range. Second type of error is due to the misalignment of the sensor's measuring axis with the surface of the cam.

5.3. Run-out Error

The run-out error is a mounting error. The offset of the geometric axis of the cam and the axis of rotation of the crankshaft of reciprocating machine creates run-out error. This error distorts the profile of the cam and hence the swept volume measurements.

5.4. Sensor Offset Error

This error arises due to the offset between the sensors measurement axis and the geometric center of the cam. This error phase shifts the profile.

5.5 TDC error

This error is due to mismatch between the cam and the piston at the TDC position of the reciprocating machine. This error introduces phase shift in swept volume measurement.

6. CONCLUSIONS

From the above discussion it is concluded that the swept volume indicated by this device is in close agreement with the crank angle encoder measurements. Therefore the device could be used an alternative swept volume measuring equipment. The speed limitations of the present setup can be easily overcome by using laser displacement sensors of higher frequency response. At present laser displacement sensors with 100kHz frequency response are commercially available.

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.

NOMENCLATURE

a	Crank Radius	(cm)
D	Cylinder diameter	(cm)
BDC	Bottom Dead Centre	
R_b	Base Radius	(cm)
DSO	Digital Storage Oscilloscope	
l	Connecting Rod Length	(cm)
S	Stroke	(cm)
TDC	Top Dead Centre	
V	Instantaneous Volume	(cm^3)
θ	Instantaneous Angle	(degree)
r	radius of the cam at angle θ	(cm)
k	scale factor	

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