APPLICATION OF IMPROVED PRESSURE TRANSDUCERS FOR PRESSURE MEASUREMENTS

P. L. Mtui

Institute of Production Innovation, University of Dar es Salaam
P.O. Box.. 35075, Dar es Salaam, Tanzania

ABSTRACT

Substantial improvement of low sensitivity pressure transducers aiming at obtaining a more realistic output signal is discussed. The output signal direct from these transducers has deficiencies of amplitude attenuation and phase lag, thus the measured values are not necessarily the true instantaneous values. In order to correct for such shortcomings the unit step response of these transducers is also studied experimentally. A mathematical model is established based on the experimental results to build up a compensation circuit which is then included in the instrumentation setup to eliminate these deficiencies.

The effectiveness of the compensated transducer is demonstrated by measuring the pressure profiles close to the air inlet valve of a firing engine. The obtained results are compared with the ones taken under the same conditions but using more sensitive one (piezo type of transducer) which then acts as a comparator.

INTRODUCTION

The inlet manifold pressure of an internal combustion engine (ICE) determine greatly the volumetric efficiency of the engine[1]. In view of this, it is necessary to accurately determine the instantaneous pressure as the engine inlet valve opens.

With the advent of electronics, pressure transducers providing instantaneous signal have become dominant. Among the popular transducers are the flexible diaphragm (resistive type of transducers) on which one side is exposed to the pressure to be measured. Yet another common type of transducers are called piezo- electric transducers which contain a piezo-electric crystal which when vibrates (due to the pressure to be measured) it produces electric charge. This charge is proportional to the vibration, and this gives the valuae of pressure to be measured through calibration.

For research purposes requiring accurate pressure measurements, the transducer must be selected with a great care. Important considerations in the choice of pressure transducer include the signal linearity, temperature sensitivity, vibration sensitivity, etc. Usually the PET are superior almost in all aspects when compared with the resistive type of transducers. However, the PET are substantially higher in terms of price when compared with a resistive transducer capable of measuring the same range of pressure (but with lower sensitivity).

In view of the high costs of PET's and low sensitivity of resistive transducers, it is important to looking for ways of improving the resistive transducers to the level of performance of PET's, but still keeping the price low. Such an improvement combines the knowledge of the transfer functions of first order instruments as well as their experimental behaviour for a unit step input signal.

TRANSDUCER TRANSFER FUNCTION

In practice it is assumed that the mathematical modelling equations to simulate the system to be studied is much the same way as the laboratory model simulation. When properly derived, the mathematical model will reflect (within certain limits of accuracy) the characteristics of the physical process being analyzed. The limits of the mathematical model are determined by the assumptions used in the derivation. A poor set of assumptions can, and usually does, lead to erroneous conclusion being drawn from the simulation.

The response characteristics of the resistive transducer is slow because of the inertia effect of the moving parts (diaphragm). The slow response together with the damping effect the moving parts of the transducer introduces attenuation and phase lag of the measured signal. To eliminate these undesired effects, a transfer function is established to allow for the correction of the signal. The transfer function of the transducer was approximated as shown in Figures. 1 and 2 The experimental signal was obtained

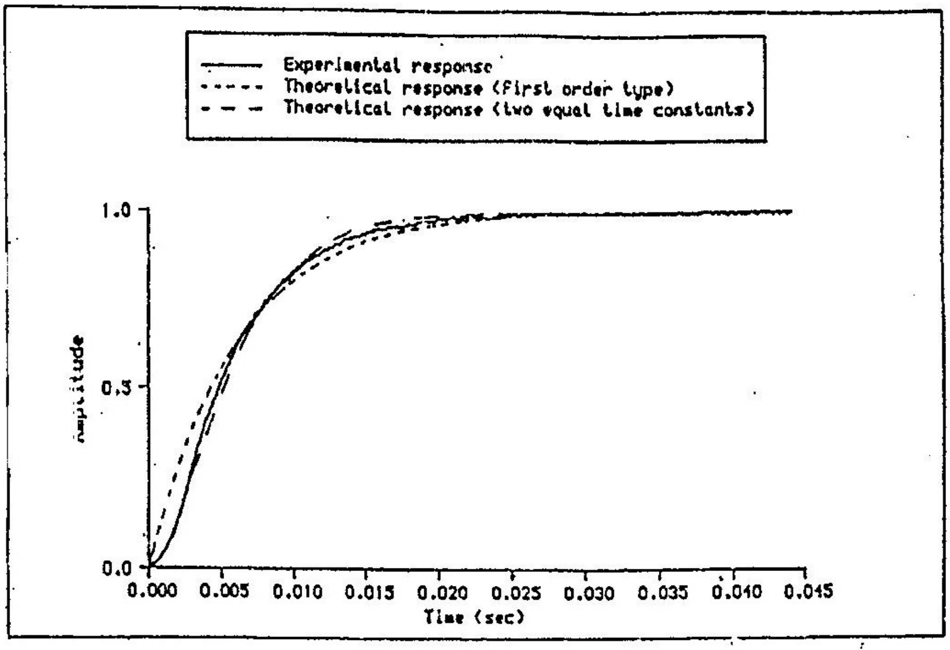

Fig. 1: Pressure transducer responce (type SA15)

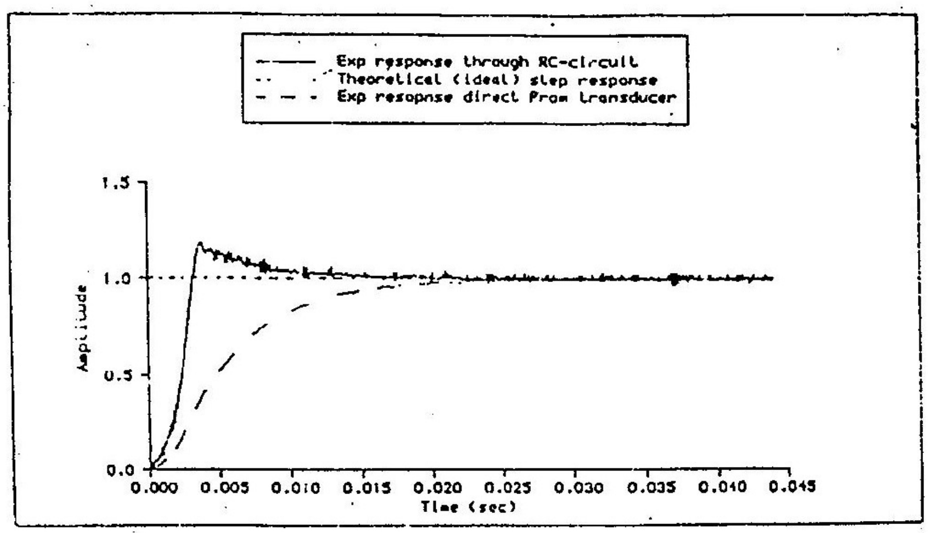

Fig. 2: Pressure transducer response (type SA15)

by creating a vacuum in the transducer (by sucking and release quickly). The release was made quickly so as to closely reproduce an ideal signal. The signal from the pressure transducer (Fig.1) was passed through a charge amplifier for amplification (Fig. 11). The amplified signal is digitized by using Apple II Computer while the signal was instantaneously displayed on an oscilloscope as well as stored in a floppy disk for further analysis.

The transfer function through two equal time constants depict better representation of the experimental response than the single time constant, especially so at the early stage of the signal input (Fig 1). The close matching is mainly due to the effect of time in the pre-exponent of the two equal time constant approximation.

The aim of these mathematical modelling is to build up a "correcting" circuit based on the experimental findings. Although the two equal time constants agree much better with experiment than the single time constant (Fig. 2), for simplicity in the build up of the circuit the single time constant model was chosen. The experimental unit step input was repeated while the signal passing through the correcting circuit (RC-circuit of Fig. 3) and the results are shown in Fig. 2 together with the theoretical (ideal) step response.

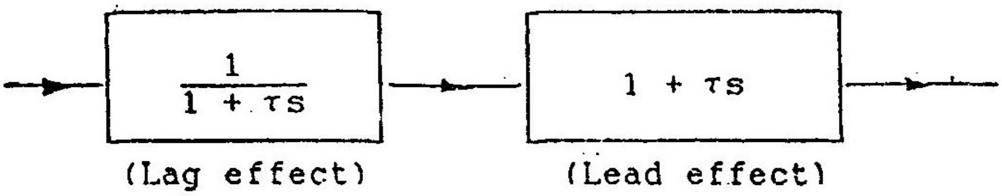

Fig. 3: Lead-lag block diagram

THE COMPENSATING CIRCUIT (RC-CIRCUIT)

The two mathematical models to approximate the experimental step input are the first order of single time constant (eqn.1) and of two equal time constants (eqn. 2)

$$H(t) = [1 - \exp(-\frac{t}{\tau})] \quad (1)$$

$$H(t) = [1 - \{1 + \frac{t}{\tau}\} \exp(-\frac{t}{\tau})] \quad (2)$$

From the results (Fig.1), it was found that if the response is assumed of first order type, the time constant, =6.3msec. This time constant is, by definition, the time elapse for the signal reaches 63.2% of the maximum value (2). Thus, the time constant was extracted from the experiment on this basis. On the other hand, with two equal time constants to achieve the same 63.2%, the two time tend to be 1= 2=3.31msec (which equals to half of a single time constant).

First Order Instruments

The first order instruments, by definition, they follow the general governing equation given by:

$$a_1 \frac{dH}{dt} + a_o H = b_o G \quad (3)$$

$$\frac{a_1}{a_o} \frac{dH}{dt} + H = \frac{b_o}{a_o} G \quad (4)$$

where: b_o/a_o = K = static sensitivity (=gain factor)
and a_1/a_2 = τ = time constant

The experimental time constant from the input signal was found to be 6.3 msec. In this analysis it was assumed the gain factor. K ≈ 1.0.

Thus from equation 4 it follows that

$$\tau \frac{dH}{dt} + H = G \quad (5)$$

The initial conditions for the equation 5 are: at $t = 0$; $H = 0$

Hence the complete solution of the equation 5 is

$$\frac{H(t)}{G(t)} = (1 - \exp\frac{-t}{\tau}) \qquad (6)$$

Taking the Laplace transform of equation 6 we get

$$\frac{H(s)}{G(s)} = \frac{1}{1 + \tau s} \qquad (7)$$

Equation 7 represents a simple lag (inherent in the transducer) whose attenuation and phase lag effects are shown by the Bode plots on Figs. 4 and 5.

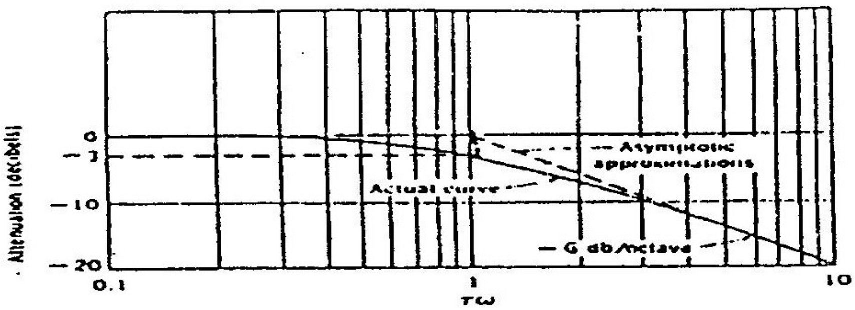

Fig. 4 Attenuation diagram for 1/(1+ τs)

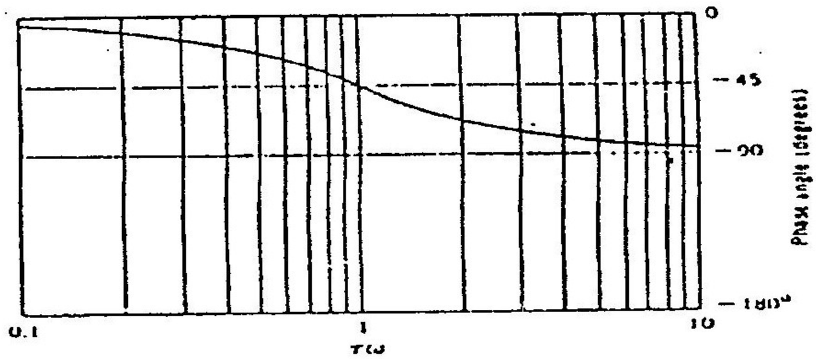

Fig. 5 Phase angle diagram for 1/(1+ τ s)

To correct this effect of signal distortion produced by the transducer, an RC-circuit was build based on this transfer function and then incorporated in the instrumentation as shown in Fig. 3. From the knowledge of operational amplifier characteristics, it was possible to build a compensating circuit. Fig. 6 depicts the principle of operational amplifier.From the knowledge of operational amplifier characteristics, it was possible to build a compensating circuit. Fig. 7 depicts the principle of operational amplifier.

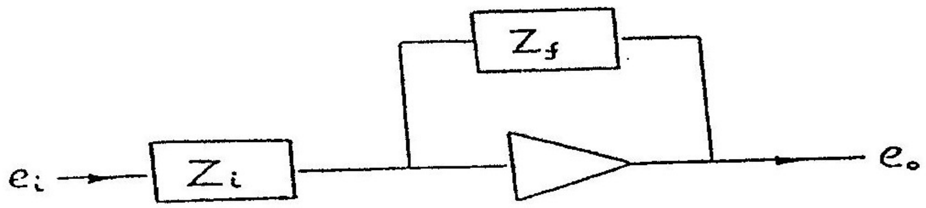

Fig.6 Operational amplifier analysis and impedance configuration

Since the internal impedance of the amplifier (Fig. 6) is very large it follows that:

$$\frac{e_o}{e_1} \approx -\frac{Z_f}{Z_i} \tag{8}$$

The equation 8 is the basic transfer relationship for analog computer amplifiers.

The RC-circuit (i.e lead-circuit) was then build up on the knowledge of this transfer relationship together with the time constant obtained from the experimental unit step input. The operational amplifier (Type 714) was used in conjunction with a fixed capacitor and two resistors of equal magnitude. Fig. 7 shown the working principle of the RC-circuit as derived from equation 8. Fig. 8 shows the actual representation of the circuit build up.

The values of the resistors and capacitors were chosen arbitrarily (neglecting other factors like their internal impedance) so that the values of the product of resistance and capacitance (RC) gives the same numerical value as the time constant obtained from the experiment (i.e. 6.3 msec). From

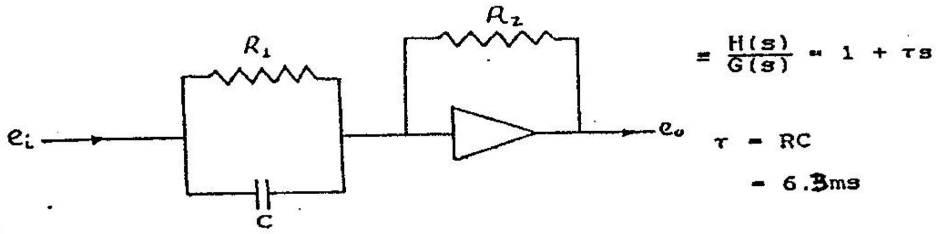

Fig. 7: Working principle of the lead circuit

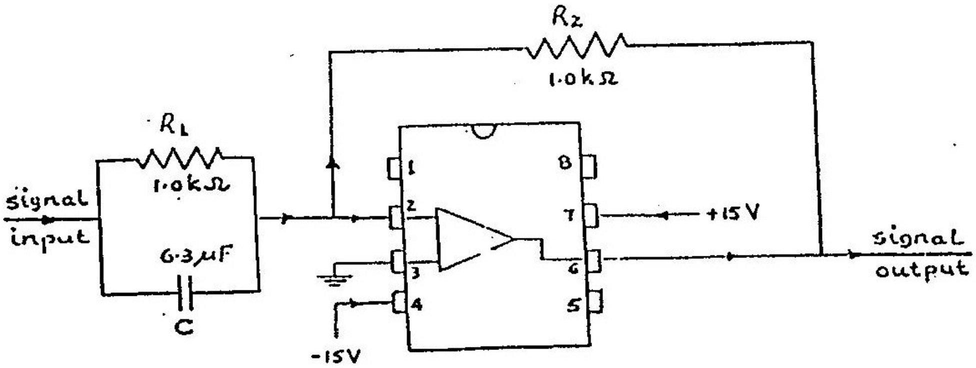

Fig. 8: Actual RC-circuit layout

Fig. 7 it is clear that for the relationship H(s)/G(s) = 1+ τ to hold then R_1 = R_2 = R. It was then arbitrarily chosen that R = 1.0 kΩ and C =6.3 μC.

From the same line of reasoning, the simple lead (1+ τs) can be represented by Bode plots for signal attenuation and phase lead diagrams as shown in Figs. 9 and 10 respectively.

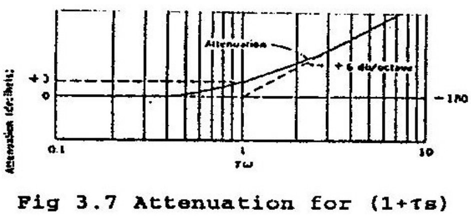

Fig. 9: Attenuation for (1+ τs)

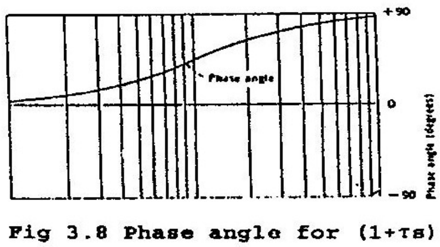

Fig. 10: Phase angle for (1+ τs)

From Bode plots in Figs. 4 and 9, if they are addedalgebraically the attenuation effect will be minimized if not eliminated completely. Similarly when the Bode plots in Figs. 5 and 10 are added together the phase lag will be reduced significantly. From this point of view it can be seen in Fig. 2 that the introduction of the RC-circuit produces an improved experimental unit step response as it is shown to match reasonably well with the ideal case. However, an overshoot is observed for the corrected signal, and this is pronounced at the early stage of the signal input. This shortcoming might be brought by the following:

(1) Arbitrary choice of the resistors and capacitors, as the criteria was based only on the time constant
(2) The experimental unit step input was only an approximate

VALIDATION OF THE IMPROVED TRANSDUCER

The improved transducer was employed practically by measuring the inlet manifold pressure of a firing engine. The pressure history at the inlet manifold close to the engine inlet valve was picked by a set of two transducers and the signal was displayed on the oscilloscope as well as getting a hard print out from the plotter. The signals of interest which were picked up were:

(1) Signal picked up by PET and passed through the charge amplifier

(2) Signal picked up by the resistive transducer via the RC-circuit

(3) Signal picked up by the resistive transducer without passing through the lead circuit

Individual Calibration of the Transducer

In order to be able to use the transducer for any practical pressure measurements, it was necessary to calibrate them. Since the manifold pressure to be measured are or just at atmospheric pressure (not supercharged engine), it was necessary to calibrate both the transducers by means of vacuum pump rig (Bundenberg type) whose mercury level was 760mm.

Calibration of the Resistive Type of Transducer

Under steady state of the mercury level column it was possible to obtain the output voltage from the digital voltmeter (DVM) while calibrating the resistive type of transducer.

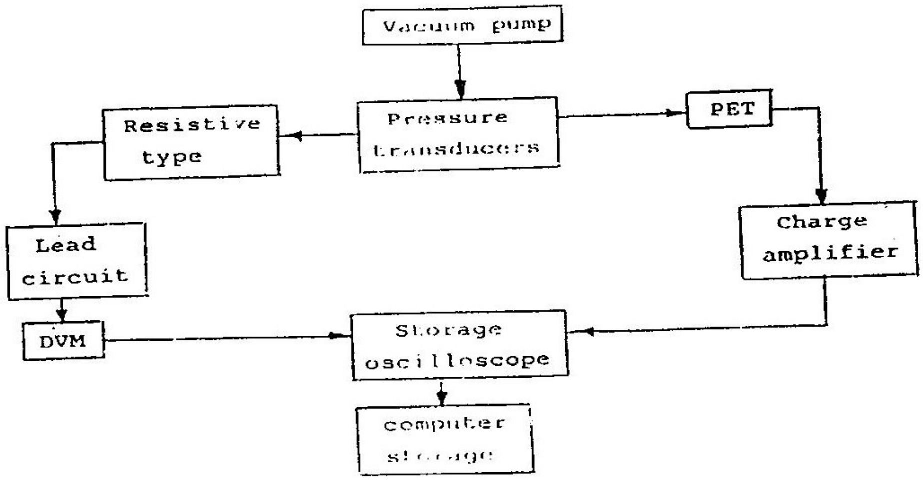

Fig. 11 Transducer calibration setup

The calibration procedure was such that (Fig. 11) the mercury column was maintained at different levels and the DVM reading gave the voltage output corresponding to a particular level of the mercury column at a given moment. The level of this mercury was then converted to an equivalent absolute pressure. The experiment was repeated for reasonable levels of mercury to provide sufficient data which was used to determine the calibration factor of the transducer. This factor was found to be 0.204 bar/volt which is the slope of the curve in Fig. 12. The procedure was repeated while the signal from the resistive transducer passes through the lead circuit. For the case of the passing the signal through the RC-circuit, the calibration factor was found to be 0.208 bar/volt (Fig. 13). The ratio of the later factor to the former gave the gain of the lead circuit to be 1.02 which appears to be approximately the same as ($K \approx 1.0$) was assumed.

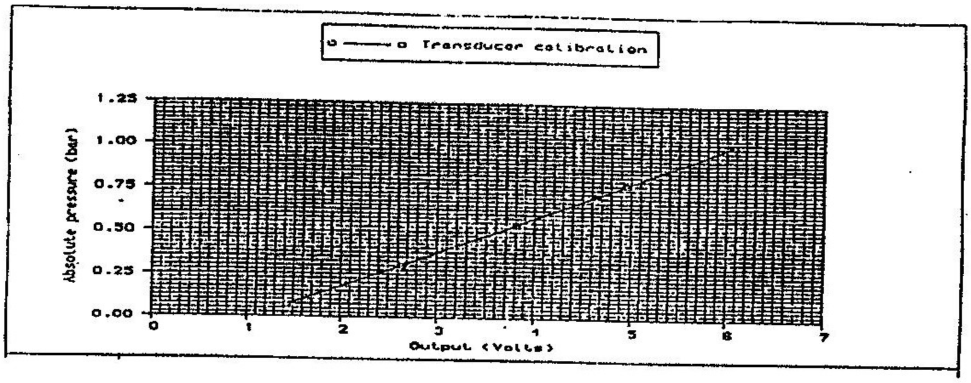

Fig. 12: Calibration of pressure transducer (type SA15)

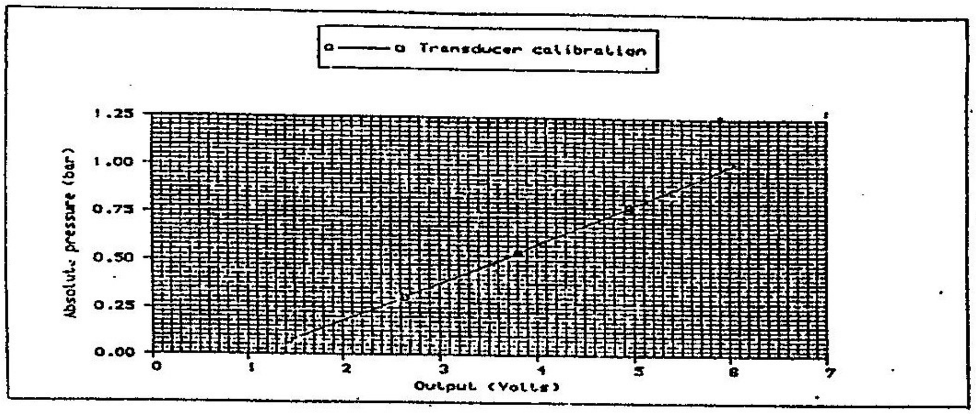

Fig. 13: Calibration of pressure transducer (type SA 15) through RC-circuit

Calibration of the Piezo Electric Transducer

The PET was not calibrated under the steady state condition of mercury column due to the drift effect, i.e the output voltage from the charge amplifier drifts away form the initial steady state value making it impossible for this method of calibration. The drift effect was overcome by calibrating the transducer under a non steady condition. As shown in Fig. 11, the mercury column was raised and allowed to fall slowly. As the mercury height drops, the corresponding voltage output was monitored by an oscilloscope. At any desired mercury column height, the oscilloscope was armed and the data acquired by the Apple II computer and stored in a floppy disk.

The oscilloscope was released and the procedure was repeated to give a reasonable set of data. The data stored in the floppy disk was converted to corresponding voltage while the mercury level was converted to its equivalent absolute pressure. The data were plotted and the calibration curve (Fig. 12) was obtained which gives a calibration factor of 0.219 bar/volt.

MANIFOLD PRESSURE DATA COLLECTION

The data collected by the set of transducers during the steady state running of the engine were monitored by the storage oscilloscope. The recorder records 1024 entries on each of its two channels; collection mbeing controlled manually. Instrumentation set up is as shown in Fig. 14.

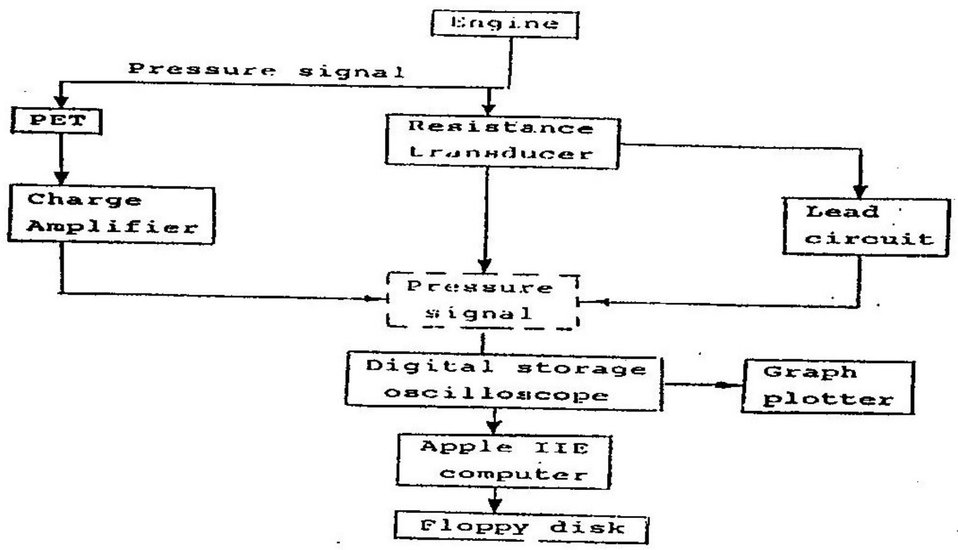

Fig. 14 Instrumentation and data collection

The data collected covered three different steady state engine speeds, namely 1300 rpm, 1580 rpm and 2090 rmp with a standard inlet manifold of 740 mm length.

DISCUSSION OF THE RESULTS

The pressure history results are shown in Figs. 15 and 16. In all the above mentioned figures, the pressure signal direct from the resistive transducer

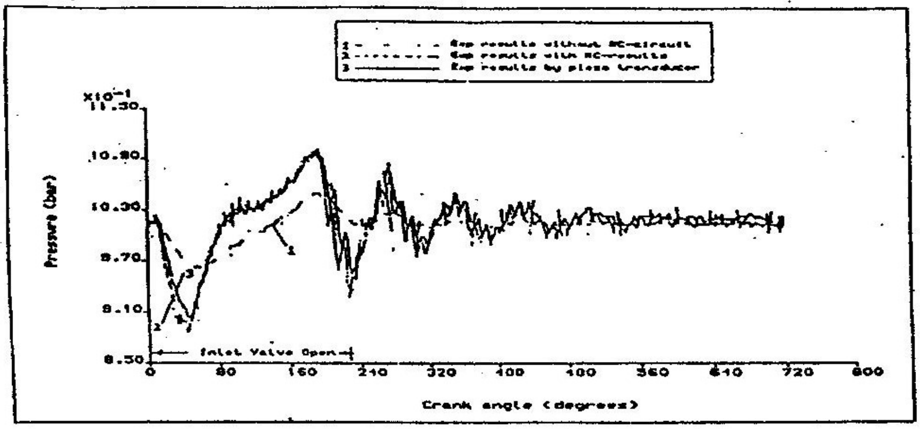

Fig. 15: Manifold pressure (N-1580 rpm, L = 0.715 mm)

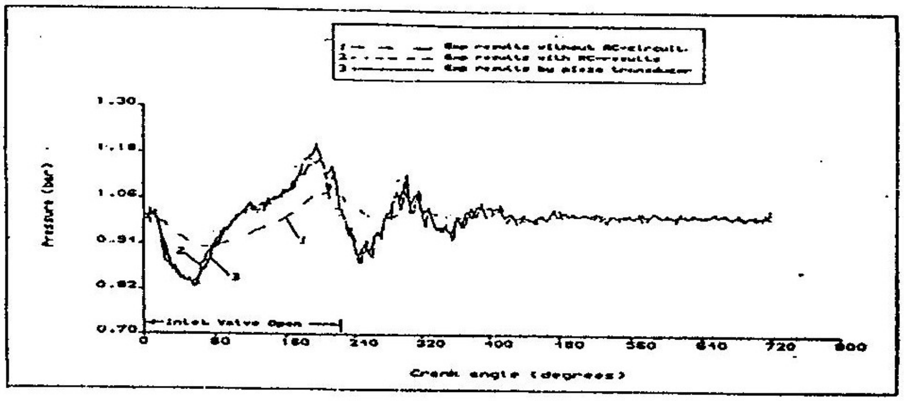

Fig. 16: Manifold pressure (N-2090, L=0.715 mm)

depicts a phase lag and amplitude attenuation when compared with the same signal measured by PET. On the other hand it is observed that the pressure signal from the resistive transducer through the lead circuit responds instantaneously almost similar to that of PET in the given same conditions. Collectively, it is seen that the pressure signal through the PET and that measured by a resistive transducer but passing through the RC-circuit agree reasonably well. aa

There exist some pressure irregularities in the pressure signal which passes through the RC-circuit. This is likely to be due to the fact that as the RC-circuit is basically a differentiator; when an incoming signal is differentiated the errors (irregularities) are magnified.

CONCLUSION AND RECOMMENDATIONS

It has been demonstrated that, by just utilizing the response characteristics of the transducer it was possible to compansate for the signal distortion and thus obtain a good approximation of the pressure signal without embarking on an expensive transducer like a PET.. It is recommended that a more realistic results could be obtained by improving the instrumentation, in the sense that the RC-circuit could be built from two equal time constants. Furthermore, some other determining factors should be looked into for the choice of the resistors and capacitors instead of basing only on the numerical values.

NOMENCLATURE

Symbol	Definition	Units
C	Capacitor	Farad
DVM	Digital Volt Meter	-
e	Instantaneous voltage	Volt
PET	Piezo Electric Transducer	-
R	Resistance	Ohm
t	Time	Second
Z	Impendence	Ohm
τ	Time constant	Second

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