Problems of Pressure Indication in Internal Combustion Engines

Rudolf Pischinger and Günter Kraßig
Institute for Internal Combustion Engines
and Thermodynamics of the Technical University Graz
Kopernikusgasse 24, 8010 Graz

Josef Glaser
COM Gesellschaft für Computerorientierte Meßtechnik

ABSTRACT

Pressure measurement within the combustion chambers of IC engines is made almost exclusively by means of quartz pressure transducers and charge amplifiers. Analyses of this measurement instrumentation and its associated data processing systems have shown that the pressure transducer itself is the source of many measurement errors. These are caused, amongst other things, by electrical interference and shock as well as by mechanical and thermal distortion of the transducer. Short-term temperature drift caused by the latter phenomenon is particularly troublesome because, unlike other errors, it cannot be eliminated or compensated for.

Methods have been developed which enable the causes and magnitude of this error to be determined. The approach adopted involves the comparison of measured combustion chamber pressures with those values predicted by accurate calculation. In addition, transducer behaviour has been examined in a test rig designed to subject the transducer, under atmospheric conditions, to cyclic thermal loading similar to that found in a running engine.

1. INTRODUCTION

The Combustion Engine and Thermodynamics Department of the Graz Technical University has for a long time occupied itself with the analysis of the processes occurring within the combustion chambers of IC engines. An important pre-requisite for such an analysis is the ability to measure pressures with the utmost accuracy. For that reason cylinder pressure measurements are made within the Department exclusively by means of piezo-electric quartz transducers.

For various cycle calculations it is necessary that an accuracy of 1/10 bar in 200 bar be achieved in high pressure measurement, during gas exchange an accuracy of 1/100 bar is required (1, 2). In most cases, however, even the most carefully made measurements produce data containing significantly greater errors. Cycle calculations which rely upon such data frequently produce unbelievable or contradictory results.

In order to eliminate these problems associated with pressure measurement, an analysis of the complete measurement system was undertaken (3) and methods of system evaluation developed (3, 4).

2. MEASUREMENT SYSTEM AND ENGINE TEST-BED

The quartz transducer measurement system is comprised of the following elements (Fig. 1):
- the quartz pressure transducer, which provides an electrostatic charge proportional to pressure;
- the charge amplifier, which converts this charge into an output voltage;
- the output display instrument.

Fig. 1 Schematic arrangement of measuring system

Pressure signals which are required for numerical analysis are digitised in a data logging system and stored. Sufficiently fast and accurate logging systems have only become available in the last few years. The system used in this investigation, which was developed in conjunction with the company COM of Graz, is computer controlled and capable of digitising 400 000 readings per second per channel with a resolution of 1 in 4095. A storage capacity of 64 K readings per channel is provided. The crank degree signals required are obtained from a shaft encoder providing a resolution of 1/8° crank.

This system enables several engine cycles to be measured sequentially with fine crank
degree resolution even at high engine speed. The recorded pressure data can be processed without difficulty in the machine itself, transmitted to an oscilloscope or plotter, or be transferred via magnetic tape to a large computer.

Engine pressure measurements were carried out on a single cylinder diesel engine coupled to a DC motoring brake, thus enabling operation under motoring conditions. This installation permitted the measurement of all parameters required for cycle calculation. In addition to two combustion chamber pressure transducers, transducers were provided in the intake and exhaust manifolds.

3. CLASSIFICATION OF THE MOST IMPORTANT CAUSES OF TRANSDUCER ERROR OCCURRING THROUGH ENGINE MEASUREMENT

The measurement system is required to provide an output signal which is linearly proportional to pressure. This requirement cannot always be satisfied however, even if all external sources of interference are eliminated (3). The largest transducer errors are caused by the influence of the engine itself.

The following table shows a list of common instrument errors and external error sources together with the individual components which are affected.

<table>
<thead>
<tr>
<th>Instrument error</th>
<th>Pressure Charge Data</th>
<th>Shaft Transducer Amplifier Logger Encoder</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrical drift</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>linearity</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>stability</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>hysteresis</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

External interference

<table>
<thead>
<tr>
<th>electrical interference</th>
<th>++</th>
<th>++</th>
<th>++</th>
<th>++</th>
</tr>
</thead>
<tbody>
<tr>
<td>vibration</td>
<td>++</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>deformation of the transducer installation bore</td>
<td>++</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>thermal shock</td>
<td>++</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

++ strong influence
+ influence possible

4. INSTRUMENT ERROR

It is relatively easy through the selection of suitable components to assemble a measurement system which, under ideal conditions, provides a high degree of accuracy. Hysteresis, for example, has been shown during transducer evaluation to have essentially no effect (3, 5). Since the pressure that is to be measured changes very rapidly, electrical drift caused by decay of the electrostatic charge produced by the transducer is also of little importance (6).

Significant errors are caused only by transducer non-linearity (0 - 1 %), transducer and amplification instability (0 - 1 % and 0 - 0,3 % respectively). Instability is most common with transducers which are new or have been subjected to extreme operating conditions. In any event, suitable checks must be made when accurate measurements are to be carried out.

5. MEASUREMENT ERROR CAUSED BY ENGINE AND TEST BED

5.1 Amplifier and Data Logger

System components which are not engine mounted can be protected to a large extent from external interference. In many cases however, electrical interference cannot be avoided with the result that indicated pressure values may include errors as high as several tenths of a bar. Such interference can also affect the transducer itself, the consequences of which will be discussed in greater detail.

Components such as the transducer and crankshaft encoder (degree marker) which are mounted on the engine have to operate in a far more hostile environment.

5.2 Crankshaft Encoder

The encoder is mounted on the engine crankshaft and provides signals which are used by the data logging system to control the measurement sequence. If some of the signals are missing or electrical interference causes the registration of false signals, then distortion of the measured pressure curve occurs. In order to obtain the required degree of reliability under hostile engine operating conditions, it was found necessary to undertake in-house encoder development.

The data logging system used monitors the crank signals during measurement and checks not only the number of signals received, but also the interval between them. The occurrence of an error is displayed automatically.

5.3 Pressure Transducer Errors

The largest measurement errors are caused by the transducer itself. In addition to deterioration of the transducer characteristics (stability in particular), a number of quite distinct sources cause the introduction of errors which are difficult to handle. Some of these error sources are described below.

5.3.1 Electrical Interference. This usually affects the whole measurement system. The most common phenomenon is interference in phase with the mains voltage and can lead to pressure errors of several tenths of a bar. This is demonstrated by Figs. 2 and 3 which show cylinder pressure curves for the same engine operating point. The gas exchange phase is shown magnified. The third curve in each figure was obtained from a transducer under constant atmospheric pressure but subjected to the same electrical interference as the rest of the measurement system. Fig. 2 shows the pressure trace for a single engine cycle while Fig. 3 contains the average of 16 engine cycles measured in sequence. In this case the engine cycle frequency was out of phase with that of the interference source resulting in a change from cycle to cycle in the phase shift between the pressure and interference signals. The re-
Fig. 2 Signals from identical transducers mounted a) in engine b) open to atmosphere

Fig. 3 Measurements as for Fig. 2 average of 16 cycles

Fig. 4 Influence of coolant in a directly cooled pressure transducer

5.3.2 Vibration. In vibrating, the transducer experiences acceleration forces which, through their action on the quartz element itself, produce pressure signals. Most vibrations are transmitted from engine components at a frequency of several kHz and accelerations of up to approximately 100 g. One typical cause of excitation is the valve closing process to be seen in Fig. 2. Such oscillations can lead to errors in indicated pressure of several bar. They can be almost entirely accounted for, however, by the above averaging procedure or by numerical methods. At very high engine speeds vibration of the engine itself causes acceleration errors of up to 1/10 bar. In this case the error signals are in phase with the process being measured and can only be quantified with difficulty through measurement of the acceleration responsible.

In this respect directly cooled transducers are particularly sensitive since the coolant is contained within the transducer body. Usually the coolant has a greater influence over the acceleration sensitivity of the transducer than the solid components (3). Fig. 4 shows as an example the measured acceleration sensitivity of a directly cooled transducer over exciting frequency, both with and without coolant. Methods of compensating for the large influence of the coolant on the acceleration error have not yet been developed.

5.3.3 Deformation of the Transducer Bore. Deformation of the transducer bore and seat which occurs during measurement can, via the transducer body, cause the quartz element to be loaded. Incorrect pressure readings were obtained for this reason, for example, from the exhaust transducer of the single cylinder engine used during this investigation. The error was found to be of the same order as, and in phase with, the pressure signal.

Great care must be taken in designing a transducer installation to ensure that changes in assembly load occurring during operation are as small as possible.

5.3.4 Change in Transducer Sensitivity. The most significant inaccuracies are caused by the influence of temperature.

Transducers which are located in the combustion chambers of engines are subjected to very high heat fluxes. The resulting increase in temperature causes a change of several percent in the sensitivity of the quartz element. This error can be reduced significantly, however, by the use of quartz elements which have been cut to provide a particular orientation of the crystal axes (Polystable elements) (6). By means of direct cooling, errors can be almost eliminated. It should be noted that, when closed cooling systems without secondary cooling are employed the coolant temperature itself can become very high.
6. TEMPERATURE DRIFT

Changes in temperature of the transducer cause not only changes in sensitivity of the quartz element, but also thermal stress and deformation of the transducer housing. In this way forces are brought to bear on the quartz element which cause a distortion of the true pressure signal. Every change in heat flux to the transducer results in a temperature change which in turn leads to a change in the indicated pressure;—a temperature drift (3).

When measuring consecutive cycles in a combustion engine, "long term drift" is defined as the average drift in indicated pressure which occurs over a measurement period comprising many cycles due to changes in the temperature of much of the transducer. "Short term drift" is the error in indicated pressure which is caused by changes in transducer temperature occurring within a single engine cycle, and which are therefore repeated. The cyclic variations in transducer surface temperature reach to a depth of a few tenths of a millimeter.

Fig. 5 shows a pressure signal measured during engine warm-up together with the temperature drift component. The long term drift essentially produces a time dependent shift in the pressure curve, while short term drift causes a significant deformation of the curve during each cycle.

![Graph showing temperature drift](image)

**Fig.5** Influence of temperature-drift on the indicated pressure. Short-term-drift has been magnified 10x

6.1 Long Term Drift

When uncooled transducers are used, long term drift can easily cause a zero error of up to 100 bar. An error of up to several bars is possible even with direct cooling. This error is considerably greater than the errors caused during measurement by electrical interference.

Long term drift only causes difficulty, however, when measurements are made during transient operation. In this case the effect of drift must be eliminated using numerical methods. Under stable operating conditions, regular grounding of the transducer prevents the accumulation of electrostatic charge due to thermal strain. Determination of the absolute pressure level is achieved numerically.

6.2 Short Term Drift

During the course of these investigations, short term drift, which produces a deformation of the pressure curve, proved itself to be the most trying of all measurement disorders. Its influence is most critical when data is required for thermodynamic cycle calculation (7).

As can be seen in Fig. 5, pressure errors occur during the compression and combustion phases when heating is taking place, and reduce again during the exhaust and intake strokes. The effect of this phenomenon on the cycle calculation is as follows: an exaggerated rate of pressure rise caused by drift during the combustion phase results in the calculation of too high a rate of heat release; too high a pressure level during the expansion phase leads to the over-estimation of internal work; high cylinder pressure during the exhaust phase leads to the assumption of incorrect pressure drops across the exhaust valve and thus to incorrect exhaust mass flow.

All the transducers that were tested demonstrated short term drift and in only a few cases could its influence be described as small. The development of methods of eliminating this error source, or of compensating for it numerically, was the goal of this investigation.

6.2.1 Test Rig for Investigation of Short Term Drift. Since no suitable apparatus was available for the measurement of short term drift, amongst others, the test rig shown in Fig. 6 was developed. A transducer is

![Test rig diagram](image)

**Fig.6** Apparatus for the investigation of short-term-drift
subjected to similar thermal loading as found in an engine (up to approx. 200 W/cm²), under atmospheric pressure, by an electrically heated radiating surface. The heat flux flowing to the transducer can be measured by replacing it with a heat flux sensor. Intermittent heating cycles are achieved by rotation of a disc-like mask located between heater and transducer.

In this apparatus it is possible to measure short term drift under controlled conditions. The measured drift of several different transducers under identical heating conditions is shown in Fig. 7. The lowest curve shows the heat-flux flowing to the transducer. It can be seen that not only does the magnitude of the drift differ, but also the characteristics. It is easy to imagine how different the results would be if transducer types 1 and 3 were used to measure pressure under identical conditions.

The lowest curve was obtained from a transducer whose surface had been coated with a 0.5 mm layer of temperature resistant silicone material. It can be seen that this flexible protective coating largely eliminates temperature drift. Similar material which is able to withstand combustion chamber temperatures is, unfortunately, not currently available.

To a certain degree, soot produces the same effect. In many cases carboned transducers exhibit less short term drift than clean ones. Advantage was taken of the insulating effect of silicone to enable a close examination of the sources of short term drift. By selectively coating only parts of the transducer surface, essentially the influence of the uncoated area alone is measured. The contribution to drift of the individual transducer components was established using this method. These findings enabled the explanation of the different characteristics of the various transducer types.

In most cases, the total short term drift is the summation of two or more drift components which partially compensate for each other, see Fig. 8. In the design of several commercially available transducers, deliberate use is made of this phenomenon to reduce the total effective drift. This measure is only effective, however, for a particular temperature distribution through the transducer. If other conditions exist, caused, for example, by poor installation design or soot insulation of only part of the transducer surface, then very large drifts can result. In many cases the relative magnitudes of the drift components change with heating frequency, with the result that the effectiveness of the drift compensation is extremely engine speed dependent.

![Graph showing short term drift of several pressure transducers. Test rig results at 500 rpm](image)

**Fig. 7** Short term drift of several pressure transducers. Test rig results at 500 rpm

![Graph showing partial compensation of short term drift](image)

**Fig. 8** Partial compensation of short term drift (direct injection diesel engine: speed 4000 rpm, IMEP 10 bar)
Fig. 9 shows the short term drift of a transducer at four different engine speeds. The results obtained from the test rig enable only qualitative comments to be made about short term drift under engine operating conditions. In order to quantify the drift characteristics of a particular transducer, a mathematical model is required. The model created enables the calculation of the instantaneous temperature distribution, and thus drift, within the relevant transducer components for a defined heating cycle. From the measurements carried out it was possible to limit the calculations to just a few areas of the transducer. Good correlation was obtained between calculated and measured drift for both test rig and engine.

The calculation of drift for cylinder pressure measurement is, however, very costly in time since it is necessary to establish the instantaneous heat flow to the transducer. If the transducer is sooty, or if access cannot be obtained to the transducer parts which cause drift in order to measure heat flow, then calculation is practically impossible.

The mathematical model does, however, enable the quick determination of the influence of material properties and transducer dimensions. Together with the test rig, it represents a useful tool for the development of new transducers.

Parallel to the investigation of individual measurement errors, work was undertaken to develop methods of appraising the accuracy of pressure measurements obtained from engines themselves.

7. PRESSURE MEASUREMENT ACCURACY EVALUATION THROUGH THERMODYNAMIC CALCULATION

In most cases, cylinder pressure obtained by thermodynamic calculation is less accurate than measured pressure. The exception is the motored engine where the pressure for both the high pressure period and the gas exchange period can be calculated.

7.1 Analysis Using a Motored Engine

In fact not all of the parameters required for the calculation can be measured with sufficient accuracy, even under motored conditions. It is only possible to make an accurate calculation of the pressure because the developed evaluation analysis itself permits the identification and correction of incorrect test rig input data.

The analysis consists essentially of the comparison of the calculated pressure curve with the measured pressure curve, and the comparison of the wall heat losses and polytropic exponents calculated for these two curves. The latter parameters exhibit quite definite characteristics which indicate which, if any, of the calculation input parameters are in error.

As an example, when the above analysis was first used the characteristics of the control parameters continuously indicated a higher compression ratio than had been calculated from volume measurements. The engine was therefore accounted for this apparent volume "error".

Fig. 10 shows the result of such an analysis. In the upper part of the figure the polytropic exponent and heat loss characteristics from measured and calculated pressure curves are shown. (dashed line is measured, full line is calculated). Below is a curve representing the difference between the measured and calculated curves (dashed) and, for comparison, the calculated curve (full line). In the example shown a calculated pressure curve, which had been deliberately evaluated using a compression ratio which was 2.5 too high was treated as a "measured curve". The displacement of the peak heat transfer rate relative to TDC and the disproportionately large pressure in the region of TDC are characteristics of this input data error.

In a similar way it is possible to determine the location of the measured pressure curve relative to TDC and also the absolute pressure level. Deviation from an accurate pressure curve calculated in this way indicates the presence of an error for which the measurement system is responsible.

This measurement error is, of course, the sum of many individual errors. If several significant measurement disorders occur simultaneously, then repeat analyses of the same transducer can produce quite different results. It is then impossible to determine which error sources are responsible. By eliminating avoidable error sources and using averaged measurements, good, repeatable results can be achieved.
Fig. 10 Comparison by means of thermodynamic calculation between:
- correctly calculated pressure curve
- and a pressure curve with 2% raised compression ratio

Fig. 11 Analysis of a measured pressure curve by means of thermodynamic calculation
Fig. 11 shows the result of an analysis. Fig. 12 shows for comparison how a calculated curve with superimposed short term drift is analysed. The drift curve was deduced from the instantaneous temperature distribution in the transducer using the method previously described. It can be seen that basic agreement is achieved between the curves.

In summary, short term drift of the measurement signal cannot be eliminated even when measurements are carried out with the greatest care, but the above analysis procedure enables determination of the short term drift error for measurements made in the combustion chamber itself. The disadvantage of this procedure is its limitation to the high pressure phase of motored operation and the relatively large amount of computation necessary (7).

7.2 Analysis of the Gas Exchange Phase

When it is possible to measure pressure directly behind the inlet and exhaust valves, cylinder pressure during the gas exchange period can be calculated.

Pressure transducers which are located in the intake and exhaust systems are relatively easily protected from external error sources and therefore provide very accurate measurements. Other parameters required, such as gas flow and charge mass, can also be measured with sufficient accuracy. The determination of the difference between the measured and calculated curves provides the measurement error directly.

Comparison with calculated temperature drift shows that, as before, the error contained in most measurements is caused by short term drift.

CONCLUSIONS

The work that has been carried out has shown that the greatest problems incurred in measuring IC engine cylinder pressure are caused by the pressure transducer, which is affected by a series of powerful error sources. It was possible to show that most of the resulting errors could be avoided by averaging the measurements.

The most critical measurement error is short term temperature drift since it is currently unavoidable. However, drift measurement and analysis procedures have been developed which enable the selection of the least sensitive transducers and also the effects of drift on pressure measurements to be determined. In addition, the developed procedures represent a powerful tool for the further development of transducers.
ACKNOWLEDGEMENT

We want to express our thanks to the COM-Gesellschaft für computerorientierte Meßtechnik mbH.

Since there were no suitable data recording systems, when we started our investigations, this company has developed together with our institute a data acquisition system to meet all demands of IC engine research, particularly in regard to accuracy, sampling rate, memory capacity and handling. For this system a new crankshaft encoder has been developed to guarantee a precise coordination of measurement value and crank angle.

Further our thanks are directed to Dr. Lienhart, who carried out the thermodynamic analysis for the motored engine.

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