SUBMINIATURE INDUCTIVE TRANSDUCERS USED WITH HIGH CARRIER FRENQUENCIES

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Summary This paper describes the development and construction of subminiature inductive transducers which can be operated with carrier frequencies up to 400 Kcs. Two types have been developed for operation at 150°C which are able to withstand an acceleration of 2000g, and a high-temperature (600°C) transducer is now in the final stage of development. The body of the low-temperature transducer is made of high-temperature epoxy resin, and that of the high-temperature transducer of ceramic material.

Iron wire is used as core material to reduce eddy current losses. The dimensions of the transducers are 0.25 inch diameter and 0.5 inch long, and 0.125 inch diameter and 0.25 inch long, including terminations.

A linear displacement of the armature material can be measured at distances up to 0.01 inch, and because of the high carrier frequency, the vibration of this armature can be up to 30 Kcs. Both ferrous and non-ferrous armature material can be used for displacement measurement.

The inductive transducers have been used to measure piston movement at right angles to the cylinder axis in an internal combustion engine, in conjunction with a lead-out system. Tests using a telemetry system (radio link) are now being carried out.

Details of the construction and performance are described and future development discussed.

The use of the inductive transducer as a pressure transducer is also mentioned.

Introduction The inductive transducers to be described were developed to replace the capacitive transducer in an FM telemetry system. [1] The capacitive transducer was built into the piston skirt to measure the piston movement at right angles to the cylinder axis in an internal combustion engine.

However, owing to the change of oil film thickness in the air gap of the capacitive transducer (and therefore, change in the dielectric constant), the interpretation of the true distance measurements was difficult.

Therefore, investigations were started to produce an inductive transducer with the following requirements:

1. small and light in weight.
2. easy mounting and machining of active face to any curvature.
3. ability to withstand temperature changes up to 150° C and accelerations up to 2000g without appreciable change in sensitivity.
4. contactless measurements up to 0.01 inch with a resolution of 0.0001 inch and good linearity.
5. armature frequency measurements up to 15 Kcs using both ferrous and non-ferrous materials.
6. measurements not affected by the presence of gases or fluids in the air gap.

Construction The electrical and magnetic characteristics must first be considered. The carrier frequency should be at least 5 to 6 times higher than the expected armature frequency. This eliminates solid core materials with low permeability and high eddy current losses. The Curie point of the core material must be well above the working temperature.

The self-resonance frequency of the transducer must be above the highest carrier frequency used to allow for resonance shift due to the capacitance of the connecting cable. Wire with insulation capable of withstanding 180° C is used for the transducer coil.

Pure iron wire 0.01 inch diameter is used as core material to reduce eddy current losses, and in an annealing process in air, the relative permeability is increased and the oxide layer formed acts as an insulation. The Curie point of this material is 770° C.

Figure 1 shows the production stages. High-temperature epoxy resin is used as transducer body throughout. Depending on the size of the transducer, a number of iron wires is cut and fed through two sleeves of different lengths. The coil is wound round the iron wires between the two sleeves and soldered onto the wire termination or printed circuit. The iron wires projecting through the small end sleeve are bent backwards to lie equally distributed around the circumference of the two sleeves. This assembly is then plotted with epoxy resin in a mould. The air gap of the transducer is fixed by the wall thickness of the sleeves, but the ratio air gap to core length can be altered by machining the face of the transducer.

Transducer Characteristics In Figure 2, two types of inductive transducers are shown. The transducers can be fixed in the required position by the use of a resin or, as shown in Figure 2, by means of an adaptor sleeving. The smaller transducer was successfully used for the detection of piston ring movements, but its length was reduced to 0.160 inch.

Transducer dimensions, weights, and limiting parameters are given in Table I.

Figure 3 shows the variation in transducer inductance with carrier frequency, with open air gap, and steel and aluminum as armature material. Magnetic materials will increase inductance, whereas nonmagnetic materials will decrease the inductance, depending on the eddy current losses introduced and taking air as reference. The curves were obtained with a lead and stray capacitance of 50 pF, which limits the carrier frequency to 300 Kcs because of resonance shift.

Figure 4 shows the variation in transducer inductance with armature spacing from 0 to 0.01 inch using mild steel and aluminum as armature materials, and a frequency of 150 Kcs. The maximum working temperature is 150° C. This limit is set by the epoxy resin used.

If the active face of the transducer is machined to a desired curvature, a recalibration is necessary due to change in the air gap.

Table I

Transducer Type	P/40/150	P/16/150
length	0. 4601"	0.430"
diameter	0. 250"	0.160"
weight	0.6g	0.4g
Limiting parameters		
Max. carrier frequency with 50 pF parallel capacitance	300 Kcs	300 Kcs
Max. modulating frequency	50 Kcs	50 Kcs
Max. ambient working temperature	150° C	150° C
Max. acceleration	2000g	2000g
Max. carrier voltage across transducer	30V pk-to-pk	30V pk-to-pk
Max. AC current through transducer	10mA	10mA
Self-resonance frequency	1 Mcs	1.3 Mcs

Inductance with open air gap at 100 Kcs	4.5 mH	0.75 mH
DC resistance	66 ohms	33 ohms
Q factor	2.8	2.8

Application and Results

Associated Circuitry For AC conditions, such as vibration or dynamic displacements, a simple detecting and demodulating circuit can be used, as shown in Figure 5. Care must be taken to keep the parallel capacitance of the transducer leads and stray capacitance as low as possible, if carrier frequencies near the maximum are to be used.

The filter must attenuate the carrier frequency satisfactorily and should have negligible phase-shift. [2] The matched load inductor in series with the transducer can be replaced by a resistor of suitable impedance for the carrier frequency used.

For measurements of static displacements, a bridge circuit should be used with matched transducers to eliminate DC drift with temperature variations.

Lead-out System Figure 6 shows a lead-out system for a 1500cc, 4 cylinder internal combustion engine. This system, which is also used in conjunction with thermistors and strain gauges, will be described with results by the Group Research and Development unit of Associated Engineering Limited.

It has been found that the capacitance effect of the flexing springs can be ignored up to a carrier frequency of 120 Kcs. This would permit a modulation frequency of 25 Kcs, which is adequate for this application.

The active faces of the transducers were machined to the curvature of the piston skirt. The transducers were statically calibrated by closing the air gap with an armature piece of the same material and curvature as the liner, fitted to a micrometer. The calibration was carried out from 0 to 0.012 inch. Using a carrier frequency of 80 Kcs and 30V peak-to-peak across the transducer, a sensitivity of 30mV per 0.001 inch was obtained. The results were not affected by oil in the air gap, nor by rise in temperature up to 150° C. The DC drift was not considered in this application.

Some piston movement records from this linkage system are shown in Figure 7. Four inductive transducers were fitted to the piston, two of which can be seen in Figure 6. Traces 1 and 3 are from the transducers at the botton and top of the piston skirt respectively, on the thrust side of the major axis. Traces 2 and 4 are from the transducers at the bottom and top of the skirt respectively, on the non-thrust side. Transducers 2 and 4 have opposite polarity to transducers 1 and 3.

A, B, C, and D film traces show the piston movements at different engine speeds and loads. Traces 1 and 2 show troughs and peaks respectively, at bottom dead centre (BDC). These are due to the low positioning of transducers 1 and 2 at the bottom of the skirt. At BDC, these two transducers partly emerge out of the liner and therefore have large air gaps. It can be seen that the piston movement at right angles to the cylinder axis is much greater at the top of the skirt than at the bottom. Traces 3 and 4 in A show a slow lateral movement of the piston after TDC firing, whereas in trace B, there is a fast movement. C and D show similar effects at higher engine speeds.

FM Telemetry System with Inductive Transducer Figure 8 shows the layout and block diagram of the system to measure piston movement in an internal combustion engine. The difficulty was to produce a signal connecting linkage between the transducer fixed at any desired position on the piston skirt and the connecting rod, on which the multivibrator (transducer carrier frequency) with demodulator and transmitter with modulator are fixed. However, the signal connecting linkage from piston to connecting rod has now been adapted from the successfully tested lead-out system (Figure 6). Tests using the complete system in a running engine are now being carried out.

High-Temperature Transducer P/40/600 This type of transducer has the same dimensions as the P/40/150, but high-temperature ceramic and glazing are used as body materials. At the moment there is still difficulty in avoiding absorption of the oxide layer of the iron wire by the glazing during heat treatment. The coil of the transducer is wound with resistance wire having as insulation a high-temperature resistant oxidised surface and is welded to the connecting termination. The DC resistance is about 2000 ohms. In Figure 9, the inner core and outer ring of the iron wire ends can be seen because of machining to determine the penetration of glaze. In its final form, the transducer face is also glazed, but is machined flat so that the thickness of the glazing on the face is not more than 0.002 inch. Glazing of the face is necessary to avoid oxidation of the exposed iron wire ends at high temperatures.

The transducer will operate up to 600°C because the iron wire used has a Curie point of 770°C, the resistance wire used for coil has a resistance change of only ±2 per cent at 700°C, and the high-temperature ceramic sleeves and Hazing material are stable up to 1000°C.

It would therefore present a useful research tool in cases where the temperature is well above 150°C - - e.g. , for measurements of piston movement at the top land near the piston crown and in ring grooves. Full investigations for the final production of this transducer are now in progress.

Conclusions The transducers described have been successfully tested in the internal combustion engine, and results show that after 20 hours' running test, no change in electrical parameters or physical deterioration has occurred. Gases or fluids in the air gap do not change the true distance measurement. These subminiature transducers will have many more applications as sensing devices combined with miniature telemetry systems.

Investigations will be carried out to use this transducer to sense pressure. Modified as a pressure transducer, it should have a fast response to pressure changes, and therefore, will be a useful instrument for the investigation of measuring pressure changes in the cylinder of an internal combustion engine.

Interest has been shown by the medical profession in the development of these transducers as low pressure transducers for internal pressure measurements in human beings.

Acknowledgments The author would like to acknowledge the work done on the design and development of the lead-out system by the Mechanical Engineering Section of Associated Engineering Limited, Group Research and Development, Cawston, Rugby, and to thank the Directors for permission to publish this paper.

References

1. Westbrook, M. H., "A Telemetering System for Piston Engine Research," International Telemetering Conference, London 1963, Volume 1, pp. 154-161.

2. Steinbrenner, H. and Dugge, K. W., "Error Limitations of Some of the Present-Day Carrier-Frequency Methods for Measuring HighSpeed Mechanical Phenomena in Engines and Vehicles," MYZ, 1961, 22, May, pp. 160-165 (German).

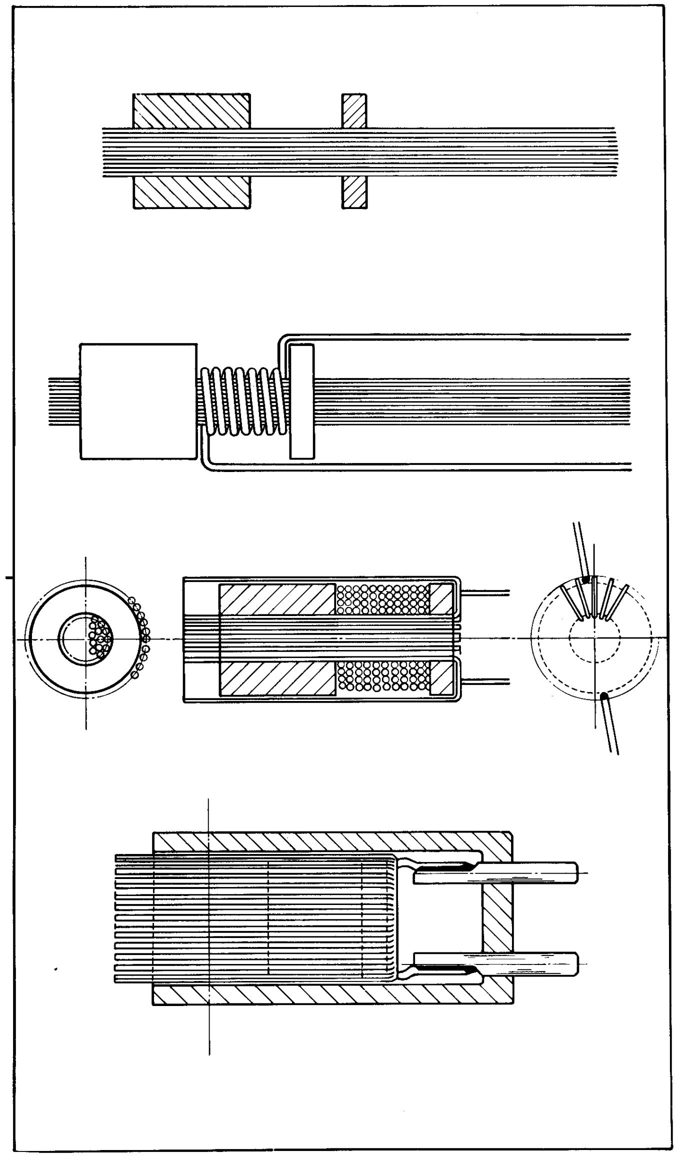

Fig 1. Construction Stages of a Subministure Inductive Transducer

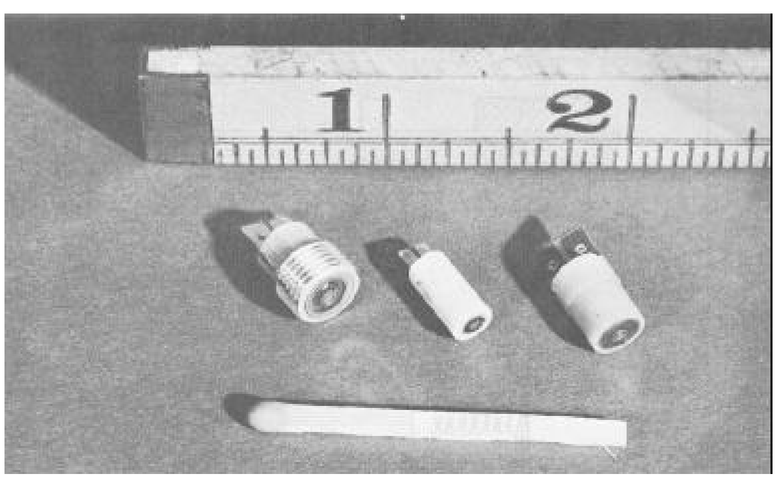

Fig 2. Inductive Transducers Type P/40/150 and P/16/150. Type P/40/150 With and Without Adapter Sleeve

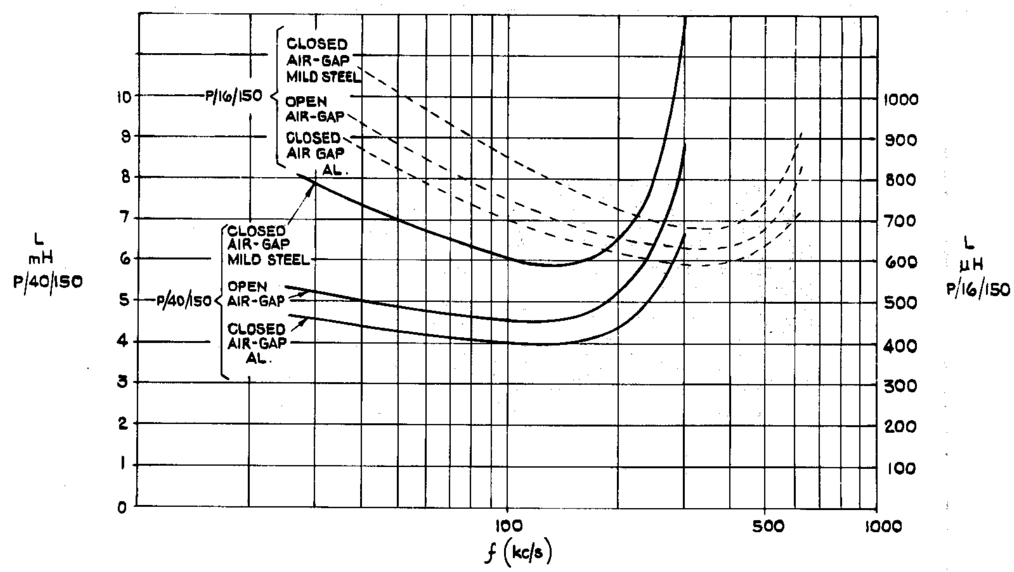

Fig 3. Variation in Transducer Inductance with Carrier Frequency, Open Air-Gap, Steel and Aluminim as Armature Material

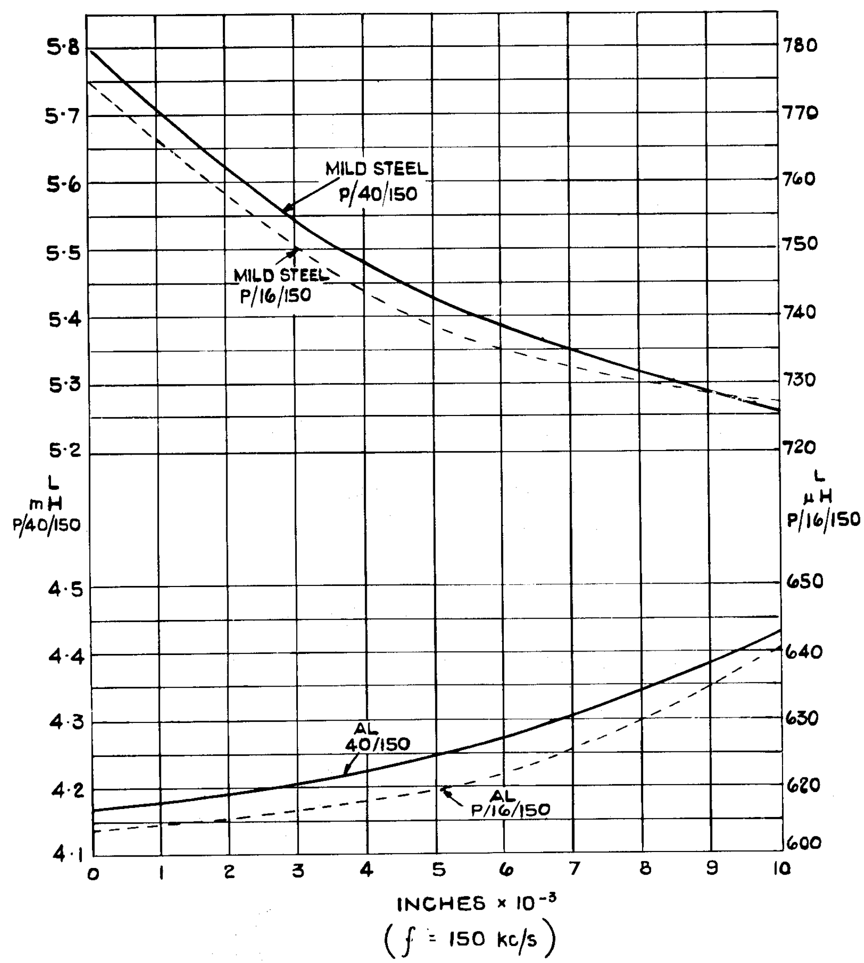

Fig 4. Variation of Transducer Inductance with Armature Spacing Frequency 150 Kc/s

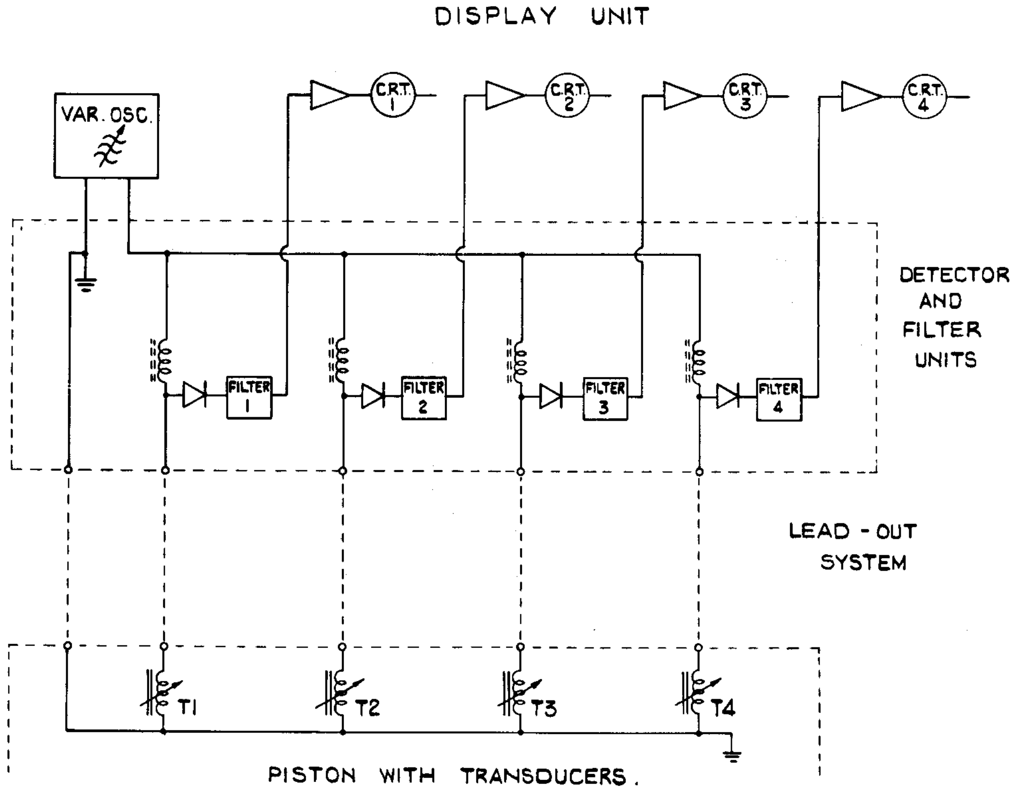

Fig 5. Block Diagram of Instrumentation for Measurement of Piston Movement in an I.C. Engine

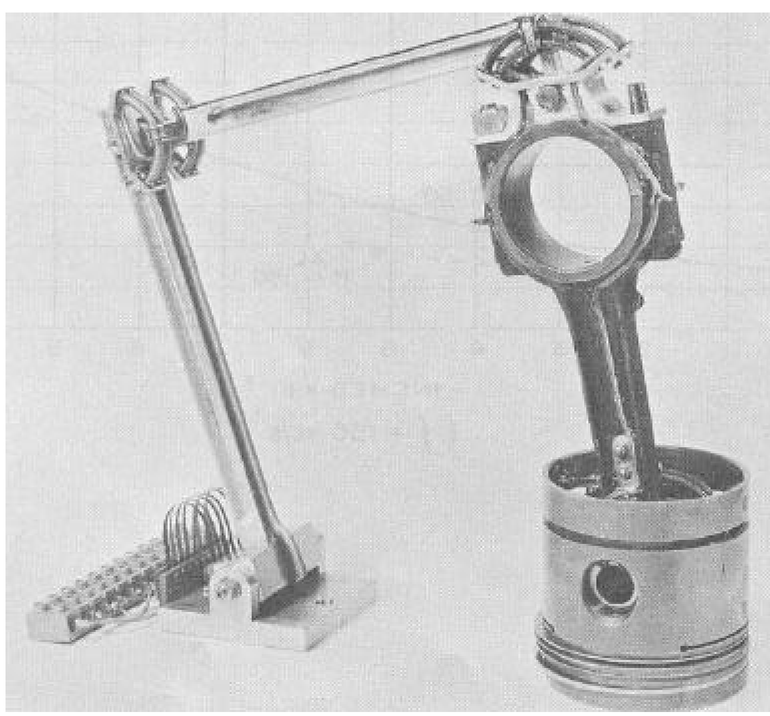

Fig 6. Piston Fitted with 4 Inductive Transducers and Lead-out System

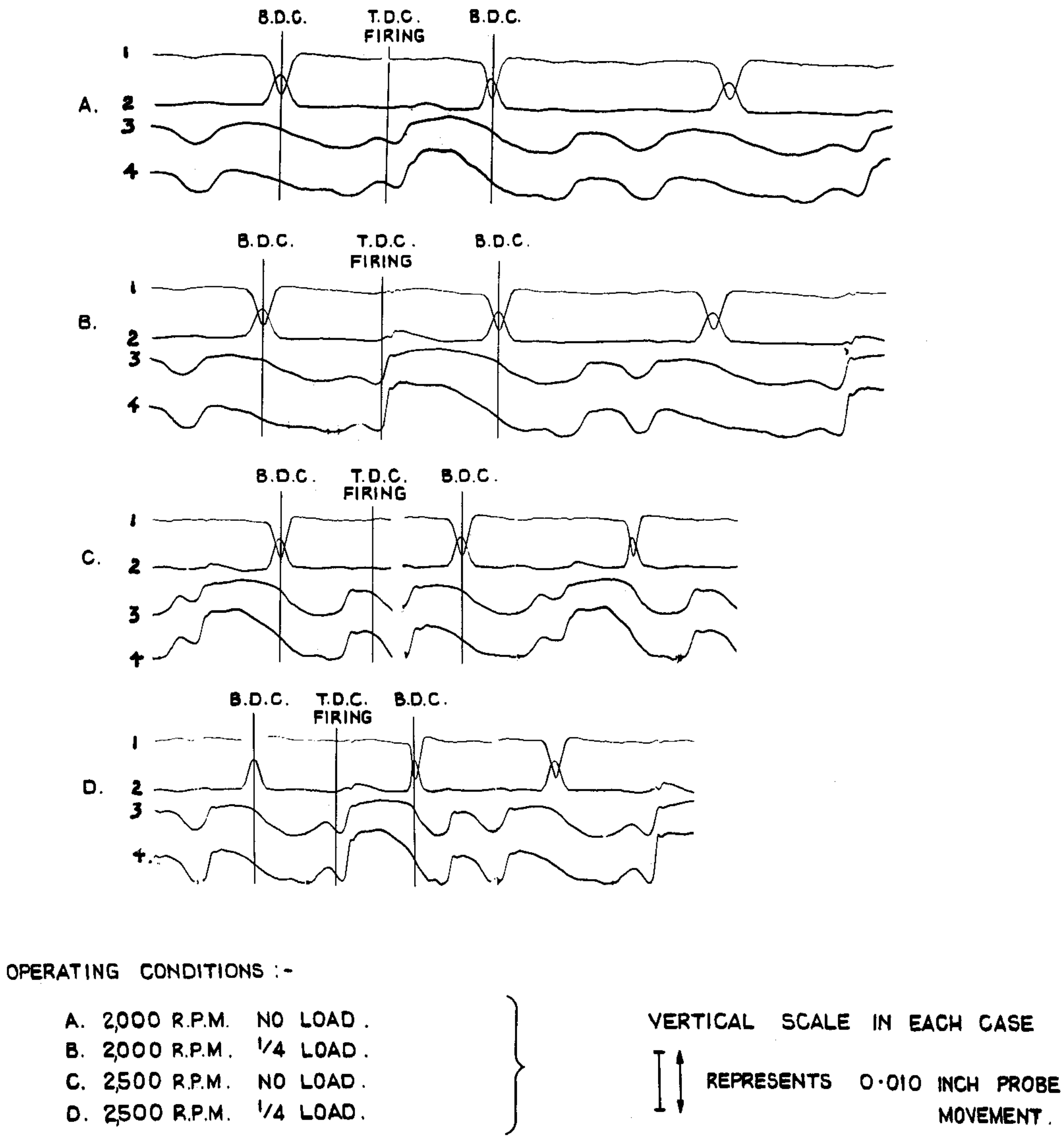

Fig 7. Results of Piston Movement Obtained Using Inductive Transducers and Lead-out System Fig. 6, and Instrumentation as in Fig. 5

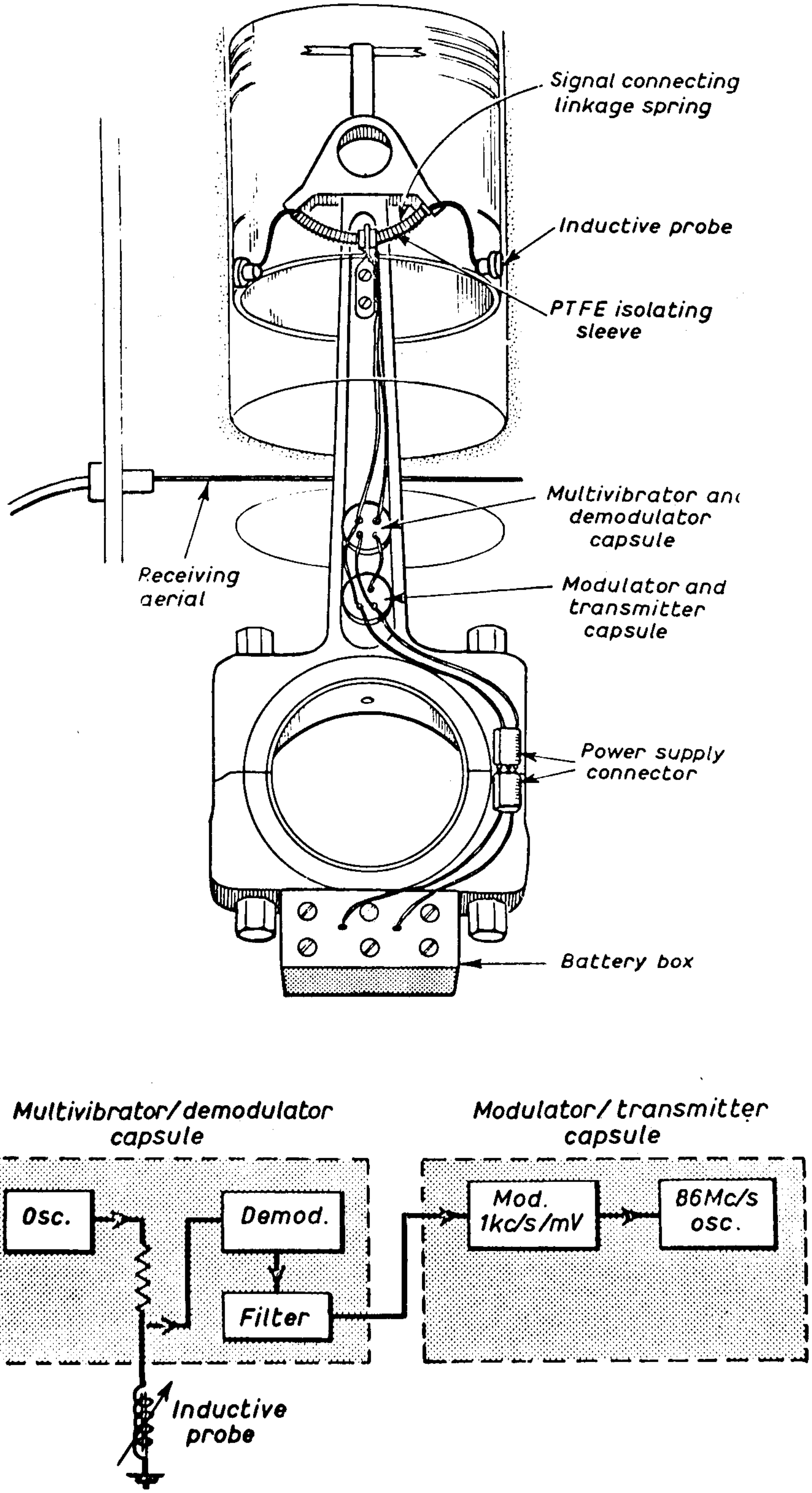

Fig 8. F.M. Telemetry System with Inductive Transducer for the Measurement of Piston Movement in an I.C. Engine

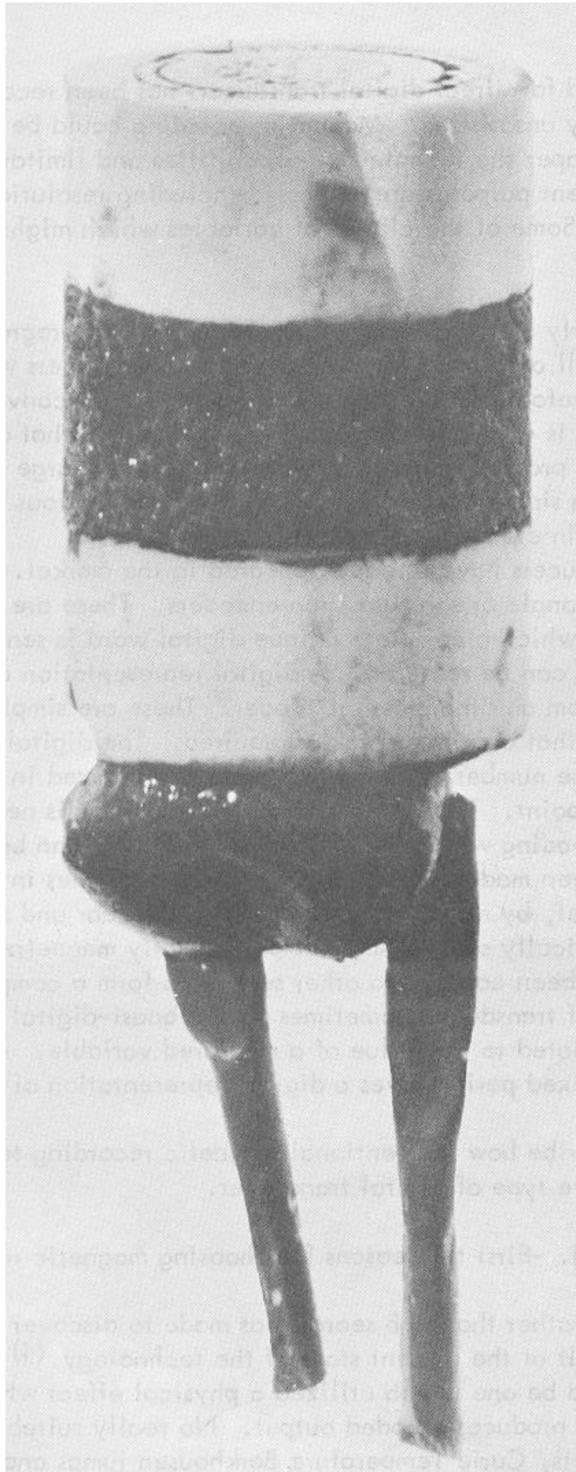

Fig 9. High-Temperature Transducer P/40/600