A NON-CONTACTING PROBE FOR
PISTON KINEMATIC MEASUREMENTS

by

P. L. CLEMENS

RHODE-SAINT-GENESE, BELGIUM

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*Visiting Professor, von Karman Institute for Fluid Dynamics, and Assistant Manager, Aerophysics Instrumentation Branch, von Karman Gas Dynamics Facility, ARO, Inc., Arnold Engineering Development Center.
ABSTRACT

Non-contacting, variable-reluctance probes of simple design and construction are applicable to measurement of piston kinematics in pump tubes, overcoming such disadvantages of previous methods as the need for shot-by-shot refurbishment (as with shorting probes), sometimes erratic performance (shorting probes and pressure transducers), and expense (microwave systems). The new probe produces signals adequate for triggering oscilloscopes and gating chronographs. Its accuracy and resolution are expected to be at least equal to those obtained with shorting probes and pressure transducers. A small piston ring of magnetic material must be used with the probe. Use of more than one ring enables measurement of piston velocity at each probe rather than averaged over widely separated stations as with earlier probe methods. A simple test rig is useful in optimizing probe geometry for particular applications.
ACKNOWLEDGMENTS

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INTRODUCTION

The accurate measurement of piston kinematics is of importance both in optimizing and in monitoring the performance of two-stage, light-gas launchers. For these purposes, electrical shorting probes and pressure transducers have long been used as annunciators of piston arrival at observation stations distributed along the length of the launcher pump tube. Mean piston velocities over the usually wide distance intervals separating adjacent probes or transducers then have been computed from measurements of the time intervals separating the annunciation signals. More recently, the early in-barrel microwave reflectometry work which was begun by Pennelegion (Ref. 1) and later extended by Hendrix (Ref. 2) has been successfully adapted by Hancy and others (Refs. 3 and 4) to the measurement of piston ballistics. These and several other methods have been reviewed comprehensively in Ref. 5.

These previous methods suffer several shortcomings:
The resolution of the shorting and of the pressure probe systems is quite obviously limited by the number of probes installed through the wall of the pump tube, two of these probes being required for a single velocity measurement. Shorting probes must be rebuilt prior to each shot, and they sometimes perform erratically. In some operating regimes, time measurements obtained from pressure transducers may become uncertain because of response delays attributable to their tubulation. In work with pistons of some designs, the x vs t data provided by pressure transducers seem not to be self consistent. Presumably this arises because of random variation, along the piston surface, of the longitudinal position at which sealing against the pressure differential is effected. While the microwave method affords excellent resolution, its installation cost is comparatively high.

This paper describes a non-contacting, variable-reluctance probe which was developed and applied to the
measurement of piston velocities in the Piston-Driven Shock Tube of the von Karman Institute for Fluid Dynamics (The Piston-Driven Shock Tube appears in Fig. 1; it is described in detail in Ref. 6). Experience with the probe has demonstrated its suitability for use in the pump tubes of two-stage, light-gas guns. The probe may be re-used without limit and requires no adjustment or replacement of parts between shots. The technique does require, however, that the piston be fitted with one or more simple metal rings. If but one ring is used, the passing of the piston results in a single electrical pulse from the probe. If two rings separated by a measured distance are installed on the piston, then a pair of pulses is developed from which velocity can be calculated.

Probes used initially in the development of the technique described here were built at the von Karman Institute, and they functioned satisfactorily. As the work continued, similar probes which had been designed for use as displacement transducers in 100-kHz carrier amplifier systems were found to be available from a commercial source. Because their cost was low and they performed adequately in the d-c circuit which is a part of this system, these commercial transducers were adopted. The results described here were obtained with their use.
OPERATING PRINCIPLE

The essential elements of the variable-reluctance probe are shown schematically in Fig. 2. The probe structure is made a part of a high-pressure gland assembly which is mounted in the wall of the pump tube. A coil is wound about a cylindrical magnetic core located concentrically within the probe, and the face of the core (i.e., the tip of the probe) is positioned to lie just outside of the plane of the inner pump tube wall.

A diagram of the electrical circuit used with the probe appears in Fig. 3. A direct current through the probe coil supplies the magnetomotive force for a magnetic circuit. This magnetic circuit is completed through the probe structure and the pump tube wall, and it includes a high-reluctance air gap at the probe face. As a piston ring made of a magnetic material passes the probe face, the reluctance of the magnetic circuit drops abruptly. The total flux linking the coil increases correspondingly, and a transient voltage pulse results at the coil terminals. Because the flux alternately increases and then returns to normal, the voltage pulse which is produced has symmetrical positive and negative lobes. A voltage null separating these lobes marks the instant the piston ring lies geometrically centered beneath the probe face. A portion of the probe voltage pulse appears as an output signal across the series resistor, shown in Fig. 3, where it may be used to trigger an oscilloscope or to gate a chronograph. The capacitor shown reduces signal losses across the internal impedance of the power supply and the variable current adjusting resistor.

1 Care must be taken not to allow the probe to protrude inside the pump tube were it would be damaged by the passing piston. In the work reported here, the face of the probe was deliberately positioned to fall short of the plane of the inner pump tube wall by 0.1 mm. Similarly, the mild steel piston rings used were recessed 0.35 mm below the piston outer diameter to ensure against the possibility that they might scar the pump tube wall.
A typical output voltage waveform appears sketched in Fig. 3. An approximate expression for the instantaneous output voltage provided by this circuit is derived in the Appendix, where it is shown that the amplitude of the output signal varies directly as probe coil current, directly as the square of the number of probe coil turns, directly as the rate of change of magnetic reluctance, and inversely as the square of reluctance itself:

$$e_0 = -\frac{R_0}{R_0 + R_p} \left[ R^{-2} K_2 (M_{R} n + K_1 n^2 I) \frac{dR}{dt} \right]$$  (See Appendix)

The term $M_{R} n$, as explained in the Appendix, represents the effect of magnetic retentivity of the probe core.
TESTS AND RESULTS

Several similar probe configurations have been tested, both made locally and procured commercially. Differences in their performance have been largely those which would have been expected on the basis of differing coil designs. The results reported here were obtained using a commercially available probe which was intended for another purpose but which functions quite well in this application despite having somewhat fewer coil turns than might be desirable. Assembled in its high-pressure fitting, it is shown in Fig. 4. A table of its pertinent characteristics follows:

<table>
<thead>
<tr>
<th>Probe Outside Diameter</th>
<th>5.96 mm</th>
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<tr>
<td>Coil Core Diameter</td>
<td>1.0 mm</td>
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<tr>
<td>Coil Resistance</td>
<td>35 ohms</td>
</tr>
<tr>
<td>Max. Allowable Continuous Current</td>
<td>15 ma</td>
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<tr>
<td>Coil Turns</td>
<td>450</td>
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A test rig, shown in Fig. 5 was assembled to enable convenient testing of the probe and its circuit. An electric motor was used to rotate disks which carried teeth simulating piston rings past the probe tip. Disks of several thicknesses and materials were used, and tooth widths were varied as a guide to optimizing the width of the piston rings to be used. A moveable steel collar was fitted to the probe tip. Its position could be varied to determine the distance by which the probe tip might be recessed within the pump tube wall. This distance was fixed at 0.1 mm in obtaining the results reported here. The width of the air gap separating the disk teeth from the probe collar was varied to determine the distance by which the rings might be recessed below the outside diameter of the piston. Probe coil excitation current and disk tooth velocity were varied.

1 Contactless Displacement Transducer -- 100-kHz Carrier Ckt. -- Type TW6-100/A -- Mfg.: Vibro-Meter A.G., Fribourg, Switzerland -- Approx. Cost: $33.00/each.
Because the air gap is the overwhelming contributor to the reluctance of the magnetic circuit, the selection of the magnetic material from which to make the disk -- and later the piston rings -- proved not to be a very critical one. Results obtained with ordinary mild steel disks were quite satisfactory, and mild steel was used in the work being reported here. Again because of the influence of the air gap, disk thickness -- representing piston ring thickness in the radial dimension -- proved not to be particularly critical. However, no disk thickness less than 3.0 mm was used in this work. As would have been expected, the selection of tooth width -- corresponding to piston ring width -- was shown to be of importance in determining the waveform of the output signal. With tooth width too great, a "dwell" is realized at the signal null which separates the two symmetrical lobes, and temporal resolution suffers. If tooth width is made too little, the amplitude of the output signal is reduced. These effects are independent of velocity.

Results of tests using a mild steel disk and a tooth width of 3.0 mm appear in Figs. 6-a, 6-b, 6-c and 6-d. These curves are largely self-explanatory with the exception, perhaps, of two apparent anomalies: the plots representing peak output signal as a function of excitation current fail to pass through the origin (Figs 6-a and 6-b), and the curve corresponding to an air gap of 0.1 mm (Fig. 6-a) is discontinuous. A single factor, evident in the derivation presented in the Appendix, is responsible for both. The probe core has finite magnetic retentivity. Thus, the magnetomotive force does not fall to zero when the excitation current is reduced to zero. In taking the data plotted for the discontinuous curve of Fig. 6-a, current was accidentally increased to a momentary value greatly exceeding the coil rating. The abrupt increase in retentivity produced a curve of identical slope but, as would be expected, having a higher Y-axis intercept.

A typical oscillogram of the probe circuit output signal produced by the toothed disk appears as Fig. 7. The
symmetrical signal lobes induced by the four disk teeth are evident.

On the basis of test results such as those shown in Figs. 6 and 7, a piston was constructed for use in the pump tube of the VKI Piston-Driven Shock Tube. The 92-mm-diameter piston (Fig. 8) was provided with three, mild steel rings, each 3.0 mm in width and spaced on 40-mm centers. Ring diameter was 0.7 mm less than the pump tube bore. Use of the probe with this piston in the pump tube produced oscillograms such as Fig. 9. Piston velocity in this case was 19 meters per second. Signals produced by the passing of each of the three rings have peak-to-peak amplitudes of about 40 millivolts. This agrees not too badly with the results from the use of the test rig; data plotted in Fig. 6-c indicate an output signal amplitude of about 63 millivolts for the same velocity, excitation current, and air gap. The difference is attributed to failure of the test rig to replicate exactly the magnetic circuit found in the pump tube and also to the variable magnetic retentivity of the probe, mentioned earlier.

The approximate expression for output signal amplitude derived in the Appendix indicates the importance of piston velocity. It is also evident that a probe coil design using many turns of fine wire is favored over one using a smaller number of turns of wire but having higher current capacity. Significantly, piston velocities in the work whose results are reported here were lower than those which are generally found in work with two-stage launchers, and the transducer used as a probe was outfitted with a coil of only 450 turns. Significantly also, the excitation current could have been increased by a factor of 1.5 over that used in these tests without exceeding the coil rating.
CONCLUSIONS

Non-contacting, variable-reluctance probes of simple design and construction are applicable to measurement of piston kinematics in pump tubes. The probes can be re-used continuously without need for refurbishment between shots. Their use requires that small rings of magnetic material be incorporated into piston design. If used with pistons fitted with two or more rings spaced at measured intervals, the multiple signals from each of these probes then can be used to compute piston velocity realized at each single probe rather than averaged over the greater distance separating adjacent probes. Used as a simple annunciator of piston arrival, there is no reason to believe that the accuracy of this probe would be less than that of either the wire shorting probes or the pressure transducers often used in such applications. Its reliability would be expected to exceed that of the sometimes-erratic wire shorting probes.

The performance of the probe follows the general form of the behaviour predicted by the approximate analytical expression developed in the Appendix. The simple test rig which has been described provides a convenient means for evaluating performance and optimizing the geometry of the probe/piston ring/air gap combination for any particular application of the probe. Amplitudes of the output signals produced by the probe when used in the von Karman Institute Piston-Driven Shock Tube are adequate for triggering oscilloscopes and gating chronographs. Signals having still higher amplitudes would be expected from application of the probe in the pump tubes of two-stage hypervelocity launchers.
REFERENCES


APPENDIX - CONSIDERATION OF FACTORS
GOVERNING OUTPUT SIGNAL

For analytical purposes, the actual probe circuit (Fig. 3) can be replaced by an equivalent a-c circuit:

![A-C Equivalent Circuit Diagram]

The source impedance, $Z_s$, may be expressed as:

$$Z_s = \frac{(R_c + R_B)(-jX_c)}{R_c + R_B - jX_c}$$

Allowing $R_s = R_c + R_B$ and rationalizing, this expression becomes:

$$Z_s = \frac{X_c R_s}{R_s^2 + X_c^2} - j \frac{X_c R_s^2}{R_s^2 + X_c^2}$$  \hspace{1cm} (Eq. 1)
With care in selecting a sufficiently large bypass capacitor and for reasonable values of the series current-adjusting resistor \( R_c \), it will be true at all but extremely low piston velocities that

\[ X_c \ll R_s \]

Using this, Eq. 1 may be simplified to

\[ Z_s \approx -jX_c \quad \text{(Eq. 2)} \]

Output voltage \( e_0 \) may be expressed as a function of the induced probe signal \( e_p \) as follows:

\[ e_0 = e_p \frac{R_0}{Z_s + R_0 + jX_{LP}} \]

... or, using Eq. 2:

\[ e_0 \approx e_p \frac{R_0}{R_0 + R_p + jX_{LP} - jX_c} \quad \text{(Eq. 3)} \]

For most probe systems of the sort described here, the term \( X_{LP} \) will be negligibly small except, possibly, at very high piston velocities. Thus:

\[ |X_{LP} - X_c| \ll R_0 + R_p \]

This allows Eq. 3 to be rewritten as, simply

\[ e_0 \approx e_p \frac{R_0}{R_0 + R_p} \quad \text{(Eq. 4)} \]

Considering now the magnetic circuit involving the probe, the total magnetomotive force \( M_T \) can be considered as the sum of two components: a current-induced part varying directly as coil turns, \( n \), and current, \( I \), per
\[ M_I = K_1 nI \]

... and a retained part, \( M_R \), attributable to magnetic coercivity (see next page). Thus,

\[ M_T = K_1 nI + M_R \]

The flux, \( \phi \), induced by this magnetomotive force is expressed as a function of the variable reluctance of the magnetic circuit, \( R \), as:

\[ \phi = \frac{M_R + K_1 nI}{R} \]  \hspace{1cm} (Eq. 5)

An expression for the induced probe signal, \( e_P \), may be written as a function of the time derivative of the flux linking the \( n \) turns of the coil:

\[ e_P = K_2 n \frac{d\phi}{dt} \]

Differentiating Eq. 5 and substituting:

\[ e_P = - R^{-2} K_2 (M_R n + K_1 n^2 I) \frac{dR}{dt} \]  \hspace{1cm} (Eq. 6)

Equations 4 and 6 then give an approximate expression for probe circuit output voltage:

\[ e_0 \approx - \frac{R_0}{R_0 + R_p} \left[ R^{-2} K_2 (M_R n + K_1 n^2 I) \frac{dR}{dt} \right] \]

The variation of the reluctance of the magnetic circuit in response to the changing position of the piston ring lends itself poorly to an exact analytical treatment because of the effects of flux leakage and fringing. However, an approximate graphical treatment readily shows the anticipated form of the voltage pulse induced in the probe coil by the passing of the ring. This is shown in the sketches, next page.
Magnetic Circuit and Graphical Approximation of Output Signal
Fig. 1--THE VKI PISTON-DRIVEN SHOCK TUBE
Fig 2 - Schéma Sketch of Probe and Piston

$ a = 0.1 \text{mm} \quad \} \quad \text{See text} \quad b = 0.35 \text{mm} \quad \}$
Probe Coil

Piston rings pass under probe center at instants $t_1$ and $t_2$

Fig 3 Probe Circuit
Fig. 5 -- PROBE TEST RIG
Fig 6-a -- Peak Output Signal for Several Air Gaps--Current Varied
Fig 6-b -- Peak Output Signal for Several Velocities--Current Varied
Fig 6 -c - Peak Output Signal for Several Currents - Velocity Varied
Fig 6-d--Peak Output Signal for Several Currents--Air Gap Varied
Disk Tooth Velocity = 29.5 meters/sec.
Probe Coil Current = 10 ma.
Probe Tip Recess = 0.1 mm
Air Gap = 0.35 mm
Peak-to-Peak Output Signal = 102 mv

Fig. 7 -- Test Rig Oscillogram
Fig 8 -- PISTON
Probe Coil Current = 10 ma.

Probe Tip Recess = 0.1 mm

Air Gap = 0.35 mm

Piston Velocity = 19 meters/sec.

Peak-to-Peak Output Signal ≤ 40 mv

Fig. 9 -- Pump Tube Oscillogram