Magnetic Detector for Projectiles in Tubes

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A new wall-mounted, magnetic detector is presented for measuring projectile passage times in tubes. The detector has the advantages of simplicity over laser and microwave techniques and has other advantages over the electrical contact wire technique. Representative data are presented. The detector is shown to be very insensitive to strong pressure waves and combustion, but able to detect the passage of the projectile (carrying one or two magnets) clearly. Two modes of operation of the detector are described and the use of these detectors to measure projectile velocities, accelerations, and spin rates is discussed.

I. Introduction

EARLY on in experiments carried out on a ramjet-in-tube concept,[1] a simple, accurate method of measuring projectile passage times at various stations along the tube was sought. The projectile geometry is shown in Fig. 1. The projectile consists of two parts—nose and body, screwed together. The nose is conical and the body is octogonal, tapering, and has 4 fins, as shown. The tube has a number of generic diagnostic ports as shown in Fig. 1a.

The following velocity or position measuring techniques were considered: microwave techniques,[2,3] laser velocity interferometry,[4] whisker gauges,[5,6] and the use of coils surrounding the flight path[7,8] when the projectiles are in free flight. The microwave and laser techniques were ruled out because of complexity and expense and the unknown effects of diaphragms, fill gases, and the conical nose of the projectile acting as a reflector. Whisker gauges were ruled out because of the necessity to move the wires inwards between shots, the likelihood of leaks, projectile damage, and the sensitivity of the results to projectile orientation. The techniques of Refs. 7 and 8 cannot be used here because of the shielding effect of the tube.

II. Description of the Detector

The new wall-mounted magnetic detector with the sensing coil normal to the tube axis is shown in Fig. 2. The detector body and cap are made of nonmagnetic stainless steel. The sensing coil consists of 250–300 turns of #34 magnetic wire. The wire holes are sealed with Devcon "5 minute" clear epoxy. To avoid shorting out the coil, the coil is insulated on all sides from the probe body and cap using electrical tape. The coil resistance ($\sim 6\Omega$) is monitored during construction to watch for shorts. The detector is pressure checked at ~ 100 atm before installation in the ram accelerator tube.

The current version of the magnetic detector (Fig. 2) depends upon epoxy to make pressure seals. A modified version, to be implemented shortly, avoids this weakness in design. In the modified version, the detector body and detector cap become one solid piece, with a flat bottom hole extending to ~ 0.1 cm from the detector face. The coil is wound around a Lexan rod, with one end grooved like a bobbin to take the windings. The coil assembly is then placed inside the detector body.

Figure 2 also shows a section through the ramjet-in-tube projectile, showing the locations of the magnets. The magnets are constructed from sheets of rubber magnetic material of the type used in the construction of signs. The throat magnets are annular rings and the rear magnets are disks. Two layers of the rubber magnet material, each 0.075 cm thick, are used. The field of the rubber magnet material is magnetized normal to the surface by inserting each sheet between the poles of two powerful permanent magnets. Note that the throat magnet is completely shielded from the hot working gases by a metal lip to avoid possible ignition and burning of the rubber magnet material.

III. Results

Figure 3 shows a typical result from the magnetic detector (upper trace) and from a pressure transducer opposite the

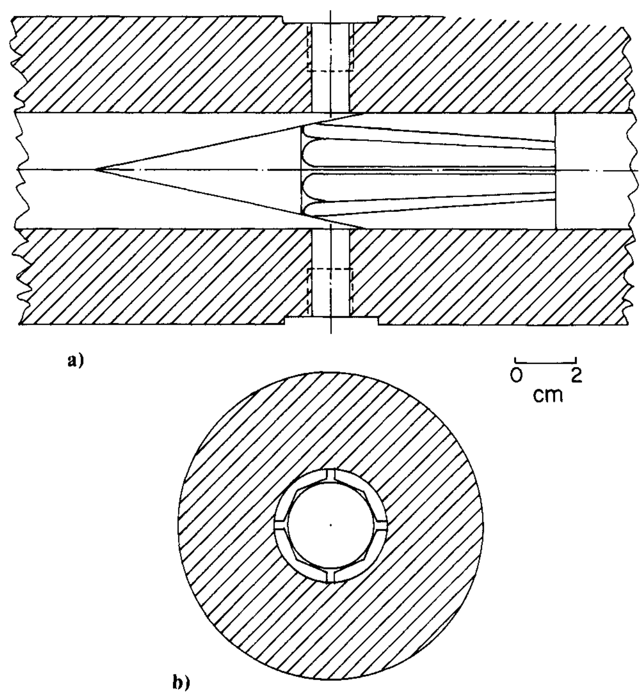

Fig. 1 Ram accelerator projectile; a) two empty instrumentation ports.

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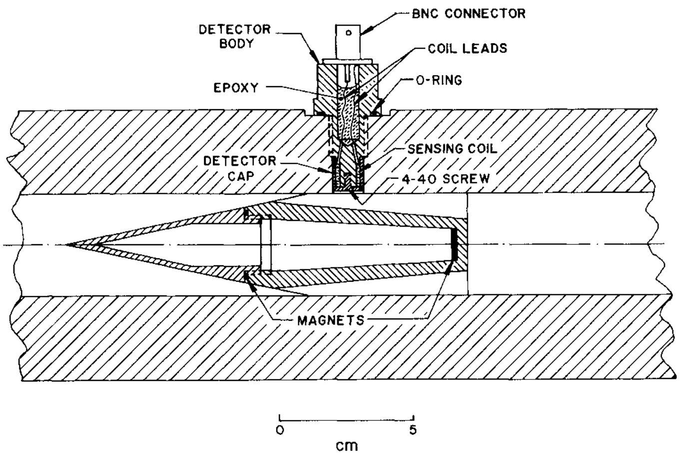

Fig. 2 Magnetic detector and section through ramjet-in-tube projectile to show the location of the rubber magnet. The fins have been rotated slightly to be out of the section plane.

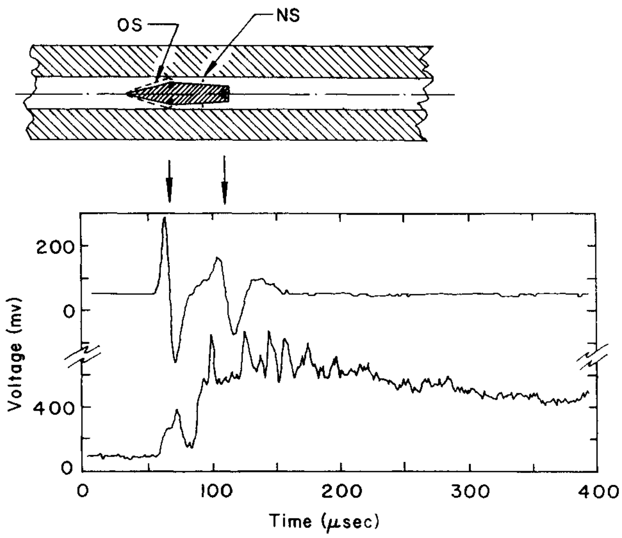

Fig. 3 Representative magnetic detector trace (upper trace). The lower trace is from a pressure gauge opposite the magnetic detector. The projectile is moving at ~1730 m/s. The magnetic detector signal has been amplified by a factor of 100. The projectile has been shown solid and without fins, for simplicity. OS denotes oblique shock waves and NS, normal shock wave system. Heavy lines denote magnets aboard projectile. Also, see text.

magnetic probe (lower trace). The projectile is operating in the thermally choked mode[1] and the leading shocks of the strong pressure wave system are stabilized on the rear part of the projectile. The projectile is moving at ~1730 m/s in a mixture of $5CH_4 + 2O_2 + 2.5He$, initially, at a pressure of 33 atm in the tube. The time scale of Fig. 3 is 50 μs/division, the voltage scales are 100 mv/division for the magnetic detector and 200 mv/division for the pressure gauge. The first pulse from the magnetic detector in Fig. 3 (from the throat magnet) has a peak-to-peak amplitude of ~230 mv. The magnetic detector signal has been amplified by a factor of 100. Six magnetic detectors were multiplexed in parallel for the data of Fig. 3. This has been found to reduce the output of each magnetic detector by a factor of 6. Hence, the unmultiplexed, unamplified output of a magnetic detector for the throat magnet for the conditions of Fig. 3 can be estimated to be $(450/100) \times 6 = 27$ mv. The first and second zero crossings (arrows) of the magnetic detector signal are used to define the time of passage of the projectile throat and the projectile rear magnet, respectively. Velocities are generally calculated using the times of the zero crossings of the pulses from the throat magnet at two successive stations along the tube.

Using the thickness of the end of the detector cap (0.114 cm) and representative electrical conductivity for the 300 series of stainless steels, the effect of the cap on the magnetic field can be estimated numerically. The magnetic field can be shown[9] to obey a diffusion equation inside the stainless steel. We omit the details of the calculations, but give some results here. The first magnetic detector pulse in Fig. 3 can be approximated by one cycle of a sinusoid with period $\sim 1.9 \times 10^{-5}$ s. For a continuous sinusoid with this period, one can readily estimate that the amplitude at the sensing coil will be ~0.54 times that within the tube and the phase at the coil will lag $\sim 1.8 \times 10^{-6}$ s behind that in the tube. This delay should, however, be consistent among detectors, allowing accurate velocities to be obtained directly from zero crossings recorded at successive detectors.

Note that the magnetic detector is rather insensitive to the pressure wave system and its accompanying combustion. Initially, the detector bodies were made out of medium carbon steel. These steels have a tendency to become magnetized even when no attempt is made to magnetize them. Detectors made out of these steels typically showed large high-frequency hash signals from the normal shock region on the tapering rear part of the projectile through the combustion zone behind the projectile. The hash was equal to, or even two or three times greater in peak-to-peak amplitude than the signals from the projectiles' magnets, making it difficult to discern the latter signals. On removing the carbon steel magnetic probes from the ramjet-tube, they were found to have become noticeably magnetized. Switching to nonmagnetic stainless steel detectors and caps greatly alleviated this problem, as is evident in Fig. 3.

The use of two magnets on the projectile demonstrates the measurement of projectile velocities using a single, wall-mounted detector. Sampling the magnetic detector signal at 1 MHz allows "single detector" projectile velocities to be measured to within ±3% at velocities of ~2 km/s.

The spin rates of projectiles having two on-board magnets have been investigated as follows. The rear magnet is symmetrical, consisting of two disks, as usual. The throat magnet is asymmetrical; it consists of one complete annular ring magnet and one 180 deg sector of an annular ring magnet. The rear magnet serves to "calibrate" the magnetic detectors, which have varying sensitivities. When compared to the pulses produced by the rear magnet, the asymmetric throat magnet produces stronger or weaker pulses accordingly, as the double or single portions of the magnet pass by the detector in question.

Figure 4 shows magnetic detector traces obtained using this technique. The four detectors are located 90 deg apart azimuthally, but are at the same axial location. From the ratios of the peak-to-peak amplitudes of the throat magnet pulses to the corresponding rear magnet pulses, the azimuth of the center of the double sheet part of the asymmetric throat magnet can be estimated to be 70 deg ± 20 deg to the right of top. (The magnetic detector locations are labelled as viewed in the direction of projectile motion.) If sets of four detectors, disposed azimuthally as described above, are at a number of axial locations along the tube, the projectile orientation at each axial location and, thence, the spin rate can be determined.

IV. Further Discussion

One may think of two modes in which to operate the magnetic detectors. In the first, or "passive" mode, there is no DC excitation of the sensing coil (or any other nearby coil), no magnet inserted into the coil, and the detector is made of nonmagnetic materials. Ideally, such a detector would be sensitive to moving magnets or moving currents and would not be sensitive to moving conductors. This is how the detectors were operated in our experiments. The magnetic detectors could, however, be operated in the "active" mode, in which the sensing coil (or another coil close by or surrounding the sensing coil) carries a dc current, or a magnet is inserted into the coil. The

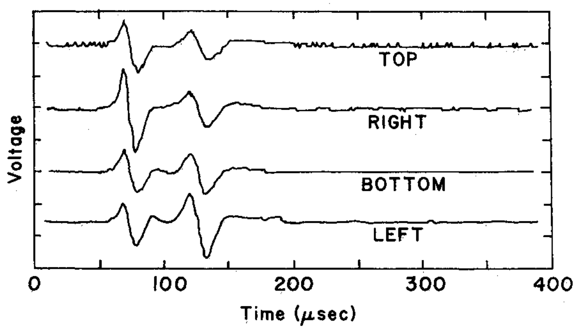

Fig. 4. Magnetic signal traces from four magnetic detectors located at the same axial position but 90 deg apart azimuthally. The projectile has a throat magnet with a weak side and a strong side and a symmetric rear magnet (see text). The projectile is moving at ~1400 m/s. The aximuthal locations (top, right, bottom, left) are as viewed in the direction of projectile motion. The scales for the *y*-axes of the plots are (in order, top to bottom) 100, 200, 500, and 200 mv per division.

active mode would be sensitive to moving conductors as well as to moving magnets or moving currents. Apart from our inadvertent experience in the active mode referred to earlier, we have little experience in this mode.

We will illustrate some of the further possibilities of magnetic detectors (in comparison to whisker gauges) by considering the problem of tracking the motion of a polyethylene piston making single or multiple strokes in a steel tube. The whisker gauge has an obvious advantage—it can be used with the unmodified nonmetallic pistons. The magnetic detector cannot. If the pistons were grooved circumferentially, one or more split metallic rings with outside diameters slightly less than the piston diameter could be placed around the piston, after the fashion of automobile piston rings. The magnetic detectors could operate in the passive or active mode and the rings could be magnetized or not, accordingly.

If one is willing to modify the pistons in this way, several advantages of magnetic detectors over whisker gauges appear. First, the magnetic detectors need not be adjusted between shots, with the attendant possibility of creating leaks. Also, the magnetic detectors will not damage the piston. If there are multiple passes of the piston over the same detector, all passes can be recorded. If one puts two or three (or more) rings on the piston, velocities and accelerations, respectively, can be obtained at each detector, regardless of other detectors. Finally, if a projectile does not fill the entire tube, but has a body supported away from the tube by fins, accurate measurements of projectile passage times can be made.

V. Conclusions

A new type of magnetic detector for measuring projectile passage times in a tube was presented. It has the advantage of simplicity and low cost over microwave and laser techniques, and, in many cases, has a number of advantages over the electrical contact (whisker gauge) technique. The construction of the gauge was described. Representative data were presented and the effect of magnetic diffusion through the stainless steel cap over the sensing coil was described. If operated in the proper mode, the detector was found to be very insensitive to strong pressure waves and combustion, but to pick out the projectile passage time clearly. Extensions of the technique to yield velocity and acceleration with a single wall-mounted detector were discussed. Extension of the technique to yield projectile spin rates was also discussed.

Acknowledgments

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