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September 11, 1974

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Prepared for U. S. Atomic Energy Commission under contract no. W-7405-Eng-48

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MAGNETIC PROBES AS PARTICLE VELOCITY DETECTORS*

ABSTRACT

Two types of magnetic probes, the stirrup and axially-symmetric magnetic (ASM) probes, are examined for measuring particle velocity in detonation products. Although the stirrup probe is simple in operation and provides voltage data relatively easy to translate into velocity, it has serious electrical noise limitations. The ASM-probe is more complex and provides data more difficult to translate, but does not have the noise problems associated with the stirrup probe. This study, therefore, indicates that the ASM-probe is the more effective detector of particle velocity.

INTRODUCTION

Two types of magnetic probes can be used in studying particle motion in high-explosive detonation products: the stirrup probe and the ASM-probe (also referred to as the magy-probe). Following is a description of these probe techniques and a discussion of their relative advantages and disadvantages in determining particle motion in explosive detonation products.

Magnetic probes for measuring particle velocities in the hydrodynamic regime of strong shocks and detonations are based on the Lorentz force:

$$\vec{F} = q (\vec{u} \times \vec{B}). \quad (1)$$

This is a vector relationship relating the force on an electrically charged particle q to the curl of its velocity u in a magnetic field B . The vectors are mutually orthogonal and follow the right-hand rule. To demonstrate, set your thumb, index, and middle fingers mutually perpendicular; call the index finger u and curl it toward the middle finger, which represents B ; the thumb then points in the direction of force F .

Since voltage is the primary observable in all cases of interest to us, the basic expression is transformed to the simple scalar expression¹

$$V = Bud, \quad (2)$$

by noting that $F/q = E$ (the electric field strength) and $E = V/d$ (where d is the length of the electric field).

This simple expression is the algorithm for voltage generation by magnetohydrodynamic techniques. In power stations, u represents burning coal flowing in a metal channel. The stirrup probe used by Dremín in Russia and Jacobs at the Naval Ordnance

*Seminar presentation at LLL July 8, 1974.

Laboratory (Fig. 1) has been used to study particle motion in the detonation products of high explosives. In this system, a high-conductivity metal stirrup is immersed in a media, such as nitromethane, which is then detonated from the bottom to the top. When the detonation reaches the crossmember, it moves with some particle velocity, disregarding for the moment any transient disturbances. The voltage across the stirrup, then, is a measure of the crossmember velocity, or, assuming this velocity to be the same as that of local particles, to be the particle velocity behind the detonation front.

STIRRUP PROBE

My first encounter with the stirrup probe was in 1963. Like others, I was attracted by its simple principle of operation. However, for the unwary, this probe has severe limitations, the most notable of which is a plane one-dimensional magnetic field requirement. Coupled with a plane magnetic field is the necessity of having a fairly strong field to maintain a reasonable signal-to-noise ratio. Electrical noise is common in shock and detonation experiments. In fact, detonation fronts generate electrical charges, which can be a source of noise. Heterogeneous explosives are particularly noisy. Otherwise, the earth's local homogeneous magnetic field could be used in determining particle velocity. I once tried using this field to measure the particle velocity of nitromethane products in the most electrically-quiet environment I could devise. I was completely unsuccessful even though with modest amplification of the predicted voltage (half a millivolt) there should have been a signal.

Horseshoe magnets or Helmholtz coils must be used to obtain moderate magnetic fields. In addition to having quite limited plane areas, these devices are large and cumbersome and have to be replaced after each experiment.

Another stirrup probe limitation is the vertical cuts in condensed explosives needed to bring out the ends of the crossmember. In addition to upsetting normal hydrodynamic flow, shock interactions at these locations cause excess noise. The leads can be cut, sheared, torn, or bent resulting in signal interruption, loss of signal, or even signal enhancement. Moreover, jets can, and frequently do, cause serious electrical noise.

Finally, the stirrup probe is limited by the apparent change in location of the crossmember when a conducting media, such as detonation products, occupies the interior region of the probe. For example, a typical stirrup crossmember might be 1 cm long, 1/2 cm wide, and 25 μ m thick. If it is copper, its normal resistance would be about 1.5 m Ω . As a low-source, impedance-generator resistance this value is quite good. However, for the same base area, the detonation products of TNT 1.3 cm high would exhibit about the same resistance. Thus, the effective particle location is not at the crossmember, nor is the probe registering a local velocity.

In summary, while the stirrup probe is attractive in terms of operating simplicity, it has fundamental problems that make it difficult and unattractive to use in measuring particle velocity.

Fig. 1. Sketch of typical stirrup probe for measuring the velocity of the crossmember of length d . Plane external B field is orthogonal to the direction of velocity u and voltage V .

AXIALLY-SYMMETRIC MAGNETIC PROBE

With an ASM-probe (Fig. 2), a divergent magnetic field replaces the plane field of the stirrup probe, a loop of wire replaces the corresponding crossmember, and velocity is that of a free foil or unattached surface ahead of the coil.

This system for free-surface velocity measurements was first suggested and demonstrated by Bob Caird of the Los Alamos Scientific Laboratory (LASL) magnetics group. Initially, the technique had several drawbacks. It used a pulsed solenoid to generate the magnetic field and a multi-turn pickup coil to detect the signal. My contribution to the magy-probe technique was to use permanent magnets and single-turn pickup coils and to adapt it for use in explosive products. Joe Fritz, also of the LASL magnetics group, wrote the original and the current computer program for unfolding the voltage-time oscilloscope record to velocity space.²

Conceptually, the ASM-probe overcomes many of the mechanical problems associated with the stirrup probe. Verticle cuts are not needed in the test material because lead wires are not required to contact the moving foil. The main difficulties of the ASM-probe concern hydrodynamic changes due to the presence of an imbedded foil. Before discussing this point, however, let me describe magy-probe operation in more detail.

From the Lorentz voltage expression, let us define a sensitivity function S as

$$S = V/u = dB, \quad (3)$$

where dB depends only on the coil and magnetic field. In this case, d , which was for the stirrup, now represents coil circumference $2\pi\rho_c$, and B becomes B_ρ (a function of coil radius and coil-to-foil distance). Thus,

$$S = 2\pi\rho_c B_\rho (\rho_c, Z = Z_{ff} + Z_{cf} + L/2), \quad (4)$$

where L is the length of the magnet, Z_{cf} is the coil-to-foil distance, and Z_{ff} is the magnet face-to-foil distance. Note that selection of B_ρ rather than B_z is necessary to preserve the right-hand rule for the mutually-orthogonal functionals V , u , and B .

A diagram of the magy-probe system is shown in Fig. 3. The geometric center of a dipole magnet serves as the reference of a cylindrical-coordinate system. The real coil, magnet, and foil are initially placed coaxially on the positive Z axis, with their enclosed surfaces parallel to the X - Y plane. Circular symmetry is assumed.

A simplified, diagramatic explanation of magy-probe operation is given in Fig. 4. Initially, a diverging magnetic field emanates from the magnet. Consider a single field line passing to the left of the pickup coil and continuing through the foil. It remains in this position until the foil moves. If the foil is a high-conductivity metal, when the foil moves the field line is pinned to it by an Eddy current, and the magnetic field line bends cutting the coil. Flux linkage through the coil generates voltage in the same manner that a car generator produces voltage. The fact that an Eddy current is necessary to pin the field line means that the foil material must be a very good

Fig. 2. Sketch of an ASM-probe on a phenolic circuit board material with an etched single-turn coil. Lead wires connect to a transmission line. Small permanent magnet provides a divergent magnetic field.

Cylindrical Reference Frame

ρ_c - coil radius

L - magnet length

D - magnet diameter

0 - source and reference center

$Z = Z_{ff} + Z_{cf} + L/2$ image coil distance

Z_{ff} - magnet face-to-foil distance

Z_{cf} - coil-to-foil distance

$$r = \sqrt{Z^2 + \rho_c^2}$$

$$y = \rho/Z$$

$$\theta = \tan^{-1} \rho/Z = \tan^{-1} y$$

V - output voltage

Fig. 3. ASM-probe layout, relationships, and reference frame.

Fig. 4. Illustration of magnetic field line pinning by an Eddy current. Generated circular current loop is an action-reaction event designed to hold the field line at the point of foil penetration.

conductor and must maintain its integrity throughout the observation period. Otherwise, the bent field line will return to its original position.

INITIALIZING THE ASM-PROBE SYSTEM

Final unfolding of a voltage-time oscilloscope record must be done by computer because computations involving coils and magnets involve elliptic integrals and Legendre polynomials.³

The B field for our system is obtained from the magnetic scalar potential A using the relationship⁴

$$\vec{B} = -\nabla A. \quad (5)$$

The general solution for this relationship is

$$A = \sum_{\ell=0}^{\infty} \alpha_{\ell} \frac{P_{\ell}(\cos \theta)}{r^{\ell+1}}, \quad (6)$$

where α is a coefficient dependent on magnet shape and strength, $P_{\ell}(\cos \theta)$ is the Legendre function, and r is the observation distance. For a uniformly-magnetized sphere, only the $\ell=1$ term survives the expansion, which becomes

$$A = \frac{4\pi}{3} a^3 M r^{-2} \cos \theta. \quad (7)$$

Here, $4\pi a^3/3$ is the volume of the spherical magnet and M is its magnetization. For commonly-used barium ferrite magnets, an average value for M is 3730-G. This corresponds to 4π the saturation of flux density; the value to use for other types of magnets.

Equation (7) is the first term of the dipole expansion series and, since the higher order terms drop off quite rapidly, it is a good approximation for cylindrical magnets:

$$A = vM \frac{\cos \theta}{r^2} \quad (8)$$

This approximation is a convenient form of magnetic scalar potential, with v being the volume of the magnet. Thus

$$\vec{B} = -\nabla \left(vM \frac{\cos \theta}{r^2} \right), \quad (9)$$

which simplifies to

$$B_{\rho} = \frac{3vM}{r^3} \sin \theta \cos \theta \quad (10)$$

and

$$B_z = \frac{vM}{r^3} (3 \cos^2 \theta - 1), \quad (11)$$

using $z = r \sin \theta$ and $\rho = r \cos \theta$.

We can now write

$$S = 2\pi\rho_c \frac{3vM}{r^3} \sin \theta \cos \theta = \frac{6\pi vM}{Z^2} \frac{y^2}{(1+y^2)^{5/2}}, \quad (12)$$

where $y = \rho_c/Z$. The term y is a dimensionless function that starts at zero, reaches a maximum, and then approaches zero again as an asymptote. The peak of the function occurs at $y^2 = 2/3$. Calling F the ratio of the function to its maximum value,

$$F = f(y)/f_m = \frac{y^2}{0.1859(1+y^2)^{5/2}}. \quad (13)$$

A curve of the above function is shown in Fig. 5. The final sensitivity expression takes the form

$$S = 2.79 v B_s F / Z^2, \quad (14)$$

which accounts for the dimensions usually encountered in shock and detonation exercises [v in cm^3 , B_s in kilogauss (3.73 for BaFe magnets), and Z in cm].

The sensitivity curve is only a first step in an initializing problem, however. Next, a graphical solution is needed to be able to include magnet, coil, and foil dimensions. To this end, we find that from the sensitivity expression

$$\frac{Z}{S} \frac{\partial S}{\partial Z} + \frac{\rho}{S} \frac{\partial S}{\partial \rho} = -2, \quad (15)$$

the error expression for the sensitivity function with regard to the accuracy of coil and foil placement.

The first term of Eq. (15) can be written

$$\frac{Z}{S} \frac{\partial S}{\partial Z} = 1 - \frac{5}{1+y^2}, \quad (16)$$

which allows the error expression to be plotted as a function of y , the dimensionless distance function (Fig. 6).

The peak of the sensitivity curve occurs when $\partial S / \partial \rho = 0$. More interesting, however, is the presence of the point $\partial S / \partial z = 0$. For this value of y , there is no change in the sensitivity function with respect to a change in foil position, and probe output voltage depends only on foil velocity. In other words, $\partial S / \partial z = 0$ is an initializing point where the magy-probe functions exactly like the stirrup probe, but without stirrup-probe disadvantages.

One final point is evaluating a few special y values:

Fig. 5. Functional form of nonlinear, y -versus- F relationship.

Fig. 6. Sensitivity function error expression plotted to show its relationship to function F.

$$\begin{aligned}
y &= 1/2 \text{ for } \frac{\partial B}{\partial \rho} = \frac{\partial B_z}{\partial z} = 0, \\
y &= \sqrt{2/3} \text{ for } F = F_{\max}, \\
y &= \sqrt{3/2} \text{ for } \frac{\partial B_z}{\partial \rho} = 0, \\
y &= 2 \text{ for } \frac{\partial B}{\partial z} = 0 \text{ and } V_{\text{out}} = V_{\max}.
\end{aligned} \tag{17}$$

The first line indicates that magnetic field lines inside the $y = 1/2$ value do not participate in generating voltage. A hole can be made in the foil in this region, if it is necessary to look behind the foil or if a liquid fill hole is needed. The $y^2 = 3/2$ line is the turnaround point of a magnetic field line. This line is used to judge the extent of the foil. I'll come back to this point shortly. The final point to notice is that, for $\partial B / \partial z = 0$, $y = 2$. This is just another way to express that we are working in a constant B field for this condition. It also corresponds to the maximum voltage output from the coil.

Now we can put it all together on a Z-versus- ρ graph (Fig. 7). Consider just the first quadrant. From the origin, lay out lines for $y = 1/2$, $\sqrt{2/3}$, $\sqrt{3/2}$, and 2. Next, select a magnet and center it at the origin. For mechanical as well as graphical convenience, locate a coil in the plane of the magnet face and, as an illustration, put it out at a radius of 2.5 cm. Now, draw a vertical line through the coil. If you know the run distance (e.g., free surface motion), add this height to the coil location to note the free surface location and include an additional length to determine the image coil position. This total height, then, is the Z parameter. But y is the ratio of ρ to Z. Find the value of F from the F-versus-y curve and, knowing magnet shape and size, solve for the sensitivity factor. Multiply this value by the expected foil, or free surface velocity, and you have the expected initial voltage from the probe. This suggested procedure proves successful as a graphical means for initializing ASM-probe problems.

ASM-probe output voltages do not reflect a one-to-one correspondence with foil velocity. If the coil image is located above the $y = 2$ line, for a constant foil velocity, output voltage will increase with time. If the image is below the $y = 2$ line, output voltage will decrease with time, for a constant foil velocity. Close to the $y = 2$ line and for small foil displacements, output voltage is very nearly a record of foil velocity. This raises the question, "How close should the foil, or free surface velocity, approximate the infinite extent first postulated?" To be on the safe side, the metal surface should extend as far as practical. A rule of thumb, however, is that the turnaround line ($y^2 = 3/2$) should cover the metal. If the coil image is above the $y^2 = 3/2$ line, the metal need only extend to the coil radius. To determine the minimum "safe" extent below this line, draw a horizontal line from the $y^2 = 3/2$ line above the coil until it intersects the ray from the origin through the coil image.

Fig. 7. Initializing graph for typical magy-probe exercise.

EXAMPLE EXPERIMENTS

Finally, let me return to the noise and interference problems associated with using the ASM-probe to measure particle velocities of explosive detonation products. Figure 8 shows a record from a quarter-inch magnet system like the one shown in Fig. 2. In this system, the driver and acceptor explosives were Composition B (25- and 6.35-mm thick on a P-40 plane wave, respectively). Total observation time was about 800-nsec, dictated by the detonation velocity of Composition B. This time was verified by eight 100-nsec timing marks.

The straight line through the record is a zero voltage line. This line also depicts minimum system noise. To the left of the first bump on the signal trace, this line represents run-up time and the noise level of the amplifier in the system. A 25- μ m thick copper foil was used in this experiment. It covered the driver explosive and was overlaid with acceptor explosive. The bump in the trace indicates when the detonation wave in the booster contacted the foil. The sudden electrification of the foil by the detonation front was picked up by induction. This electrical interference subsided quickly, and the foil began to move.

In Fig. 8, the first reverberation in the copper foil is quite distinct, but the trace immediately following is not clear. The interference bumps smooth out quickly, however, and only relatively low-level noise rides the main signal. The upswing appearing at the end of the trace indicates the approach of the electrified detonation wave to the coil.

The main signal initially appears as a spike followed by a rarefaction. However, this is a bit deceiving because the signal is in a rising mode while the foil is in a falling mode. Interpretation comes with experience and on knowing where on the sensitivity curve the system is operating.

Another test, using PBX-9404-05 explosive, displayed a similar trace (Fig. 9). In this case, the magnet and coil were only 2.5 mm from the foil (nearer the $y = 2$ line) and the foil was made of 75- μ m thick aluminum. As in the Composition B record, you can see the electrification bump, or signal jump, when the active part of the foil was struck, but followed by a much less noisy signal thereafter. In fact, the record is "quiet" enough to show up imperfections in the transmission system, as evidenced by the small disturbance in the middle of the main trace. There is no evidence of a detonation-wave spike for this explosive.

A final test with PBX-9404-05 explosive cleared up most of the disturbing electrical signals (see Fig. 10). Component alignment was the same in this test as in the previous test, except that the foil was bent back at the edges to contact the expansion wave and detonation front of the driver explosive. This arrangement kept the main foil at the electrical potential of the detonation products and essentially eliminated all electrical interference. Only the magnetic signal and some hydrodynamic imperfections remained. These imperfections included: wave tilt, long and short second-order wavelengths of arrival simultaneity, and initiation problems associated

Fig. 8. Oscilloscope record of 0.25- μ m thick copper foil embedded in Composition B explosive. Large timing marks are 100 nsec apart.

Fig. 9. Oscilloscope record of 75- μ m thick aluminum foil embedded in PBX-9404-05 explosive. Large timing marks 100 nsec apart.

Fig. 10. Repeat of test recorded in Fig. 9, but with embedded aluminum foil bent back to contact the detonation front and expansion wave of detonating explosive.

with start up of the detonation mode of propagation after the main detonation was quenched by the embedded foil. There may not be a solution for this type of problem.

CONCLUSIONS

Magnetic probes can provide reasonably good characterizations of particle velocities in the detonation products of high explosives; reasonably good in the sense that the metallic inserts (foils) necessary to detect voltage signals disturb normal hydrodynamic flow patterns. The stirrup probe requires connections through the unreacted explosive as well as the detonation products. The ASM-probe couples to an external signal coil by mutual inductance. Both systems relate output voltage generated by a Lorentz force to the velocity of the embedded foil. The stirrup probe offers the advantage that output voltage is directly proportional to particle velocity (at least in theory), but this technique is plagued by electrical noise. The magy-probe is much quieter, but suffers the disadvantage that computer processing is required to translate the voltage record into velocity information. When hydrodynamic factors are considered, however, the stirrup probe advantage of simplicity is outweighed by the magy-probe. Here, there is no contest: the magy-probe, with its single-sheet foil, introduces the minimum disturbance possible to a plane-wave system. The ASM-probe, therefore, is considered to be the more effective particle velocity detector.

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