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A METHOD OF CONTINUOUS
SHOCK FRONT POSITION MEASUREMENT

Livermore, California

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Front Position Measurement

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ABSTRACT

A method for continuously measuring the position of a shock front in a solid, opaque medium has been developed. The sensing element is a shorted transmission line which forms part of the inductance of an oscillator. As the stress wave moves along the line, it crushes the cable progressively, thus changing the cable inductance and the oscillator frequency. The oscillator output is recorded as a function of time. This frequency record is converted to uncrushed cable length, and finally to a position-versus-time relation.

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INTRODUCTION

The measurement of stress-wave velocity has long been an important tool in studies covering physical properties of solids. At stress amplitudes where the material behaves elastically, longitudinal and shear wave velocities together with density are used to determine the elastic constants. In the hydrodynamic region the shock wave velocity, when combined with the equation of state of the material, is sufficient to determine the material velocity and the stress perpendicular to the wave front.^{1,2} Similarly, in high explosive research, the detonation velocity is one of the factors determining the detonation pressure.^{3,4}

The standard methods of measuring velocities of high amplitude stress waves in solids include high-speed photography,^{5,6,7} pulsed x-ray techniques,^{8,9} and disturbance arrival-time measurement with electrical contactors (pins).^{10,11} Only the streaking camera method, which by its nature is limited to surface effects or to transparent media, measures the instantaneous velocity; the others measure an average velocity between discrete points, although in certain instances very high accuracy has been achieved over small distances.¹²

In the method reported here, an electrical transmission line is embedded in the medium under study in such a direction that the stress wave will move

along the cable from maximum length to minimum length monotonically. If the line is a small perturbation in the medium and is physically weak compared to the stress amplitude, the line will be shorted at the shock front, and this short will then move with the local shock velocity in the medium. The transmission line is used as the inductive element of an oscillator whose frequency becomes a measure of the position of the short on the cable.

The system to be described was designed specifically to measure shock velocities near underground nuclear detonations, and the various parameters have been optimized for this purpose. For example, the transmission line used most frequently consists of an air-dielectric coaxial cable, 3/8 inch in diameter, with a solid outer conductor. The length of cable employed is about 175 feet, and the initial operating frequency is around 500 kc. This frequency affords an accuracy of about 6 inches in determination of the position of the shock front, which is comparable with other inaccuracies present in this situation. For applications where smaller distances are involved and a higher accuracy is needed (as, for example, in determining detonation velocity as a function of radius in a cylinder of high explosive), very much higher frequencies, with correspondingly improved spatial and time resolution, can be employed.

THE OSCILLATOR

Figure 1 shows the circuit presently in use. It consists of a Colpitts oscillator, with the feedback taken from a tap on the capacitor side of the resonant circuit. With this circuit the feedback ratio is independent of the length of the shorted line. The 10- μ H inductance between the shorted line and the capacitor prevents higher modes of oscillation, for which the shorted line would have an electrical length in excess of one-quarter wavelength. This oscillator is followed by a simple cathode follower to drive a 50- Ω line.

The present hard-tube oscillator has been chosen over a transistor type for its superior frequency stability under temperature changes and its ability to operate in the presence of large radiation background. The frequency drift over a 15-minute warm-up period is about 2 kc. Dropping the supply voltage from its normal value of 180 V to 50 V results in a frequency change of less than 0.2 kc. A common line is used for the plate voltage and output signal to minimize cable requirements. A signal amplitude of about 2.5 V, peak to peak, is delivered to a 50-Ω load, without noticeable distortion.

FREQUENCY-DETERMINING RELATIONS

The behavior of the oscillator as a shorted location indicator can be analyzed by using the simple resonant circuit of Fig. 2, in which L_i is the internal inductance of the oscillator, C the equivalent (internal) capacitance, and L_ℓ is the inductance of the shorted external line of length ℓ . If we denote the frequency with zero length of external line as f_0 , and the frequency corresponding to the length ℓ as f_ℓ , then we have

$$\left(\frac{f_\ell}{f_0}\right)^2 = \frac{L_i}{L_i + L_\ell} \quad (1)$$

The inductance of the shorted transmission line less than $1/4$ wavelength long is given by

$$L_\ell = \frac{Z}{2\pi f_\ell} \tan \frac{2\pi \ell f_\ell}{\beta C} \quad (2)$$

where Z is the characteristic impedance, and βC the propagation velocity in the cable. Substituting (2) into (1) and solving for L_i yields

$$L_i = \frac{1}{\left[(f_0/f_\ell)^2 - 1\right]} \frac{Z}{2\pi f_\ell} \tan \frac{2\pi \ell f_\ell}{\beta C} \quad (3)$$

Equations (1) to (3) are valid for any cable length less than $(1/4)\lambda$. By using a known cable length ℓ and measuring f_0 and f_ℓ , the internal inductance L_i can be calculated. By then applying Eqs. (1) and (3) to a line of unknown length x , corresponding to an inductance L_x and frequency f_x , a relation between x and f_x can be derived. By performing the indicated operations, we obtain

$$x = \frac{\beta C}{2\pi f_x} \arctan \left[\frac{2\pi f_x}{Z} L_i \left(\frac{f_0^2}{f_x^2} - 1 \right) \right]. \quad (4)$$

Figure 3 is a representative plot of x versus f_x for the system used in measuring ground shock velocities, using an expression equivalent to Eq. (4).

DATA RECORDING AND ANALYSIS

Figure 4 shows the block diagram of the recording system presently in use. The signal is taken from the plate supply line and mixed with a local oscillator signal in a solid state diode mixer. This circuit is shown in Fig. 5. Both oscillator signal amplitudes should be about equal for optimum operation of the mixer. The crystal-controlled local oscillator is very stable, and will operate with crystals of frequency from 425 kc to 525 kc. No serious difficulty has been encountered in modifying this circuit to operate at very much higher frequencies. Heterodyning permits convenient recording on magnetic tape, and increases readout accuracy of the signal.

In parallel with direct recording of the sine-wave signal, a voltage proportional to the frequency is recorded on oscilloscopes. The frequency-to-voltage converter used is a General Radio frequency meter Model 1142A with 1.5-Mc upper frequency limit and 10- μ sec response time. Figure 6 shows a typical example of a record obtained in this fashion. For this type

of record the oscilloscope gain is set so that a 50-kc signal into the frequency-to-voltage converter gives a 1-cm deflection on the scope. The flat portion of the signal near the start of the sweep is the original oscillator frequency, before the stress wave has reached the shorting line.

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FOOTNOTES

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Fig. 1. Shorted cable oscillator.

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Fig. 2. Resonant circuit for analysis of frequency vs cable length.

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Fig. 3. Typical frequency-to-cable length conversion curve.

Fig. 4. Block diagram of recording system for two oscillators.

Fig. 5. Mixer oscillator.

Fig. 6. Typical output record from frequency-to-voltage converter.

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