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THE COLLEGE OF AERONAUTICS

CRANFIELD

A VARIABLE DELAY LINE

by

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SUMMARY

A variable delay line has been designed and built which can be used as an accurate means of measuring time intervals between 10 and 200 μ seconds. The use of such a device for the determination of the temperature coefficient of Youngs Modulus is described.

1.1. Introduction.

There is a need in many branches of applied physics for an accurate means of measuring time intervals of the order of 10 to 200 μseconds. The method described in this report utilises the magnetostrictive effect[*] whereby a pulse of electrical energy is converted into a pulse of acoustical energy and after being propagated through a variable distance is reconverted to an electrical signal. The time interval depends on the velocity of sound in the medium. Using such a delay line as a comparator, the delay time can be assessed by a coincidence method. This system can then be used for such diverse purposes as measuring distances between one or more echoes on a radar screen and echoes in geoprospecting.

1.2. The variable delay line.

The magnetostrictive effect is encountered in many metals and alloys from nickels to alfer. Nickel is probably the most readily available in suitable forms but it does have an appreciable temperature coefficient of delay. If, however, the delay line can be calibrated for a range of temperatures, or if the temperature of the line is kept constant, this disadvantage can be overcome.

The longitudinal polarizing field can be provided by a small bar magnet and the change in magnetizing force produced by varying the current in a coil surrounding the nickel. (It is important that the polarizing

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[*] When a change in magnetizing force occurs on certain materials a strain appears which is proportional to the change in the magnetizing force and to the initial flux density. This is a reversible process.

field should not be too great otherwise saturation occurs with the corresponding reduction in the effect of the signal). Most of the magnetostrictive materials have a high permeability so that the penetration of the magnetic flux into the material is small. Unless complete flux penetration results, there is an increased insertion loss compared with the case when there is complete flux penetration. The magnetostrictive material should thus be in such a form that there is a high ratio of surface area to thickness. Under these circumstances an insertion loss of 30 - 40 db can be expected.(1) The ideal form for the material is that of a tape but this results in something which is not very robust mechanically because for minimum insertion loss it would only be some 0.008 inch thick.(2) One could use several strands of very fine wire (which should be quite free from kinks) or a thin walled tube. A thin walled nickel tube is used in the construction of the line described in this report because of its efficiency and mechanical robustness.

The coils both for transmitting and receiving are wound on thin walled formers which are long compared to their diameter in order to improve the electromechanical coupling and increase their pulse length.(2) These coils have to be translated longitudinally with respect to each other so that no"flap" takes place. Fig. 1 shows a photograph of a receiver coil and its associated traversing gear. A rod R, supported in two sets of ball races B, can be translated by means of a micrometer screw M (to which it is connected in a spring loaded fashion). Using suitable spacers S which slide in a groove between the micrometer and the rod, this movement can be extended to four inches. The coil C is connected to the rod by means of an arm A which slides along a brass guide G. The receiver coil and traversing gear is mounted on a carriage T which can be manually adjusted to approximately the correct position and then clamped onto an aluminium base plate P in the form of an I bar, the top of which has been planed to within 0.005 inch. The nickel tube N is clamped at each end in an absorbing pad of polythene D in order to damp out reflections and the backward wave. Fig. 2 is a photograph of the complete line with transistorized preamplifier units U for the receiver coils.

1.3. Calibration of the delay line.

While changes in delay can be determined very accurately by such a line, it is not possible to measure the actual delay time with any degree of accuracy because the effective distance between the transmitter and receiver coils is not known. If the system is made regenerative however, one can obtain, for any separation of the two coils, a frequency which is the reciprocal of the delay time between them. Fig. 3 gives a block diagram of the circuit. An astable multivibrator is used to set the system up and enable the received pulse to be shaped, the background noise removed and the amplitude set to a prescribed level.≠ A monostable multivibrator is then substituted for the astable multivibrator and if there is sufficient energy in the system then it becomes regenerative (Fig. 4). The frequency of the oscillation can be compared to the output from a standard frequency generator and if the temperature is known then the delay of the line for a particular setting of the micrometer can be calculated for a standard temperature (in this case 20°C). This is repeated for a number of settings of the micrometer and a calibration curve for the line produced. Table 1 shows a typical calibration the standard deviation being 0.015 μ seconds.

1.4. Use of delay lines for measuring time intervals.

A coincidence method is used for measuring time delays and Fig. 5 shows the block diagram of the equipment. After shaping the pulse from the amplifier of the system under test, the amplitude is adjusted to the same height as the pulse from the standard line. Both pulses are then allowed to trigger separate monostable multivibrators which produce

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≠ It is essential to adjust the gain of the receiver to give a fixed pulse height for each reading because the monostable multivibrator is triggered at a particular voltage level and, unless the rise time of the leading edge of the pulse is infinitely short, this will occur at different times for pulses of different heights.

rectangular pulses of about two microseconds duration. After being differentiated these pulses are compared for coincidence. It was found that the delay could be measured by this method with a probable error of 0.03 μ seconds. Fig. 6 shows a series of photographs taken of two such pulses on a C.R.O. screen as the micrometer of the standard line is varied in 0.020 inch steps. Coincidence obviously occurs between e and f.

1.5. The comparator method used for the determination of the temperature coefficient of Young's modulus.

As the velocity of sound can be expressed in terms of Young's modulus E and density ρ by

$$V = \sqrt{\frac{E}{\rho}}$$

then the delay time T of a sample of length L is

$$T = L\sqrt{\frac{\rho}{E}}$$

this will change with temperature θ so that

$$\frac{dT}{d\theta} = \frac{\partial T}{\partial L}\frac{dL}{d\theta} + \frac{\partial T}{\partial \rho}\frac{d\rho}{d\theta} + \frac{\partial T}{\partial E}\frac{dE}{d\theta}$$

$$= \sqrt{\frac{\rho}{E}}\frac{dL}{d\theta} + \frac{L}{2\sqrt{\rho E}}\frac{d\rho}{d\theta} - \frac{L}{2}\sqrt{\frac{\rho}{E^3}}\frac{dE}{d\theta}$$

$$= L\sqrt{\frac{\rho}{E}}\left\{\frac{1}{L}\frac{dL}{d\theta} + \frac{1}{2\rho}\frac{d\rho}{d\theta} - \frac{1}{2E}\frac{dE}{d\theta}\right\}$$

$$\frac{1}{T}\frac{dT}{d\theta} = \frac{1}{L}\frac{dL}{d\theta} + \frac{1}{2\rho}\frac{d\rho}{d\theta} - \frac{1}{2E}\frac{dE}{d\theta}$$

As $\frac{1}{\rho}\frac{d\rho}{d\theta} = -\frac{3}{L}\frac{dL}{d\theta}$

$$\frac{1}{T}\frac{dt}{d\theta} = -\frac{1}{2}\left\{\frac{1}{L}\frac{dL}{d\theta} + \frac{1}{E}\frac{dE}{d\theta}\right\}$$

$$\alpha_T = - \frac{1}{2} \left\{ \alpha_L + \alpha_E \right\}$$

α_T, α_L and α_E being the temperature coefficients of delay time, length and Young's Modulus.

Therefore, if the velocity of sound in a material is measured as its temperature changes and the temperature coefficient of length is known, then the temperature coefficient of Young's Modulus can be determined. This compares very favourably with normal mechanical stress/strain methods where the specimen is usually under continual stress and its temperature is not known accurately.

The Longitudinal velocity of sound in a rod when the ratio of the wavelength to the diameter of the rod approaches infinity (one of the limiting values of the longitudinal velocity) can be measured by a resonance method or a pulse method.(4),(5) The former is very suitable for such measurements because if it is excited electrostatically then the whole equipment can be inserted in a furnace, however when the Q of the resonant system varies (which happens when internal damping varies) the method can become unreliable. A pulse system however can be used until the attenuation of the acoustic wave is so great that the signal to noise ratio has been reduced to a very low value. By using a similar system to the variable delay line such a pulse system could be made regenerative but this was found to become difficult when the signal to noise ratio of the acoustic signal was reduced below about two to one. By comparing the received signal with that from the calibrated variable delay line (as described in Section 1.4) this system could be operated down to very low signal noise ratios.

The means of injecting energy into the specimen was by joining it to a nickel tube by means of solder or araldite and injecting energy into the nickel tube by a magnetostrictive method as described in Section 1.2. In order to ensure that the temperature of the working section of the specimen is as constant along its length as possible and to match the specimen and the nickel tube, one end of it is tapered and protrudes from the bottom of a vertical furnace (see Fig. 7) where it is joined to the nickel tube.(4) The specimen is of circular cross section and the tapered portion B fits as a plug into a hole near the bottom of the furnace. The taper of B is from $\frac{1}{4}$ inch to 1/16 inch diameter and section C is 1/16 inch diameter. D is the nickel tube. A shoulder is cut into the specimen such that the echoing area of the shoulder sends approximately half the energy back along the line and allows the rest to pass into the working section of the specimen A. Transmitter and receiver coils are placed close together on the nickel tube and at the receiver coil a complex signal is received which, apart from reverberations, back echoes from the lower end of the line and any discontinuity in the structure of the specimen, include echoes from each end of section A. Fig. 8 shows a typical pattern. If, therefore, a pulse is applied simultaneously to the transmitter coils of the specimen line and a calibrated line (which has two sets of receiver coils and traversing gear mounted on it) and the outputs are treated as described in Section 1.4, then the delay produced by portion A of the specimen can be calculated.

A number of metals and alloys have been tested with this equipment in the range 20 - 500°C and the results for one of them, Nimonic 90, are shown in Table 2.

References.

1.	Bradburn	- Elect. Comm. 28. 46. 1951.
2.	Epstein & Stram	- I.R.E. Trans. on Ultrasonic Eng. 5.1.57.
3.	Bordoni & Nuovo	- Nuovo Cimento. 11. 127. 1954
4.	Bell	- Phil. Mag. 2 No. 21. 1113. 1957.
5.	Purcey & Pyatt	- Jou. Scie. Insts. 31. 248. 1954.

Acknowledgements.

The author wishes to thank R.O.Harlow for his great help in the construction of the delay line. Mr. Harlow was also entirely responsible for the mechanical design of the traversing mechanism.

TABLE I

Micrometer Reading in inches	Frequency F in Kilocycles	Delay Time D in Microseconds
1.731	7.020	142.45
1.646	7.000	142.86
1.570	6.980	143.27
1.492	6.960	143.68
1.409	6.940	144.09
1.328	6.920	144.51
1.245	6.900	144.93
1.164	6.880	145.35
1.083	6.860	145.77
.998	6.840	146.20
.911	6.820	146.63
.828	6.800	147.06

Calibration of standard line taken at 18.5°C
(i.e. uncorrected for the standard temperature of 20°C).

TABLE II

Temperature T°C	$\dfrac{\text{Youngs Modulus at Temperature T}^\circ\text{C}}{\text{Youngs Modulus at }20^\circ\text{C}}$
20	1.000
60	.992
120	.978
220	.951
320	.922
420	.894

The results in the second column have been corrected for change in delay produced by change in length with temperature.

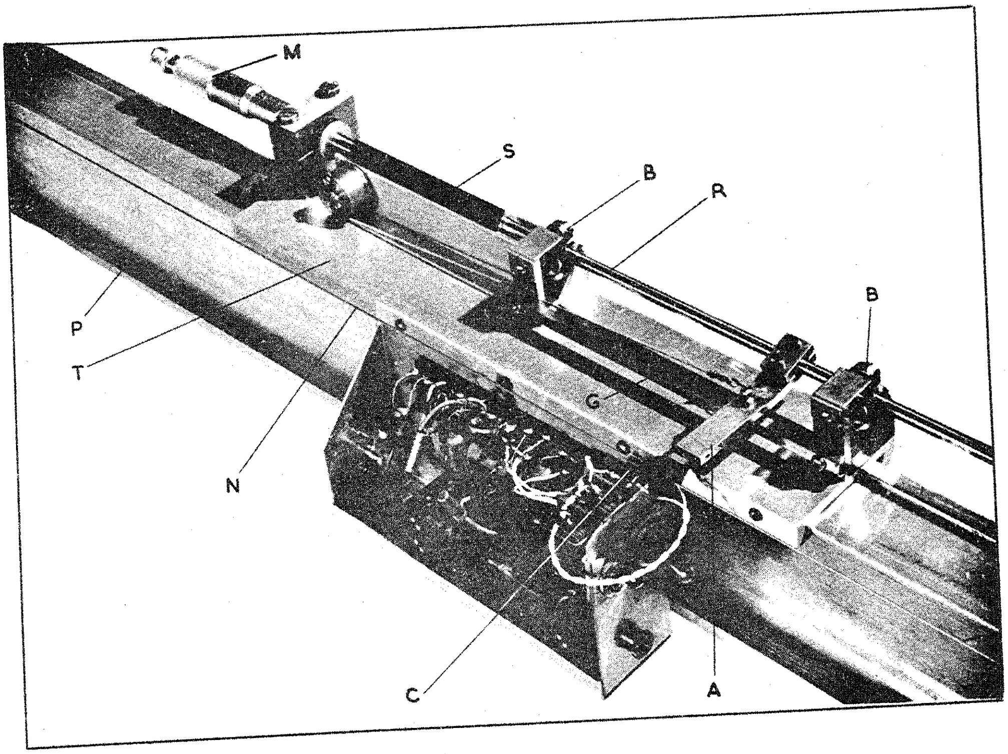


FIG. 1 THE VARIABLE DELAY LINE (a)

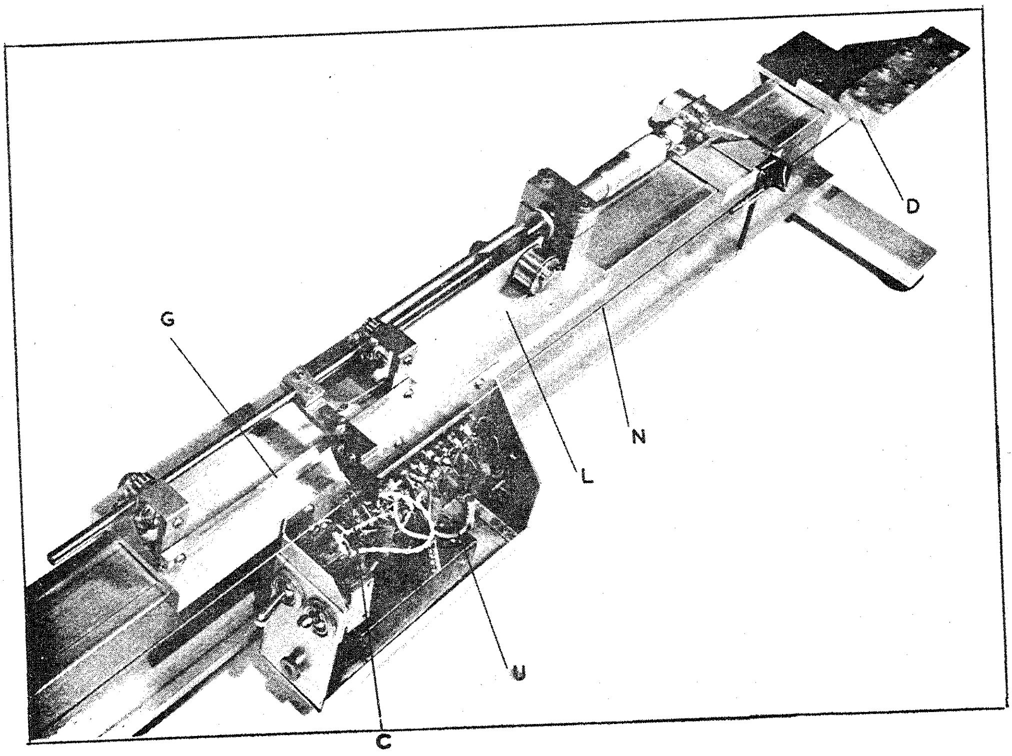


FIG. 2 THE VARIABLE DELAY LINE (b)

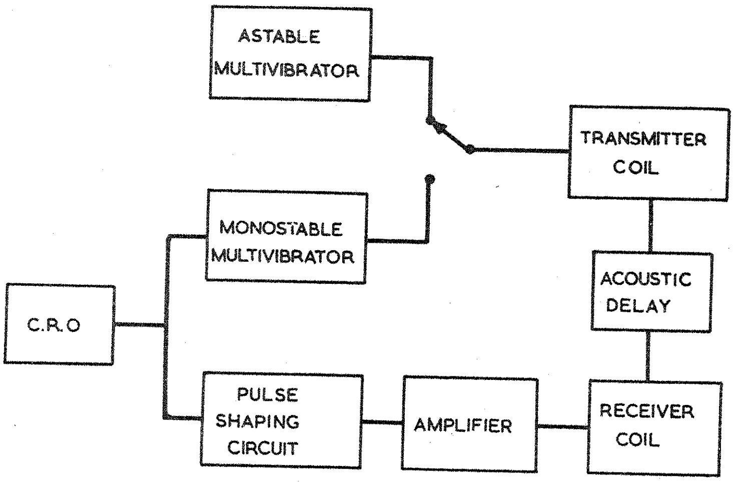


FIG. 3 BLOCK DIAGRAM OF THE CIRCUIT USED TO CALIBRATE THE REFERENCE DELAY LINE.

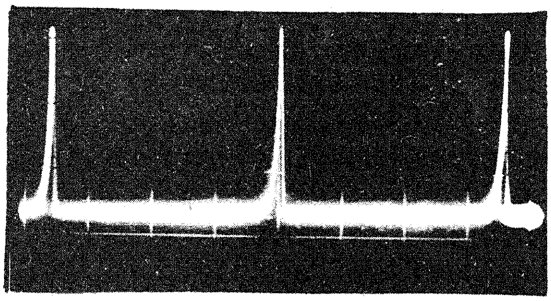


FIG. 4 C.R.O. PHOTOGRAPH OF OUTPUT OF THE CIRCUIT SHOWN IN FIG. 3

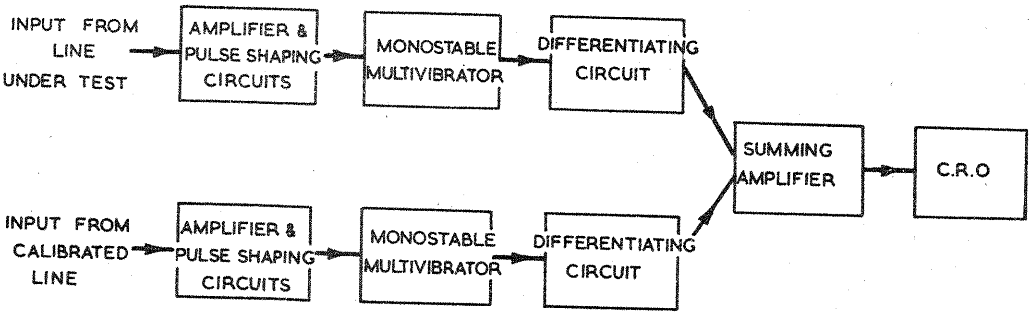
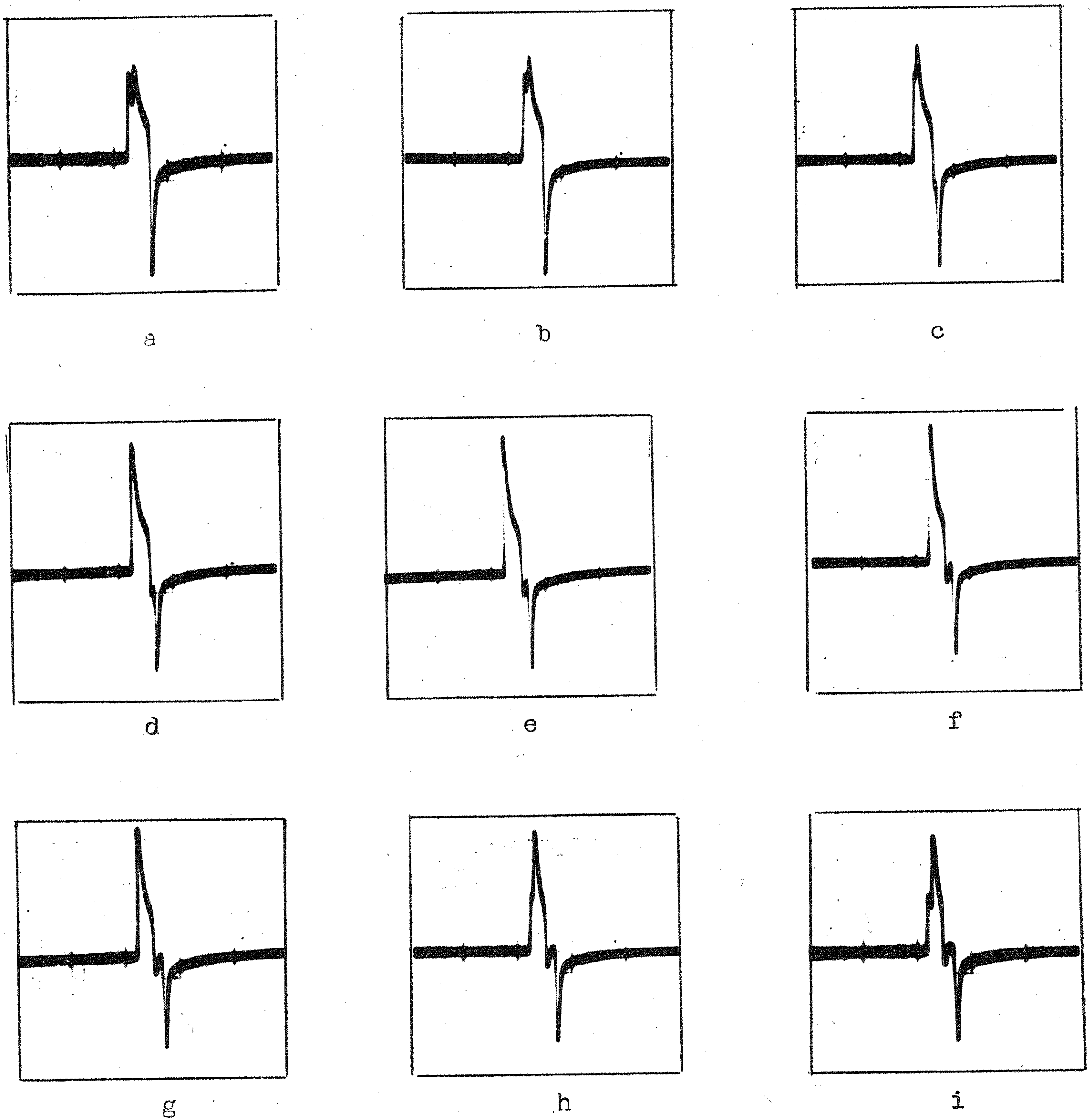


FIG. 5 BLOCK DIAGRAM OF THE CIRCUIT USED TO COMPARE THE DELAYS IN THE REFERENCE LINE AND THE LINE UNDER TEST.



a b c d e f g h i

FIG. 6 C.R.O. PHOTOGRAPHS OF THE OUTPUT OF THE CIRCUIT SHOWN IN FIG. 5 AS THE DELAY IN THE REFERENCE LINE IS VARIED.

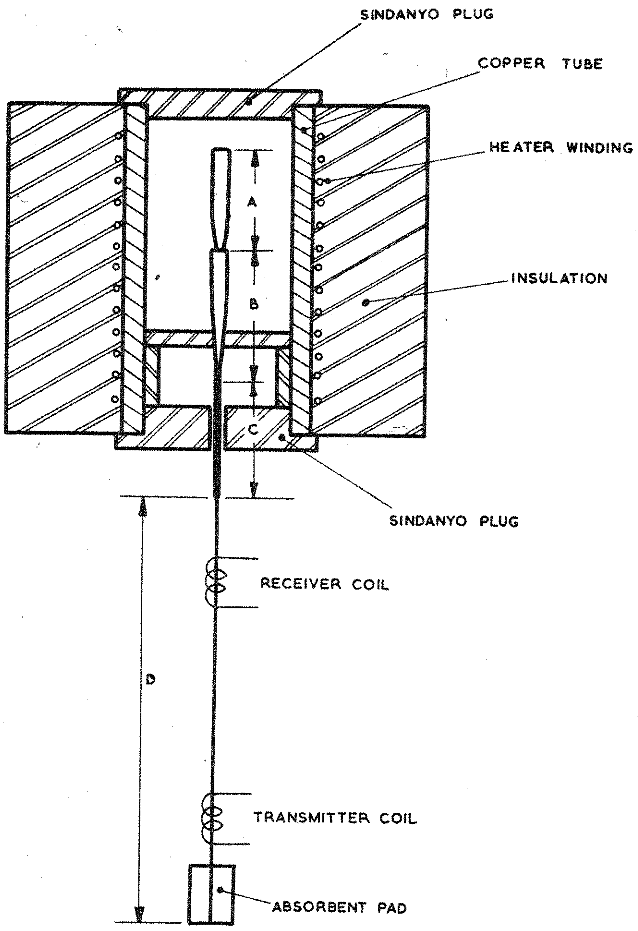


FIG. 7 THE TEST LINE IN THE FURNACE

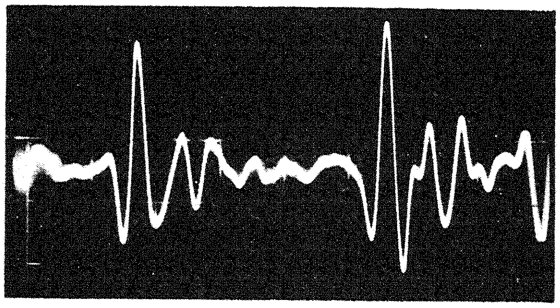


FIG. 8 C.R.O. PHOTOGRAPH OF THE OUTPUT OF THE
TEST LINE AMPLIFIER SHOWING TWO LARGE ECHOES.