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A 2·5ms delay unit suitable for use in a television field delay

TECHNOLOGICAL REPORT No. T-171

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SUMMARY

This report describes the design and construction of a 2·5 ms delay unit which has been developed as part of a field delay for television applications. A brief description of the ultrasonic delay-line used is given, together with a detailed description of the input and output amplifiers and the ancillary circuits necessary to achieve an overall gain of unity and a delay stability of the order of ± 2 ns. The design of a suitable network for the equalization of the response/frequency characteristic of the delay-line is also described.

1. INTRODUCTION

In the past ultrasonic delay-lines using mercury or fused-quartz as the transmission medium have been used to delay television signals by one or two television scanning line periods.[1,2,3,4] There are other applications in television engineering, however, which require signals to be delayed by periods of one or two television fields[5] (i.e., by periods of 20 ms and 40 ms for 50-field systems, and by periods of 16.2/3 ms and 33.1/3 ms for 60-field systems). The technology of ultrasonic delay-lines is not yet sufficiently advanced for single delay-lines having delays of this order to be produced with a performance adequate for television purposes. The maximum delay which can be achieved in a single delay-line with an adequate performance is approximately 3 ms to 4 ms and for this magnitude of delay the adequacy of the performance is, at the present time, marginal. One high quality delay-line which is available and which has a performance that permits the cascading of a number of units to form a field-period delay is the "2·5 ms delay-line Type YL2104/09" developed by the Mullard Research Laboratories and manufactured by the M.E.L. Equipment Co. Ltd. This report describes the design and construction of a 2·5 ms delay unit based on this delay-line and it was intended to use eight of these units in cascade to produce a 20 ms delay suitable for television applications.

2. THE 2·5 ms FUSED-QUARTZ ULTRASONIC DELAY-LINE TYPE YL2104/09

The principles of design and operation of fused-quartz ultrasonic delay-lines are well documented.[6,7,8,9] The 2·5 ms delay-line Type YL2104/09, which is shown in Figs. 1 and 2 is a "double-decker" line with a delay of 1·25 ms provided by each deck; the ultrasonic signal is transferred from one deck to the other by means of a corner reflector. The transmission-path length for a delay of 1·25 ms is in the region of 5 m and in order to contain this in a fused-quartz block of reasonable dimensions, a folded transmission path is used. The fused-quartz block is ground into a fifteen-sided irregular polygon in which the signal is made to undergo 31 reflexions in each deck as shown in Fig. 2. In order to obtain a good compromise between insertion loss and ultrasonic bandwidth, the delay-line uses unbacked Y-cut quartz-crystal transducers which operate in the

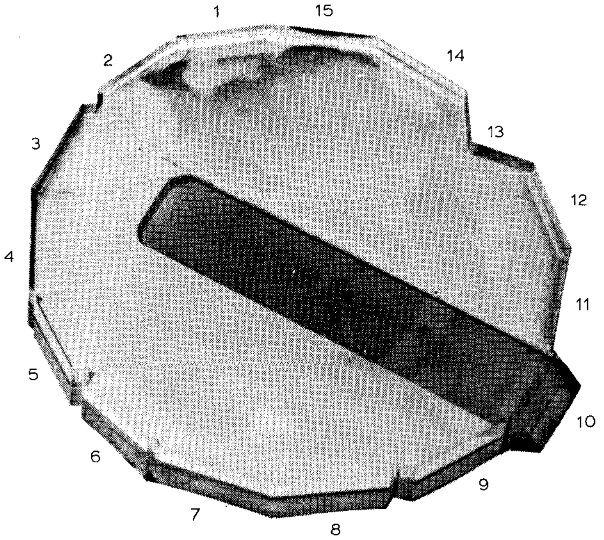
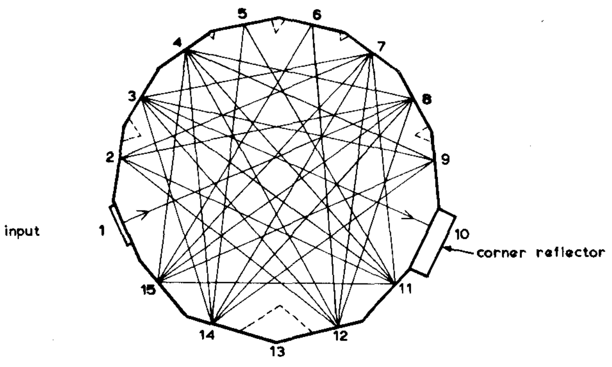


Fig. 1 - The 2·5 ms ultrasonic fused quartz delay-line Type YL2104/09



The signal transmission path.

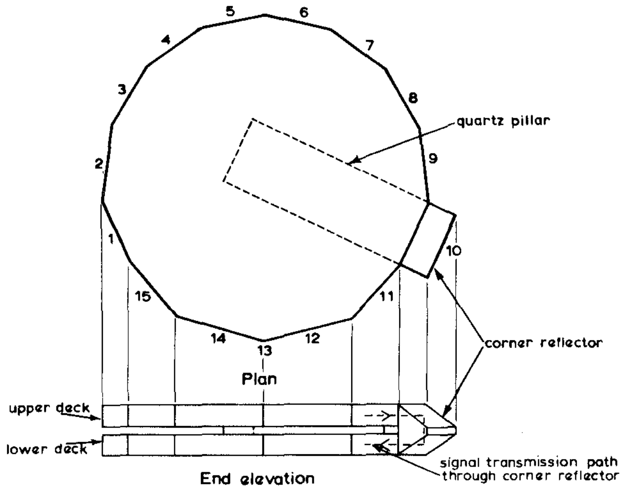


Fig. 2 - The signal transmission path and geometry of the 2·5 ms delay-line Type YL2104/09

transverse mode and have a capacitance of approximately 200 pF. Unwanted secondary responses of the delay-line are kept to a minimum by the removal of sections of the fused-quartz block which are not traversed by the wanted signal but which might be traversed by the unwanted signals and also by placing ultrasonic absorbing material on the edges of the block where necessary. Cross-talk between the two decks is avoided by cutting away as much material as possible between them. The details of the performance required from the delay-lines are given in Table 1 and the response/frequency characteristics of the eight delay-lines intended to be used as a field delay, as measured at their specified operating temperature, are given in Fig. 3.

3. THE DESIGN AND CONSTRUCTION OF A 2·5 ms DELAY UNIT

The component parts necessary for the construction of a 2·5 ms delay unit using an ultrasonic delay-line are shown in Fig. 4. The delay-line is mounted in a thermally-insulated container so that it may be conveniently maintained at its specified operating temperature, and a servo-control system is provided to keep the operating temperature constant to within the required tolerance limits. The input and output amplifiers are necessary in order to compensate for the insertion loss of the delay-line and the equalizing network is required to equalize the ultrasonic response/frequency characteristic over as wide a frequency range as possible. The design of the amplifiers and the equalizing network must be directed towards obtaining as large a signal as possible (consistent with adequate linearity) across the input transducer so that the noise factor of the unit is as low as possible.

3.1. The Temperature Control of the 2·5 ms Delay Unit

The stability of the delay provided by each 2·5 ms delay unit of the eight such units required to provide a field-period delay is approximately ± 2 ns and, in order to achieve this accuracy, the operating temperature must be maintained within

TABLE 1

*Specification of the M.E.L. 2·5 ms Delay-Line Type YL2104/09**

Delay	2,485 μs
Tolerance on delay	+0, -3·5 μs
Band centre frequency	30 MHz
Ultrasonic bandwidth**	10 MHz between -6 dB points
Secondary responses	<1% with respect to the wanted signal
Insertion loss at 30 MHz	<40 dB using 75 Ω terminations
Operating temperature	343°K
Temperature coefficient of delay	75 × 10^{-6}/°K (approximately)
Transducer capacity	200 pF ± 10%

* These delay-lines use a delay medium prepared from naturally occurring quartz. Recent developments in the preparation of synthetic fused-quartz have made possible the production of delay-lines with performance characteristics better than those given in Table 1.

** The ultrasonic bandwidth includes the effects of all bandwidth limitations in the transducers and fused-quartz transmission medium but neglects limitations of bandwidth occurring in the electrical circuits associated with the delay-line. Factors controlling the ultrasonic bandwidth include the mechanical resonance of the input and output transducers, the variation with frequency of the directivity of the transducers and the variation with frequency of the attenuation of the fused-quartz transmission medium.

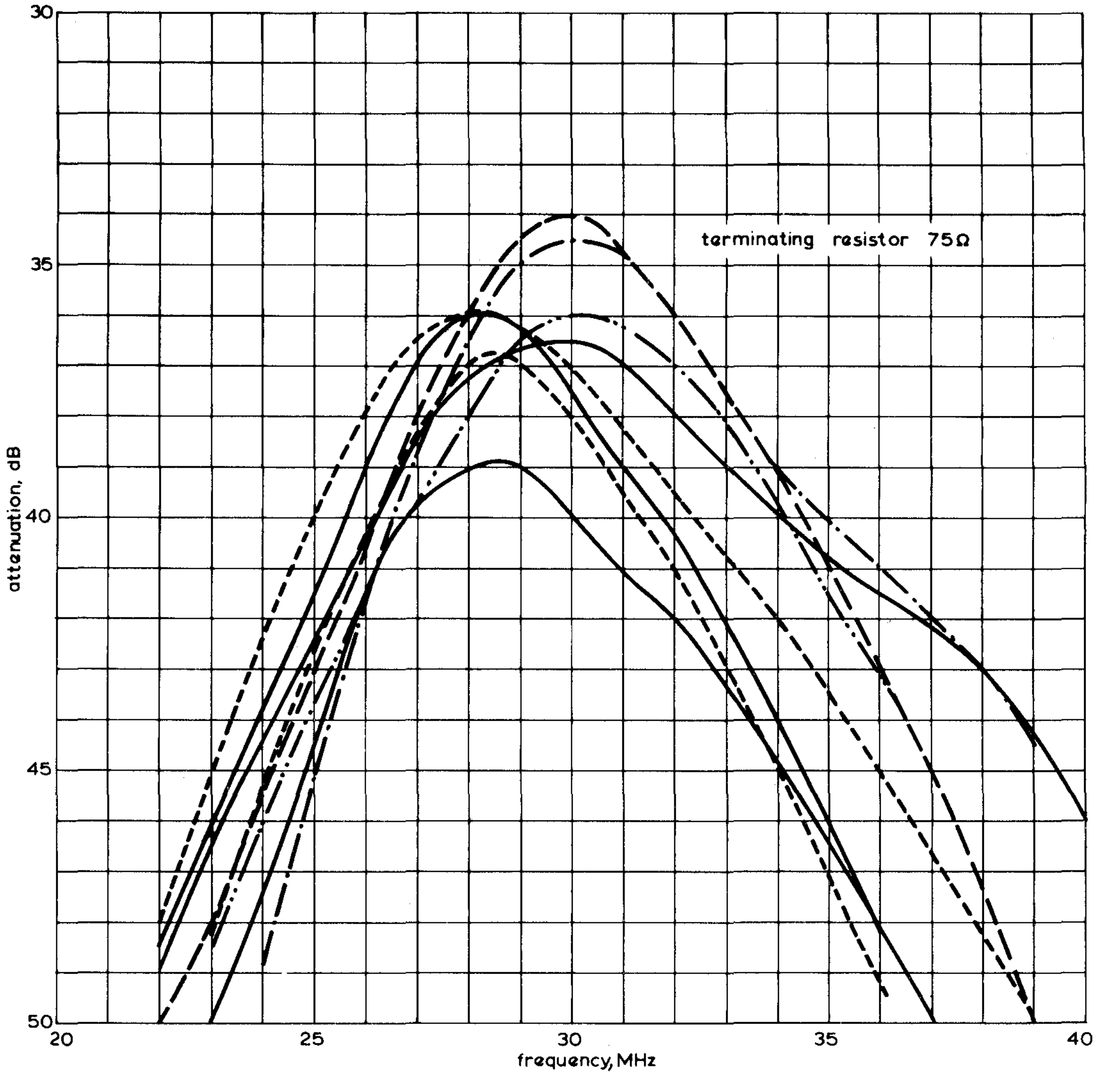


Fig. 3 - The response/frequency characteristics of the eight 2·5 ms delay-lines

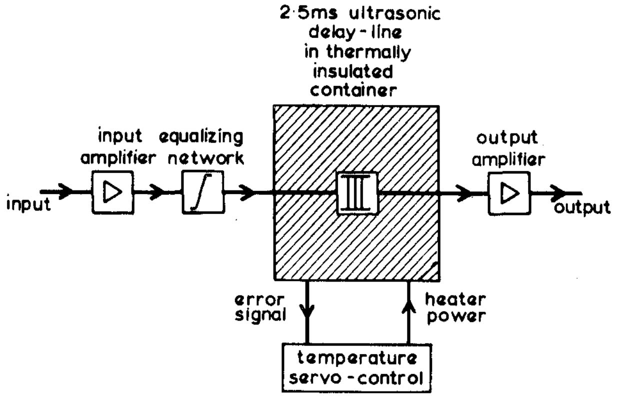


Fig. 4 - The block diagram of the 2·5 ms delay unit

± 0·01°K of the nominal value.[10] The design of a constant-temperature enclosure with this degree of precision has been described previously[11] and is illustrated in Fig. 5.

3.2. The Design of the Equalizing Network

The network required to equalize the ultrasonic response/frequency characteristic of the delay-line may be placed at any point in the circuit of the unit, but it has been found that the most convenient position is between the input amplifier and the delay-line.[1] The characteristics of the eight delays to be used in the field delay, which are shown in Fig. 3, are to some extent dissimilar. In order to avoid designing eight separate equalizers, it was decided to employ a common design based upon the average characteristic of the eight delay-lines; this is shown in Fig. 6(*a*), and to adjust each equalizer individually so as to obtain the best overall response.

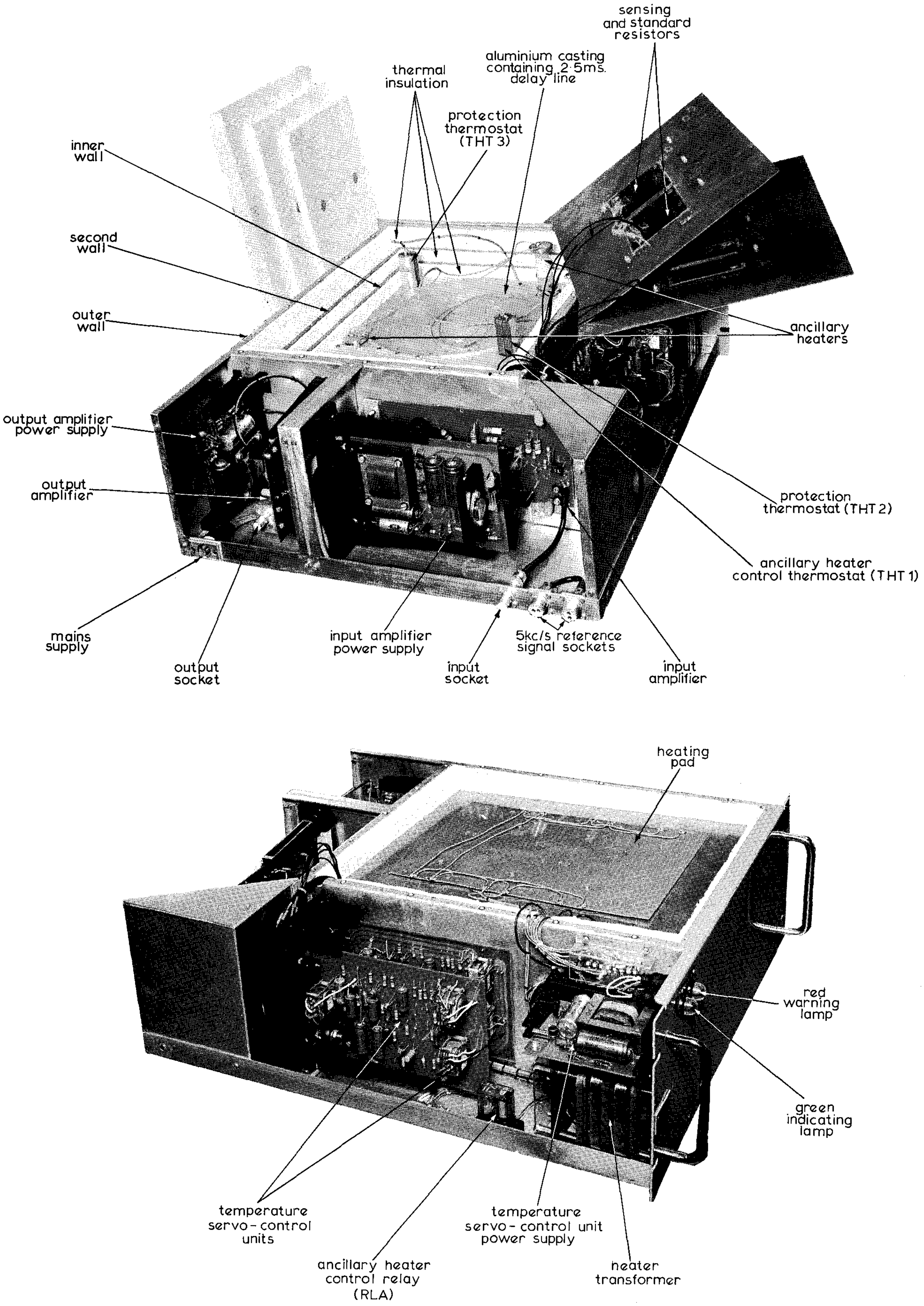


Fig. 5 - The 2·5 ms delay unit

In order to calculate the equalizing network for the delay-line, it is convenient to transform the band-pass characteristic shown in Fig. 6(*a*) into the equivalent low-pass characteristic shown in Fig. 6(*b*). An inspection of the average characteristic given in Fig. 6(*a*) shows that it is very similar to that of a pair of cascaded tuned circuits which have the same resonance frequency (29 MHz) and

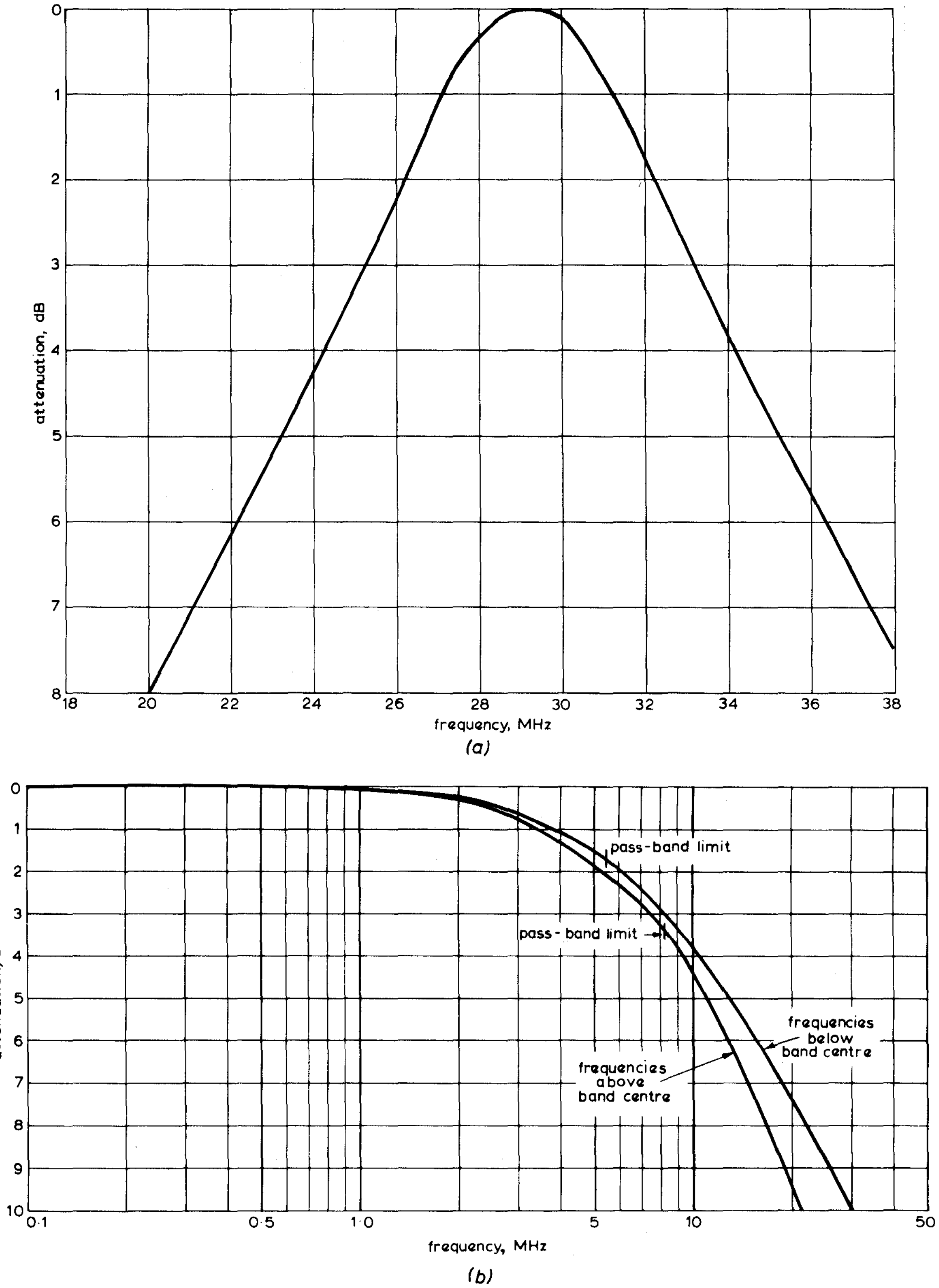


Fig. 6 - The average response/frequency characteristic of the eight delay-lines and the equivalent low-pass characteristic

(*a*) the average response/frequency characteristic (*b*) the equivalent low-pass characteristic the same bandwidth.* In this case the expression for the equivalent low-pass characteristic $|A(f)|$ must be of the form:

$$|A(f)| = \frac{1}{1 + (af/10)^2} \qquad (1)$$

where f is the frequency in MHz and the frequency at which the response of the equivalent low-pass characteristic has fallen by 6 dB gives $a = 0{\cdot}8$. The equalization of the low-pass characteristic may be investigated by multiplying Equation (1) by a characteristic which has the same form as the modulus of the transfer function of a suitable equalizing network. The input impedance of the transducer is purely capacitive and, therefore, the equalizing network must include this capacity; Fig. 7 shows the circuit diagram of a low-pass network which will be shown to be suitable for this purpose. The modulus of the transfer function of this network $|B(f)|$ is of the form:

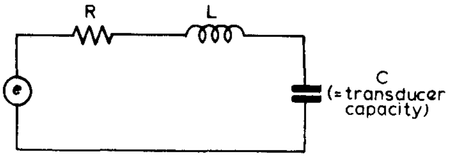


Fig. 7 - The equivalent low-pass equalizing network

$$|B(f)| = \frac{1}{[1 - (b_1f/10)^2 + (b_2f/10)^4]^{½}} \qquad (2)$$

The expression for the equalized response, $|E(f)|$, is therefore:

$$|E(f)| = |A(f)| \times |B(f)|$$

$$= \frac{1}{[1 + (2a^2 - b_1)(f/10)^2 + (a^4 - 2a^2b_1^2 + b_2^4)(f/10)^4 + (2a^2b_2^4 - a^4b_1^2)(f/10)^6 + a^4b_2^4(f/10)^8]^{½}} \qquad (3)$$

In order to achieve a flat response/frequency characteristic in the required passband, investigation shows that Equation (3) should have a characteristic which is a close approximation to the Chebychev type given by:

$$|C(f)| = \frac{1}{[1 + 18K(f/10)^2 - 48K(f/10)^4 + 32K(f/10)^6]^{½}} \qquad (4)$$

where $2K$ is the peak to peak magnitude of the permissible ripple.

The coefficients of the denominator of the transfer function of the equalizing network given in Expression (2) and the magnitudes of the ripples of the equalized characteristic may be determined by equating the first three coefficients of the denominator of the right-hand side of Equation (3) with those of the denominator of the right-hand side of Equation (4) and substituting a value of $a = 0{\cdot}8$. The magnitude of the ripple can be shown to be approximately ± 0·1 dB and the characteristic of the equalizing network to be:

$$|B(f)| = \frac{1}{[1 - 1{\cdot}118\,(f/10)^2 + 0{\cdot}619\,(f/10)^4]^{½}} \qquad (5)$$

By comparing Equation (5) with the modulus of the transfer function of the circuit shown in Fig. 7, equations may be derived from which the circuit component values of the network can be obtained in terms of the transducer capacitance (200 pF). The low-pass network so obtained can then be transformed into the band-pass network shown in Fig. 8. The attenuation/frequency characteristic for this network is given in Fig. 9 together with the average characteristic of the delay-lines and the average equalized characteristic. It can be seen that the latter characteristic is substantially flat over a bandwidth of 8 MHz; however, because the characteristics of the delay-lines are somewhat dissimilar, the equalized characteristics of the units as obtained in practice will differ slightly from that shown.

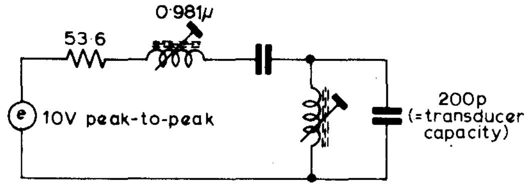


Fig. 8 - The bandpass equalizing network

In order to place the equalizing network as closely as possible to the input transducer, the reactive components are assembled on a printed circuit board which is mounted in a screened compartment in the aluminium casting alongside the

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* This fact was first pointed out by C.F. Brockelsby, formerly of Mullard Research Laboratories who had also calculated a similar equalizing network independently.

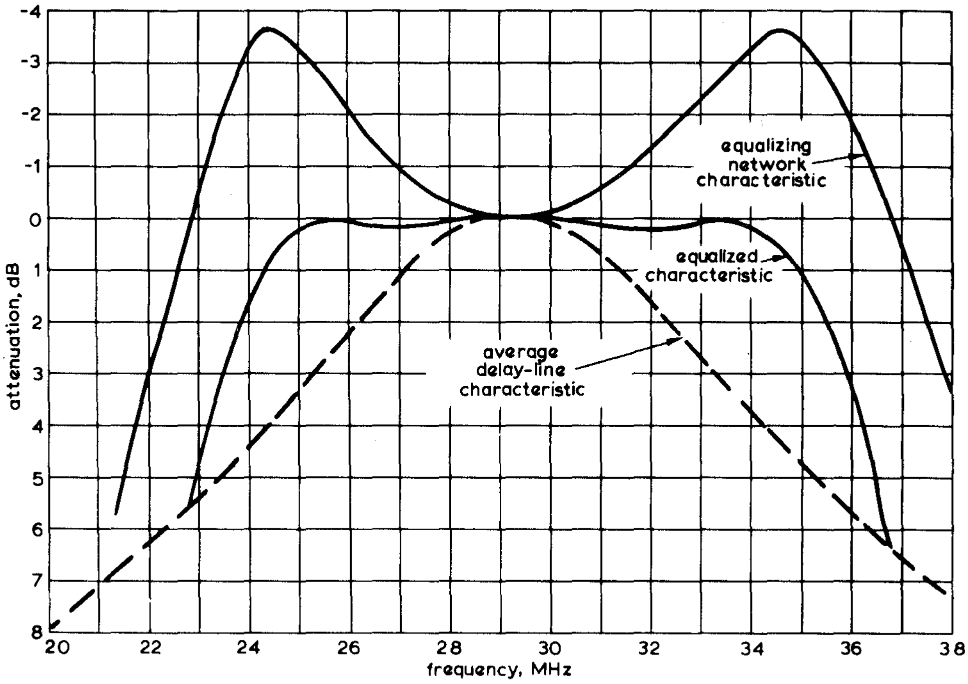

Fig. 9 - The response/frequency characteristics of the equalizing network and the equalized response

transducer.* The input amplifier is designed to have an output impedance which provides the correct resistive component of the network.

3.3. The Input Amplifier

The input amplifier has a gain of 20 dB in order to raise the level of the input signal from 1 V peak-to-peak to 10 V peak-to-peak. Because a transistor amplifier has an output impedance high compared with that required by the equalizing network, it is convenient to modify the equalizing network so as to be suitable for use with a constant-current source. The circuit of the modified equalizing network is shown in Fig. 10 and it can be seen that the amplitude of the current required is approximately 200 mA peak-to-peak. A circuit diagram of the complete amplifier (and equalizing network) is given in Fig. 11.

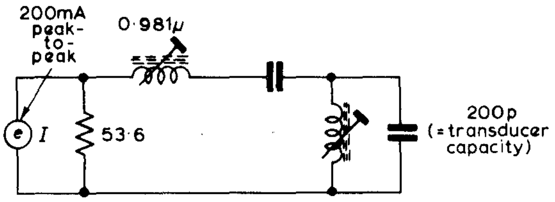

Fig. 10 - The bandpass equalizing network modified to suit a constant current source

The input signal is passed through a 75 Ω attenuating network, which is used to adjust the overall gain of the delay unit to be exactly unity. The attenuator is terminated by the 300 Ω resistor (R2) across the secondary of the transformer (T1) which has a turns ratio of 1 : 2. The first stage of the amplifier (TR1) uses a grounded-emitter configuration in which some current feedback is provided by means of a resistor (R5) in the emitter circuit. The coupling circuit between the collector of the first stage and the input of the push-pull second stage (TR2 and TR3) is, in effect, a tightly-coupled tuned transformer with a centre-tapped secondary; in practice, the construction of such a transformer, with an accurately balanced secondary and the minimum of effective stray capacity between the windings, is quite critical and for this reason a transformer (T2) wound on a small ferrite core is used together with a tuning inductor (L1) across its primary.* The turns ratio of the coupling transformer was determined by the maximum voltage-swing at the collector of the first stage obtainable without significant non-linear distortion. This method of design was found to give a more than adequate bandwidth in this particular case. The transistors in the push-pull second stage are used in the grounded-base configuration. When driven from a high impedance source as compared with the input resistance of the transistor the linearity

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* These networks were in fact constructed and pre-aligned by the Mullard Research Laboratories so as to equalize the characteristic given in Fig. 9.

* This technique has the additional advantage of making the amplifier more flexible with regard to changing the gain, centre frequency or bandwidth for use with other delay-lines.

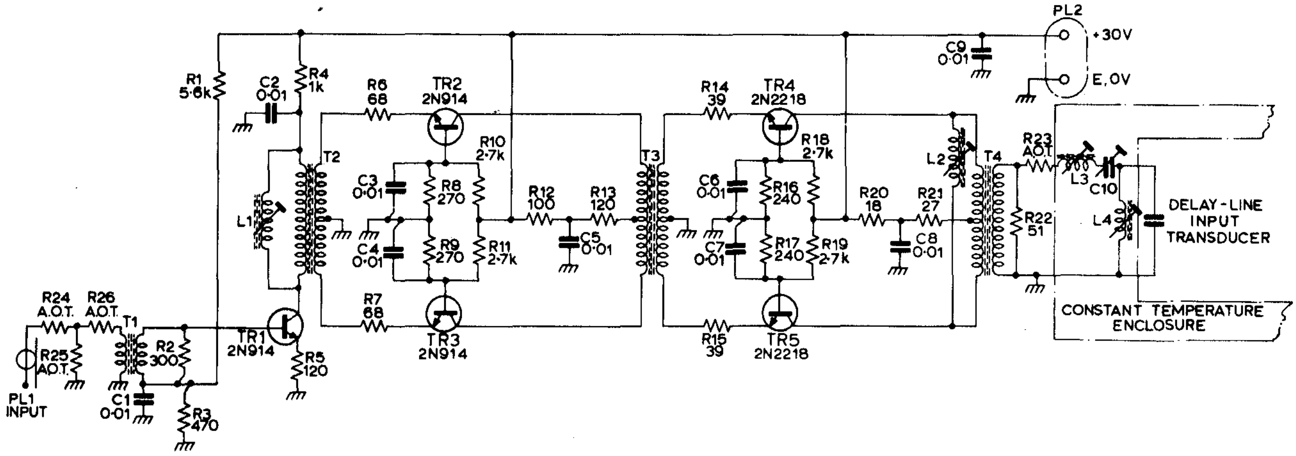

Fig. 11 - The input amplifier and equalizing network circuit diagram

of this type of circuit is excellent; in practice, because the input resistance of each transistor is very low (10 Ω to 20 Ω), small resistors are placed in series with the emitters in order to make the circuit less dependent upon the transistor parameters.

The reactive component of the input impedance of the grounded-base amplifier used is inductive and therefore does not narrow the bandwidth of the amplifier. The internal feedback of the transistor is less troublesome than with a grounded-emitter stage which eases the practical construction and alignment of the amplifier. The output current of each transistor differs from the input current only by that current which flows through the base connection; therefore, the voltage gain of the amplifier is principally decided by the coupling-transformer ratios.

The output of the second stage is coupled to the input of the push-pull final stage (TR4 and TR5) by means of another tightly-coupled transformer (T3) wound on a ferrite core; again the turns ratio of the transformer was decided by the maximum permissible voltage swing at the collectors of the second stage. In this case, however, the effective damping of the circuit proved to be so low that it was unnecessary to tune the coupling transformer in order to obtain a good bandwidth characteristic. It was found empirically that the performance of the circuit could be improved by placing a resistor (R13) in series with the centre-tap of the primary winding of the coupling transformer. This, in effect, reduced the signal current flowing in the centre-tap because of unbalance and caused the electrical centre-tap to be different from the physical centre-tap so far as the signal was concerned.

The principles of design of the final stage (TR4 and TR5) follow the design principles of the second stage, but use transistors capable of a greater dissipation. The output transformer (T4) is again a transformer wound on a ferrite core but has an unbalanced secondary winding; in this case a tuning inductor (L4) across the primary was found to be necessary. The terminating resistance (R22) of the amplifier was made a little less than that required for the equalizing network so that a small series resistor (R23) could be included in order to make small adjustments to the circuit.

The amplifier was constructed on a printed-circuit board which was carefully designed to keep the signal paths as short as possible and to preserve the symmetry of the circuit. All the transistors except TR1 were fitted with appropriate heat-sinks and, in the case of the output transistors where the heat-sinks were mounted on the printed-circuit, the copper was etched from beneath them so as to preserve the low stray-capacity of that stage. It has been found, so far, that with the types of transistor used in the push-pull stages it is not necessary to select matched pairs. In the design of the amplifier it was thought that the fact that the output transformer was tuned would not have an appreciable effect on the performance of the equalizing network because of its relatively low impedance. In practice it was found that adjusting the tuning of the output transformer had some effect in that, over a small range of adjustment, it modified symmetrically the degree of peaking in the equalizer response; it could therefore be used as a fine adjustment of the degree of equalization.

3.4. The Output Amplifier

The output signal obtained from an ultrasonic delay-line with quartz crystal transducers may be regarded as a constant current from a high impedance source with a capacitance equal to the transducer capacitance across the output terminals.

The insertion loss of the delay-line is defined as the ratio of the voltage which this current would develop across a specified terminating impedance to the voltage applied across the input transducer;[9] in the case of the 2·5 ms delay-line in question, therefore, the output current for a 10 V peak-to-peak input signal would be approximately 1·33 mA peak-to-peak. Thus the equivalent circuit of the output of the delay can be represented as shown in Fig. 12.

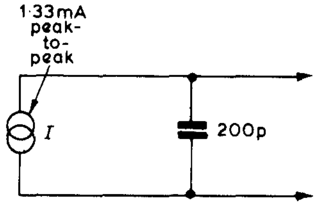

Fig. 12 - The equivalent circuit of the delay-line output

With a current of the order of 1 mA peak-to-peak a good signal-to-noise ratio can easily be obtained provided that all the current is used effectively. As the output is of interest only over a certain band of frequencies, the transducer capacitance can be tuned by means of a shunt inductor, and an optimum value of shunt resistance chosen to damp the circuit. If the input resistance of the amplifier were lower than the optimum, a useful current gain could be obtained by means of a transformer; in this case, however, the input resistance of a transistor in the grounded base configuration has approximately the optimum value.

The circuit diagram of the output amplifier is shown in Fig. 13. It consists of three grounded-base stages in cascade which are connected by tightly-coupled tuned transformers. The transformers in the collector circuits of the first and second stages (TR1 and TR2) comprise a stagger-tuned pair. The primary inductances of the transformers are designed to resonate at the stagger-tuning frequencies and the turns ratios of the transformers are chosen to transform the input resistance of the following stage to the required damping resistance across the tuned circuit; in the design of this type of amplifier some allowance must be made for the internal feedback of the transistor. The output stage of the amplifier (TR3) is designed to provide a 75 Ω output impedance over the whole of the passband. The output obtained from the amplifier for a 1 mA peak-to-peak input is 1 V peak-to-peak across 75 Ω. The amplifier was constructed on a printed-circuit board carefully designed to keep the signal paths as short as possible and small adjustable capacitors (C3 and C6) were provided across the collector circuits of TR1 and TR2 in order to compensate for variations in transistor capacitance.

3.5. The General Form of Construction

The general form of construction of the delay unit can be seen in Fig. 5. The internal construction of the constant-temperature enclosure which comprises the main part of the assembly has been described in Reference 11; the printed circuit boards bearing the temperature servo-control circuits, and the heater transformer, can be seen mounted to the side of the constant temperature enclosure. The input and output amplifiers are at the rear of the unit, mounted in separate screened compartments in order to avoid direct crosstalk between the two, and are positioned so as to provide the shortest possible connections to the transducer circuits inside the enclosure. Small separate regulated power supplies[12] are used for the amplifiers in order to avoid the possibility of crosstalk via common power supply leads.

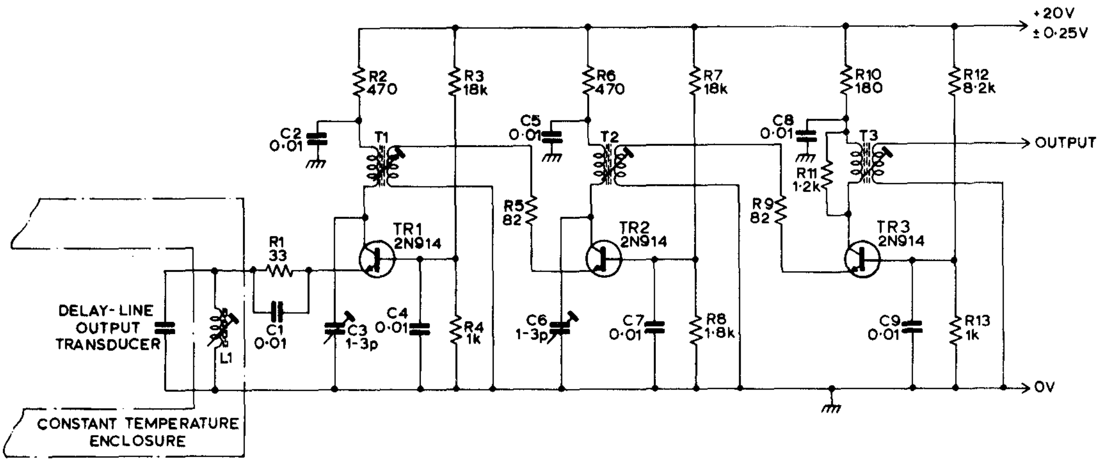

Fig. 13 - The output amplifier circuit diagram

4. PERFORMANCE

Because the delay units are intended to be used together as a field delay, precise measurements on individual units have not been made. Measurements have been made of the delay stability and these show that the heating and servo-control systems are satisfactory.[11] Test measurements have shown that the insertion losses of the delay-lines have a spread of 5 dB, each unit should therefore have an overall gain lying between 0 dB and +5 dB; as mentioned in Section 3.3, the gain of the input amplifiers can be adjusted so as to make the overall gain equal to unity. Tests carried out on the feasibility of producing satisfactory overall response/frequency characteristics using the equalizing networks have shown the latter to be adequate. The measured signal-to-noise ratio of the prototype unit is greater than 60 dB. Experiments have been carried out in which television pictures and waveforms have been recirculated through one unit eight times, thus providing a 20 ms delay; the results indicate that the performance of a unit is satisfactory for use as part of a television field delay.

5. CONCLUSIONS

A 2·5 ms delay unit has been described which has a performance enabling eight such units to be cascaded so as to provide a delay of 20 ms.

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