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NON-DESTRUCTIVE INSPECTION

AND VOLUME FRACTION

DETERMINATION OF CFRP USING AN

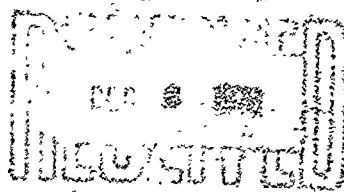
EDDY CURRENT METHOD

by

P. F. Dingwall

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NON-DESTRUCTIVE INSPECTION AND VOLUME FRACTION DETERMINATION OF
CFRP USING AN EDDY CURRENT METHOD.

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SUMMARY

The Report describes work on the non-destructive inspection of carbon fibre reinforced plastic (CFRP) laminates using an eddy current technique. Attention is drawn to the use of the technique for estimating the volume fraction of a laminate, including local variations in volume fraction, but it is shown that at present there are difficulties in the application of the technique as a routine NDT method for cross ply material.



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1 INTRODUCTION

The principles used in this work were originally suggested by work carried out under MOD Contract by C.N. Owston and R. Prakash at the Department of Materials of the Cranfield Institute of Technology¹. If a probe consisting of a coil wound on a ferrite core is used to form the inductance in the tank circuit of an oscillator and the probe is brought near a conducting material, then eddy currents are induced in the latter by the magnetic field from the former. The field produced by such eddy currents opposes the field due to the coil and reduces its effective reactance, thus changing the frequency of the oscillator. A resistive loss is also introduced. The frequency change in the oscillator can be converted to a voltage by a suitable discriminator and amplified. Thus a system is produced which varies its output voltage in response to variations in the magnitude and nature of the eddy currents induced in the material. Such a system can therefore be used to investigate those properties of the material which affect the eddy current path or its magnitude, and in the work described in this Report is used to examine non-destructively both unidirectional and cross ply carbon fibre reinforced plastics (CFRP).

2 INSTRUMENTATION

The instrumentation consists of a probe forming the inductance of an attached oscillator circuit which is connected to a discriminator and dc amplifier. The system works at approximately 10-12MHz.

2.1 Circuits

The oscillator circuit is shown in Fig.1. It is a simple Colpitts oscillator with a grounded base, the tank circuit in the collector being driven by feedback from the emitter. Some care is required in the choice of the capacity ratio to obtain stable operation with a reasonably good waveform, although a pure sinusoidal waveform is not essential for the purpose. A single stage amplifier is used, preceded and followed by emitter-follower buffer stages; the output from the second emitter-follower being about 4V peak-peak.

In order to avoid the complications of a Foster-Seeley discriminator or ratio detector with their necessary inductance, a pulse-counting discriminator is used. This type of discriminator generates a pulse of uniform height and width for each positive-going cross over of the input signal. The result is a constant amplitude train of rectangular pulses whose mark-space ratio varies with the incoming frequency. The average value of this train is therefore also proportional

to frequency. Thus after filtering out the carrier frequency components a steady state voltage is left which is proportional to the incoming frequency. The circuit has two disadvantages; firstly it is very inefficient and the output requires dc amplification; secondly the maximum frequency which can be handled depends on the shortest pulse which the circuit can generate and this is the limiting factor in the design. The pulse width must be such that at the highest anticipated incoming frequency the mark-space ratio of the output is not worse than about 1:1. Above this the pulse width varies with the mark-space ratio and non-linearity results. The circuit has the advantage that it can be constructed from a simple integrated circuit monostable. The shortest pulse which can be generated by the SN 74121 used in this circuit is 20-50ns which for the upper figure limits its use to 10MHz or less. The circuit of the discriminator and subsequent dc amplifier which has a gain of $\times 500$ is shown in Fig.2. It may be seen from this figure that the input is ac-coupled and then clamped at the negative peaks by a diode, in order to drive the monostable from a fixed datum. The output is filtered by a simple RC filter. The time constant of this filter must be sufficiently long to eliminate all carrier frequency components, yet sufficiently short to allow the output to follow the fastest change which will be encountered in practice, e.g. when scanning a crack in CFRP. The time constant of this filter is in fact 0.1ms so that the response is 3dB down at about 1500Hz. In common with all discriminators this circuit gives an output at the centre frequency (corresponding to the probe being in air), which in this case is large compared to the variable output caused by the presence of the CFRP. This output has to be backed-off by a negative voltage. In order to reduce drift as far as possible this voltage is supplied by a separate stabiliser in addition to the stabilisation on the main power rails. The stabiliser is of conventional design and is shown in Fig.3. It has coarse and fine controls and uses a 5.3 volt zener diode in conjunction with a balanced pair of transistor amplifiers in order to reduce temperature drift.

Finally, the output of the dc amplifier is buffered by a balanced emitter-follower shown in Fig.4 to provide an increased output current. This circuit gives zero volts out for zero volts in and the offsets due to the base-emitter voltage V_{be} of the transistors are cancelled by operating PNP transistors and NPN transistors in complementary pairs.

2.2 Probes and mechanical rigs

Two types of probe have been used with the equipment. In both cases the probe forms the inductance in the tank circuit of an oscillator working at

10-12MHz. The first type of probe is non-directional and consists of a simple linear winding on a cylindrical slug of ferrite. The distribution of the magnetic field and the resulting eddy currents are shown in Fig.6. The probe itself consists of $7\frac{1}{2}$ turns of 26 swg wire on a 5mm diameter ferrite slug. The coil has an inductance of about $4\mu\text{H}$ at 1kHz and about $3.3\mu\text{H}$ at 10MHz. The resulting coil is embedded in a cylinder of Perspex using Perspex cement so that the ferrite slug has its end flush with the cylinder. The whole cylinder is then spring loaded inside a further Perspex cylinder to ensure that the probe remains in contact with the surface of a CFRP panel whilst being scanned across it.

For convenience the Perspex casing is mounted on a Tufnol arm attached to the scanning system of an ultrasonic tank; a Tufnol plank across the tank supports the specimen to be scanned.

Using the ultrasonic system's quantiser the recorder pen gives different shades of grey for different finite voltage levels. The probe and recorder pen perform the same rectilinear scan resulting in the production of a 'C scan' record which gives a plan view of the specimen with voltage levels displayed as tone changes. The photograph in Fig.5 shows the ultrasonic tank with the probe attached. For convenience, and to reduce the length of probe lead, electronic boards are carried on the probe arm. In use the ferrite end of the probe makes contact with the specimen and is drawn across it by the scanning arm. Only slow rates of scan can be used because of the friction between probe and specimen.

The second type of probe is designed to give a directional field and hence directional as opposed to circular eddy currents. It consists of a toroidal ferrite core of 9mm outside diameter, as used for magnetic core stores, ground down so as to form a horseshoe section. The core is wound with 12 turns of 34 swg wire, so as to form a toroidal coil with an air gap, and is mounted in a probe with the gap downwards. The flux lines are then as shown in Fig.7. It may not be obvious at first sight what form of eddy current this probe induces. However, the lines of flux crossing between the ends of the core build up and collapse as the current in the coil varies and have an effective motion into and out of the surface of a CFRP sample brought up to the probe. Application of Fleming's right hand rule then shows that the current paths lie in the plane of the material and are concentrated between the ends of the core at right angles to the plane of the core and approximately in a straight line. They then follow more or less circular paths round each limb of the core. This distribution of current paths gives the probe a directional property which may be used to reveal the anisotropy of materials such as CFRP. When the straight current path where

the current is most concentrated lies along the fibres the response is a maximum; conversely when it lies across the fibres the response is a minimum.

This second type of probe is mounted above a rotating turntable as shown in the photograph of Fig.8. The probe can be lowered on to a specimen of CFRP mounted on the turntable. The CFRP is isolated from the effect of the metal turntable by a layer of Tufnol 12mm thick. A rotary potentiometer under the turntable supplies a voltage proportional to rotation and thus a rotary scan of a specimen can be translated into a longitudinal display on an X-Y recorder.

3 PRINCIPLE OF OPERATION ON CFRP

Unidirectional CFRP consists of numerous continuous thin carbon fibres (approximately $7\mu\text{m}$ diameter) uniformly distributed and running parallel, or nearly so, in a matrix of resin. Since the transverse conductivity of the composite material is not zero these fibres must touch at intervals, but micro-photographs of sections of CFRP prepared from commercial preimpregnated (prepreg) material show fibres touching only occasionally and it seems likely that there is a surface tension effect tending to keep the fibres separate. Thus a conducting path is provided along numerous fibres but the transverse conducting path is tortuous and may involve a relatively long route along the fibres before a crossing point is reached. Now if a probe forming the inductance of an oscillator tank circuit is used, the field distribution is roughly as shown in Fig.6 for a simple probe with a straight core, and the path of the eddy currents in a conducting medium near the end of the probe is a series of circles concentric with the axis of the probe. In the case of CFRP these currents have to follow a path parallel to the surface across the fibres through the capacitance between fibres except on the occasions on which a pair of fibres are touching. With cross ply material a transverse path is of course provided, but the current still has to pass across the capacity between layers of prepreg material. A mathematical model for the system is thus as shown in Fig.9 where the primary circuit represents the tuned circuit of the oscillator and the CFRP is represented as a simple circuit of inductance, capacitance and resistance coupled to the primary. A shunt resistance R_s represents a possible transverse path due to fibres touching as an alternative to the capacitive path. The model is analysed in Appendix A for the case where the shunt resistive path is negligible and for the case where it forms a significant current path. The results of these analyses show that with a purely capacitive path the primary reactance is always reduced by the presence of the CFRP and the frequency of oscillation correspondingly

raised; conversely when the shunt resistive path becomes significant the reactance of the primary is increased at frequencies below resonance of the secondary circuit and the frequency of oscillation is correspondingly reduced. Above the resonant frequency of the secondary the frequency is increased. Thus the response on bringing a probe up to a sheet of CFRP can be either an increase or a decrease in frequency depending on whether there are significant numbers of fibres touching. Experience with an oscillator and probe working at a frequency of 10MHz shows that the response is invariably an increase in frequency, and so we conclude that either the path is essentially capacitive or that at 10MHz we are working above the resonant frequency of the secondary.

The actual values of LC and R in the equivalent circuit for CFRP decide the resonant frequency of the secondary. These values are not known of course and it is difficult to form an accurate estimate of them because of the multiple paths that an eddy current can take in CFRP. Some approximation to the effective path length may be obtained from Figs.10 and 11 which show scans using an eddy current probe. In Fig.10 there is a 2mm hole drilled in the unidirectional specimen in the central left region. The response of the probe to the hole can be seen to be an approximately oval area 15mm long by 7.5mm wide. This supports the hypothesis that the eddy currents have a relatively easy path along the fibres and a more difficult path through the stray capacitance across the fibres. This is further borne out by Fig.11 which shows the response on a cross ply material with a different resin system. Here either a 2mm or 1mm hole both give a response area which is circular and about 7.5mm in diameter in contrast to the oval response in a unidirectional material. If we assume then that in unidirectional material we are dealing with an area of eddy current some 15mm by 7.5mm consisting of longitudinal paths along the fibres and transverse paths across the inter-fibre capacity, the values of inductance and capacitance may be very approximately assessed. The relevant calculations are given in Appendix B where it is shown that the resulting resonant frequency is about 24MHz. This is in fair agreement with Owston's measurements¹. Of course the resonant loop considered in Appendix B is only one of many and the interactions between these loops have been ignored. It is further shown in Appendix B that if the relevant values of LC and ω are substituted into the expression for the secondary reactance

$$-j\omega A(L_2[1 + \omega^2 c_2^2 R_s^2] - c_2 R_s^2) \quad (1)$$

from equation (A-2) in Appendix A it emerges that at frequencies below 24MHz (and therefore at the frequency of 10MHz employed in the tests reported here) this

reactance is inductive and negative for values of R_s below about $29k\Omega$ and inductive and positive for values above this. Thus the probe frequency is only reduced below secondary resonance for values of shunt resistance greater than $29k\Omega$. This value of R_s represents a 70-80mm total path along a single fibre; moreover, the shunt capacitive reactance of the inter-fibre capacity at 10MHz is about $58k\Omega$, so such resistive shunt paths would appear to be perfectly feasible and would carry a large proportion of the current. However, it is unlikely that they would occur in more than a small proportion of the fibres forming a current loop and they may well represent only an unavoidable uncertainty in the probe readings by tending to reduce certain readings slightly.

It is clear from the above model of the CFRP-probe interaction that the greater the volume fraction of the CFRP, the greater will be the number of conducting paths and the greater the response of the system. Thus we would expect an output which varied with volume fraction. Again with cross ply materials an easy transverse path is provided for the current and the capacitances between the fibres in successive layers are in parallel, rather than in series as in the unidirectional material. These effects will increase the current considerably and we would expect an increased response from cross ply compared with unidirectional material.

4 RESULTS FROM NON-DIRECTIONAL PROBE

4.1 Resolution

The resolution clearly depends on the area of eddy currents generated by the probe. This area is theoretically infinite in extent, with the currents reducing in amplitude, probably experimentally, as the paths are further removed from the probe. Thus a discontinuity in the CFRP will be displayed as an area of response of an indefinite extent. No matter how small the discontinuity some effect will be produced on the response, but if the discontinuity is small this response may be lost in the noise level of the instrumentation. The chief cause of noise in this experiment is short-term drift, and it is necessary to revert to an experiment to determine the resolution in practical terms.

In Fig.10 is shown a C scan of a piece of unidirectional CFRP. The scan is in two parts because the specimen of CFRP contained a large hole in the centre which prevented a continuous traverse. The response to this hole is clearly seen on either side of the centre division. To the left of the centre hole a 2mm diameter hole has been drilled in the CFRP. This has been registered by the probe as a roughly oval area 15mm by 7.5mm using 500mV steps in the quantiser.

On the other hand a 1mm hole, also drilled in the same sheet, has not registered at all at this discrimination level. A further scan was tried with 250mV discrimination but this too failed to reveal the 1mm hole. Random short term drift on the equipment sets the limit to finer discrimination and the quantiser cannot discriminate between levels much less than 250mV. With cross ply CFRP there is a different situation (see Fig.11). Here a 2mm hole is clearly revealed as a 7.5mm diameter area with a 500mV discrimination level on the quantiser. The change is from black to white with three levels set on the quantiser, so that a change of over 1 volt was registered. A further scan of a 1mm hole with a discrimination level of 250mV revealed the 1mm hole as a white area, so that the change was greater than 500mV. It is significant that neither area shows any appreciable grey shading round it (corresponding to the intermediate level from the quantiser) so that the eddy current paths are fairly abruptly limited, and the resolution of the system may be taken as a circle of 7.5mm diameter (compared with the 3mm diameter ferrite tip of the probe). A curious effect is the increase in response when the probe is directly over the hole giving the black centres in Fig.11. The most likely explanation of this is that when the probe is not central over the hole, the eddy current path is interrupted by the hole and the current has to take a larger path round it, so that its amplitude is reduced. When the probe is directly over the hole the currents flow symmetrically round the hole without interruption and a normal response is obtained. It is significant that the black areas in Fig.11 are approximately 3mm in diameter.

To summarise, then, the probe converts a small discontinuity in cross ply CFRP into an area of response 7.5mm in diameter. With unidirectional CFRP the resolution is not so good; a roughly oval response is obtained for a circular discontinuity and the sensitivity to small discontinuities is poorer. With cracks, however, good resolution is obtained. Referring again to Fig.10, there is a long through-thickness crack in the specimen at the top of the picture. This crack, which is well resolved, tapers in size from left to right and at the region opposite the central hole it is approximately 0.11mm in width. Two further cracks which are resolved extend to the right from the region of the central hole. They average 0.07mm in width so that the sensitivity to a long crack is considerably better than to a circular hole. This is to be expected since the interruption to the eddy current flow is much greater.

4.2 Depth of penetration and effect of specimen thickness

A simple experiment was conducted to determine the depth of penetration at 10-12MHz. This consisted of placing a sheet of aluminium under various thicknesses

of unidirectional and cross ply material. It had previously been found that a metal surface gave a very high reading, outside the range of the instrument, when the probe was placed on it. Therefore a change in reading when a metallic sheet was placed under CFRP indicated that the eddy currents were penetrating as far as the metal. With a sheet of unidirectional CFRP 7.3mm thick the reading just changed but with a sheet 10.65mm thick there was no change. It was concluded that the depth of penetration with unidirectional CFRP is about 8mm. With cross ply on the other hand a specimen 2.1mm thick showed no change when an aluminium sheet was introduced but a specimen 1.7mm thick showed a slight change. The depth of penetration in this case is evidently about 1.8-2mm. The effect is clearly a measure of the efficiency of the CFRP to act as a magnetic screen at high frequencies. With the better conducting paths available in cross ply material, heavier currents are induced which tend to cancel the applied field sooner. As might be expected, cross ply material gives a considerably greater response than unidirectional material under all circumstances.

Within the limits of the depths of penetration for unidirectional material, increased thickness gives a greater response. The variation with thickness is plotted in Fig.12 for a limited range of thicknesses of unidirectional CFRP. With cross ply CFRP a similar experiment was undertaken, but anomalous results were obtained. The table shows the readings obtained from a stepped sample of cross ply with three different probes.

<u>Thickness of material in</u> mm	<u>Output volts</u>		
	<u>Probe 1</u>	<u>Probe 2</u>	<u>Probe 3</u>
0.34	13.33	12.69	16.72
0.60	15.62	11.96	16.67
1.10	15.78	10.75	19.15
1.58	15.11	9.97	18.40
1.82	15.38	9.68	18.31
2.00	15.08	9.91	18.15

Thus with two out of three probes a maximum reading was obtained for a thickness of 1.10mm. With probe 2 however a maximum was obtained for the thinnest material and the reading tended to fall with increasing thickness. All three probes were nominally of the same construction and no explanation has presented itself for the different behaviour of probe 2.

It may be that the existence of an optimum thickness as shown in the table is associated with the effects produced by a metallic sheet. If a metallic sheet is brought into contact with the probe, the output increases considerably

more than with CFRP as might be expected. Similarly if a metallic sheet is inserted under a piece of unidirectional CFRP which is in contact with the probe, the reading rises. But if a metallic sheet is introduced in the same way under cross ply the reading falls. Now it can easily be shown by an extension of the argument used in Appendix A that if three coupled circuits are involved, representing the probe, the CFRP and the metal respectively, the reactance of the secondary circuit is reduced by the tertiary circuit and so the effect of the former on the primary circuit is reduced. This applies if there is mutual inductance only between secondary and tertiary circuits and not between primary and tertiary. If the coupling between primary and tertiary predominates the opposite effect is of course obtained. With cross ply and a metallic sheet it would appear that the metallic sheet couples with the cross ply and reduces its reactance so that the effect on the probe is reduced. Similarly different layers of cross ply may well couple in such a manner, so that a thicker layer produces a smaller response. What is not clear is how the metallic layer couples directly with the probe in unidirectional material and not in cross ply. The obvious difference is that the eddy currents are carried transversely by a capacitative path in unidirectional and by an inductive or resistive path in cross ply, but the mathematical model is not sufficiently developed to explain the effect precisely.

Thus in measurements of volume fraction on unidirectional material it is important to calibrate the system allowing for the thickness of the material. With cross ply rather unpredictable results are obtained with varying thickness and calibration would apparently involve the use of one unique probe.

4.3 Edge effect

It has been demonstrated in section 4.1 that the important part of the eddy current path covers an area 7.5mm in diameter on cross ply and 15×7.5 mm on unidirectional CFRP. As might be expected, this results in an edge effect which arises when part of the eddy current path is cut off by the edge of the CFRP. A smaller output is then obtained compared to that from regions further from the edge and the output falls almost to zero as the probe approaches the edge of the material. This proves a disadvantage when scanning specimens, as the edge area has to be ignored. It also inhibits investigation on narrow specimens. The effect is purely due to the absence of a conducting path for the currents: this was demonstrated on a piece of unidirectional CFRP by moving the probe in a direction parallel to the fibres. As the probe approached the edge the output voltage fell almost to zero. The edge of the specimen was then coated with

conducting paint and the output voltage rose to a higher figure than had been obtained at the centre of the specimen.

4.4 Response to volume fraction

As was anticipated from the theoretical discussion in section 3, the system responds to volume fraction in both unidirectional and cross ply CFRP. A local measurement of volume fraction in CFRP would be of considerable interest and the system would have great value if it could be used for this purpose. A series of wet lay-up specimens of unidirectional CFRP covering a wide range of volume fractions were used to calibrate the system and the results are plotted in Fig.13. A smooth curve was obtained by taking the mean of seven readings on each specimen and plotting these against the volume fraction of a sample of the material obtained by the usual densimetric and acid burn off method³. Where the volume fraction was too low for the density column a microphotograph of a section of the sample was used to count fibres in a given area. The specimens were of constant thickness. However one specimen which the destructive tests showed to have the highest volume fraction (65%) gave an output voltage approaching zero and even on occasions a negative one. This result clearly bears no relation to the others on the graph and is not plotted in Fig.13. It should be noted however that the specimen was very dry and gave clear indications of resin starvation in places, so that it is likely that there were many areas where fibres were touching.

With cross ply CFRP made from pre-impregnated material it was necessary to vary the pressure in the autoclave in order to vary the volume fraction. Some anomalies were initially encountered but eventually a meaningful relationship between volume fraction and pressure was obtained, the volume fractions being measured destructively. Eddy current measurements showed some variation over the area of the specimens and the mean values, when plotted, show that the majority of the points fall on a straight line (Fig.14) but that some points exhibit scatter, the maximum apparent error in volume fraction being of the order of 3%. It is possible therefore that apart from volume fraction some other factor is influencing the readings. In an attempt to reduce the scatter the samples which gave scattered readings were rechecked destructively and the volume fraction of the portion of the specimen taken for analysis is not in doubt. Fresh eddy current readings were taken close to the area removed for analysis but the readings still showed some scatter. In addition void content was measured, in case this was affecting the readings, but it was found to be small and reasonably uniform from sample to sample. It is tentatively suggested that the effect might

be due to random contact of fibres between the plies. Such contact would give an entirely resistive path for the eddy currents and would result in a high reading if it occurred in the upper layers and probably a low reading if it occurred in the lower layers, following the argument developed in section 4.2. Certainly microphotographs of these particular specimens showed appreciable contact between the layers. Thus volume fraction measurements taken with unidirectional material showed a smooth calibration curve (with the exception of one rogue specimen) but with cross ply material it appeared that a certain amount of scatter was inevitable and the system would not be suitable for accurate measurements of local volume fraction such as might be obtained from a 'C' scan of the material. It would however serve the purpose of determining average volume fraction with an accuracy of perhaps 3%, but some caution is needed when the effect which caused the scatter is unknown and could possibly cause larger errors in special circumstances.

5 RESULTS FROM DIRECTIONAL PROBE

As explained in section 2.2 the directional probe gives an eddy current pattern which is concentrated across the centre of the probe and therefore has a directional property. When applied to unidirectional carbon fibre a maximum response is obtained when the fibres lie in the same direction as the concentrated line of eddy currents. The probe was mounted above a circular turntable as shown in the photograph of Fig.8 and x-y plots representing the polar variation of the eddy currents in different configurations of carbon fibre were taken. The plot for unidirectional carbon fibre is shown in Fig.15.

From the theory of Owston and Prakash² it should be possible to distinguish between the number of cross ply layers in a cross ply laminate. A series of samples were made up containing the following arrangements of ply. In each case seven plies were used.

0	0	0	90	0	0	0
0	0	90	0	90	0	0
0	0	90	90	90	0	0
0	90	0	90	0	90	0

These specimens were scanned with the horseshoe probe by rotating the turntable and the variation in output voltage plotted on an x-y plotter. The material averaged 1.7mm in thickness so that the eddy currents should have penetrated the full depth of the material. The results are shown in Figs.16 to 19. As may be seen from the plots, the presence of a cross ply is always indicated by a secondary output from the system. The response to 0 90 0 90 0 90 0 material

(Fig.19) shows pronounced peaks for both orientations of the material, but the cross ply responses are less pronounced for other lay-ups. All the curves including the unidirectional response show asymmetry of the peaks which occur when the eddy current axis is aligned with the various fibre directions. This may have been due to asymmetry in the construction of the probe, resulting in a more concentrated eddy current path leaving the probe on one side than on the other. However it is not clear why such asymmetry should cause a distinction between the two cases when the probe axis is normal to a particular fibre direction and the effect has not been explained as yet. It was felt that the directional probe was of limited interest since the investigation of the lay-up of a particular material is a relatively minor requirement in the non-destructive evaluation of CFRP. Where some confusion as to lay-up can arise, this can be obviated by the introduction into the pre-impregnated material of lead-glass tracer fibres which are relatively opaque to X-rays. Accordingly no work was undertaken to establish the resolution of this type of probe or to examine the other effects which were thought to be of importance in the non-directional probe.

6 DISCUSSION

The programme showed some promise as a method of investigating the fibre volume fraction of CFRP laminates, especially as C scans could be taken of a piece of material showing local variations in volume fraction. Analysis of such local variations is difficult to carry out by any other means and it could be used to render more explicit the measurements of void content taken by means of ultrasonic attenuation measurements⁴ by providing local measurements of volume fraction. Measurements of volume fraction require an accurate calibration of the equipment and for this purpose it is necessary to know the thickness of the sample. Probe responses vary considerably so that each probe would have to be individually calibrated. Variation in the permittivity of the resin in different resin systems would result in different inter-fibre capacities so that the same response might not be expected from every resin system and there was some evidence of this. This effect would involve calibration for each resin system. What is required is a set of families of curves giving the variation of output against volume fraction with thickness as a parameter. One family would be required for each resin system and each probe. While there are difficulties in obtaining the specimens to produce such curves the difficulties are not insuperable, and a viable system of measuring volume fraction seems possible. With unidirectional material this could be fairly accurate, but with cross ply material there would appear to be basic limitations to the accuracy which can be obtained. More work

is required on volume fraction measurements of both cross ply and unidirectional material to establish the spread of errors likely to be encountered in practice, but if the reason for the variable results in cross ply is indeed fibres touching then this would appear to be a variable which cannot be controlled.

7 CONCLUSIONS

A mathematical model has been developed for unidirectional CFRP which is in agreement with most of the observed effects such as depth of penetration, shape of the eddy current path, variation of output with volume fraction and edge effects. Good calibration curves for this variation of frequency (or output voltage) with volume fraction and material thickness have been obtained for unidirectional material.

With cross ply material there is agreement with theory in the magnitude of the frequency change, in the resolution of the non-directional probe and in the effect of introducing a metallic sheet under a specimen. On the other hand no fully satisfactory mathematical model for cross ply has been developed and the observed results giving the variation with thickness of material and volume fraction exhibit anomalies. Further work is required on cross ply materials before the technique can be fully assessed.

Experimental work with a directional probe has shown that intermediate cross plies can be detected, but it is not really practicable to determine the lay-up order.

Acknowledgment

The authors wish to acknowledge the considerable assistance given to them by Mr. R. Childs who prepared the volume fraction specimens and carried out the destructive volume fraction measurements.

Appendix A

THE INTERACTION BETWEEN CFRP AND A NON-DIRECTIONAL PROBE

From Fig.9, the following relations hold if R_s is ignored:

$$i_1(R_1 + j\omega L_1 + 1/j\omega C_1) + i_2 j\omega m = E_1$$

$$i_2(R_2 + j\omega L_2 + 1/j\omega C_2) + i_1 j\omega m = 0$$

Substituting for i_2 gives

$$i_1 = E_1 / \{R_1 + j\omega L_1 + 1/j\omega C_1 + \omega_m^2 / (R_2 + j\omega L_2 + 1/j\omega C_2)\}$$

so that the primary impedance

$$Z_1 = R_1 + j\omega L_1 + 1/j\omega C_1 + \omega_m^2 / (R_2 + j\omega L_2 + 1/j\omega C_2)$$

Normalising the right hand expression gives

$$Z_1 = R_1 + j\omega L_1 + 1/j\omega C_1 + (R_2 - j\omega L_2 + j/\omega C_2) \omega_m^2 / \{R_2^2 + (\omega L_2 - 1/\omega C_2)^2\} \quad (A-1)$$

At the resonance of the secondary circuit

$$\omega L_2 = 1/\omega C_2$$

and there is no change in the reactance of the primary circuit when the secondary circuit is coupled to it. A resistive term

$$\omega_m^2 / R_2$$

is introduced into the primary circuit.

For resonant frequencies of the primary circuit above the resonant frequency of the secondary circuit, the term $-j\omega L_2$ predominates and, apart from adding a resistive term, the coupling to the secondary reduces the primary inductance and increases the resonant frequency of the primary circuit. Similarly for frequencies of the primary circuit below the resonant frequency of the secondary circuit the term $j/\omega C_2$ or $-1/j\omega C_2$ predominates and again increases the resonant frequency of the primary circuit.

If however the shunt resistance R_s becomes significant, the situation is different. The following relations then hold:

$$i_1(R_1 + j\omega L_1 + 1/j\omega C_1) + i_2 j\omega m = E_1$$

$$i_2(R_2 + j\omega L_2 + R_s/[1 + j\omega C_2 R_s]) + i_1 j\omega m = 0,$$

whence

$$i_1 = E_1 / \{R_1 + j\omega L_1 + 1/j\omega C_1 + \omega^2 m^2 / (R_2 + j\omega L_2 + R_s/[1 + j\omega C_2 R_s])\}$$

and therefore

$$Z_1 = R_1 + j\omega L_1 + 1/j\omega C_1 + \omega^2 m^2 / (R_2 + j\omega L_2 + R_s/[1 + j\omega C_2 R_s]).$$

Normalising the last expression in the right hand side

$$Z_1 = R_1 + j\omega L_1 + 1/j\omega C_1 + A \left\{ R'_s - j\omega (L_2 [1 + \omega^2 C_2^2 R_s^2] - C_2 R_s^2) \right\} \quad (A-2)$$

$$\text{where } A = \omega^2 m^2 (1 + \omega^2 C_2^2 R_s^2) / \{R_s'^2 + \omega^2 (L_2 [1 + \omega^2 C_2^2 R_s^2] - C_2 R_s^2)^2\}$$

$$\text{and } R'_s = R_s + R_2 (1 + \omega^2 C_2^2 R_s^2).$$

This derivation has been given by Owston¹ except that R_2 is assumed to be negligible.

For the reactive component of the secondary to be zero, the resonant frequency of the secondary is given by

$$L_2 (1 + \omega^2 C_2^2 R_s^2) - C_2 R_s^2 = 0$$

$$1 + \omega^2 C_2^2 R_s^2 - \frac{C_2}{L_2} R_s^2 = 0,$$

and so

$$1/L_2 C_2 - \omega^2 = 1/C_2^2 R_s^2$$

$$\omega^2 = 1/L_2 C_2 - 1/C_2^2 R_s^2. \quad (A-3)$$

For frequencies below resonance

$$\omega^2 < 1/L_2 C_2 - 1/C_2^2 R_s^2$$

$$R_s^2 \omega^2 L_2 C_2^2 < C_2 R_s^2 - L_2$$

$$L_2 [1 + \omega^2 C_2^2 R_s^2] - C_2 R_s^2 < 0 \quad . \quad (A-4)$$

Thus by inspection of equation (A-2), at primary resonant frequencies below secondary resonance the inductance of the primary is increased and the frequency lowered. Similarly, by reversing the above inequality, the primary inductance is seen to be reduced above secondary resonance and the primary frequency increased.

At first sight the low frequency result might appear to be contrary to Lenz's law, since an increase in inductance implies an increase in the field associated with the primary current and this in turn increases the eddy current which increases the inductance, an unstable condition which is contrary to experience. However for $R_s \rightarrow \infty$ the model reverts to the form shown in equation (A-1) and for $R_s \rightarrow 0$ inspection of equation (A-2) shows that the primary inductance is reduced by an amount

$$\omega L_2 \omega_m^2 / (R_2^2 + \omega^2 L_2) \quad .$$

It is only for intermediate values of R_s that the primary inductance is increased. For intermediate values of R_s , even where $R_2 = 0$ a resistive term

$$R_s \omega_m^2 (1 + \omega^2 C_2^2 R_s^2) / \left\{ R_s^2 + \omega^2 (L_2 [1 + \omega^2 C_2^2 R_s^2] - C_2 R_s^2) \right\}$$

is introduced into the primary. This reduces the primary current and it seems reasonable to suppose that it more than compensates for the increase in inductance.

Appendix B

CALCULATION OF THE CIRCUIT PARAMETERS

The area delineated by the eddy currents from the non-directional probe in unidirectional CFRP is about $15\text{mm} \times 7.5\text{mm}$. This represents the outer boundary of the currents, so we may take as a typical current path a rectangle 7.5mm long and 3.75mm wide. A typical thickness for the material is 2mm , and it is assumed that the field fully penetrates this depth (see section 4.2). This rectangular current path is partly along the fibres throughout the depth of the material and partly across the inter-fibre capacity. We shall calculate approximate values for the inductance and capacitance of the path.

(a) Capacitance across the path

Referring to Fig.20 it can be shown that for ideal hexagonal packing of the fibres in 60% volume fraction material $d/s = 0.8134$, where d is the diameter of a fibre and s is the distance between fibres. Taking the standard expression for the capacitance between two long parallel conductors, the inter-fibre capacity C_f is given by

$$C_f = 12.06\epsilon_r \left/ \left[\log_{10} \left\{ \frac{s}{d} \left(1 + \sqrt{1 - \frac{1}{(s/d)^2}} \right) \right\} \right] \right. \text{ pF/m} \quad (\text{B-1})$$

where for resin $\epsilon_r = 3.5$ approximately.

This gives on substituting for ϵ_r and s/d ,

$$C_f = 1.096425 \text{ pF/7.5mm in resin.}$$

Referring again to Fig.20 a unit cell is shown which repeats vertically through the material at $\sqrt{3}s$ intervals and horizontally at intervals of s ; the vertical sides of these cells form vertical lines of fibres through the thickness of the material and we may consider the capacitance between two such vertical lines. All the capacitances in the cell are of value C_f but the horizontal capacitances are shared with neighbouring cells. Therefore the capacitances between the two vertical sides of the cell are as shown in the diagram at the bottom of Fig.20. The sum of these capacitances is

$$4 \times C_f/2 + 2 \times C_f/2 = 3C_f.$$

Now since the average diameter of a carbon fibre is about $7\mu\text{m}$ the number of cells in a 2mm thickness of the material is

$$\frac{2 \times 10^{-3} \times 0.8134}{\sqrt{3} \times 7 \times 10^{-6}} = 134 .$$

Therefore the total capacitance in a vertical stack of the cells is

$$134 \times 3C_f = 402C_f .$$

In a 3.75mm width of the material, these capacitances are in series. Since the number of cells across a 3.75mm width is

$$\frac{3.75 \times 10^{-3} \times 0.8134}{1 \times 10^{-6}} = 436$$

it follows that the total capacitance across a 3.75mm width having a depth of 2mm is

$$C_f \times 402/436 = 1.01 \text{ pF} .$$

The current path is in one direction through half of this capacity and in the other direction through the other half. So the total capacitance in circuit is the two halves in series or one quarter the capacitance. Thus in equation (A-2) of Appendix A

$$C_2 = 0.253 \text{ pF} . \quad (\text{B-2})$$

(b) Inductance along the path

The inductance of two parallel conductors with a diameter of d metres, a length of ℓ metres and separated by D metres is given by

$$L_f = 0.4\ell \left\{ 2.303 \log_{10} \frac{2D}{d} - \frac{D}{\ell} + \mu\delta \right\} \mu\text{H} \quad (\text{B-3})$$

where δ is a skin effect term of order unity and $\mu = \mu_r \mu_0 = 1 \times 1.257 \times 10^{-6}$ F/m. This is much smaller than the other terms and can be neglected. On substituting the appropriate values of $\ell = 7.5 \times 10^{-3}$ m, $D = 3.75 \times 10^{-3}$ m and $d = 7 \times 10^{-6}$ m we obtain

$$L_f = 0.0194 \text{ } \mu\text{H}$$

which is the inductance of a pair of conductors located on the mean path. In a 2mm thickness the conductors are spaced at $\sqrt{3}s$ intervals (see Fig.20) so the total number of conductors is 134, and in a vertical stack of conductors the fields add, so the total inductance is proportional to the number of paths squared. Hence

$$L = 348.9 \text{ } \mu\text{H} .$$

However the whole of the inductance is not in circuit for the whole of the capacitance path. Referring to Fig.21 where the half length of the path is $l = a$, it is seen that the maximum current flows at the centre of the path. As l increases the capacitance increases providing more current paths, while the inductance decreases. However, assuming that the magnetic field from the probe links uniformly with the whole of the path, the emf in circuit decreases as l increases. This balances the effect of the decrease in inductance for current paths near the centre, leaving only the effect of the capacitance. So as a first approximation we may assume the current is proportional to the capacitance. Now the capacitance is distributed, so

$$C = K l$$

where K is a constant.

Then

$$i = K' l$$

where K' is another constant

$$i = 0 \quad \text{at} \quad l = 0 \quad \text{and} \quad i = K' a \quad \text{at} \quad l = a .$$

The average current is thus

$$i_{av} = \frac{K' a}{2} .$$

Since the inductance is approximately proportional to l the effective inductance in circuit is therefore one half the total inductance. Thus in equation (A-1) of Appendix A

$$L_2 = 174.4 \text{ } \mu\text{H} . \quad (\text{B-4})$$

(c) Resonant frequency of the secondary

In the absence of any shunt resistance R_s the resonant frequency of the secondary is given by

$$\omega^2 = 1/(L_2 C_2) , \quad (\text{B-5})$$

whence $f = 24\text{MHz}$. Note that the secondary resonance with a finite R_s is given by equation (A-3) of Appendix A.

(d) Calculation of the value of R_s

In equation (A-2) of Appendix A, the reactive term of the secondary impedance is given by

$$-j\omega A[L_2(1 + \omega^2 C_2^2 R_s^2) - C_2 R_s^2] .$$

Then for an increase in frequency of the primary circuit

$$L_2(1 + \omega^2 C_2^2 R_s^2) - C_2 R_s^2 > 0 .$$

Thus at the working frequency of 10MHz the value of R_s required to give an increase in frequency of the primary circuit may be determined by substituting the values of $L_2 C_2$ and ω into the above inequality, giving

$$R_s < 28.9 \text{ k}\Omega . \quad (\text{B-6})$$

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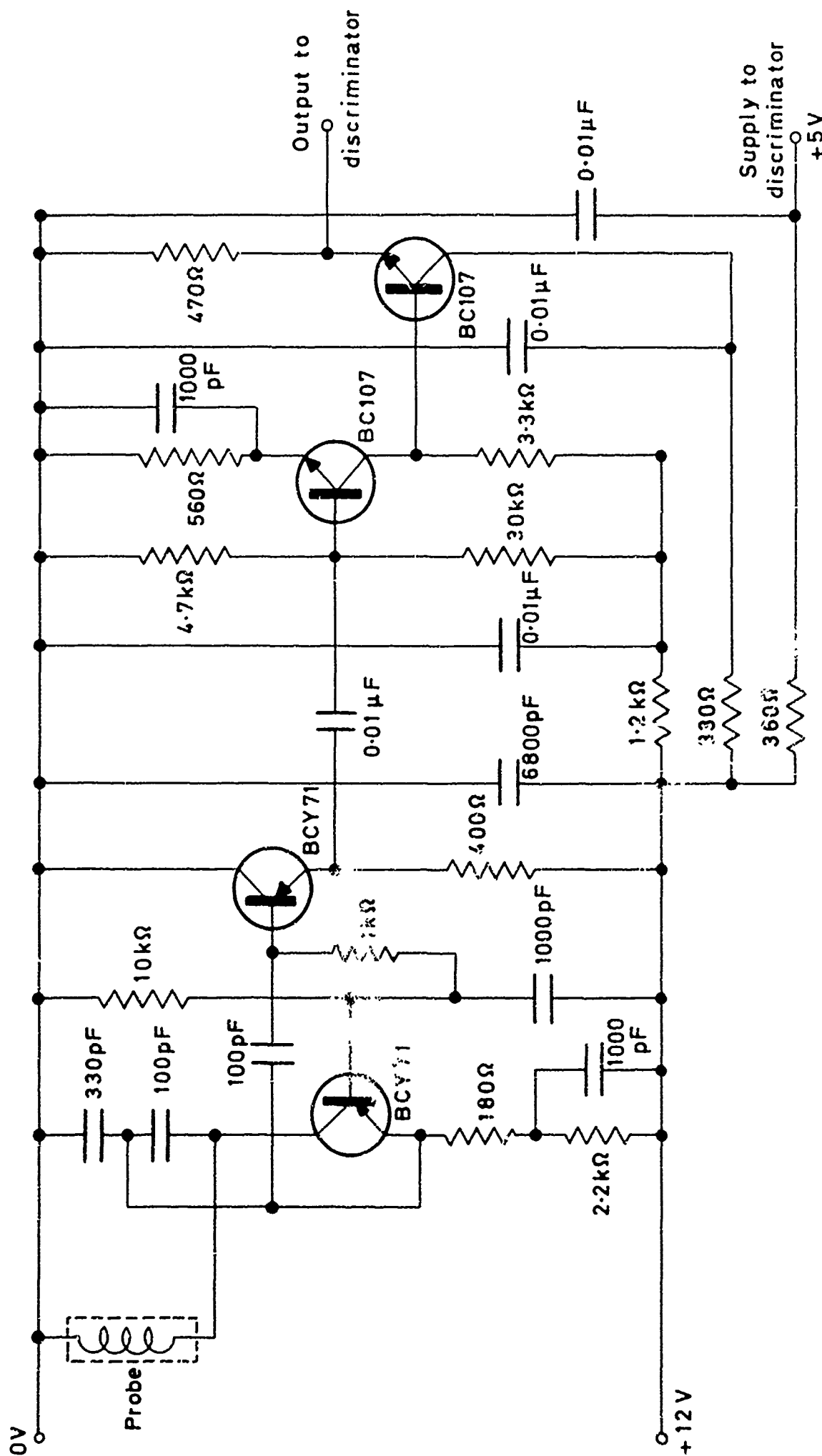


Fig. 1 Oscillator circuit

Fig. 2

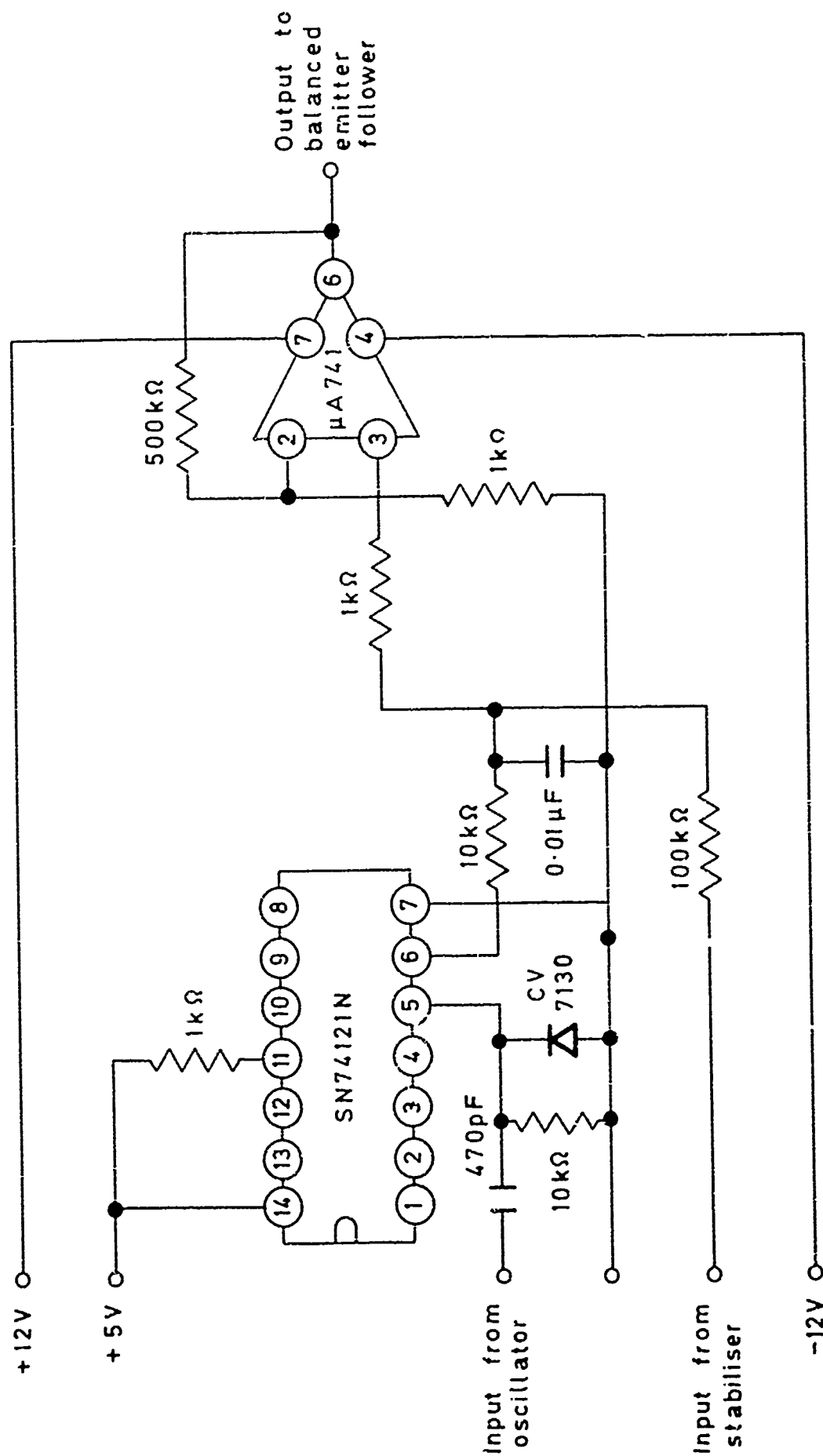


Fig. 2 Discriminator and dc amplifier

Figs. 3 & 4

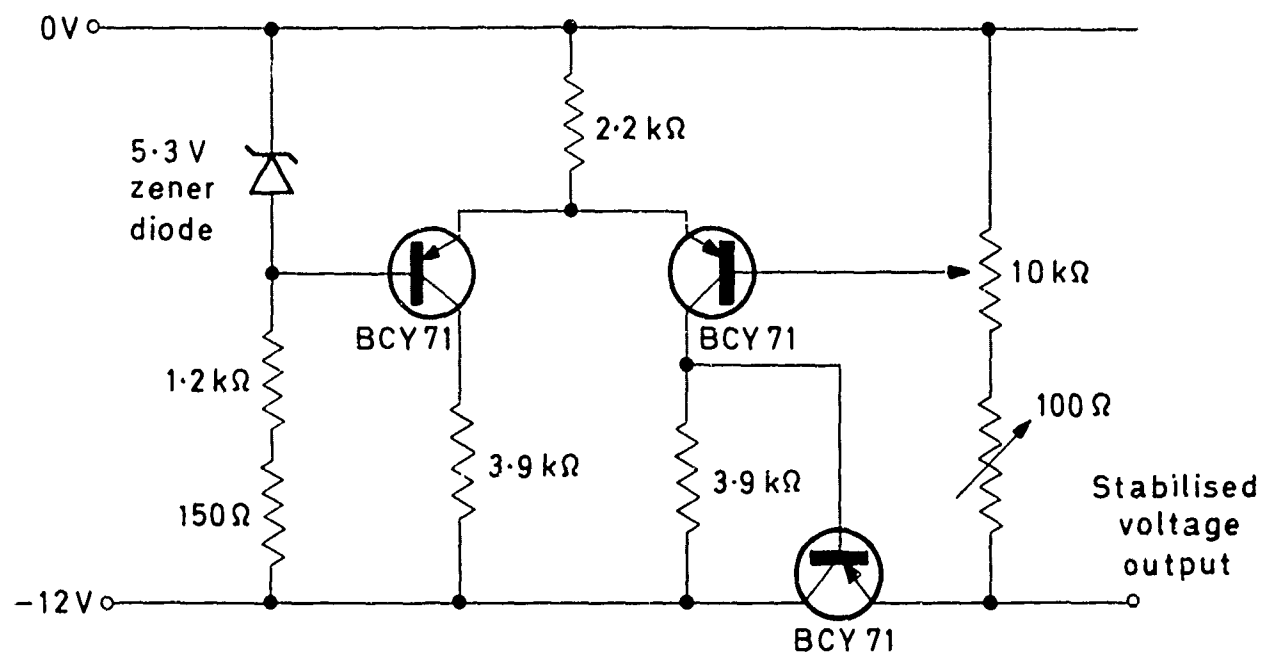


Fig.3 Voltage stabiliser circuit

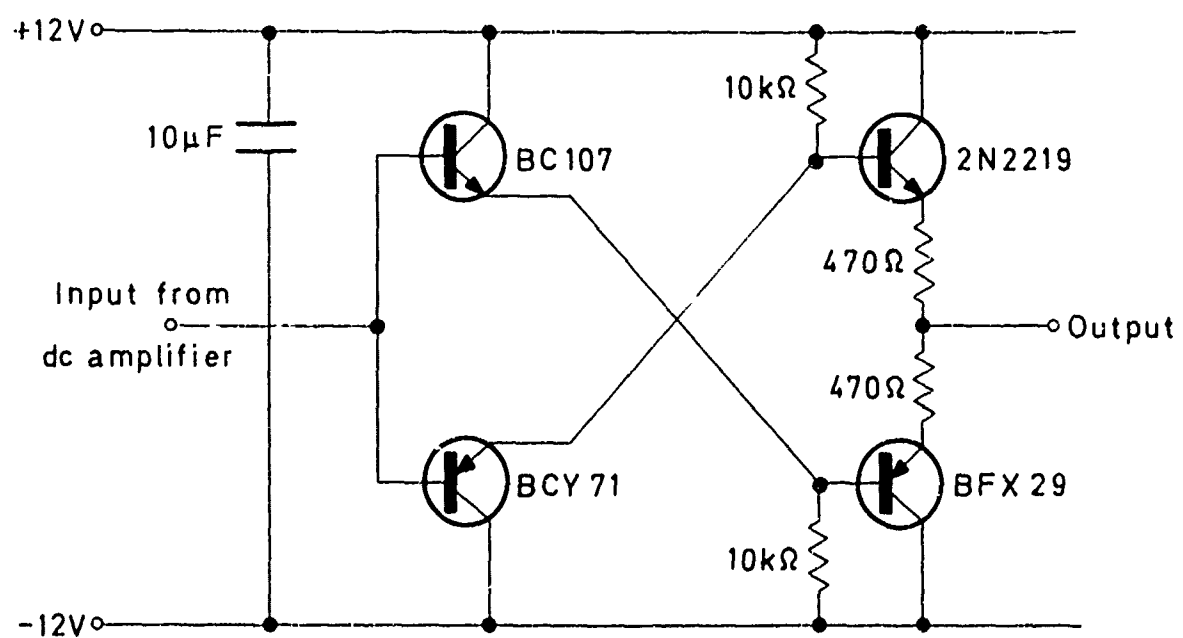


Fig. 4 Balanced emitter follower circuit

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Fig.5



Fig.5 Eddy current rig mounted on ultrasonic test tank

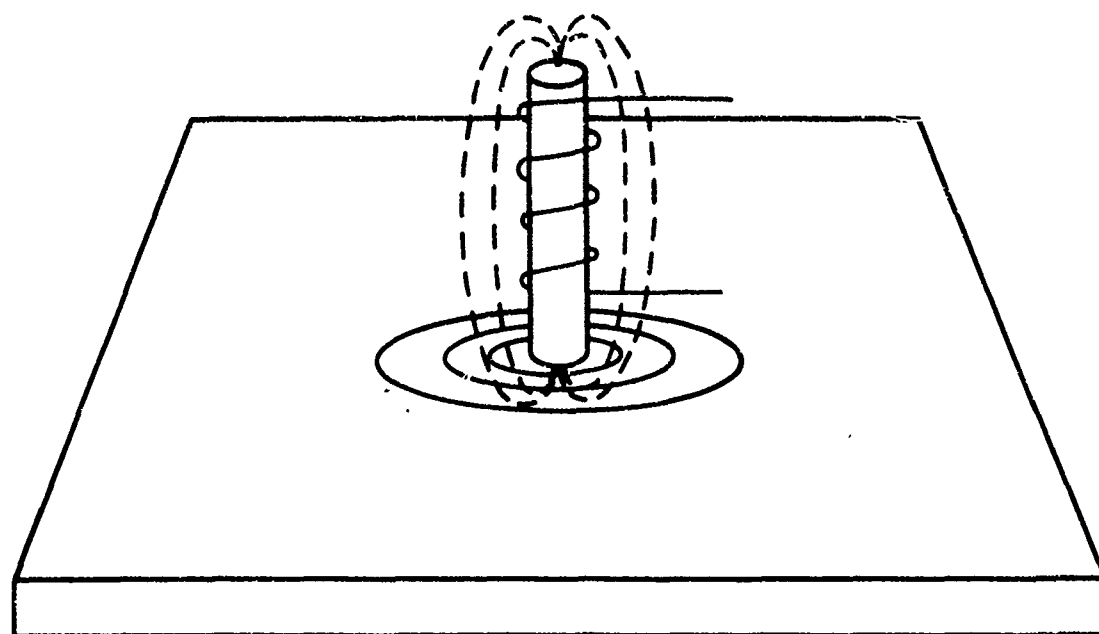


Fig.6 Non directional probe showing magnetic flux and eddy current paths

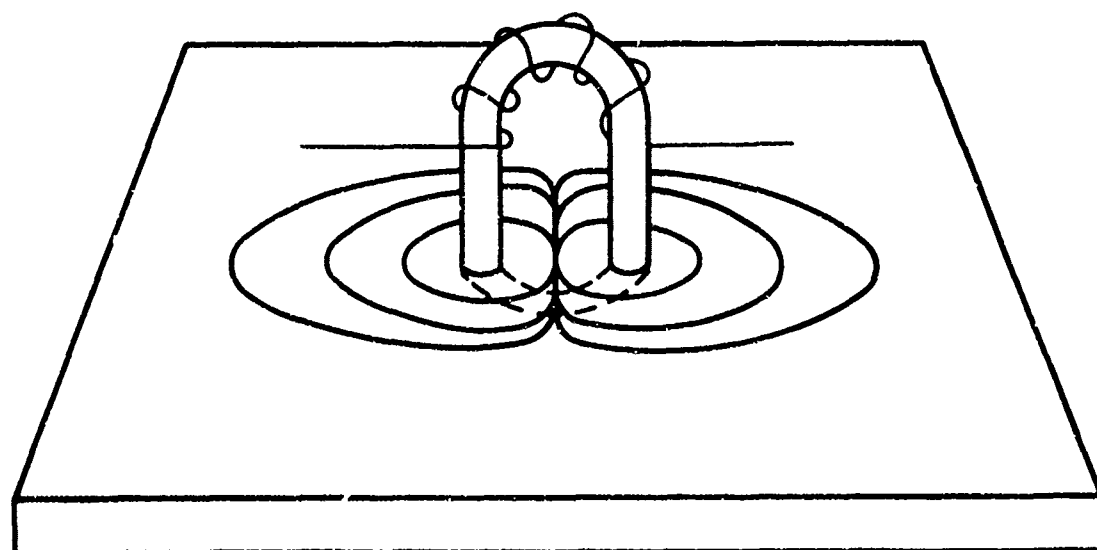


Fig.7 Directional probe showing magnetic flux and eddy current paths

Fig.8

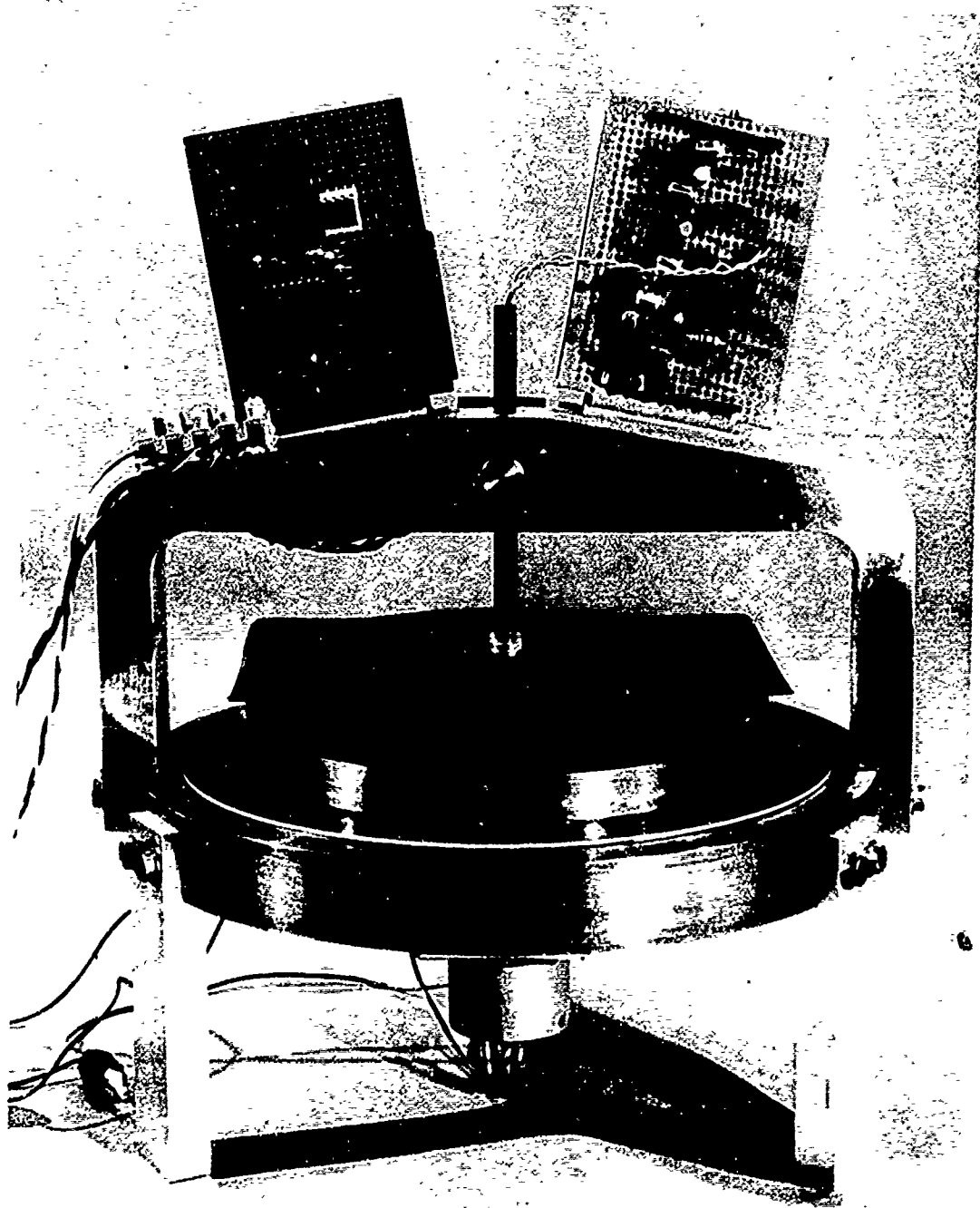


Fig.8 Horseshoe probe mounted on turntable

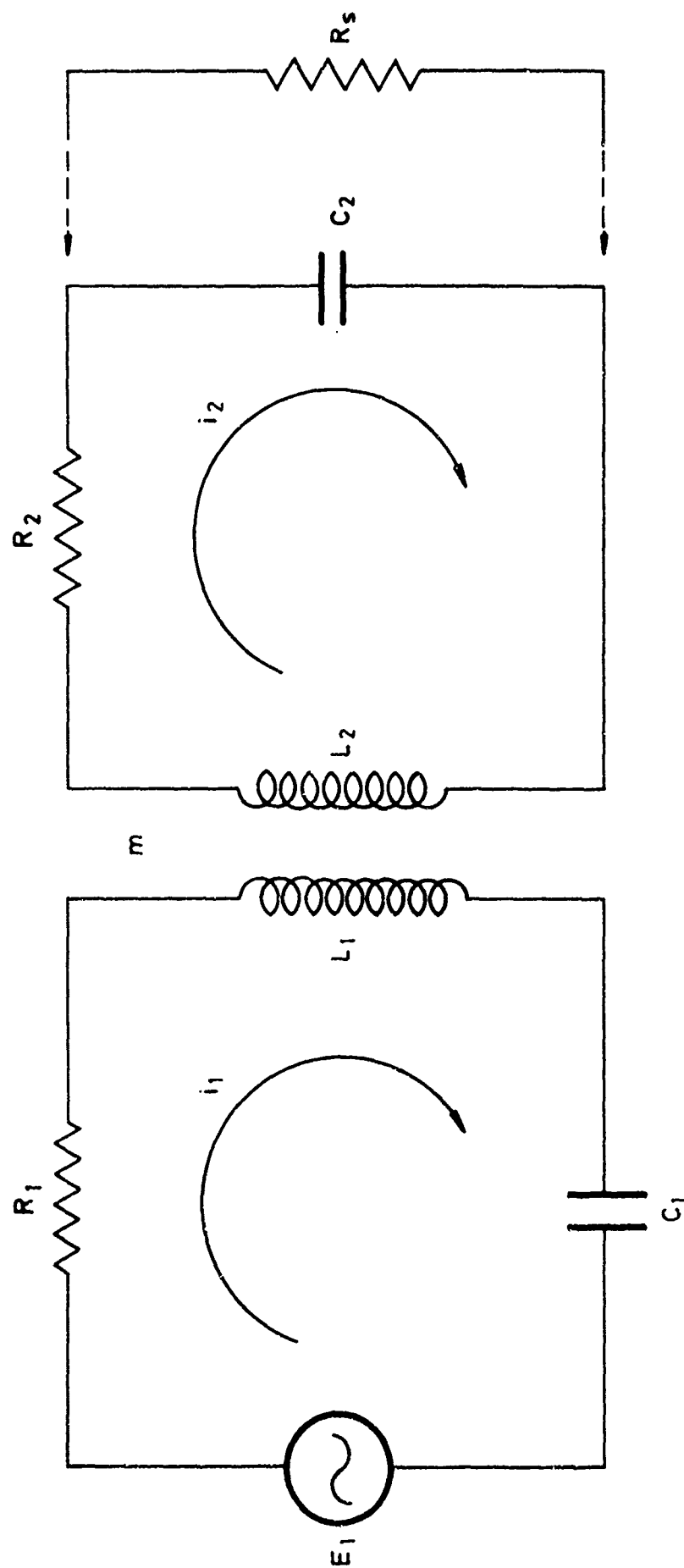
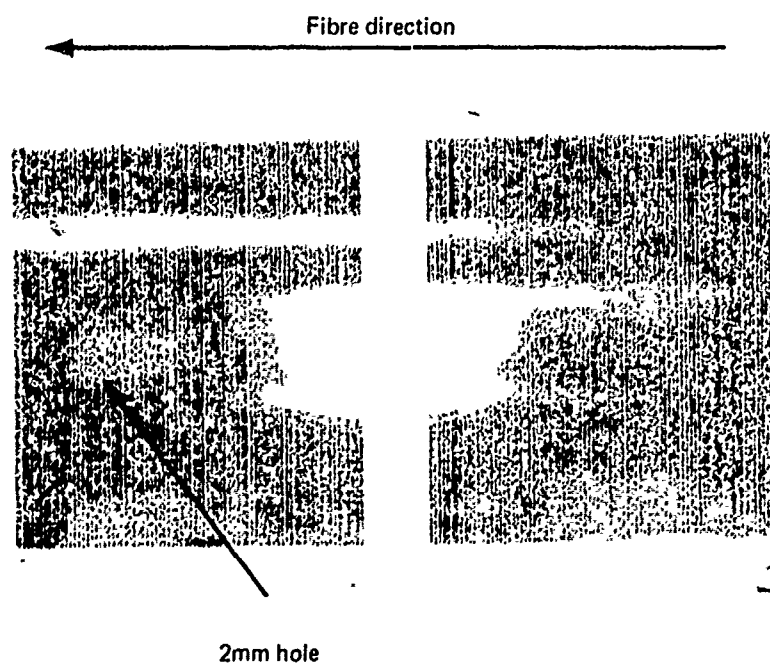


Fig. 9

Fig. 9 Equivalent circuit of probe and CFRP

Fig.10

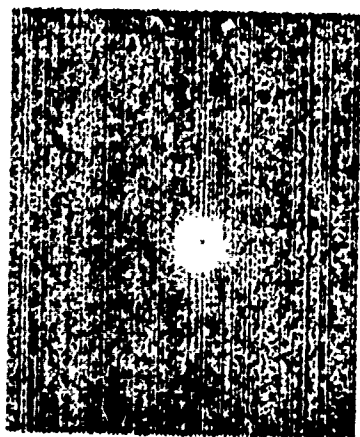


Inputs corresponding to shades of grey:—
5.8, 6.0, 6.5 volts

ERLA 4617 resin

Fig.10 Eddy current scan of CFRP unidirectional material

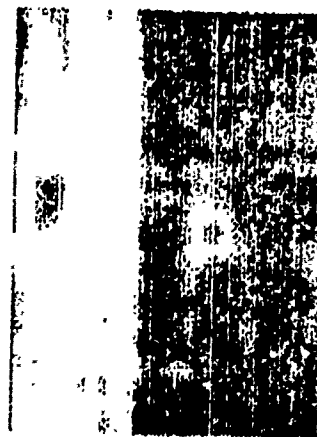
Fig.11



2mm hole

**Inputs corresponding to shades of grey:—
6.5, 7.0, 7.5 volts**

Code 69 resin



1mm hole

**Inputs corresponding to shades of grey:—
8.25, 8.5, 8.75 volts**

Code 69 resin

Fig.11 Eddy current scan of CFRP 0°, 90° cross-ply material

Fig.12

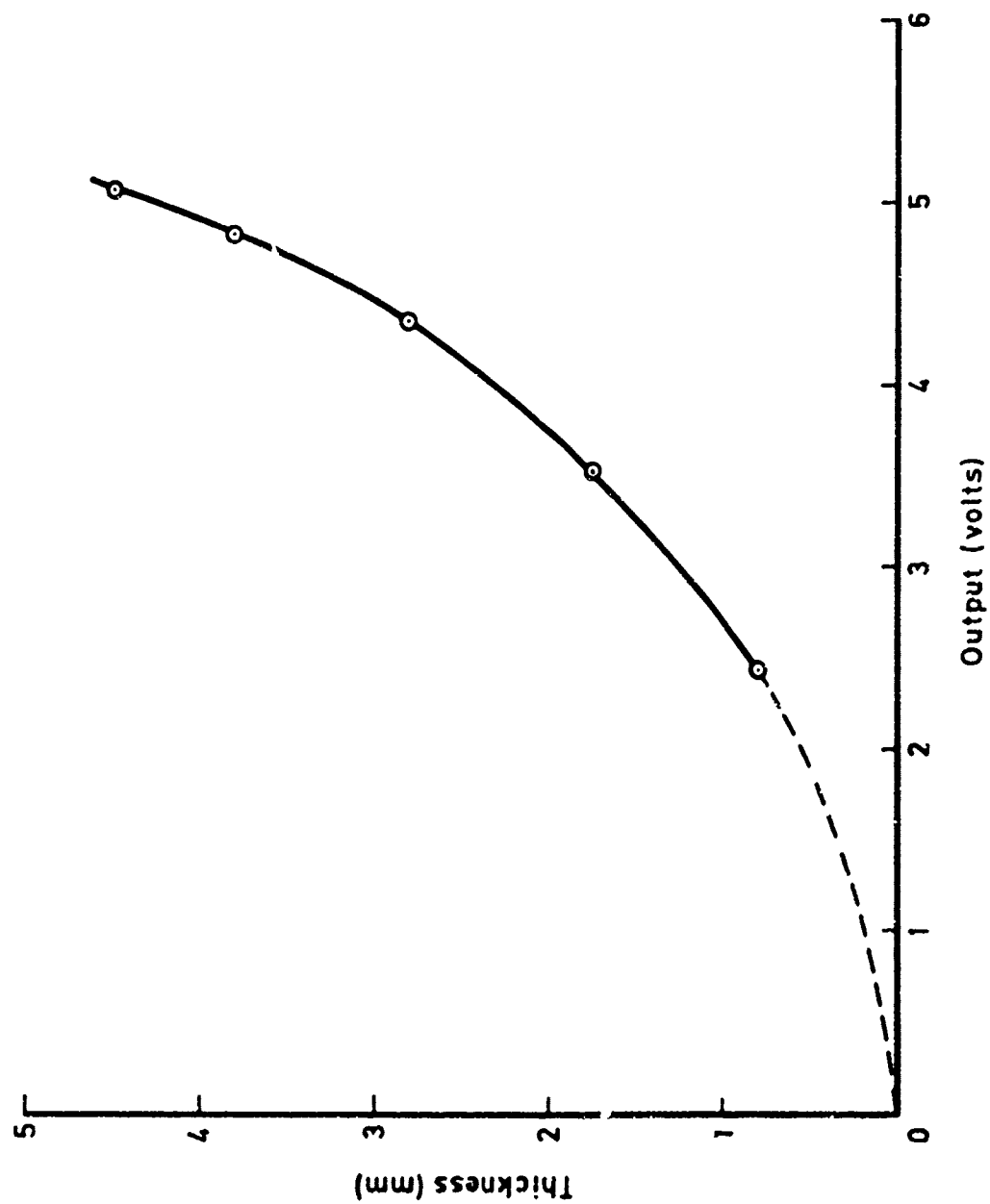


Fig.12 Variation of output with thickness of unidirectional CFRP

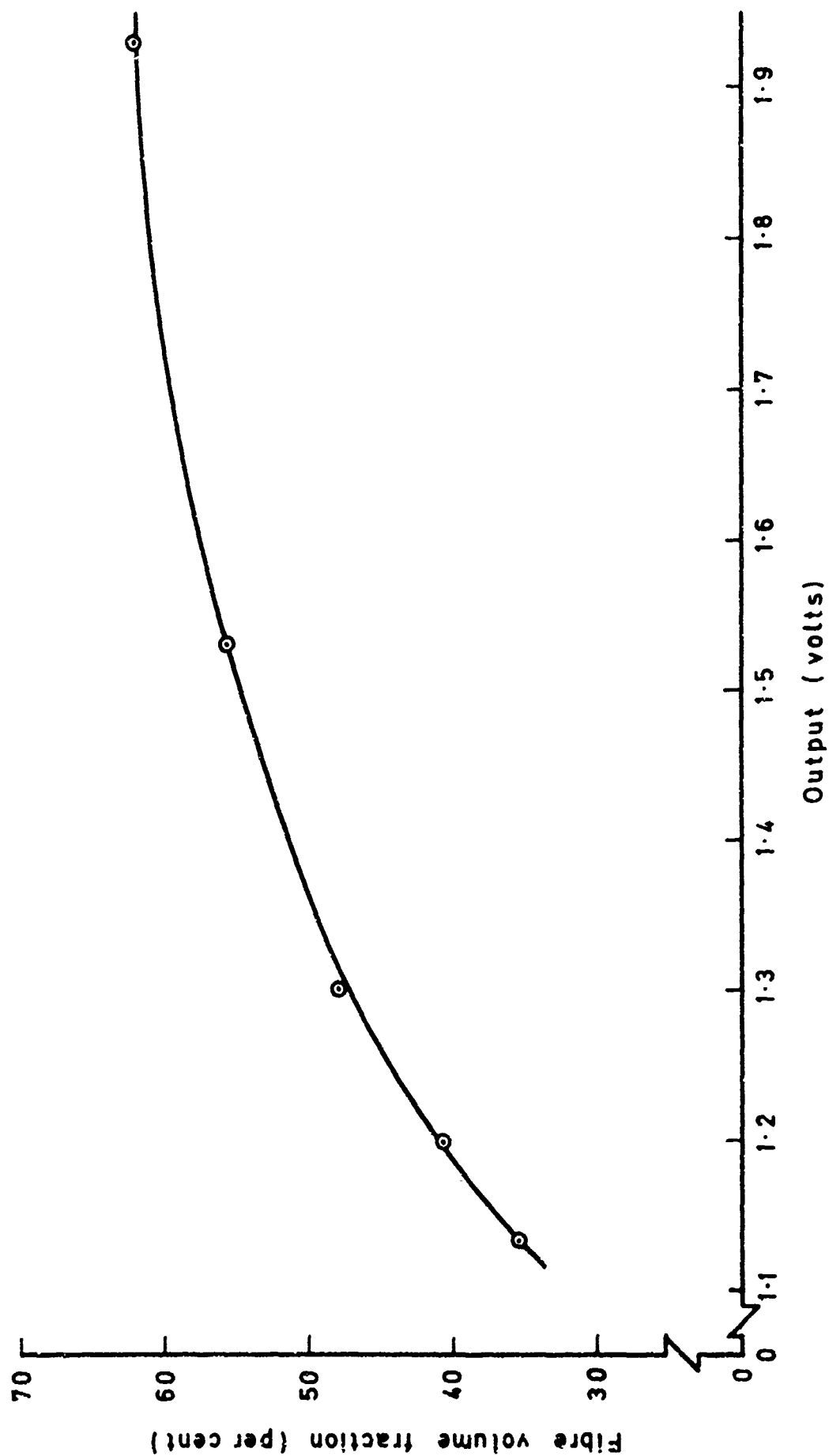


Fig.13 Variation of output with fibre volume fraction of unidirectional CFRP

Fig. 14

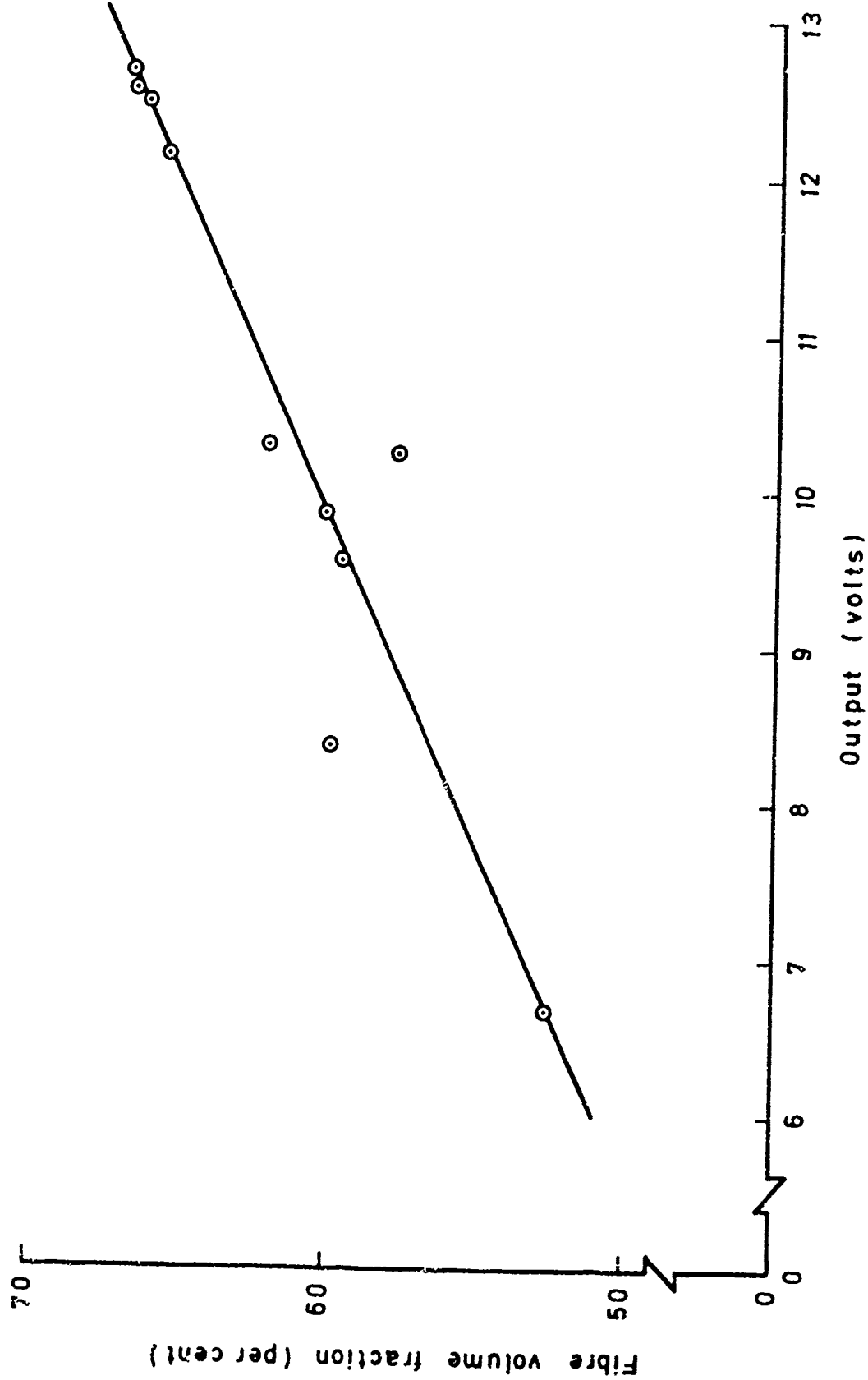


Fig.14 Variation of output with fibre volume fraction of cross ply CFRP

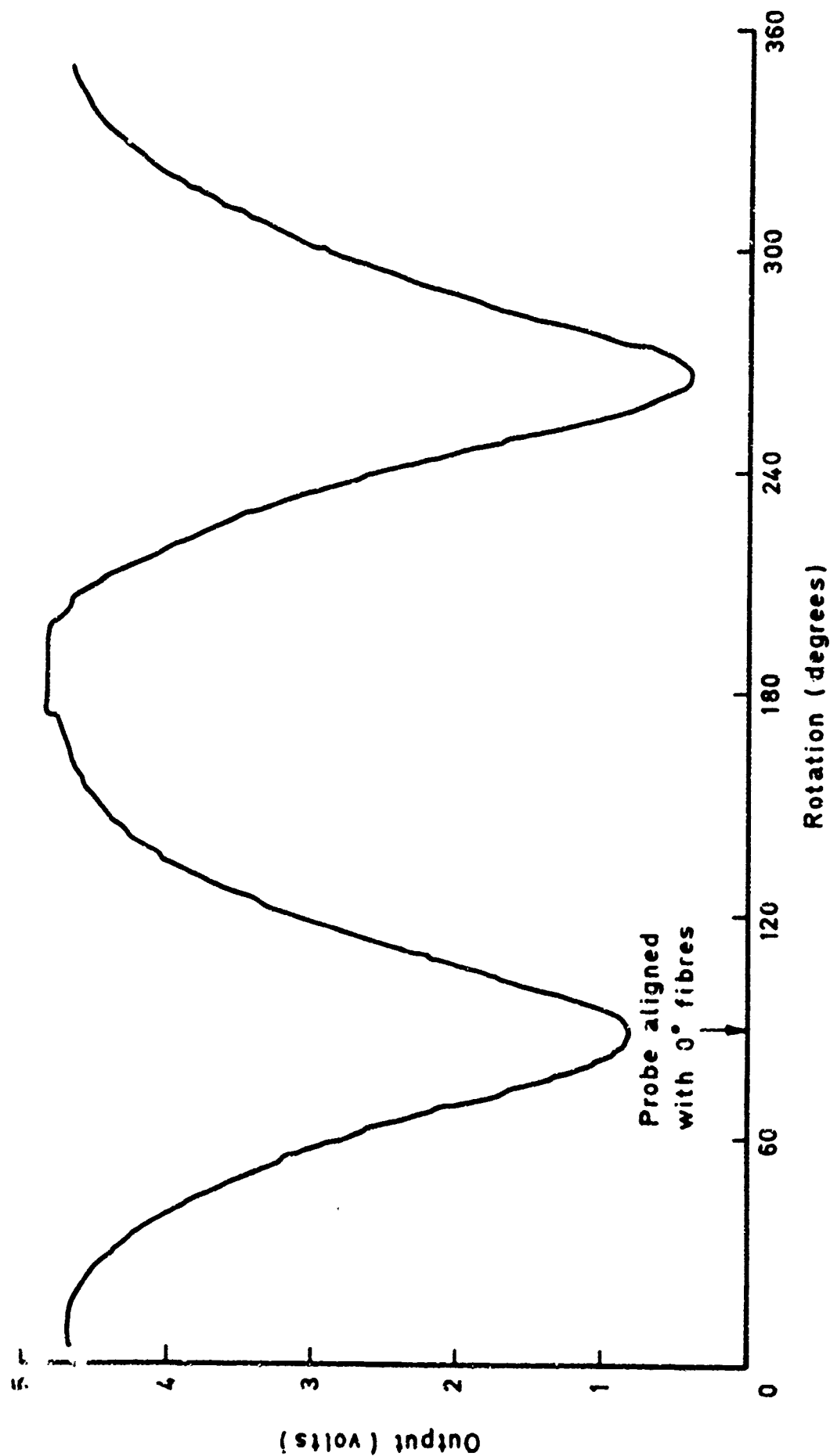


Fig.15

Fig.15 Scan of unidirectional CFRP using horseshoe probe

Fig.16

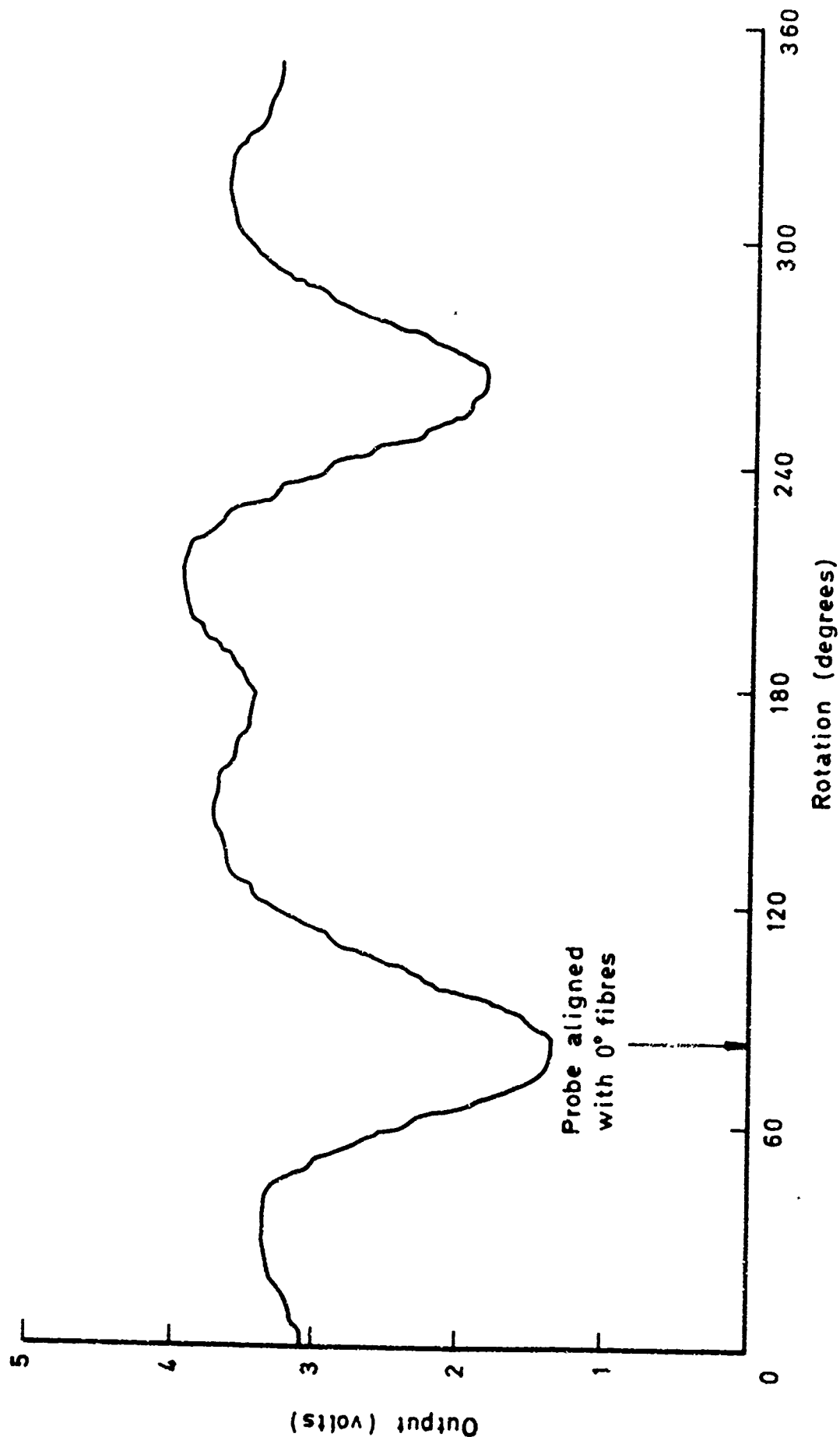


Fig.16 Scan of 0,0,0,90,0,0,0 CFRP using horseshoe probe

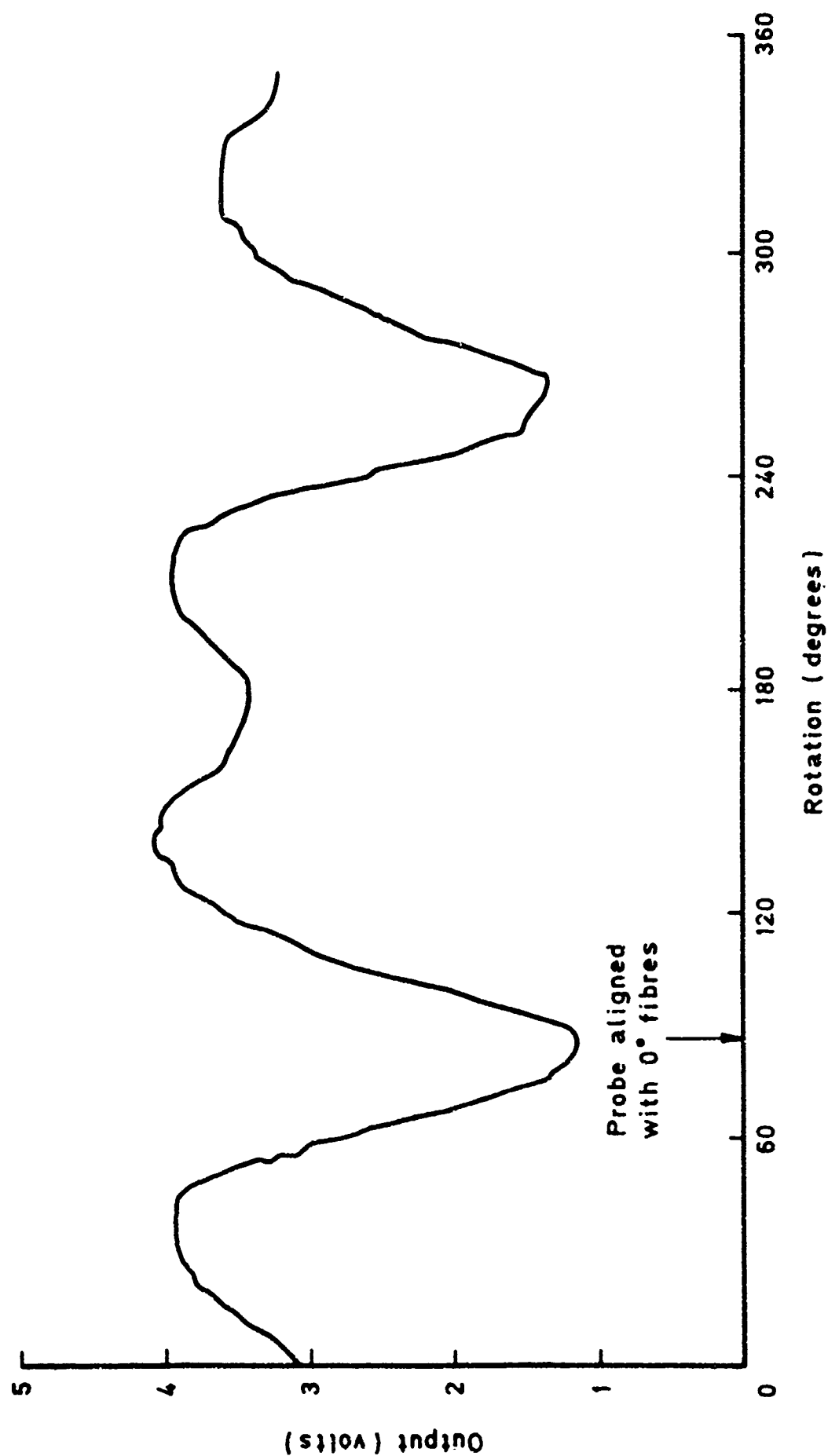


Fig.17

Fig.17 Scan of 0,0,90,0,90,0,0 CFRP using horseshoe probe

Fig.18

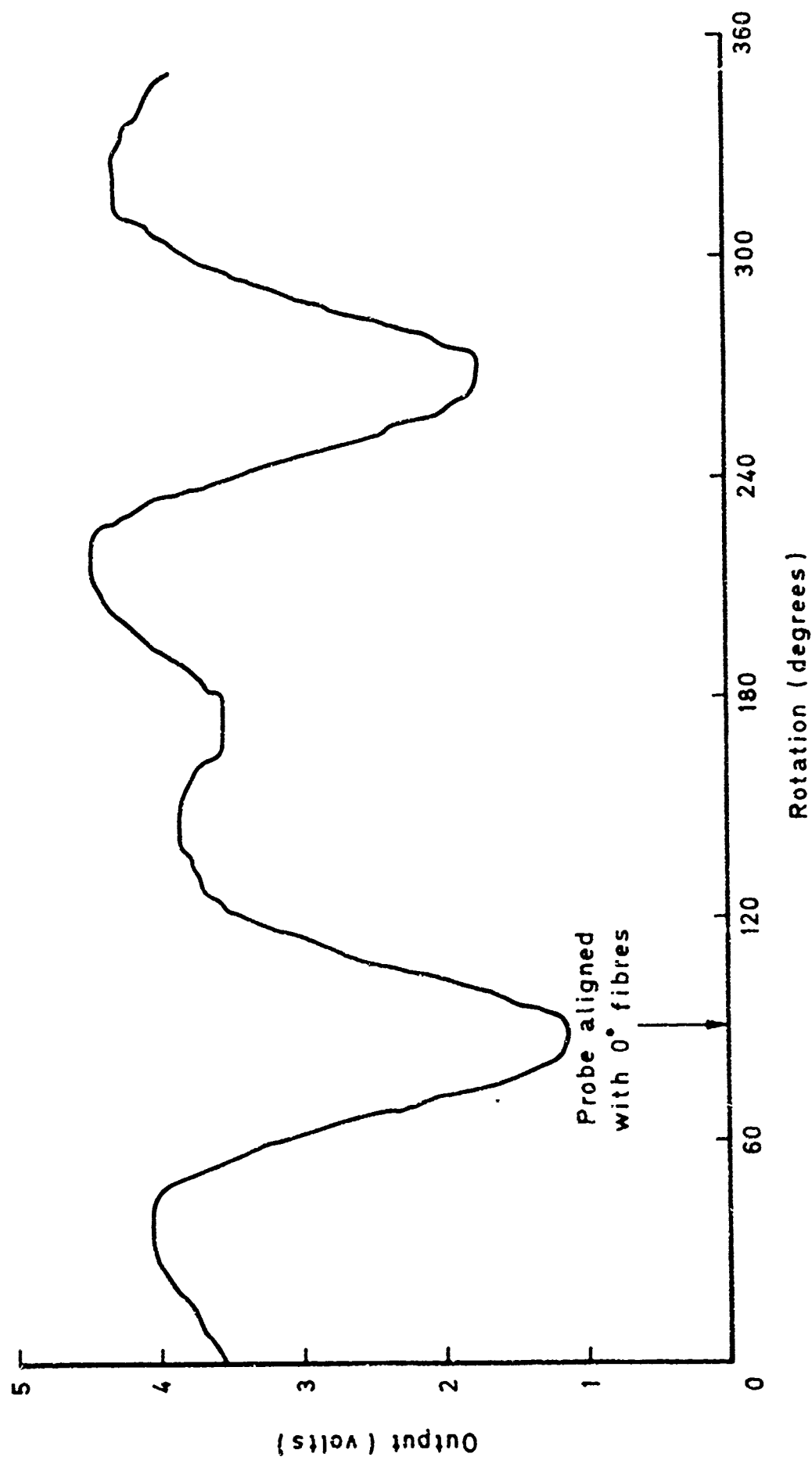


Fig.18 Scan of 0,0,90,90,90,0,0 CFRP using horseshoe probe

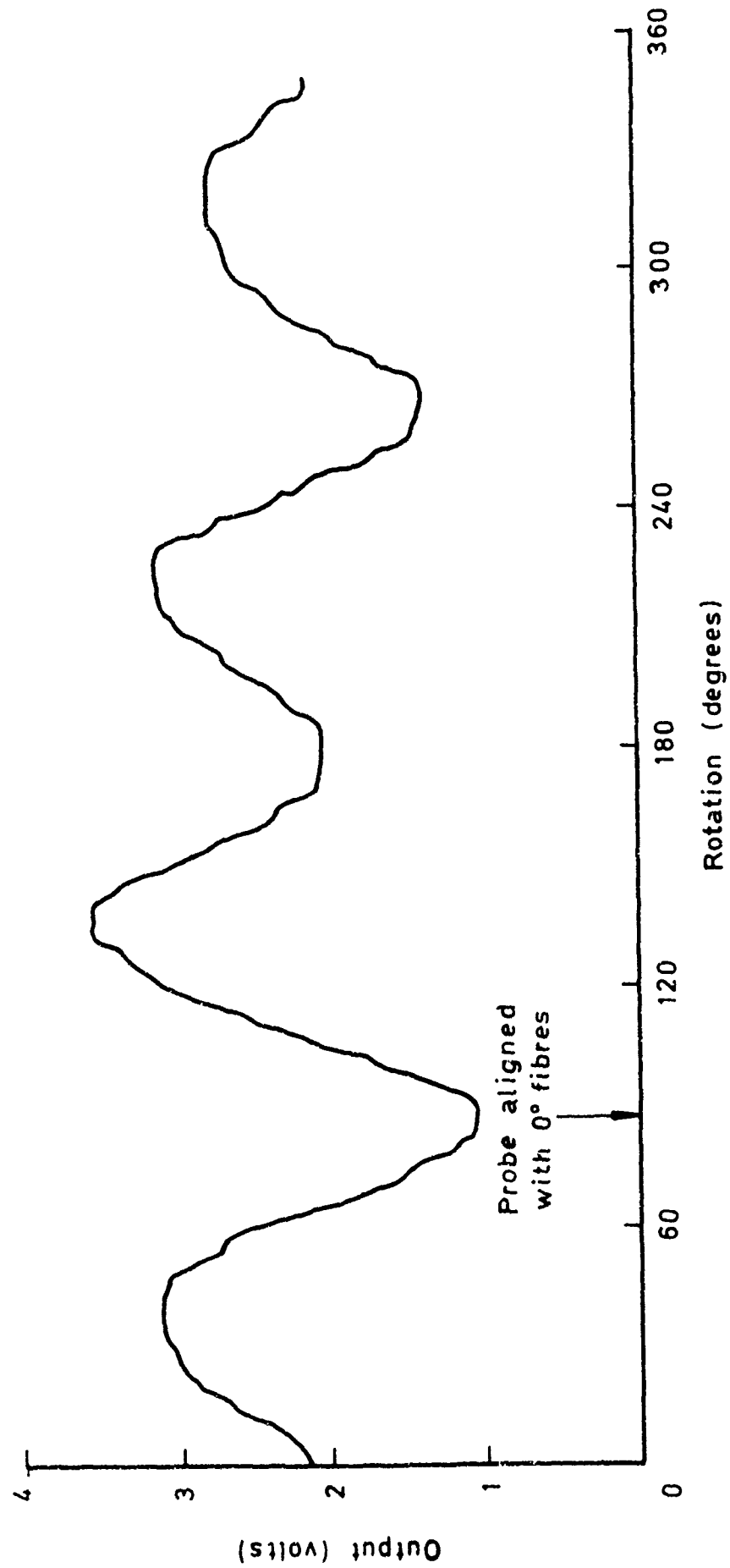
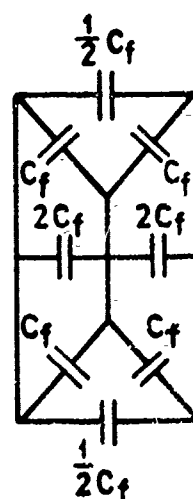
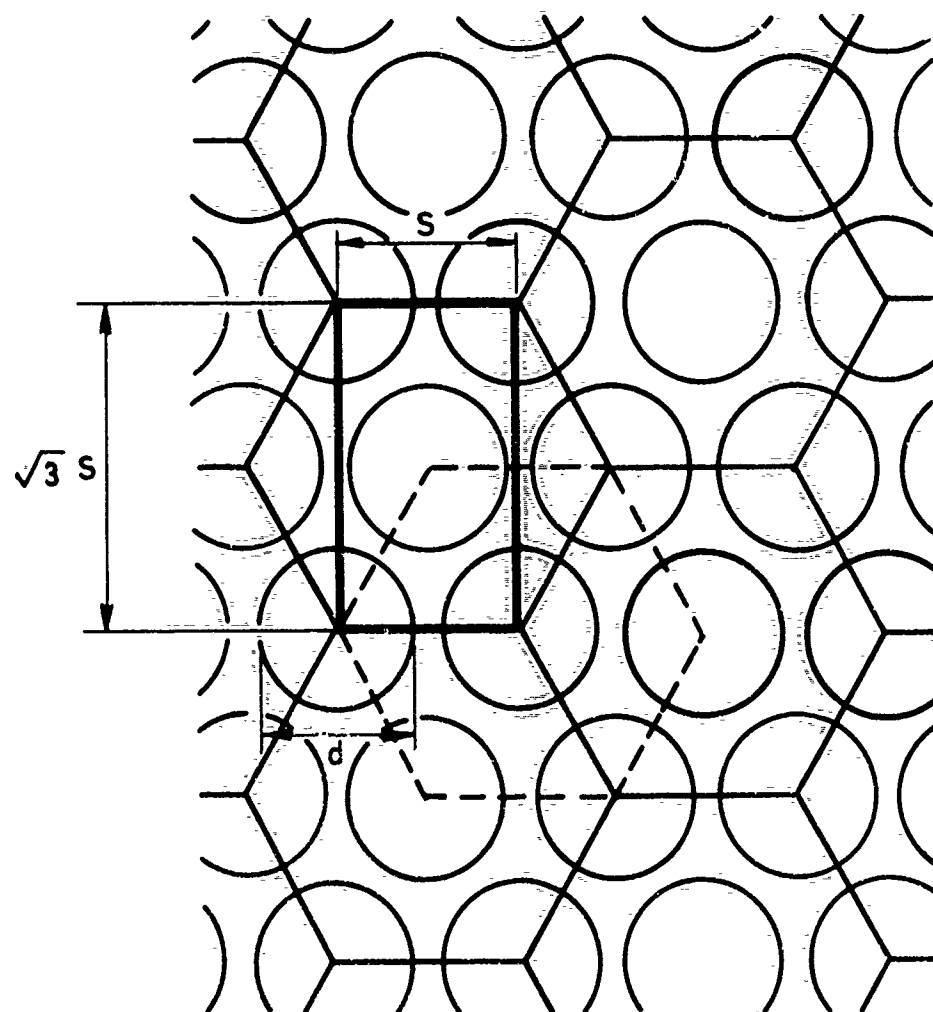


Fig.19

Fig.19 Scan of 0,90,0,90,0,90,0 CFRP using horseshoe probe

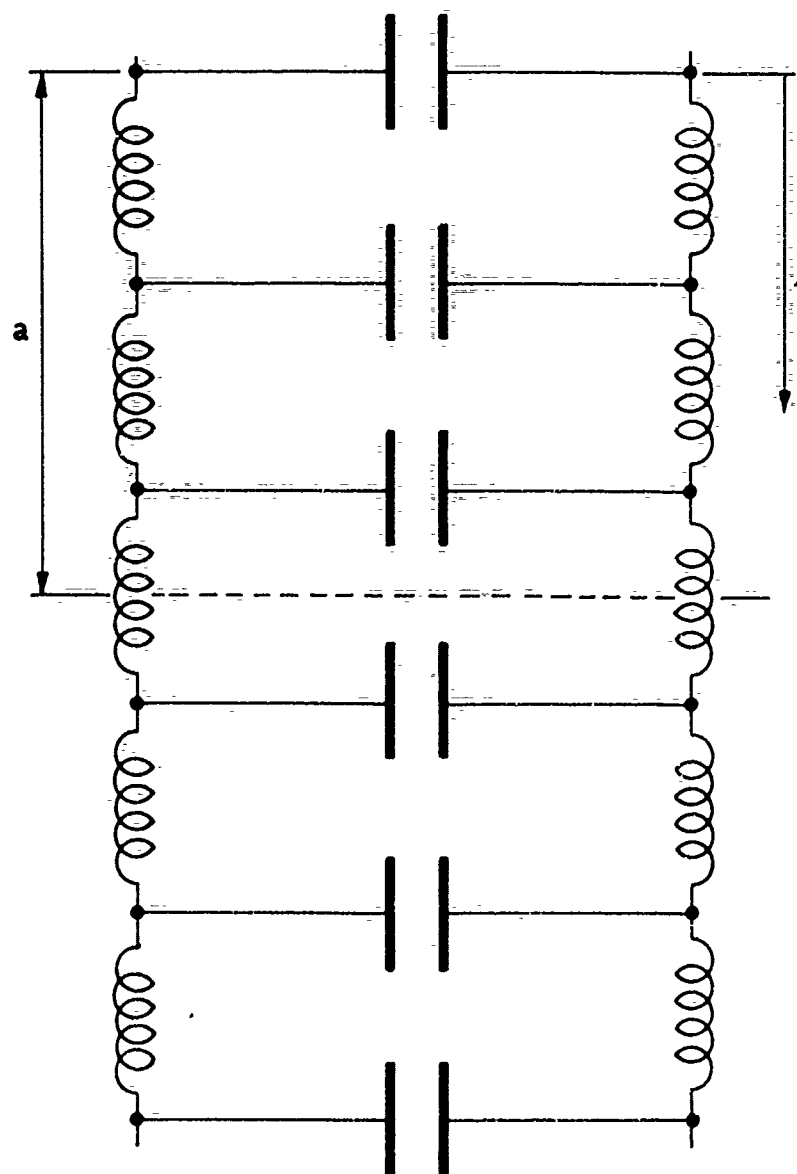
Fig. 20



Capacitance network
Equivalent to the unit cell

Fig 20 Hexagonal packing of fibres and the resultant capacitances

Fig. 21



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Fig.21 Eddy current path in CFRP

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNLIMITED

As far as possible this page should contain only unclassified information. If it is necessary to enter classified information, the box above must be marked to indicate the classification, e.g. Restricted, Confidential or Secret.

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7a. (For Translations) Title in Foreign Language			
7b. (For Conference Papers) Title, Place and Date of Conference			
8. Author 1. Surname, Initials Dingwall, P.F.	9a. Author 2 Mead, D.L.	9b. Authors 3, 4 ...	10. Date June 1976
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			Refs. 4
11. Contract Number N/A	12. Period N/A	13. Project	14. Other Reference Nos. Structures YSE/B/0617
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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST) Non-destructive testing. Composites. Eddy currents.			
17. Abstract The Report describes work on the non-destructive inspection of carbon fibre reinforced plastics (CFRP) laminates using an eddy current technique. Attention is drawn to the use of the technique for estimating the volume fraction of a laminate, including local variations in volume fraction, but it is shown that at present there are difficulties in the application of the technique as a routine NDT method for cross ply material.			