NATIONAL INSTITUTE OF OCEANOGRAPHY
WORMLEY, GODALMING, SURREY

The Performance of a Capacitance-Wire Wave Recorder

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Editorial note

Mr. Millard is a "sandwich course" student at the Portsmouth College of Technology, and did the work reported here during an industrial training period spent at N.I.O. He also spent a few weeks at sea, and so had about 5 months working on the wave recorder problem. He therefore did not have time to "tie up all the loose ends", but the results he obtained are of considerable interest and we felt that they should be put on record and made available for the use of others.

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ABSTRACT

A capacitance-wire wave recorder circuit was used in conjunction with a p.t.f.e. wire probe to establish what errors are associated with using such a system for the measurement of small waves. In the experiments the probe was moved relative to the water, rather than vico versa and both photographic and electrical methods were employed to investigate the errors introduced by the meniscus, the wetting of the wire and the effects of wire thickness on the wave shapes. The electrical methods involved accurate recording of the probe movement by means of a linear potentiometer and a comparison of this movement with the wave form produced from the circuit measuring the change in capacitance of the probe caused by its movement in the water. The effects of increasing the operation$ frequency of the recording circuit was also investigated.

Introduction

The capacitance-wire wave recorder under investigation is an instrument intended for the measurement of small waves such as might be encountered in wave tanks and models.

The principle behind its operation is that the inner-conductor of an insulated wire forms one plate of a capacitor whilst the insulation and the surrounding water form the dielectric and the other plate respectively. As a result, if the wire is placed normal to and intersecting the water surface, any change in water level results in a proportional change in capacitance.

This variation in capacitance is recorded by means of a circuit designed by Mr. M.J. Tucker at the National Institute of Oceanography (Figure 1). It consists of an oscillator tuned to its operating frequency by a bridge network of which the capacitance probe forms a part. The output from this bridge is suitably amplified and then fed, together with a reference voltage taken direct from the oscillator, to a phase sensitive rectifier. Because a change in the balance of the bridge, caused by the change of the probe capacity, causes the amplitude of the output to alter a d.c. voltage is obtained from the rectifier which, after suitable smoothing, is used to drive a recording instrument. The purpose of this series of tests was to assess, more accurately, the performance of wire-capacitance wave recorders - to establish their limitations and to appreciate the causes of their errors with a view to improving their design.

Test equipment and initial tests

The tests were carried out using a 'wave generator' which moved the probe vertically in still water rather than vice-versa. This method was considered unlikely to effect the results since inertia effects in the region of the meniscus are small and it allowed better repeatability control and monitoring of the waveforms. The wave generator consisted basically of a slide, onto which the probe was mounted, operated against a spring by a motor driven cam. Movements of this slide were monitored by means of a linear potentiometer operated by it. The wave shapes thus produced depended on the camshape and for these tests two cams were designed, one producing a sawtooth movement and the other a sinusoidal movement. Peak to peak amplitudes were kept constant at 7mm and the running speed of the motor was kept generally such that a repitition period of about 1·35 secs was maintained. (In the case of the sine cam this represented a wavelength of approximately 10cm).

In practice these recorders would sometimes be used to measure larger waves but it was felt that the errors involved would be of the same type only more significant with the smaller waves and thus easier to consider.

There are four main sources of error known. They are, (1) the errors introduced by the effects of the meniscus, (2) the absorption of water by the wire's insulation causing irregular increases in its dielectric constant, (3) the non-uniformity of the probe insulation and (4) the effects of the water's wetting action. Some previous work has been done of these effects (see bibliography) but with inconclusive results.

Initially probes were constructed using thin brass rods coated with various types of insulation, e.g. varnish, paint, p.v.c. sleeving and Vycoat Vinyl spray. Probes were also made of standard p.v.c., polythene and p.t.f.e. coated wires.

Preliminary tests were made on these probes by subjecting them to step functions by employing the sawtooth cam, arranged such that the fast rise of the sawtooth withdrew the probe from the water. Figures 2a and 2b show the results using the p.t.f.e. wire probe and the Vyspray coated rod respectively. The second of these probes had a coating of Vinyl spray 0·002 inches thick on a 0·125 inch diameter brass rod and the result obtained was typical of the better results obtained from the other forms of construction.

The p.t.f.e. wire used was produced by the Vactite Wire Company, its conductor size was 7/·0048 which gave a nominal core diameter of 0·015 inch. Its overall diameter was between 0·039 and 0·031 inches. This probe gave much superior results to the others and was thus selected for further testing.

The choice of p.t.f.e. wire overcomes the problem of water absorption and by using multiple lengths of wire (in this case it was 6) not only was the sensitivity increased but also the errors caused by non-uniformity of the insulation were reduced.

Calibration curves were produced statically for the probe when used in saltwater, tapwater and tapwater with a wetting agent additive. The measuring circuit used operated at 76kHz.

<u>The effects of meniscus</u>

Results obtained from oscillograms showing the output from the recorder as a function of time conveyed little information in themselves except that there was an obvious attenuation of the wave height and that there was, in some manner, a distortion of the shape. If however the output was displayed as a function of the input by placing them on the horizontal and vertical deflection plates, respectively, of the oscilloscope then a hysteresis curve resulted.

Figure 2c shows the output from the wave recorder with the probe operating in tapwater. The 'wave generator' displacement potentiometer (top trace) shows the displacement to be 7mm peak to peak whilst the recorder output (lower trace) suggests it was 5·6mm. Figure 2d is a typical hysteresis curve, corresponding to Figure 2c, obtained whilst the probe was operating in tapwater. The overall measurements are the same as in Figure 2c but, since the top of the curve represents the point of maximum immersion, the delay between the probe being withdrawn and the recorder following that movement is 1·45mm. At the point of minimum immersion the movement of the probe prior to the recorder following was 1·1mm.

The effects of adding 2‰ of a wetting agent to the tapwater is shown in Figures 2e and 2f. In this case the withdrawal delay is very unsure but the immersion delay is only 0·30mm. The peak to peak output would appear to be a little over 7mm but this could be caused by a slight error in calibration.

In order to explain the differences between these results and also the inability to produce any reasonable results in 35‰ saltwater (see Figure 2g) a film was taken at 64 f.p.s. of the probe operating in the three conditions.

The film showed that in tapwater the contact angle changes with the motion of the probe, from being acute as the probe was withdrawn to obtuse as the probe was immersed (the angle being measured through the water). During this period of meniscus reversal there is no effective change of water height on the probe and hence no associated change of capacitance. The meniscus height was measured from the film to be 1·4mm between being fully depressed and fully raised.

In the 2‰ solution of wetting agent the meniscus remained raised over the whole cycle with the exception of a short period around the point of maximum immersion where the meniscus was depressed as the level approached that point but was raised again as the water receeeded This is explained in Figure 3. The meniscus change in this case was measured to be 0·77mm and it occurred only at the one end.

The film of the probe operating in 35‰ saltwater was surprisingly very similar to that obtained of the previous test. This was attributed to contamination from the wetting agent on the probe and illustrated the necessity of thoroughly cleaning the probe with a suitable solvent before using it in a salt solution. There was what appeared to be a particularly thick film of water remaining around at least one of the wires as the probe was withdrawn. The meniscus measurement, which is probably reasonably valid, was 1·2mm. The oscillogram taken at the same time as the last piece of film is shown in Figure 2g.

These results seem to compare favourably with the delay values obtained from the hysteresis curves, i.e. a withdrawal delay of 1·45mm and an immersion delay of 1·1mm for tapwater which, from the film was shown to have a total meniscus change of 1·4mm at each end of the stroke. Subsequent results from salt solution hysteresis curves gave delay values of 1·1mm on withdrawal and 0·93mm on immersion which again compare with the 1·2mm observed on the film. This would tend to show that where wetting does not occur the only distortion is due to meniscus effects.

The effects caused by the wetting of the probe surface

Although one effect of wetting is to reduce errors caused by the meniscus, it also has the undesirable effect of producing unwanted capacitance changes in the probe as can be shown by the equivalent circuit shown in Figure 4.

Tucker in his paper suggested that if the resistance of this water film was sufficiently high compared to the impedance of the probe then it would be effectively isolated. This could be achieved by increasing the operating frequency of the recorder circuit. The limiting factor being that $\frac{R}{Z} < 0 \cdot 1$ where R is the resistance of the main body of water and Z the impedance of the probe.

$$\frac{R}{Z} = 10^{12} \rho k f \, [\log_e (2S/D_2)] \, / \, [1 \cdot 8 \, \log_e (D_2/D_1)]$$

where ρ is resitivity of the water

k is the dielectric constant of the insulation

f is the operating frequency

S is the effective distance between the earth connection to the water and the wire (assuming earth connection to be cylindrical and coaxial with the insulated wire).

D_1 and D_2 are the inner and outer wire measurements. Using the above equation and a typical value of ρ for tapwater the limit for the p.t.f.e. wire was calculated to be about 20mHz. For practical purposes this is too high but it was thought reasonable to increase the present frequency by a factor of 10 to approximately 1 mHz. This was achieved by altering the components to those indicated in Figure 1.

Obviously this wetting effect is much worse in saltwater owing to its increased conductivity. When using a clean p.t.f.e. wire probe in uncontaminated saltwater the wire remains unwetted and hence good results are obtainable. If, however, due to contamination, saltwater of 35‰ wets the wire the output bears little relation to the input with the 76kHz circuit (Figure 2g) and although there were definite signs of improvement using the 1mHz recorder (in fact 850kHz), the results were still unacceptable. Results were, however, considerably improved by using the higher frequency when tapwater was allowed to wet the probe. These improvements are best demonstrated in Figures 2h - 2n which were records taken at intervals after the probe was completely immersed in a wetting solution (2‰ of detergent in tapwater) and subsequently used in that solution. Figures 2h, i and j are results obtained with the 76kHz circuit whilst Figures 2k, l, m and n were obtained with the 1mHz circuit. It is interesting to note that during the drying period the probe goes through an optimum operating period from about 3 mins to 15 mins after wetting when using the 850kHz circuit.

Effects of wire thickness on wave shapes

The following tests were carried out using Lewmex coated wire. While it was appreciated that it had poor characteristics with respect to water absorption it was readily available and was considered suitable enough for the general comparison of the results obtained using it.

Probes were made of wire of 20, 28, 38 and 44 s.w.g. and were used in turn to obtain wave records using the 76kHz recorder circuit. It was immediately obvious that the shape of the output waveform improved as the thinner wires were used. Figures 2o and 2p show typical results obtained with the 44 s.w.g. wire. It was found that no appreciable difference was made in the results when the probe was operated in saltwater whether contaminated with a wetting agent or not. Any quantative measurements taken from these curves would certainly be inaccurate owing to the continually increasing dielectric constant of the insulation due to water absorption but they certainly seem to indicate that very little, if any, attenuation is suffered.

Using the equation for determining values of R/Z it was calculated that the limit for the operating frequency, using these Lewmex coated wires, was reduced by a factor of 10 to about 2 mHz owing to the change in value of D_2/D_1 and $\frac{S}{D_2}$. This means that part of the improvement observed with the 44 s.w.g. wire can be attributed to the fact that the probe was operating much nearer to its optimum frequency. The values were, however, similar for the other gauges of Lewmex wire and, as such, the test does still indicate that there is an improvement in performance brought about by the use of thinner wires.

Conclusions

The erros introduced by the meniscus reversing only become significant when the waves measured are small. This error is constant, for any one probe in a given solution, which should enable peak values of a wave form to be estimated, although the true shape of the wave is partially obscured. The amount of attenuation should have a maximum value of the distance between the meniscus in its raised and depressed positions. In tapwater it constitutes a 10% error in a 1·5 cm high wave which indicates only a 1·0% error with a waveheight of 15 cms.

From the results obtained using very thin wire it appears that problems of wetting and to a large extent, meniscus are overcome. The serious disadvantages being firstly its susceptibility to damage and secondly the unavailability of a suitable insulation material for wire so thin. Although during these tests there was not sufficient time available, a more thorough investigation might well reveal a suitable wire for the job.

The increase in the operating frequency of the recorder circuit was undoubtedly a step in the correct direction, but it needs to be increased considerably more to cope with the film of high conductivity solutions, particularly when using wires with relatively thick insulation to conductor ratios. The limiting factor in this case is not the value of R/Z, as has been shown, but that the length of the cable between the recorder and the probe becomes of the same order as the wavelength of the frequency used, resulting in resonance effects.

In general the design of a capacitance-wire wave recorder should incorporate a circuit operating at the highest practicable frequency, within the limit set by the value of R/Z, and the probe should be made, ideally, of a strong wire of comparable thickness to the 44 s.w.g. wire, with an insulation which exhibits properties similar to p.t.f.e.

Acknowledgements

The author is indebted to Mr. M.J. Tucker and Mr. R. Bowers for their valuable guidance and suggestions.

SCHEDULE FOR FIGURE 2

With the exception of a. and b. the top of the curves coincides with the point of maximum immersion. Also, where there are two traces, the upper is the waveform produced by the potentiometer attached to the wave generator (0·272 volts represents 1mm) and the lower trace is the capacitance-wire wave recorder output. (For the 76kHz recorder 76mV represents 1cm. For the 850kHz recorder 56mV represents 1cm, when used in conjunction with the p.t.f.e. wire probe.)

a. P.t.f.e probe operating in tapwater using 760kHz circuit.
Upper trace - 1·0 V/cm
Lower trace - 20 mV/cm
Time base - 0·2 secs/cm

b. 0·125 inch brass rod coated with approximately 0·002 Vinyl spray, operating in tapwater using 76·0kHz circuit.
Upper trace - 1·0V/cm
Lower trace - 20 mV/cm
Time base - 0·1 secs/cm

c. P.t.f.e. probe operating in tapwater using 76kHz circuit.
Upper trace - 1·0 V/cm
Lower trace - 20 mV/cm
Time base - 0·2 secs/cm

d. P.t.f.e. probe operating in tapwater using 76kHz circuit (asc.)
Horizontal deflection - wave generator - 0·2V/cm
Vertical deflection - capacitance-wire wave recorder - 10 mV/cm

e. P.t.f.e. probe operating in 2‰ solution of wetting agent in tapwater using 76kHz circuit (asf.)
Horizontal deflection - wave generator - 0·2V/cm
Vertical deflection - capacitance-wire wave recorder - 10mV/cm

f. P.t.f.e. probe operating in 2‰ solution of wetting agent in tapwater using 78kHz circuit.
Upper trace - 1·0V/cm
Lower trace - 20 mV/cm
Time base - 0·2 secs/cm

g. P.t.f.e. probe operating in 35‰ salt solution using 76kHz circuit
Upper trace - 1·0V/cm
Lower trace - 10 mV/cm
Time base 0·2 secs/cm

h. P.t.f.e. probe operating in 2‰ wetting agent solution using 76kHz circuit. Approximately 1 minute after wetting entire probe.
Upper trace - 0·5V/cm
Lower trace - 20 mV/cm
Time base - 0·2 secs/cm

i. Same as h. only 2 minutes after wetting

j. Same as h. only 10 minutes after wetting

k. P.t.f.e. operating in 2‰ wetting agent solution using 850kHz circuit. Taken 1 minute after wetting entire probe.

Upper trace	- 0·5V/cm	Time base	- 0·2 secs/cm
Lower trace	- 10 mV/cm		

l. Same as k. only 2 minutes after wetting

m. Same as k. only 3 minutes after wetting

n. Same as k. only 20 minutes after wetting

o. 44 s.w.g. Lewmex coated wire operating in tapwater using 1mHz circuit

Upper trace	- 0·5V/cm	Time base	- 0·2 secs/cm
Lower trace	- 20 mV/cm		

p. Corresponds to o.

Horizontal deflection - wave generator - 0·5V/cm

Vertical deflection - capacitance-wire wave recorder - 20mV/cm

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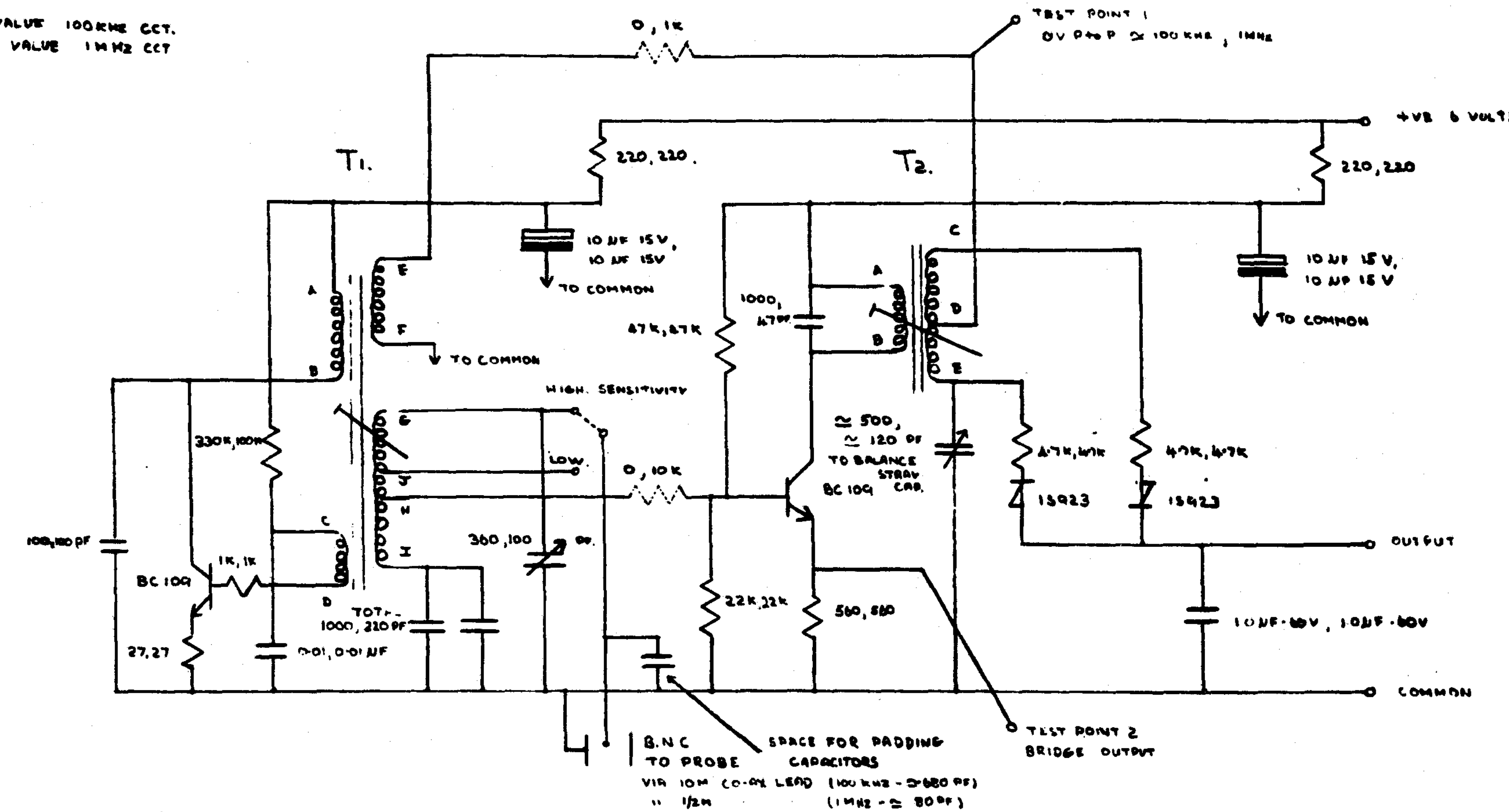
FIRST VALUE 100KHZ CCT.
SECOND VALUE 1MHZ CCT

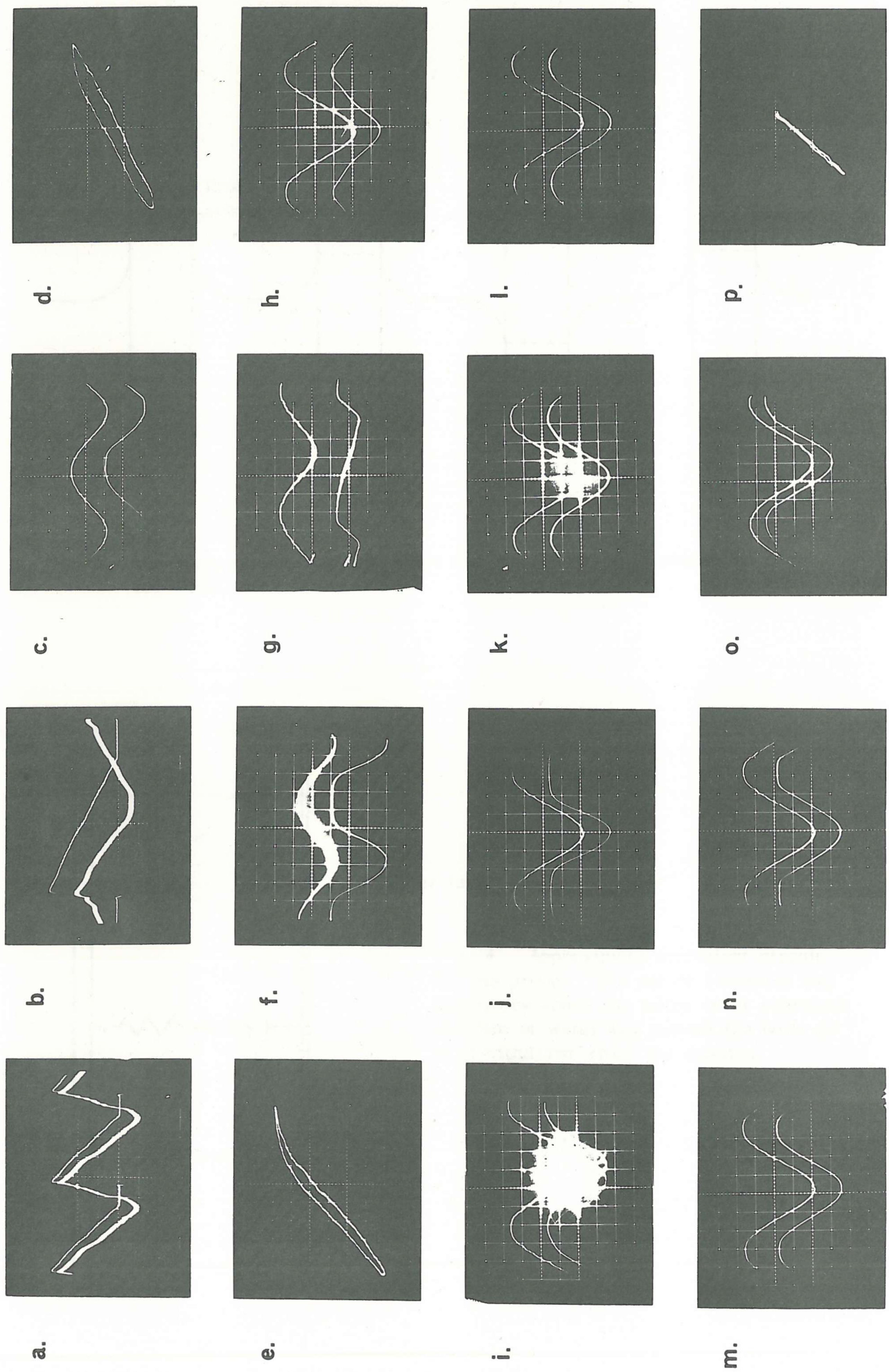


T1	100 KHz	1 MHz
A-B	80	10
C-D	4	5
E-F	40	12
G	START	START
J AT	80 }	15 }
H AT	80 } 300	20 } [illegible]
I AT	140 }	29 }

T2	100 KHZ	1 MHZ
A-B	100	67
C-E	200	133
D	C T	C T.

T1 AND T2 FOR 100 KHZ CCT - LA 2301 - 36 S.W.G LEWMEX COATED.
T1 AND T2 FOR 1MHZ CCT - LA 2508 - 30 S.W.G LEWMEX COATED.

Figure 2.



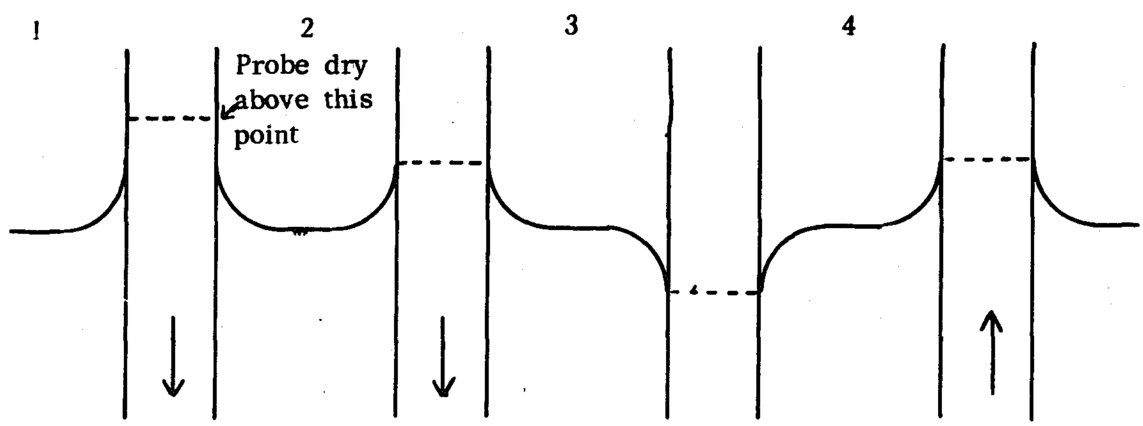


Fig. 3 Behaviour of the Meniscus when the probe surface is wetted by the water

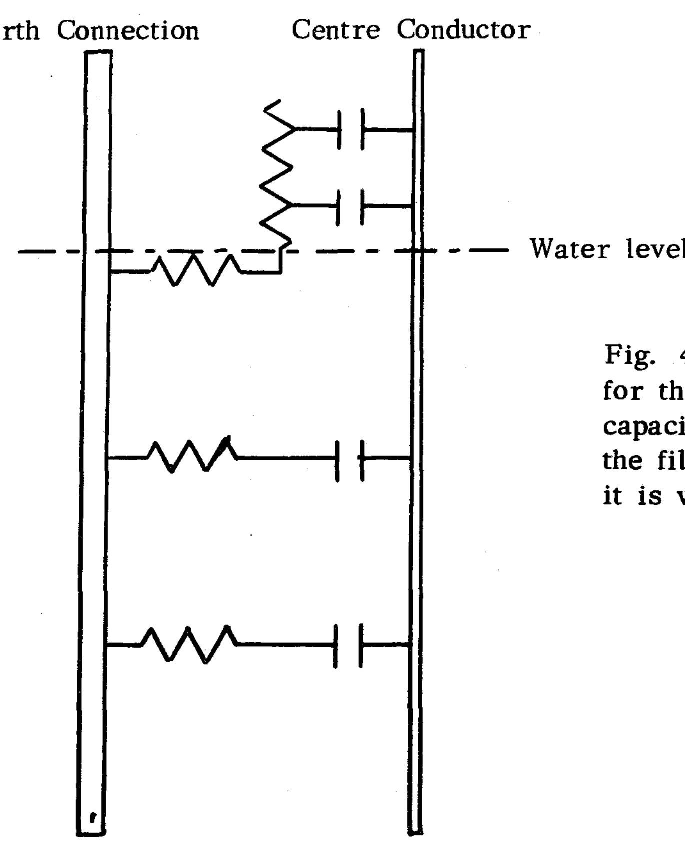


Fig. 4. Approximate equivalent circuit for the probe. The set of resistors and capacitors above the water level represent the film of water left around the wire as it is withdrawn from the solution.