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A DIGITAL

AMPLITUDE AND

PHASE MEASURING

SYSTEM (DAPHNE)

by

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MINISTRY OF AVIATION
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SUMMARY

A transportable automatic measuring and recording system has been designed and constructed for experiments concerned with oscillatory derivative measurements in wind tunnels. A "wattmeter" method is used to resolve the input signals in the frequency range 0·05 c/s to 1 kc/s into in-phase and quadrature components referred to the drive or other reference, and accurate measurement of frequency is made by an electronic counter. Results of these measurements together with reference data are automatically read out and printed. A punched-paper tape record is also produced for computation by a digital computer. This Report describes the equipment in a general manner and discusses some of the factors affecting accuracy. The system is adaptable for other work involving the measurement of the relative phases and amplitudes of a number of signals.

Departmental Ref: IR44

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CONTENTS (CONTD.)

1   INTRODUCTION

There are a large number of fields in engineering and technology in which transfer function and frequency response data is required, and a wide variety of measuring instruments have been produced to suit differing applications and techniques for presenting this data.   Measurements are usually made manually and sometimes large numbers of readings are required.   The time taken for obtaining data can be considerable, apart from being tedious.

Experiments involving work of this nature are performed in the Royal Aircraft Establishment in wind tunnels.   The time required to make and record each measurement can make tunnel running inefficient and costly if experiments are not tailored to keep this time down to a minimum.

This Report describes new automatic equipment which has been designed to improve the efficiency of this work.   At the same time, the design allows measurements to be performed on signals which are accompanied by large amounts of noise and other disturbances experienced under experimental conditions which previously made measurements impossible.   The equipment was designed specifically for use at R.A.E. Bedford, bearing in mind the potential requirements of other users within R.A.E. who were working on similar lines.

The system will, undoubtedly, have much wider applications, especially where amplitude and phase measurements are made on a sufficiently large scale to make the increased efficiency obtained by automation a significant economic consideration.

2   EXPERIMENTAL METHODS

The initial requirement was for a new system for R.A.E. Bedford. Before work commenced, a survey was made to ascertain which sections of R.A.E. were concerned with the measurement of the relative phases and amplitudes of different experimental quantities on oscillating models in wind tunnels, with a view to catering for other needs as far as possible.   Results of this survey are given in Table 1.

Oscillatory derivative measurement experiments have been in progress at R.A.E. Bedford for some time and this work, together with results, is fully described in Ref.1.   A large programme of further work using these proven techniques is now envisaged.   The following brief description of the experimental procedure hitherto used is intended to show the inadequacy of the old equipment for extended work.

2.1   Limitations of previous Bedford equipment for further work

Oscillations of a sting-mounted model are excited by means of a vibration generator which is fed from a variable frequency oscillator via a power amplifier.   The frequency is adjusted to be at or near to resonance and measurements are made on signals derived from transducers attached to selected parts of the model;   that from the transducer measuring primary motion being used as a reference.

Originally, the method of measuring the relative amplitude and phase in these experiments was to standardise the levels of each pair of signals by means of calibrated attenuators.   The signals were then added or subtracted to give a direct reading of phase angle on a specially calibrated rectifier-type voltmeter.   The quadrant of the measured angle was determined by noting the direction of the change of the meter deflection when additional phase-shift was switched in.   On each occasion that a tunnel experiment was conducted, equipment was assembled and interconnected.   Results of measurements were tabulated and preliminary computations were performed by hand prior to the manual transfer of data to punched cards for subsequent computation on a "Deuce" digital computer.   Occasionally, signals to be measured contained large amounts of noise or harmonics or had considerable variations in amplitude, and measurements of small phase angles became extremely difficult because the system of measurement gave the same reading for positive and negative angles, and fluctuations either side of zero made it impossible to estimate a mean value.

It can be easily appreciated that such experiments, which are being called for to an increasing extent, though yielding valuable results, require considerable equipment preparation, as well as extensive tunnel operating time when large numbers of readings have to be taken.

3   OBJECTIVES OF THE NEW EQUIPMENT

The new equipment has been designed to provide a self-contained transportable system to allow experiments of the kind which have been described to be performed more accurately and expeditiously and under adverse experimental conditions.

Reduction of repetitive experimental procedure to an automatic or semi-automatic routine, when large numbers of readings are required, will remove much of the tedious and time-consuming work which has hitherto been experienced. The design is aimed at minimising the possibility of human error such as

incorrect selection of signals, misreading of meter indications and the introduction of errors in manual data recording. Modular construction methods have been used to enable the equipment to be moved easily from one building to another.

4   METHOD OF AMPLITUDE AND PHASE MEASUREMENT

The algebraic summation method of measurement used in the manual experiments already described had proved to give adequate accuracy when input signals were free from noise and harmonics. When noise was encountered some of the limitations and inaccuracies mentioned were mitigated by the use of a tunable filter giving the phase-meter frequency-selective characteristics. This method did not lend itself to the automatic objectives of the present system. Alternative methods of measurement were, therefore, investigated. These included the use of phase-sensitive rectifiers, timing, and multiplicative methods.

The phase-sensitive rectification method is one in which the sense of the signal is reversed at every zero cross-over of the reference voltage. The mean value of the resulting voltage is dependent on the phase-angle, but this mean is affected by the presence of odd harmonics.

Timing methods involve the measurement of the times between corresponding zeros of the signal and the reference voltage. Noise and harmonics can produce serious errors in measurement.

In the wattmeter method, the product of the signal and a sinusoidal reference voltage is obtained. The mean value of this product is dependent on the phase-angle between the two voltages and is inherently independent of noise and harmonics in the signal. The mean may be obtained by filtering or by integration. A limitation of this method, especially at very low frequencies, can be the relatively long settling period between successive measurements due to the time constants of thermocouples and integrating amplifiers used in the measuring circuits.

Visual methods, using an oscilloscope, pen recorder or graph plotter were considered to be unsuitable. Results could not be automated, and such methods would certainly be considerably affected by noise and harmonics.

Each of these principles has limitations peculiar to particular applications. Bandwidth limitation, by filtering before measurement, could improve the accuracy of the phase-sensitive rectifier and timing methods under some conditions. It was decided, however, that as multiplicative techniques

met the important requirements without any additional measures, it was not necessary to pursue these possibilities. Analysis showed that the wattmeter principle was likely to give reasonably accurate r esults under moderately noisy input conditions and its inherent noise discriminating properties made this the most attractive method under adverse conditions. The requirements for inclusion in an automatic system could be met. The analysis is given in Appendix A. The choice remained between adapting a commercial phasemeter and the construction of a specially designed one. Investigations led to the evaluation of an instrument which had recently been developed. Results of this evaluation indicated its suitability for use in the proposed automatic system. The instrument is described in Section 5.2.3.

5 GENERAL DESCRIPTION OF THE AUTOMATIC SYSTEM

The block diagram, Fig.1, shows the general arrangement of units in the new system in relation to existing equipment typical of that used for oscillatory derivative experiments in wind tunnels. Figs.8 and 9 show the general front and rear views of the completed equipment.

Signals from transducers on the oscillating model are fed to a patch panel, and selected signals are connected one at a time via a filter to the resolved components indicator where phase and amplitude measurements are performed. D.C. levels representing the in-phase and quadrature components of the input signal are measured in turn by the digital voltmeter. The oscillator drives the model and provides the reference signals for the measurement of phase. The electronic counter measures the oscillator frequency. The digital outputs of the digital voltmeter and frequency counter, together with instrument range settings, and digitised reference data, are recorded by the teleprinter equipment. Signal selection, data read-out and printing operations are controlled by the control and scan unit. All measuring instruments give a visual indication of measurements made, and two oscilloscopes give visual signal monitoring facilities. The system is built in eight modules which can be easily disconnected mechanically and electrically to facilitate transportation.

5.1 Excitation of models

Oscillations are excited by means of a vibration generator which is fed from a variable frequency oscillator via a power amplifier. The model is sting-mounted and the mechanical arrangement is such that the model can have up to three degrees of freedom of movement. Fine adjustments of the drive frequency can be effected to tune the model to the resonant frequency of the

mode of oscillation it is desired to induce. By working near resonance, the forces required to maintain a suitable amplitude of oscillation are minimised. Transducers attached to the model give signals proportional to the acceleration or to the displacement in the planes of movement for which they are designed, and these signals are arranged to frequency modulate nearby oscillators. Some of the signals on which measurements are performed result from the demodulation and amplification of these signals by the FM units.

Artificial damping can be effected by selecting an appropriate model signal and manually adjusting its amplitude and phase and then combining the modified signal with the normal drive from the oscillator.

Selection of the required signal from the model is made at the patch panel (5.2.1) from where it is connected to the excitation unit (5.1.2). Here the amplitude and phase adjustments are made prior to closing the feed-back loop. To facilitate adjustments of the amplitude and phase of the signal to be fed back, the relationships of the input and output of the excitation unit can be monitored on either of the oscilloscopes described in Section 5.2.5.

A safety circuit is incorporated into the system to remove the oscillator drive if the model displacement becomes excessive. This feature is described in Section 5.1.2.

5.1.1 Oscillator

The front panel of this unit is shown in Fig.10. It is a Solartron Low Frequency Decade Oscillator, Model OS 103·3. It provides a four-phase sinusoidal output. Amplitude stability is achieved by a technique of squaring and limiting in the oscillator feedback network, and output level indication is by means of a thermocouple meter, which is designed to give a substantially steady response down to 0·01 c/s. The phases are balanced in amplitude to ±1% at frequencies from 0·01 c/s to 1 kc/s and the phase relationship between the outputs is accurate to ±1° over the entire oscillator range, which is 0·01 c/s to 11·1 kc/s.

A calibrated stepped attenuator will deliver rms voltages from 10 mV to 10 V, either balanced or unbalanced, into an impedance of 1 kilohm from the 0° and 180° phases. When the external impedance is very high, internal load resistors can be switched into circuit.

A single-ended continuously variable amplitude square wave at a maximum level of approximately 17 V peak/peak and at an output impedance of approximately 10 kilohms is available. The rise time is less than 1% of the periodic time at all frequencies.

A range of smooth frequency control of 0·15 to 0·4 times the setting
of the frequency range multiplier is obtainable, and over the frequency range
0·5 c/s to 1 kc/s the relative phasing error of the reference signals can be
set to less than 0·1°.

Modifications were made to the standard instrument to bring the outputs
to the rear.

5.1.2 Excitation unit

The front panel is shown in Fig.10.

An input signal derived from the model is fed to a phase-splitting
amplifier and is then fed by twin cathode followers to an RC phase-shifting
network. Coarse phase-shift is effected by switching in different capacitors;
fine control is by adjustment of a variable resistance. By reversal of the
paraphase connections to the phase-shifting network, the output can be made
to lead or to lag the input signal to the unit. The phase-shifted signal is
then fed to a cathode-coupled d.c. amplifier coupled to a cathode follower.
The amplitude of the output signal is continuously variable between zero and
250 mV when feeding a load of approximately 30 ohms for an input signal of
0·5 V rms. With the exception of one capacitor coupling from the phase-
shift network, d.c. coupling is used throughout the unit to preserve the low
frequency response.

An attenuator network in the excitation unit reduces the amplitude of
the signal from the oscillator and a fine control gives smooth variation
between the stepped attenuator settings of the oscillator.

For artificial damping (5.1) both the phase-shifted signal and the
attenuated drive from the oscillator can be applied simultaneously to the
power amplifier; alternatively, when artificial damping is not required the
phase-shifted signal can be switched out, in which case a dummy load
equivalent to the output impedance of the removed circuit is substituted in
order to prevent a step in the driving level.

The safety circuit referred to in Section 5.1 is contained within the
excitation unit, with the exception of limit contacts which are attached to
the model. Closure of the limit contacts due to excessive displacements of
the model result in the conduction of a thyratron, which operates a relay.
Contacts of this relay are arranged to disconnect the oscillator drive. If
at the same time the artificial damping loop has been completed, different
contacts of the same relay switch the gain of the feedback circuits in the

excitation unit to a maximum value, resulting in the application of a signal
to the power amplifier to give full positive damping of the model. The safety
circuit may be operated and reset manually by push-button switches on the front
panel of the excitation unit.

Controls affecting feedback signals to the model which are situated on
the front panel of the excitation unit, and which are set up before a run,
are protected by means of a transparent cover from accidental operation.

5.2 Signal selection, display and measurement

5.2.1 Patch panel

A front view of this panel is shown in Fig.11. It permits flexibility
of signal connections to suit experiments involving up to eight signal channels.
Input signals from the FM units and other sources are connected externally as
required. Screened leads and connectors are employed to minimise the possi-
bility of mutual interference and noise pick-up. Signals to be measured are
selected sequentially by dry-reed type relays situated behind the panel.
These relays are controlled either manually or automatically by the control
and scan unit, which is described in Section 5.7 of this Report. The
selected signal is fed via the input filter (5.2.2) to the resolved component
indicator (5.2.3).

Input connections to the tuning and display oscilloscopes (5.2.5) are
connected to this panel so that signals required for display purposes may be
patched, selected by push-button switches or scanned by reed relays. In the
last case the relays are controlled by the control and scan unit.

A centre-zero meter is provided for setting and checking d.c. levels
in the system.

5.2.2 Input filter

This is a low-pass filter which can be switched in or out of circuit
as required. As previously stated, the unit obtains its signal input from
the patch panel. It is included for use when the signals to be measured
contain unwanted components which are higher in frequency and larger in
amplitude than the basic signal. Such conditions are sometimes encountered
due to resonances of transducers. Large unwanted components would, if
unfiltered, necessitate reduction of sensitivity of the phase measuring equip-
ment in order to prevent overload. Overloading would destroy the inter-
ference and noise-discriminating properties of this instrument. Extreme
reduction of sensitivity would cause difficulties in resolution of the
measurements, especially at small phase angles.

An active filter was chosen for this low frequency application.
Passive filters at audio and sub-audio frequencies involve the use of high
quality inductors which are large, heavy and susceptible to hum pick-up.

The filter used[2] consists of a pair of cascaded cathode followers each
with two capacitors and two resistors wired in a low-pass filter configura-
tion. Each of the cascaded sections gives an attenuation slope of 12 dB
per octave.

The components which determine the characteristics of the filter are
wired on a plug-in circuit board to facilitate any changes which are required
from time to time to suit particular experiments. Fig.2 shows the measured
response of a low-pass filter designed to have a corner frequency of 20 c/s
and a damping factor of 0·6. Indication of the general design procedure
where different circuit or performance parameters of the same form are
required, is given in Fig.3.

5.2.3 Resolved components indicator (R.C.I.)

This unit is a modified Solartron instrument, type VP253·3, which
displays by means of two centre-zero 6 inch scale meters the 'in-phase' and
'quadrature' components of an applied a.c. signal voltage with respect to
the applied reference voltage.

The unit consists of signal and reference amplifiers which drive the
two bridge-connected thermocouple meters. The signal input is applied to a
precision attenuator and the succeeding balanced amplifiers supply signal
current to both meters. A four-phase reference signal derived from the
drive oscillator (5.1.1.) completes the input requirements. The $0°$ and
$180°$ phases drive the reference or in-phase meter bridge circuits; the $90°$
and $270°$ phases drive the quadrature meter bridge circuits.

Fig.4 gives the basic circuit of one of the "wattmeters". The
resistor arms are equal so the current in the upper thermocouple is $(I_r - I_s)/2$
and the current in the lower thermocouple is $(I_r + I_s)/2$. The thermocouple
elements are connected in series opposition and the voltage output is pro-
portional to the square of the current. Thus the voltage applied to the
meter is proportional to:-

$$\left\{ (I_r + I_s)/2 \right\}^2 - \left\{ (I_r - I_s)/2 \right\}^2$$

$$= I_r \cdot I_s$$

i.e. the product of the reference and signal. The thermocouple meters themselves are the phase detecting elements and have a response time of approximately two seconds.

The instrument is provided with reference and quadrature d.c. integrating amplifiers which may be switched into the circuits between the thermocouples and the meters by means of a three position switch on the front panel. The first position of this switch gives a direct connection between each of the thermocouples and the meters. The second position is for measurements in the range 1 c/s to 1 kc/s, giving a time constant of approximately 2 sec for both amplifiers additional to the response time of the thermocouples. The third setting of the switch gives a time constant of approximately 45 sec for both amplifiers and has been designed for use when measurements are made in the frequency range 0·05 c/s to 1 c/s.

Two independently switched gain settings of the amplifiers are available to give a X1 and X10 meter scale expansion. The X10 setting allows increased meter resolution for measuring small angles. When both the reference and the quadrature meters are switched to X10 expansion together with a corresponding increase of the input signal attenuation setting, the instrument will handle ten times more noise relative to the signal without overloading the signal input amplifiers. Outputs of the integrating amplifiers, which are unaffected by the meter expansion settings, are available for the connection of external equipment and these outputs are, in fact, used for feeding the digital voltmeter (5.3.2). When the integrating amplifiers are switched out of circuit the outputs for external equipment are not available.

Modifications have been made to the input attenuator of the resolved components indicator used in the system being described. These modifications have been made to improve the accuracy of the instrument and to provide electrical positional indication of this control for recording. These requirements have been met by (a) fitting resistors having tolerances of ±0·1% which replace those of ±2% which are incorporated in a standard instrument, and (b) by providing an additional bank to the attenuator switch wired to an additional connector on the front panel.

5.2.4 Reference resolver

This instrument, a Solartron model JX746, is designed for use with the resolved component indicator which has just been described. It simultaneously introduces 1° or 10° steps of phase-shift, with unity amplitude transmission, to each of the four quadrature channels of the reference system.

The instrument can be used to resolve a test signal into polar co-ordinate form, by shifting the phases of the reference signals, to zero the R.C.I. quadrature meter. The reponse is then available from the reading of the R.C.I. reference meter which indicates the amplitude, and the angle (in degrees) is displayed by digital indicators of the reference resolver.

The phase shifting properties of this instrument can be used to make allowance for known phase shifts which are in the test signal loop, but are not part of the system under test. Another application is its use as a backing-off source to facilitate the measurement of small angles.

5.2.5 Display and tuning oscilloscopes

Two cathode-ray oscilloscopes allow the simultaneous monitoring of signals in the system. One is for a conventional display requiring a time base, and the other is for the display of the phase relationship between pairs of signals in the form of Lissajous figures, no time base being used. The latter requires similar gain and phase characteristics for each of the X and Y deflection amplifiers.

These requirements have been met by using Solartron CD1183 oscilloscopes for each type of display. These are dual-trace instruments using plug-in modular sub-units, permitting a great flexibility of application and inter-changeability.

The main unit of each oscilloscope houses a single gun, split beam 10 cm diameter cathode-ray tube, calibration facilities for both frequency and amplitude, and power supplies.

Two types of modular deflection amplifiers are used. One is a wide-band unit (d.c. to 10 Mc/s) giving the instrument a sensitivity range of 100 mV/cm to 50 V/cm. Additional ranges allow signal measurements at increased sensitivity at reduced bandwidth. The other amplifier is a high gain differential unit (d.c. to 100 kc/s) with a sensitivity range of 100 μV to 2V/cm. Both amplifiers are interchangeable for Y_1, Y_2 or X deflection.

The time base unit, also of modular construction, has a range of 0·5μsec/cm to 5 sec/cm with additional expansion up to X10 and has comprehensive trigger and synchronisation facilities.

The display oscilloscope is equipped with one of each type of amplifier for Y_1 and Y_2 and a time base unit for horizontal deflection. The tuning oscilloscope has the same arrangement of units for Y_1 and Y_2 but the time base is replaced by a wide band amplifier to permit a Lissajous presentation. Input signals to both oscilloscopes can be selected at the patch panel (5.2.1).

5.3 Analogue to digital conversion

5.3.1 Output filter

A simple filter having alternative time constants is included between the selected output of the R.C.I. and the input of the digital voltmeter. Figure 12 shows the front panel. This unit provides additional smoothing by providing the choice of 10 sec or 20 sec time constants, which are values between the 4 sec and 45 sec provided by the R.C.I. Selection of the appropriate time constant is made by means of push-buttons and the filter may be switched out of circuit when not required.

5.3.2 Digital voltmeter

Digitisation of the resolved signals is performed by a Digital Measurements Digital Voltmeter Type D.M. 2001 Mk.2. This is a fully transistorised 5 digit instrument employing successive approximation techniques. Measurements are displayed on in-line edge-lit digital indicators. Modifications were made to "freeze" readings just prior to recording. Electrical outputs are in 1-2-4-8 binary coded decimal form. The polarity, digits and range setting are scanned externally for recording.

5.4 Frequency measurement

A square wave at the drive frequency is taken from the excitation oscillator (5.1.1) and is measured by a Rochar Type 1149 transistorised counter, chosen to meet the accuracy requirement of 1 part in 100 000. At low frequencies it is more convenient to measure the period of a number of cycles of the input rather than to measure frequency directly. The counter has facilities to select one or ten periods of input to gate timing pulses generated within the unit. The reading is displayed on digital indicators. Electrical outputs are in 1-2-4-8- binary-coded decimal form and each decade is scanned externally for recording.

Modifications were made to "freeze" the counter automatic reset just prior to recording and to inhibit printing until measurements are complete.

5.5 Tunnel and reference data

Tunnel data, relating to the conditions under which tests are performed, is often required to be recorded together with the results of special measurements. Typical tunnel data includes Mach number, total pressure, static pressure, tunnel temperature, model pitch angle, model roll angle, time, etc. In R.A.E. wind tunnels this data frequently exists in digital form from mechanical digitisers connected to the tunnel instruments.

The electrical form in which this data is commonly available is 16 bit Petherick code[3] representing four decimal digits for each quantity. When tunnel data is not available in digital form, it has to be obtained by reading instruments or control settings and provision is made when recording, for the manual setting of such quantities, usually referred to as run constants. Similarly reference data relating to a particular test has to be hand-set.

In the system which is the subject of this Report, a Petherick-to-binary-coded decimal converter is included in order to record existing tunnel data in standard form. The code converter is described in Section 5.5.1.

The constants unit dealt with in Section 5.5.2 gives the facility of selecting up to six items of digitised tunnel data or hand setting any of the six corresponding 4-digit constants, together with six additional reference data constants.

Each group of measurements together with accompanying tunnel and reference data forms a set of readings. Each set of readings is automatically given a serial number. This function is performed by the serial number counter described in Section 5.5.3.

5.5.1 Code converter

This is an internally mounted chassis which receives its input from tunnel data sources. The input consists of 16 input lines, each line representing one bit of a 16 bit Petherick word, corresponding to a four-digit decimal quantity. The data is translated to decimal by relays and then the four digits are encoded serially to binary-coded decimal by a diode matrix.

5.5.2 Constants unit

This unit is shown in Fig.14. The front panel holds 48 printed-circuit decimal thumbwheel switches which are arranged in twelve groups, each group consisting of four digits. Each switch has ten positions corresponding to the digits 0 to 9 and gives a binary-coded decimal output when the common input terminal is interrogated. Six groups have associated push-button switches to enable selection of individual hand-set tunnel constants or alternative digitised tunnel data sources. The remaining six groups are the reference constants which are always in circuit.

Relays mounted on the chassis of the unit allow serial read-out of the switch outputs, which are commoned through diodes. Sequential selection of each group is programmed in the control and scan unit.

5.5.3 Serial number counter

This unit is illustrated in Fig.13. There are four decades employing uniselectors for the counting elements, and indication of the state of the counter is made by illuminated digital displays. A trip pulse from the control and scan unit advances the units counter one digit after each set of readings. Reset push-buttons allow each decade to be set quickly to any required digit or the counter to be reset to zero.

Decimal data is read out serially by successive completion of circuits to appropriate banks of the uniselectors, controlled by the control and scan unit. Conversion to binary-coded decimal is performed by a diode matrix, external to the counter, which is shared by other units in the system.

A feature of this unit which is worth remarking on, is its ability to store readings during periods when the system is switched off.

5.6 Data recording

A simplified schematic diagram, Fig.5, shows the data recording sections of the system. Interrogation lines (connected to the various data sources, either directly or in some cases through data selection circuits in the print control unit) are scanned in sequence by the control and scan. Data is either available directly in, or is subsequently converted into binary-coded decimal form and is fed serially to the print control unit, where a parity bit is added automatically when required. Data is then in a suitable form for energising the code coils of the teleprinter. The control and scan inserts coding for special characters into the recording sequence, e.g. spaces, carriage return, line feed, etc., and controls the teleprinter via the print control unit. An example of a printed record is shown in Fig.6. Punched-paper tape is produced by an attachment which is mechanically coupled to the teleprinter.

5.6.1 Print control unit

The functions of this unit are:-

(a) To perform some of the sub-scan switching operations which are functionally part of the control and scan, but which are included in the print control unit to minimise the number of interconnections between modules.

(b) To energise the teleprinter code coils in accordance with the coded inputs when required.

(c) To convert binary-coded decimal data to Mercury code, a requirement for recording and subsequent data handling by the computer.

(d)   To control printing operations in association with the control and scan.

Function (a) is performed by relays which are in turn controlled by the control and scan to select and interrogate outputs of the frequency counter, R.C.I. attenuator and digital voltmeter.   (Other data is selected directly by the control and scan.)

Functions (b) and (c) are combined by four relays.   Binary-coded decimal inputs on a common highway have insufficient power to energise the coils in the recording equipment directly.   The four input lines are, therefore, fed to separate transistor amplifiers which operate relays according to the code when printing is required.   One contact of each of these relays connects a supply to the code coils of the teleprinter.   Other contacts are arranged to generate a parity bit (odd) when required, feeding the fifth code coil of the teleprinter.   Special printing characters, which already have the required parity bits, are connected directly to the code coils.

Function (d) is initiated by the control and scan.   Print command pulses which result from relay contact closures of the scan and sub-scan circuits of the system, control the circuits in the print control unit which performs functions (b) and (c).   At the same time these print command pulses energise a trip coil in the teleprinter to print the character or perform the printing operation required.

5.6.2   Teleprinter and paper tape punch

Data is recorded by a Creed Model 75 teleprinter fitted with a reperforating attachment.   This combination produces a written record, a typical example of which is shown in Fig.6, together with 5-hole punched paper tape in "Mercury Code" suitable for a data feed to a computer.

The teleprinter is controlled by the control and scan unit through the print control unit and its maximum recording speed is 10 characters per second. The maximum number of characters per line is 69 including spacing.   Special characters such as carriage return, line feed, space, letter and figure shifts, etc. are generated directly in Mercury Code and are not subject to the addition of parity.

The teleprinter keyboard can be operated to annotate data, in which case printing is in red.

The reperforation attachment may be switched in or out for either automatic or manual keyboard writing conditions. An automatic spooling device is used for the take-up of the punched tape.

5.7 Control and scan

This unit controls the automatic and manual selection of input signals to be measured; calls the various data sources in a programmed sequence; controls the serialising of the data outputs; and controls their recording, allowing a preset time delay between some items of recorded data to allow settling time of the measuring instruments where long time constants might be involved. The unit also generates most of the coded printing characters and print instructions to give a particular printed format. The design allows considerable flexibility and, in principle, its scope can be extended for systems having a larger number of input channels.

5.7.1 General principles of scanning method

A fixed programme is pre-determined by the connection of circuits to appropriate solder tags which are arranged in groups, one group for each line of the printed record (Fig.6). The programme is scanned using three uniselectors, each of which has a specific function. USA in effect scans one line of tags at a time, delegating sub-scanning of repetitive data patterns to USC. USB determines which line is scanned and, therefore, which one of alternatively available scan and sub-scan routines is appropriate to that line. Fig.7 is a schematic diagram to illustrate the principle which is now enlarged upon.

The contacts of uniselector USA-bank 1 are connected to the corresponding numbered solder tags of each line group, i.e. tag 1 of the tag groups for lines 1, 2, 3, ...N are electrically commoned with tag 1 of USA. Similar connections are made between the line tag groups and USA for all the tags numbered 2, 3, 4, ...50. Circuits which determine the programme are connected to the appropriate line tags and are completed through various banks of USB or through contacts of relays controlled by USB according to the line being recorded. Isolation of programming circuits having common paths through USA, is accomplished in some cases by diodes, in other cases by relays or a combination of relays and diodes. The use of common circuits allows a single bank of USA to perform all the line scanning, otherwise direct isolation would necessitate the use of one bank of USA for each line of scan or the employment of a large number of relays, not practical propositions for

a multiple line data recording system of this kind.   Silicon diodes are used
in order to maintain high resistance back-paths, an important consideration
where large numbers of diodes are employed.

Uniselector USA scans each line group until it reaches a programmed
reset.   This results in the reset of USA to tag 1 and the advancement of USB
by one step ready to select circuits for the next line.   Where a repetitive
pattern of data or print instructions is required, a sub-programme is auto-
matically called by USA scan, in which case USC takes over from USA and hands
back again when the sub-programme has been scanned.   Two banks, in fact, of
USC are employed in the system to give differing sub-scan routines.

Uniselectors USA and USB have electrical interlocked resetting facilities
employing additional banks.   Reset is prevented whilst USC is occupied in a
sub-scan.   The main and sub-scan uniselectors are arranged in a self-stepping
circuit.   These circuits are not shown in Fig.7 as their inclusion would
unnecessarily complicate the diagram.   Timing is controlled entirely by
relay contact closure time.   Resetting of the uniselectors is by a conven-
tional self-stepping and home-seeking method.

5.7.2   Control facilities

Fig.12 shows the control panel of the unit, which has facilities for
controlling the automatic scan and recording cycle and for the manual
selection of individual signals for measurement or observation.   Monitoring
facilities are provided to give visual indication of the progress of the scan
for operational and maintenance purposes.

In Section 5.7.1 the general principles of the line-by-line scanning
method have been described.   The scanning sequence used in the completed
system will now be described in greater detail.

Each run is initiated by pressing the 'record' button.   USA steps to
produce a short length of blank tape, allowing each set of data on the punched
paper tape to be separated from the previous run.   As no typewritten record
is produced, this line has been designated 'Line 0'.   At a set point of
Line 0 scan, the teleprinter is given 'new-line' instructions and a 'trip'
programmed into the scan resets USA and steps USB one step.   Line 1 is then
scanned by USA to call, interrogate and print the serial number counter state,
and then to print the mode A, B, or C according to which of the corresponding

push buttons has been selected.*   The tunnel parameters or the first six constants groups, if selected, are then called, frozen where necessary and interrogated in sequence.   Printing and spacing of this data is dealt with by a sub-scan of USC.   New line and trip set the scan ready for Line 2.

Line 2 is composed of four digits representing tunnel time followed by the settings of the remaining six constants groups, ending again with new line instructions.

At the beginning of Line 3, the scan will call the frequency counter but will not continue to interrogate and print until the counter has completed its measuring cycle.   Reset of the counter is inhibited, and when the count is complete the scan continues to interrogate and record the digits serially, again ending with new line instructions.

Up to this point of the scan, any of the oscillatory inputs to the system can be selected and measured manually by the phase measuring equipment. Selection of the required signal is made by operating one of eight push buttons;   a further push button determines selection of the measured in-phase or quadrature component, the reading of which is displayed on the digital voltmeter.   This facility allows an operator to perform any necessary final adjustments, or to make observations, with respect to a particular signal channel whilst the reference data is being recorded, thereby minimising the time of a run.   The scan will not continue until the 'Auto' push button is depressed, cancelling any manual setting and automatically selecting the first signal to be measured.   The scan will then continue to record either after a period set by the time delay or by operation of the 'Record' push button.   Whilst the automatic mode is selected the scan is programmed to select each of the input signals in turn, select alternately the in-phase and quadrature components, wait for the period set by the delay and then print the range settings of the R.C.I. and digital voltmeter together with the result of each measurement.   New line and spacing instructions are inserted at appropriate points.

Progress of the scan is indicated line-by-line by lamps and the oscillatory signals being measured are indicated by digital indicators showing 1P, 1Q, 2P, 2Q ....8P, 8Q.

At any time during the automatic scan of these quantities, manual selection of any particular signal can be initiated.   If manual selection is made during the course of recording a measurement, the scan will continue

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* A, B and C relate to the three possible modes of model excitation; the required mode for a run is selected by adjustment of the excitation frequency.   The order in which the signals are selected for measurement, with automatic annotation of the record, depends on the manual selection of the appropriate mode switch.

to finish printing out the result before the manual selection is effective. The scan will then stop and will not continue until the automatic mode is reselected, thereby ensuring that measurements are always recorded in their programmed order.

If measurements are required only on a limited number of the available input channels, the scan can be terminated at the end of Lines 5, 6 or 7.

A facility is included to produce special signals at the end of a series of runs to indicate the end of data to the computer and to indicate the end of tape to an operator handling the tape. End of tape signals can be selected at any time during a run and selection is automatically cancelled after they have been recorded. Cancellation can also be performed manually.

At the end of each run, or whenever a scan is manually reset, the serial number counter is automatically advanced by one digit.

5.7.3 Time delay sub-unit

The time delay referred to in paragraph 5.7 is controlled by a specially designed transistorised counter arranged to operate a relay after a time period selected by illuminated push-button type switches on the control panel. Until the delay period is called by the scanning programme, all the counter stages are held in a zero state. The start of a delay is initiated by the scan, which releases the zero hold, allowing the counter to operate on an input consisting of 1 sec pulses from the frequency counter. The time delay control switches connect the appropriate binary stages of the counter to an 'AND' gate which gives an output pulse when the counter state corresponds to the delay time which has been manually set. The gate output is arranged to operate a relay, which allows the scan to proceed. The time delay counter is automatically reset and remains in this state until called again by the scan.

The counting capacity of the time delay counter used is 63 seconds, governed by the use of six cascaded flip-flops. The delay period is the sum of the switched periods (1+2+4+8 ...... sec) which have been selected.

The time delay can be over-ridden by the manual operation of the 'Record' button, also the delay period can be made infinite, by switching, when it is required to hold a measurement for an indefinite period.

Power for this unit is obtained from an external outlet of the frequency counter.

5.8 Power supplies

Power for the equipment is obtained from a single phase 230V 50 c/s mains supply brought in at a panel fitted with a breaker-switch and fuse. Distribution to the various units is provided for within the rack wiring, including outlets for external ancillary equipment. Internal 13 amp sockets permit the easy removal of units requiring a mains supply, all of which are terminated with fused plugs.

A 1 kVA a.c. voltage stabiliser feeds the oscillator, reference resolver and resolved components indicator, to allow their use under tunnel conditions when loading of the mains supply can result in mains variations outside the normal limits specified for these instruments.

24V and 50V d.c. supplies are provided by mains rectifier units fitted within the equipment. Both units are fitted with electronic voltage control and cut-out facilities. They feed all relay and uniselector circuits and have sufficient reserve to operate additional external equipment if required.

Two HT power supply sub-units, fitted with voltage regulators and an interlock circuit, are installed in the excitation module to provide positive 250V, negative 250V and valve heater supplies for the excitation unit and input filter.

5.9 Cooling

The module containing the oscilloscopes is fitted with an extractor fan to assist cooling. The module containing the oscillator, HT power supplies, excitation unit and input filter is cooled by a blower, circulating air within the module. Both fans are mains operated. All modules in the system have louvred panels fitted where required for normal convection cooling.

5.10 Mechanical construction

To facilitate movement of the whole equipment, the console has been constructed in modular form and it can be quickly broken down into eight units after disconnection of the external interconnecting cables, all of which are marked for identification. A drawer is provided for their stowage. All fixed cable terminations are mounted on recessed panels at the sides and back of the modules to minimise possible damage during transit operations.

The desk unit is removable and all front wiring is in a harness within trunking which is removed as one item.

Modules can then be removed, lifting handles being provided. Where one module stands on another, the two are merely located by dowels. Trolleys are provided for use when modules have to be moved some distance.

6   SYSTEM ACCURACY

In a system of this type there are a number of sources of possible error, some of which may be summarised:-

(a) Noise and unwanted signal components.

(b) Inequality of reference signal amplitudes.

(o) Imprecision in 90° phase shift between the reference signals applied to the in-phase and quadrature measuring circuits.

(d) Phase shift and non-linearity in amplifiers.

(e) Errors in multiplication.

(f) Attenuator errors.

(g) Drift

(h) Errors in subsequent analysis.

The main sources of error are analysed in Appendix A. The effects of many can be reduced by suitable equipment calibration and others will tend to cancel out.

Precise or concise statements of accuracy are difficult to make with confidence to cover all conditions of operation. Certainly the accuracy of the various pieces of equipment used is a most important consideration but is by no means the only factor.

A summary of the relevant performance specifications of instruments used in the system is given in Appendix B. Further information can be found in the appropriate manufacturers' handbooks.

6.1   Measurements of accuracy

Comprehensive measurements to determine the accuracy of measurements under varying conditions were not possible prior to the initial wind tunnel tests mentioned in Section 7 of this Report, due to requirements to assess the general performance of the system. One test, however, was made using the equipment, to ascertain the performance of the input filter which is described in Section 5.2.2. The test is briefly described here, since it indicates the order of relative accuracy that may be expected under typical conditions of use.

The object of the tests was to confirm that the amplitude and phase responses of the input filter were the same, with or without accompanying

noise, also to check that any small phase shift of the system up to the output of the filter was constant when signals were fed through different FM channels.

A double-ended transducer, which gives outputs exactly in-phase, was attached to a calibration platform which was excited by two signals of different frequencies simultaneously. One of these signals at approximately 7 c/s was the main drive for the calibration platform, and the other was at the resonant frequency of the transducer, at approximately 80 c/s. In this way, typical transducer output signals to those obtained under wind tunnel conditions were simulated in a laboratory. The drive level of the higher frequency was adjusted so that the corresponding transducer output was ten times that of the lower frequency signal. Each of the double-ended transducer outputs was fed through a different FM channel, and successive phase measurements, using the lower frequency as a reference, were made with the input filter in circuit. The higher frequency drive signal was then removed, and measurements were repeated both with and without the input filter in circuit.

Measured phase angles under all these conditions were within 0·2°, and it was assessed that up to 10 times greater accuracy was attainable compared with measurements of a similar nature, using previous instrumentation. This shows that the equipment goes a long way to meeting the requirements under adverse conditions.

7   PERFORMANCE

The equipment described in this Report has been completed and it is now in service at R.A.E. Bedford.

The standard of engineering has proved adequate to stand up to considerable transportation and movement and the mechanical design effort to facilitate its use in various buildings has been fully justified.

Calibration of new tunnel equipment has been carried out using this automatic equipment and a series of experiments on a model has already taken place in a wind tunnel. Results are at the present the subject of detailed analysis. Confidence of the continued reliability of the equipment is high.

Measurements have been made on signals of various kinds, from good sine waves to very noisy signals. In the worst cases, the signal was of the order of 10 mV with unrelated, unwanted signals of ten to a hundred times the signal. No difficulty was experienced in taking readings.

8   <u>CONCLUSIONS</u>

    Although it will be some time before a full appreciation of the capabilities of this instrumentation under all conditions of use can be fully assessed, it promises to fulfil in a large measure the objects which were in view at the outset of its design, and the system should be capable of extension for other applications.

Appendix A

ERROR SOURCES

(See Section 6)

In the remarks on System Accuracy, a number of possible sources of error were listed. These are now considered in more detail.

A.1 Noise and unwanted signal components

For the purposes of analysis the basic experimental signal may be taken to be

$$y' = a \sin(\omega t + \phi) + b \sin(n\omega t + \varepsilon) + c \sin(\nu t + \gamma) + d$$

where the second term represents the harmonic content, the third term noise, the fourth a d.c. component and the reference signal is $y = \sin \omega t$.

In a wattmeter instrument the product yy' is formed.

$$yy' = a \sin \omega t \sin(\omega t + \phi) + b \sin \omega t \sin(n\omega t + \varepsilon)$$
$$+ c \sin \omega t \sin(\nu t + \gamma) + d \sin \omega t$$

$$= \tfrac{1}{2} a\{\cos \phi - \cos(2\omega t + \phi)\} + \tfrac{1}{2}b \{\cos (\overline{n-1}\,\omega t + \varepsilon) - \cos(\overline{n+1}\,\omega t + \varepsilon)\}$$
$$+ \tfrac{1}{2} c \{\cos(\overline{\nu - \omega}t + \gamma) - \cos(\overline{\nu + \omega}t + \gamma)\} + d \sin \omega t$$

so that the mean value of the product is $\tfrac{1}{2} a \cos \phi$. The remaining terms can be removed by mechanical or electrical filtering. Alternatively if the product is integrated over a (known) whole number of cycles of $\sin \omega t$, a voltage very accurately proportional to $\cos \phi$ is obtained.

A similar treatment can be used to analyse the case when the reference signal contains harmonics and noise, and shows that these only affect the mean value of the product when they are of the same frequencies as the harmonics and noise in the experimental signal; in this case, which will be common with harmonics, if the phases of the two components are ξ and ζ respectively there will be contributions to the mean proportional to $\cos(\varepsilon - \xi)$ and $\cos(\nu - \zeta)$. This case is particularly relevant when self-excitation techniques are being used.

If the experimental signal amplitude is varying and the signal can be represented by $y' = [a + x(t)] \sin(\omega t + \phi)$ then

$$yy' = [a + x(t)] \sin \omega t \sin(\omega t + \phi)$$

$$= \tfrac{1}{2} [a + x(t)] [\cos \phi - \cos(2\omega t + \phi)]$$

$$= \tfrac{1}{2} [a \cos \phi + x(t) \cos \phi - a \cos(2\omega t + \phi) - x(t) \cos(2\omega t + \phi)] .$$

The mean value of this expression is $\dfrac{1}{T} \displaystyle\int_{0}^{T} yy' \, dt$

i.e. $\tfrac{1}{2} a \cos \phi + \dfrac{\cos \phi}{2T} \displaystyle\int_{0}^{T} x(t) \, dt + \dfrac{1}{2T} \displaystyle\int_{0}^{T} x(t) \cos(2\omega t + \phi) \, dt.$

a can be defined so that $\dfrac{1}{T} \displaystyle\int_{0}^{T} x(t) \, dt = 0$ and for any $x(t)$ likely to be encountered the last term will be small.   If for instance $x(t)$ is periodic, it can be written $x(t) = \Sigma(a_n \sin nt + b_n \cos nt)$ so that the integral is zero.

Again if both amplitude and phase of the signal are varying,

$$y' = [a + x(t)] \sin[\omega t + \phi(t)]$$

and as before

$$yy' = \tfrac{1}{2} [a + x(t)] [(\cos \phi - \cos(2\omega t + \phi)]$$

$$= \tfrac{1}{2} [a \cos \phi + x(t) \cos \phi - a \cos(2\omega t + \phi) - x(t) \cos(2\omega t + \phi)].$$

If the phase angle is written $\phi = \phi_1 + \phi_2(t)$ and ϕ_2 is assumed small then $a \cos \phi \approx a \cos \phi_1 - a \phi_2 \sin \phi_1.$ ϕ_1 can be defined so that the mean value of ϕ_2 is zero, and then the mean value of $a \cos \phi$ is $a \cos \phi_1.$ Since once again a can be defined so that $\dfrac{1}{T} \displaystyle\int_{0}^{T} x(t) \, dt = 0$ the mean of $x(t) \cos \phi$ can also be taken as zero.   The third term in yy' can be written

$$a \cos(2\omega t + \phi) = a \cos 2\omega t (\cos \phi_1 - \phi_2 \sin \phi_1) - a \sin 2\omega t (\sin \phi_1 + \phi_2 \cos \phi_1).$$

In this expression the mean value of the terms not containing ϕ_2 is zero. The mean value of the remainder is small, since ϕ_2 is small, and is zero if ϕ_2 is periodic.   It remains to consider $x(t) \cos(2\omega t + \phi).$ The mean value of this is

$$\frac{1}{T}\int_0^T x(t)\cos(2\omega t+\phi)\,dt = \frac{1}{T}\int_0^T \{x(t)\cos(2\omega t+\phi_1) - \phi_2(t)\,x(t)\,\sin(2\omega t+\phi_1)\}\,dt.$$

The remarks made about the first term in this expression when it occurred in the previous case also apply here. The contribution of the second term is also likely to be small. ϕ_2 is small in itself and likely forms of $x(t)$ will keep the whole expression small. In particular, if $x(t)$ and $\phi(t)$ are both periodic the contribution will be zero. This can be seen if ϕ_2 is written as $\phi_2 = b\sin at$, when

$$\phi_2(t)\,x(t)\,\sin(2\omega t+\phi_1) = \tfrac{1}{2}\,bx(t)\,[\cos(\overline{2\omega-a}\,t+\phi_1) - \cos(\overline{2\omega+a}\,t+\phi_1)].$$

As in all the other cases discussed there will of course be particular frequency combinations which will yield a non-zero contribution from an expression like this. The probability of these occurring is, however, infinitesimal.

It thus appears that in all the cases considered the mean value of the product of the signal and reference voltages is the required basic signal, unaffected by noise, harmonics and periodic signal fluctuations. It should be noted, however, that some very low frequency signals may be superimposed on the mean if the frequencies of some of the disturbances are close to the signal frequency, or sometimes to one another.

A.2   Inequality of reference signal amplitudes
       Imprecision in 90° phase shift between reference signals
       Phase shift and non-linearity in amplifiers

These three potential error sources may be considered together. The reference voltages are nominally $V_1\sin\omega t$ and $V_1\cos\omega t$, but with these errors may in fact be $(V_1+\varepsilon_1)\sin(\omega t+\varepsilon_2)$ and $(V_1+\varepsilon_3)\cos(\omega t+\varepsilon_4)$ respectively, where the ε_i represent the appropriate errors, assumed small. The signal voltage is nominally $V_2\sin(\omega t+\phi)$ and may in fact be $(V_2+\varepsilon_5)\sin(\omega t+\phi+\varepsilon_6)$.

The products formed during multiplication are nominally $V_1 V_2\sin\omega t\sin(\omega t+\phi)$ and $V_1 V_2\cos\omega t\sin(\omega t+\phi)$ and are in fact, assuming for the moment perfect multiplication,

$$(V_1 + \varepsilon_1)\ \sin(\omega t + \varepsilon_2)\ .\ (V_2 + \varepsilon_5)\ \sin(\omega t + \phi + \varepsilon_6)$$

and

$$(V_1 + \varepsilon_3)\ \cos(\omega t + \varepsilon_4)\ .\ (V_2 + \varepsilon_5)\ \sin(\omega t + \phi + \varepsilon_6).$$

Consider the first of these products. It can be taken as approximately equal to

$$(V_1 V_2 + \varepsilon_1 V_2 + \varepsilon_5 V_1)(\sin \omega t + \varepsilon_2 \cos \omega t)[\sin(\omega t + \phi) + \varepsilon_6 \cos(\omega t + \phi)]$$

which can be further approximated to

$$(V_1 V_2 + \varepsilon_1 V_2 + \varepsilon_5 V_1)[\sin \omega t \sin(\omega t + \phi) + \varepsilon_2 \cos \omega t \sin(\omega t + \phi)$$
$$+ \varepsilon_6 \sin \omega t \cos(\omega t + \phi)]$$

or

$$(V_1 V_2 \sin \omega t \sin(\omega t + \phi) + (\varepsilon_1 V_2 + \varepsilon_5 V_1)\ \sin \omega t \sin(\omega t + \phi)$$
$$+ V_1 V_2[\varepsilon_2 \cos \omega t \sin(\omega t + \phi) + \varepsilon_6 \sin \omega t \cos(\omega t + \phi)]$$
$$+ \text{terms containing products of errors.}$$

The last term here can be rewritten as

$$V_1 V_2[\varepsilon_6 \sin(2 \omega t + \phi) + (\varepsilon_2 - \varepsilon_6)\ \cos \omega t \sin(\omega t + \phi)]$$

and it can then be seen that the effect of the errors on the mean value is to produce and error in the amplitude of amount $(\varepsilon_1 V_2 + \varepsilon_5 V_1)$ and to add to the mean a proportion $(\varepsilon_2 - \varepsilon_6)$ of the quadrature product.

An exactly similar analysis for the other product gives an approximate value,

$$V_1 V_2 \cos \omega t \sin(\omega t + \phi) + (\varepsilon_3 V_2 + \varepsilon_5 V_1)\ \cos \omega t \sin(\omega t + \phi)$$
$$+ V_1 V_2[\varepsilon_6 \cos \omega t \cos(\omega t + \phi) - \varepsilon_4 \sin \omega t \sin(\omega t + \phi)]$$
$$+ \text{terms containing products of errors}$$

where the last term can be rewritten as

$$V_1 V_2[\varepsilon_6 \cos(2\omega t + \phi) - (\varepsilon_6 + \varepsilon_4)\ \sin \omega t \sin(\omega t + \phi)].$$

Here again therefore, the amplitude is in error, this time by an amount $(\varepsilon_3 V_2 + \varepsilon_5 V_1)$. and a proportion $(\varepsilon_6 + \varepsilon_4)$ of the reference product is added to the mean.

A.3   Errors in subsequent analysis

Still further errors may be introduced directly or indirectly in the analysis of the results. There are various ways in which this can happen. As has been seen, the multiplication process yields ideally the products $V_1 V_2 \cos \phi$ and $V_1 V_2 \sin \phi$. The quantities normally required are $V_2 \cos \phi$ and $V_2 \sin \phi$; any instability in or errors in the measurement of V_1 will therefore further affect the accuracy of these. Again, a complicating factor in some of the experiments in which this equipment will be used is the fact that the quantities finally required (see Ref.1) are the in-phase and quadrature components of the ratios of some of the measured quantities, e.g.

$$\frac{i}{a}, \frac{b}{a} \text{ and } \frac{c}{a}$$

where i, a, b and c are signals derived from transducers giving a measure of excitation, primary motion and up to two secondary motions. If both the signals whose ratio is required are fed directly to the analysing equipment then this means only that both the ratio of the amplitudes of the two signals and the relative phase angle will be in error by the sum of the errors in the individual measurements. This is not always possible or convenient however and it may be necessary to introduce an auxiliary reference signal and make measurements relative to this. This means introducing a reference signal R and determining the in-phase and quadrature components of $\frac{i}{R}, \frac{a}{R}, \frac{b}{R}$ and $\frac{c}{R}$. If it is supposed that the phase angles between R and i, a, b and c are θ, ϕ_1, ϕ_2 and ϕ_3 respectively, then the measurements made with the equipment would be $i R \cos \theta$ and $i R \sin \theta$, $a R \cos \phi$ and $a R \sin \phi$, etc.

The required quantities are now $\frac{i}{a} \cos(\phi_1 - \theta)$ and $\frac{i}{a} \sin(\phi_1 - \theta)$ and so on. These can be obtained from the measured quantities by relations such as

$$\frac{i}{a} \cos (\phi_1 - \theta) = \frac{(i R \cos \theta)(a R \cos \phi_1) - (i R \sin \theta)(a R \sin \phi_1)}{(a R \cos \phi_1)^2 + (a R \sin \phi_1)^2}.$$

Each of the terms in this expression is subject to errors of the types discussed earlier in this Appendix, and the error in the whole expression may therefore be greater than before although fortunately there is a tendency for such errors to cancel out.   The general form of the error is readily calculated but not very illuminating and will not be reproduced here.

All the main sources of error have now been considered.   In total they make a formidable array.   The effects of many can be reduced by suitable equipment calibration, and others will tend to cancel out in experiments, such as those of Ref.1, which require the successive performance of "wind-off" and "wind-on" tests.

Appendix B

PERFORMANCE SPECIFICATIONS

B.1 **Dynamic analysis equipment**

(1) **Oscillator OS 103·3**

Frequency   0·01 c/s to 11·1 kc/s decade steps.
Continuously variable incremental control over limited range.
Harmonic distortion, less than 1%

Amplitude   <u>Signal output</u> 10V rms (max)
100 mW into 1k unbalanced
200 mW into 2k balanced

      <u>Attenuator</u> Calibrated, 108 steps 10 mV to 10V.
                  Resolution 10 mV.

      <u>Accuracy</u>   ±2%

      <u>Stability</u>   Long term better than ±5% of 10 V.

      <u>D.C. content</u> Less than 1%

Square wave   Approximately 17 volts maximum, continuously variable. Rise time less than 1% of periodic time at all frequencies. Output impedance approx. 10k.

Reference outputs   Four-phase sine wave. Phasing accuracy (0·5 c/s to 1 kc/s) can be set within 0·1°, otherwise less than 1°.
Loading not less than 1 M.
Amplitude accuracy ±2% of 0° reference.

(2) **Reference resolver (JX 746)**

Frequency   D.C. to 1 kc/s

Input   Four-phase (10V rms) Impedance 1M per phase.

Amplitude   Accuracy ±1%
                          Output impedance less than 200 ohms.
Phase   Accuracy ±1°

(3) **Resolved components indicator (VP253·3)**

Frequency   0·05 c/s to 1 kc/s

Accuracy	Standard instrument - ±3% of full scale.
	(±1% due to meter)
	(±2% due to attenuator)
	Modified instrument - in system described, is fitted with 0·1% components in the attenuator designed to give an overall accuracy of approx. ±2%.
Signal voltage ranges	With either balanced (20M) or unbalanced (10M) input impedance, to give full scale indication:-
	50 mV, 150 mV, 500 mV, 1·5 V, 5V, 15 V, 50 V, 150 V
Reference input	Four-phase 10 V, rms (6·2M) per phase.

(4.) **Mechanical reference generator**

This instrument is not used for the system which has been described, but it could replace the oscillator function for some applications.

Phase displacements between the outputs is 90° with negligible error.

Phase shift of the output with respect to input shaft is less than 1° over the entire speed range.

B.2 **Digital voltmeter   (DM2001 Mk.2)**

Accuracy	±0·05% of reading or 5 least significant digits. Lowest range, 0·15995V
Resolution	50 microvolts on the lowest range. Calibration by Standard Weston Cell on 1·599 V range.

B.3 **Frequency, time and interval period counter (A.1149)**

Frequency	0 to 22 Mc/s.
Period	1 or 10 periods of an input signal
Time base	10 Mc/s maximum. Decade steps down to 1 c/s derived from an oven controlled crystal oscillator operating at 1 Mc/s. Stability 1 part in 10^7
Count capacity	99 999 999

	Aero Bedford (old system)	
Object of experiments	Measurement of oscillatory stability derivatives	Measureme and assoc
Type of model	Rigid	Rigid
Measurements made	Frequency and amplitude of excitation. Amplitude and relative phase of primary and two secondary responses	As Bedfor oscillati
Frequency range	2-20 c/s	0.1-20 c/
Accuracy needed: Frequency	1 in 100 000	1 in 100
Amplitude	Such that accuracy of in-phase and quadrature components of	±1%
Phase	excitation or secondary response primary response is ±1% (±10% in bad conditions) (High accuracy of greatest importance for secondary responses where phase angles small)	±1% of an
Transducers used	Accelerometers, locally made, in conjunction with Southern Instruments FM equipment	Variable Southern
Signal levels	Excitation 0.2-2.0 volts Response (may have d.c. component) P. 0.5-2.0 volts S. 0-0.5 volts	0.2-20 vo 0.2-0.6 v 0.0006-0.
Method of measuring frequency	Advance Type TC1 Counter	Venner Un sampling
Type of oscillator	Muirhead 880A L.F. oscillator (continuously variable frequency)	Muirhead
Method of measuring phase and amplitude	Muirhead phasemeter with tunable filter	As Bedfor
Main difficulties encountered in making measurements	1. Slowness of taking readings 2. Readings inaccurate or impossible due to noise on occasions (up to 50% of signal on primary response, up to 100% of signal on secondary response) 3. Some signals vary in amplitude and phase and it is difficult to estimate the mean	Difficult
Frequency of noise	50 and 80 c/s	50 c/s
Most appropriate output medium	Punched cards	Paper tape
Special requirements	Adjustable phase shift between oscillator and exciter	Self-exci

Table 1

EXPERIMENTAL METHODS

Aero Farnborough	Structures
Measurement of oscillatory stability derivatives and associated aerodynamic investigations	Measurement of oscillatory loads, pressures and structural responses
Rigid	Flexible or rigid
As Bedford. Some work done on self-excited oscillations	Frequency and amplitude of excitation. Amplitude and relative phase of numerous loads, strains and pressures (22 now, more later)
0.1-20 c/s	2-300 or possibly 600 c/s
1 in 100 000 ±1% ±1% of angle to 45° and ±½°, 45° -90°	1 in 100 000 ±1% ±0.01° (at small phase angles, 2° - 3°)
Variable capacity displacement transducers and Southern Instruments FM equipment	Strain gauges, sub-miniature accelerometers and locally made strain gauge pressure transducers in conjunction with Solartron decade amplifiers. Work with R.A.E./N.E.P. pressure transducers and equipment to be done later
0.2-20 volts 0.2-0.6 volts 0.0006-0.5 volts	Suitable for direct input to phase meter (or at strain gauge levels in case of mechanical excitation) } 0.01 volts (except for N.E.P. case)
Venner Universal Counter/Timer (special version sampling to 100 or 500 cycles)	Locally made 'Dekatron' counter
Muirhead 880 L.F. oscillator	Electric motor for low frequency excitation Muirhead and Solartron oscillators for higher frequencies
As Bedford	As Bedford (Solartron T.F.A. proposed for some applications)
Difficulties with oscillations about zero	1. Turbulence in tunnel, which necessitates long time average (1 minute at frequencies below 10 c/s) 2. As (3) of Bedford. Amplitude variations 10:1
50 c/s	50 c/s
Paper tape	Paper tape
Self-excitation	High rate of recording to allow use in intermittent wind tunnels with short running times

2

REFERENCES

No.	Author	Title, etc.
1	J. S. Thompson R. A. Fail	Oscillatory derivative measurements on sting mounted wind tunnel models. R.A.E. Report Aero 2668 July 1962
2	W. D. Fryer	How to design low cost audio filters Electronics, 68-70. April 1959
3	E. J. Petherick	A cyclic progressive binary-coded decimal system of representing numbers R.A.E. Technical Note MS 15 October 1953
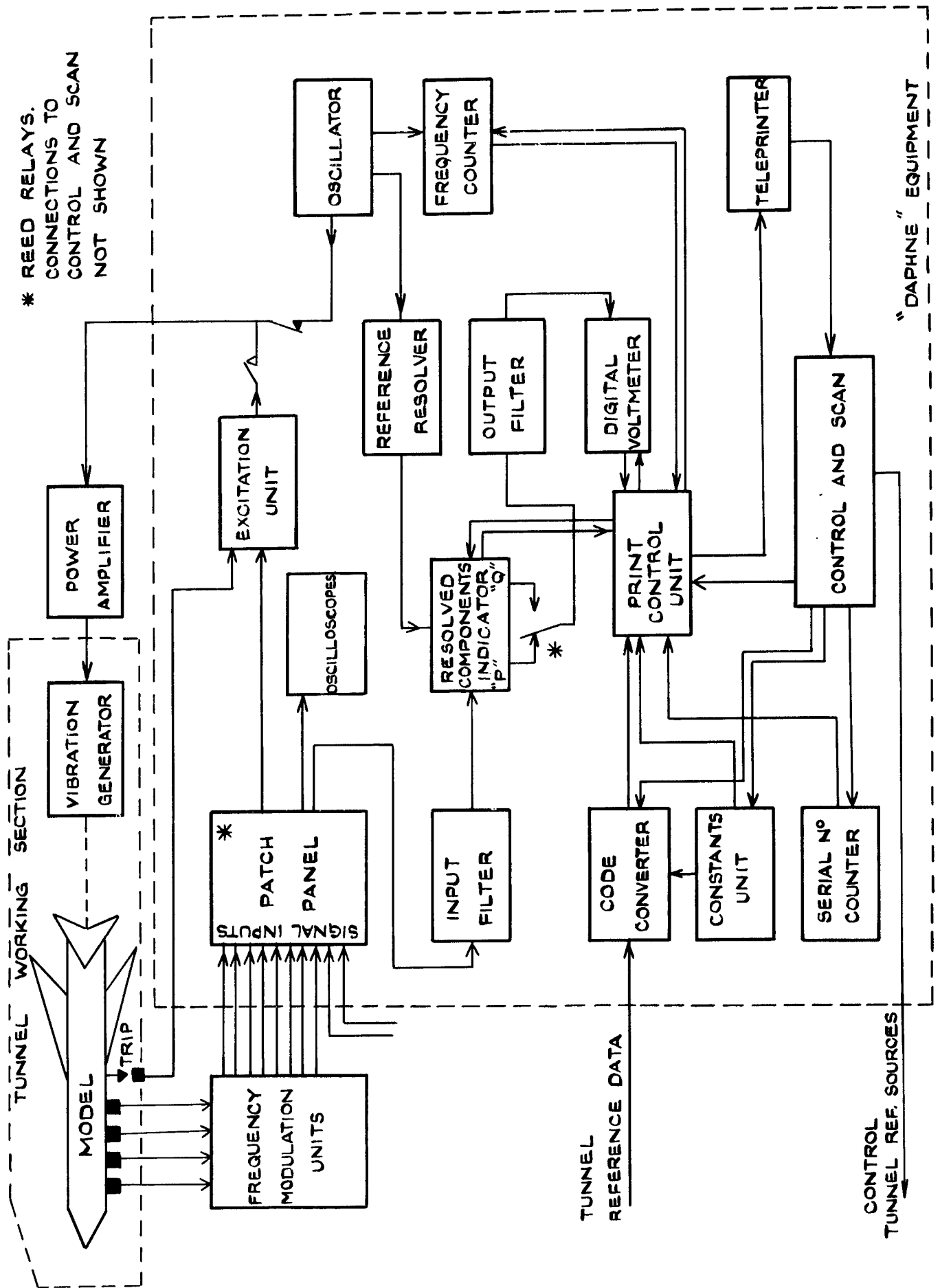
FIG.1 BLOCK DIAGRAM

Fig.2
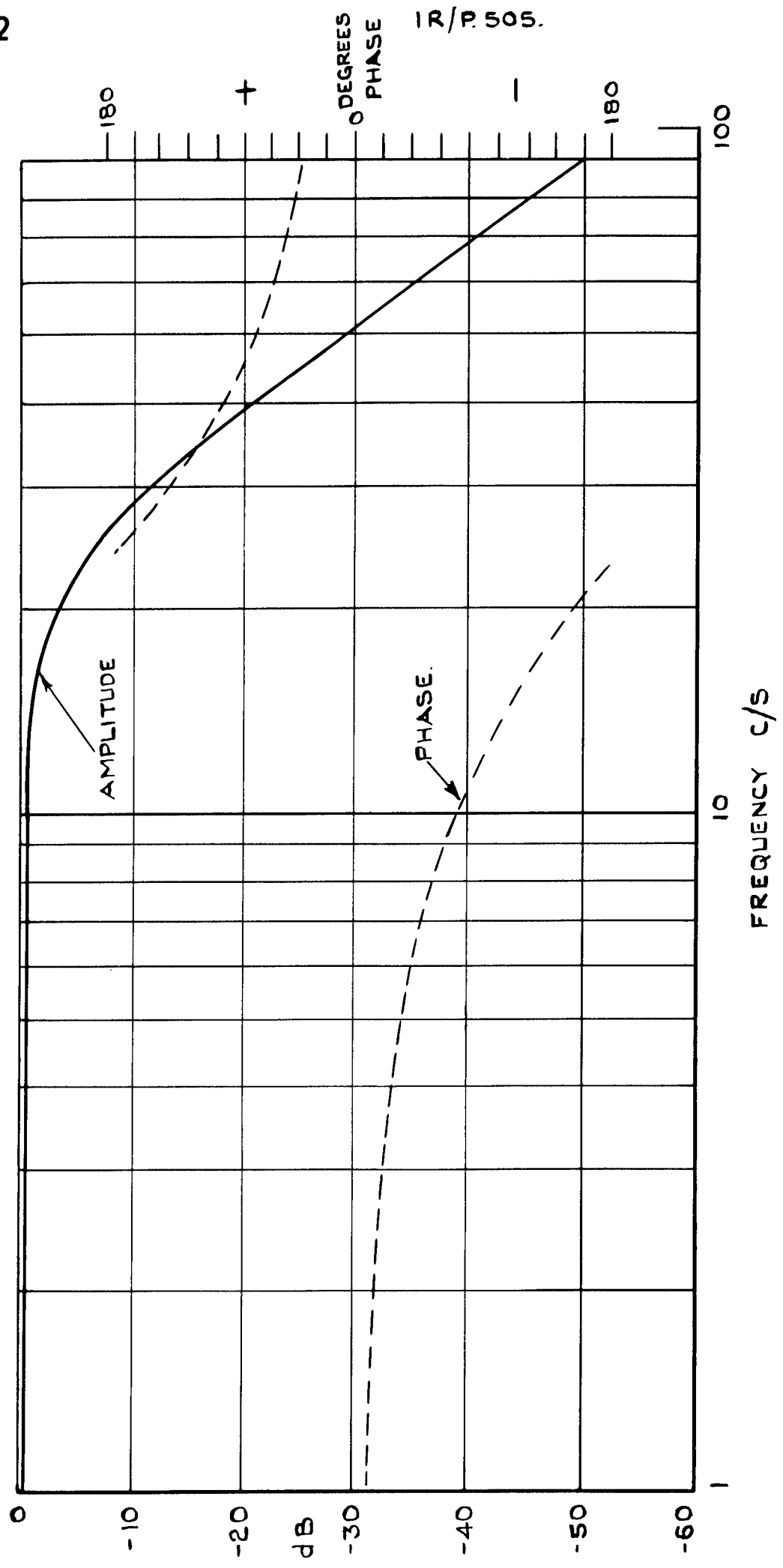
FIG. 2 INPUT FILTER-MEASURED AMPLITUDE AND PHASE RESPONSE.
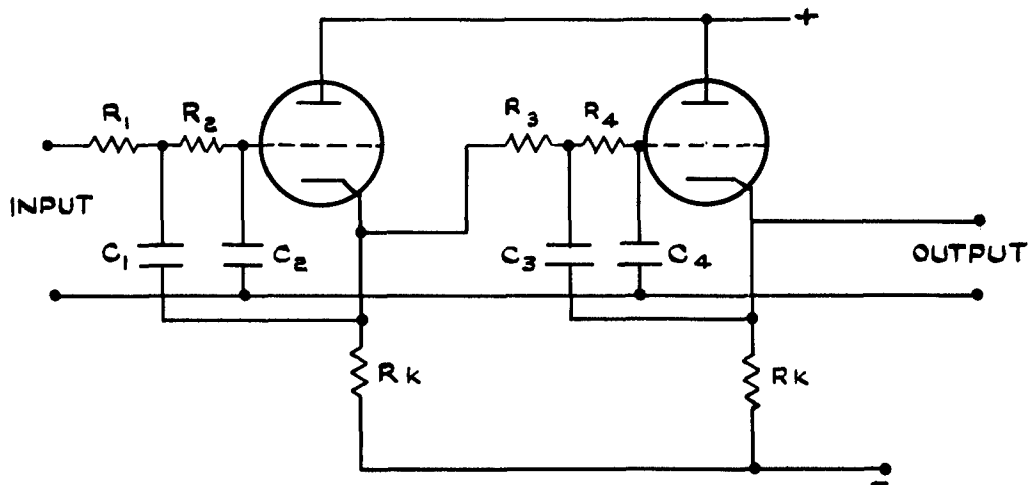
BASIC CIRCUIT OF LOW-PASS FILTER

$$\beta = \frac{\mu}{\mu+1} \cdot \frac{gm. Rk}{gm. Rk +1}$$ (CATHODE FOLLOWER GAIN)

$$\alpha = 1 - \beta$$

$$\gamma = 2\delta - \alpha = \frac{C_1 + C_2}{C_1}$$ (MUST BE GREATER THAN 1)

$$R_1 = R_3 = \frac{1}{\omega_0 C_1}$$ (C_1 IS CHOSEN ARBITRARILY)

$$R_2 = R_4 = \frac{1}{\omega_0 C_2}$$

$$C_1 = C_3$$

$$C_2 = C_4$$

WHERE μ IS THE VALUE AMPLIFICATION FACTOR
gm IS THE VALUE CONDUCTANCE
δ IS THE DAMPING FACTOR
ω_0 IS THE CORNER FREQUENCY
IN RADIANS/sec.

FIG. 3 INPUT FILTER DESIGN DATA

Fig.4   IR / P. 507.

THERMOCOUPLE
JUNCTIONS.

I_R

I_S

I_S

MOVING COIL
METER

I_R

$$I_1 = \frac{I_R}{2} - \frac{I_S}{2}$$

$$I_2 = \frac{I_R}{2} + \frac{I_S}{2}$$
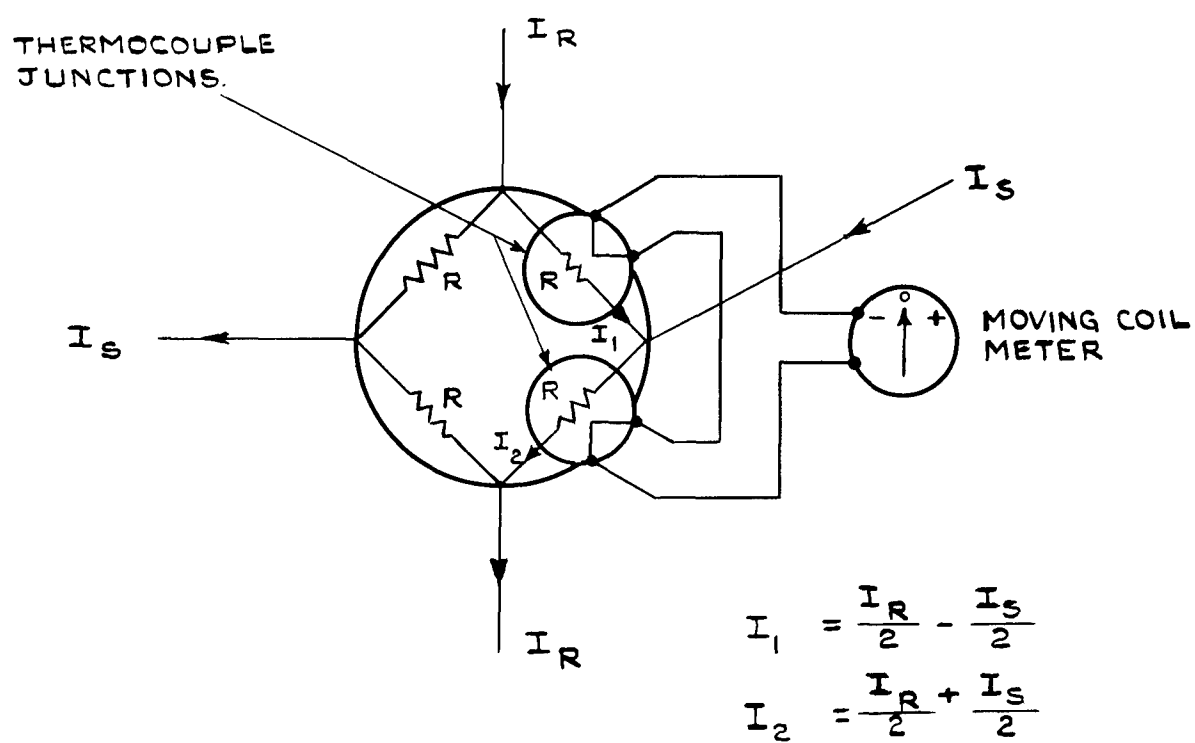
FIG. 4   BASIC   WATTMETER   CIRCUIT
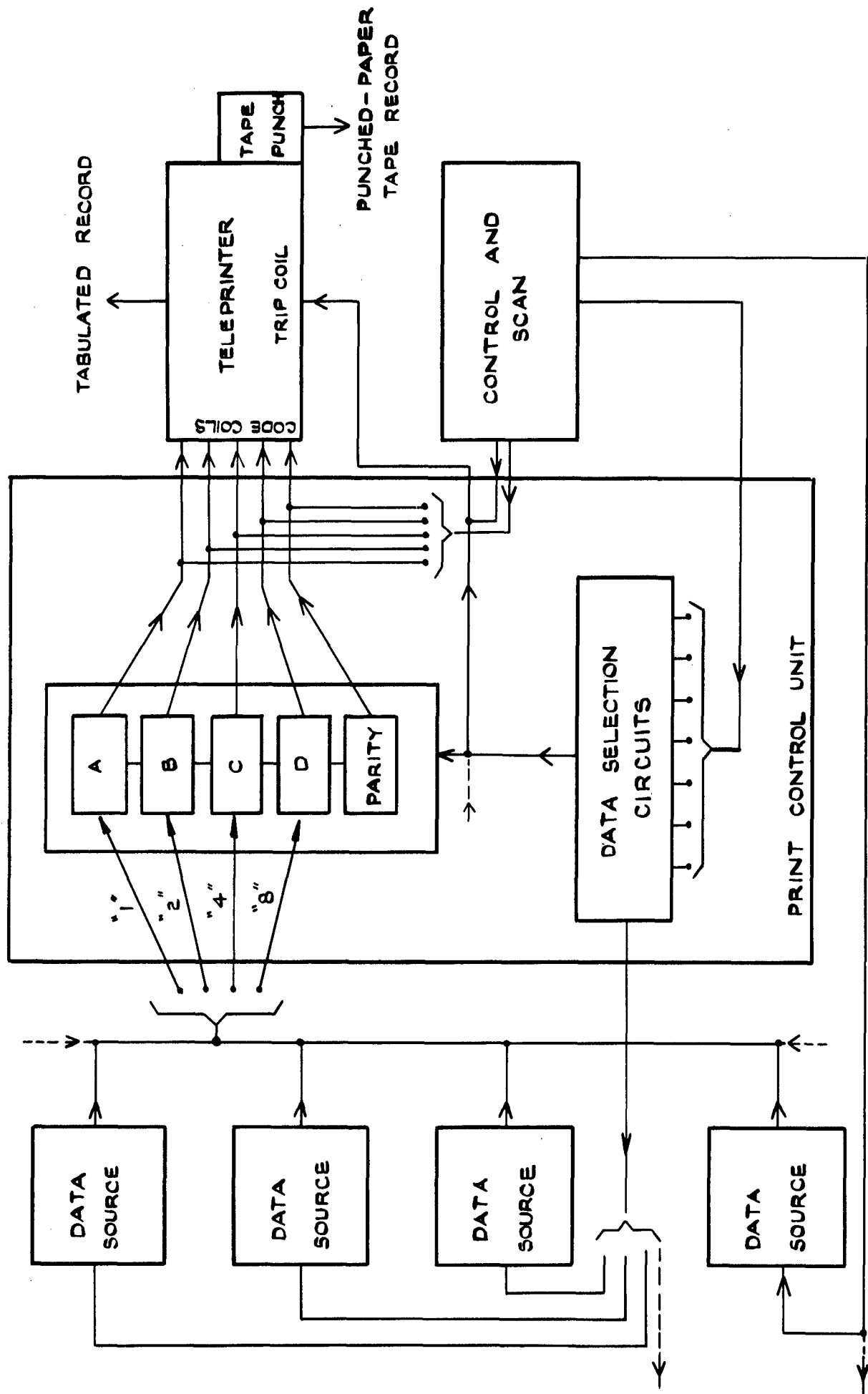
Fig.5

FIG. 5 DATA RECORDING - SCHEMATIC

Fig.6

169832

0400	A	0080	0707	0472	0207	2000	3599	
	1787	0823	2004	8801	0124	0000	0000	
31032009								
	32	-07065		32	-00010	32	00685	32	07440
	32	00815		32	00005	32	-00025	32	00005

0401	A	0080	0707	0472	0208	2200	3599	
	1803	0823	2004	8801	0121	0000	0000	
31317206								
	32	-05175		32	00010	32	00540	32	07155
	32	00715		32	00005	32	-00010	32	00005

0402	B	0080	0707	0472	0210	2200	3599	
	1821	0823	2004	8801	0116	0000	0000	
10917416								
	42	-09975		42	-00155	32	-01055	32	13165
	32	04195		32	00240	32	00020	32	00010

0405	B	0080	0704	0471	0211	1608	3599	
	1845	0823	2004	8801	0114	0000	0000	
10903008								
	42	-10250		42	00110	32	-00065	32	11470
	32	04230		32	00145	32	-00020	32	00005

0406	B	0080	0703	0471	0212	1206	3599	
	1854	0823	2004	8801	0113	0000	0000	
10895316								
	42	-09695		42	-00005	32	00390	32	10230
	32	04145		32	00085	32	00005	32	-00005

0407	B	0080	0703	0472	0212	0801	3599	
	1864	0823	2004	8801	0115	0000	0000	
10871085								
	42	-10010		42	00480	32	00490	32	07820
	32	04105		32	-00300	32	-00025	32	-00000

0408	B	0080	0703	0474	0214	0398	3599	
	1874	0823	2004	8801	0116	0000	0000	
10891501								
	42	-09650		42	-00045	32	00240	32	08160
	32	04075		32	00055	32	00000	32	-00000

0409	B	0080	0703	0474	0214	0006	3599	
	1887	0823	2004	8801	0119	0000	0000	
10884006								
	42	-09810		42	00025	32	-00590	32	09030
	32	04150		32	00045	32	00000	32	00005

XXXXX

Fig.6. Typical format of printed data

NEGATIVE
SUPPLY

USB
BANK 1

POSITIVE
SUPPLY

USB
BANK 2

SPACE

USB
BANK 3

CARRIAGE
RETURN

USB
BANK
4

LINE
FEED

USB
BANK
5

RESET
USA.

USA BAN

A

B

THOUSANDS
HUNDREDS
TENS
UNITS.

SUB-SCAN 1.

USC
BANK 1.

CONTACT OF
RELAY B.

EXTERNAL
CIRCUITS
AS REQUIRED.

CONTACT (S) OF
RELAY A.

CALL USA
AND
RESET USC.

USC

FIG. 7   SCHEMATIC   DIAGRAM   TO

NOTES:
ADDITIONAL BANKS OF USA AND USB (NOT SHOWN)
ARE USED FOR RESETTING AND INTERLOCKING.
ADDITIONAL BANK OF USC (NOT INDICATED)
IS USED FOR INTERLOCKING.

A BANK 1

50

TAG GROUPS
FOR LINE 1.

5 6 7 8 9 10   47 48 49 50

PROGRAMME
CIRCUITS AS
REQUIRED.

TAG GROUPS
FOR LINE 2.

5 21 22 23 24 25   47 48 49 50

USA RESETS

TAG GROUPS
FOR LINES
3 TO N-1.

47 48 49 50

TAG GROUPS
FOR Nth LINE

4 5 6 7 8 9 10 11   36 37 38 39   47 48 49 50

USA. RESETS

C

ACT OF
AY B.

CALL SUB-SCAN (USC)

CONTACT OF
RELAY C.

NEGATIVE
SUPPLY.

USA USC BANK 2 WIPER - SUB SCAN 2

F USC.

RAM TO ILLUSTRATE SCANNING PRINCIPLES

2

Fig.8

Fig.8. General view of 'Daphne' equipment
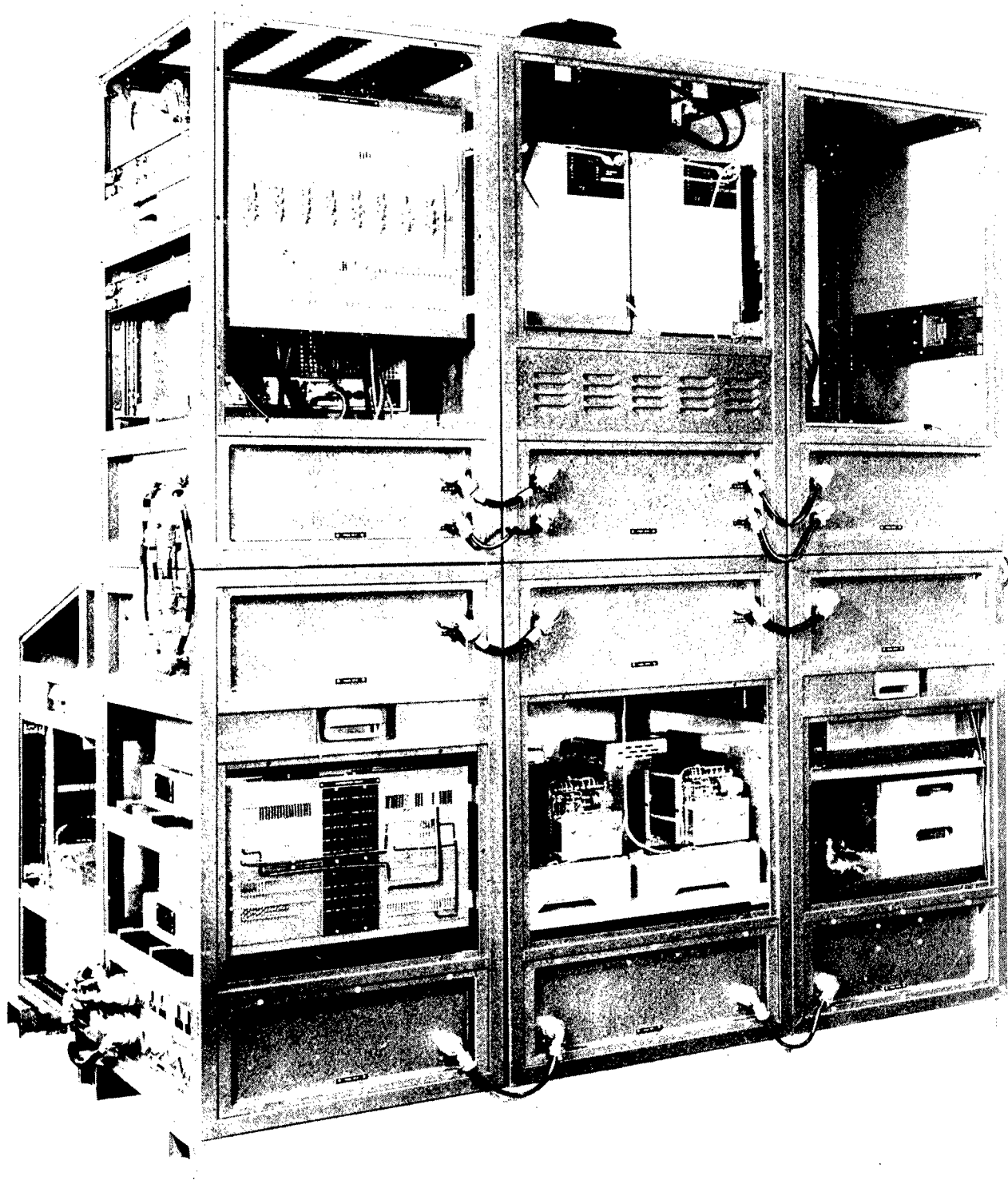
Fig.9

169834

Fig.9. Rear view, with cover panels removed
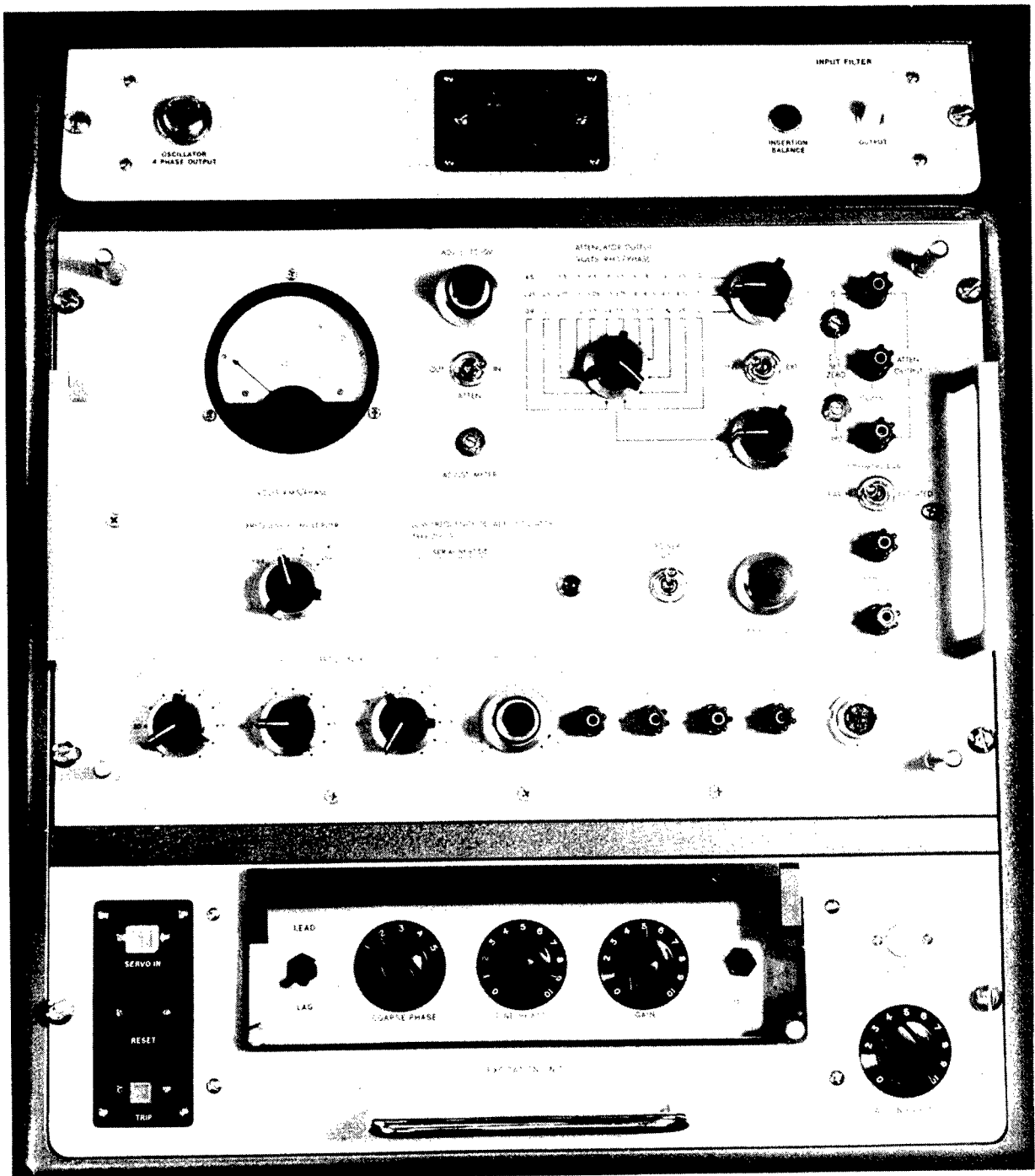
Fig.10

Fig.10. Front panel views of input filter, oscillator and excitation unit
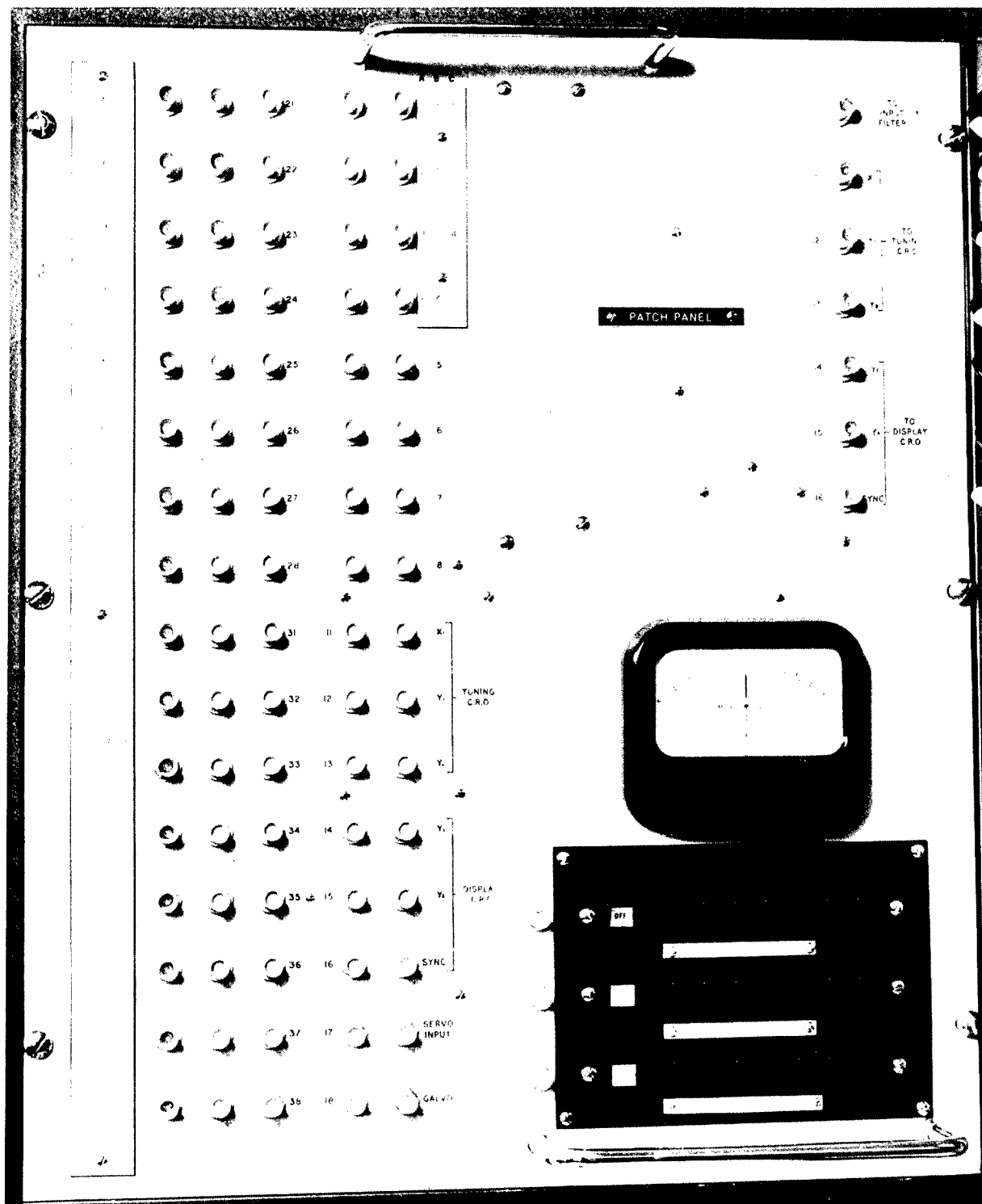
Fig.11

Fig.11. Front view of patch panel
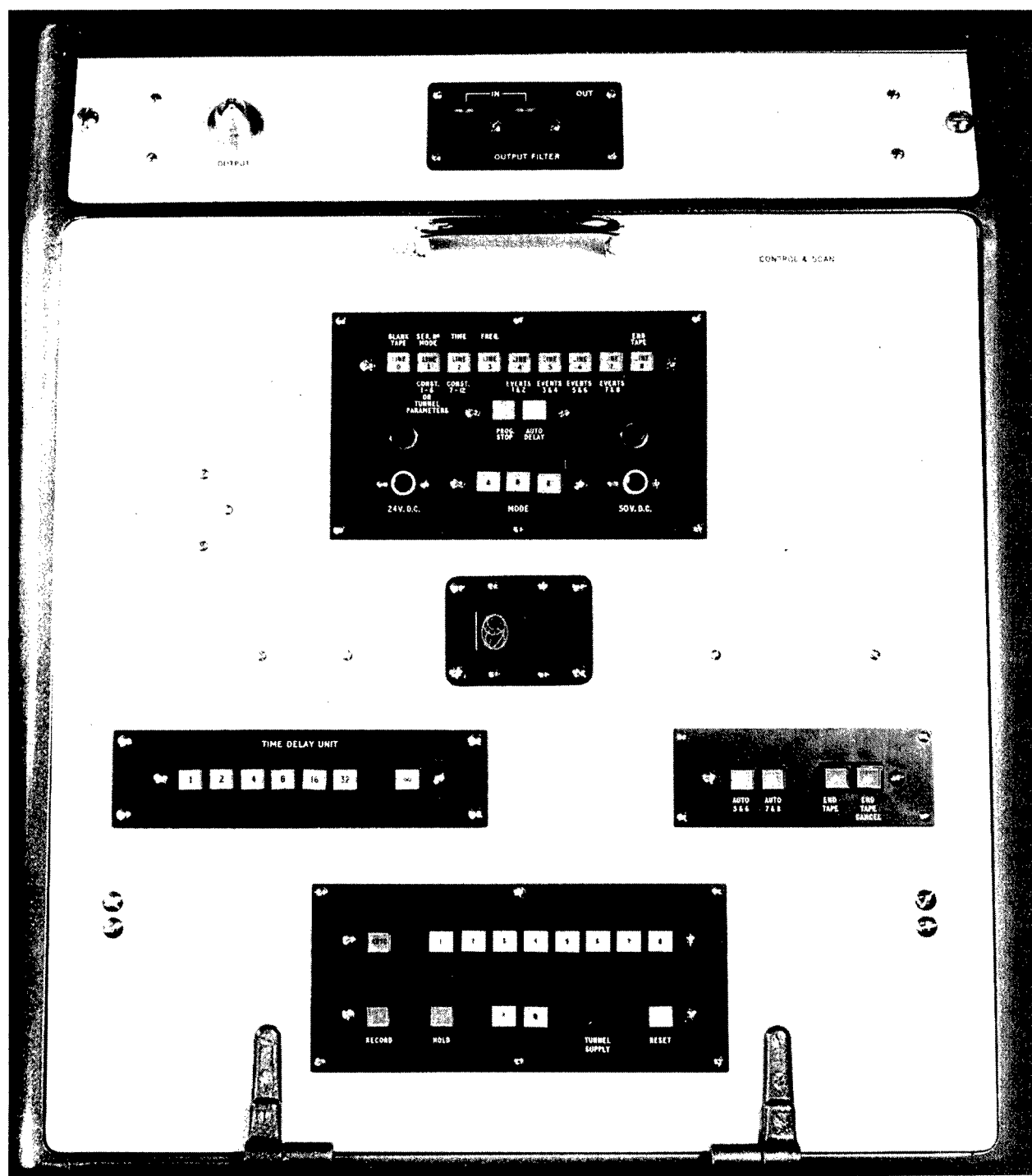
Fig.12

Fig.12. Front panel of output filter and panel of control and scan

Fig.13
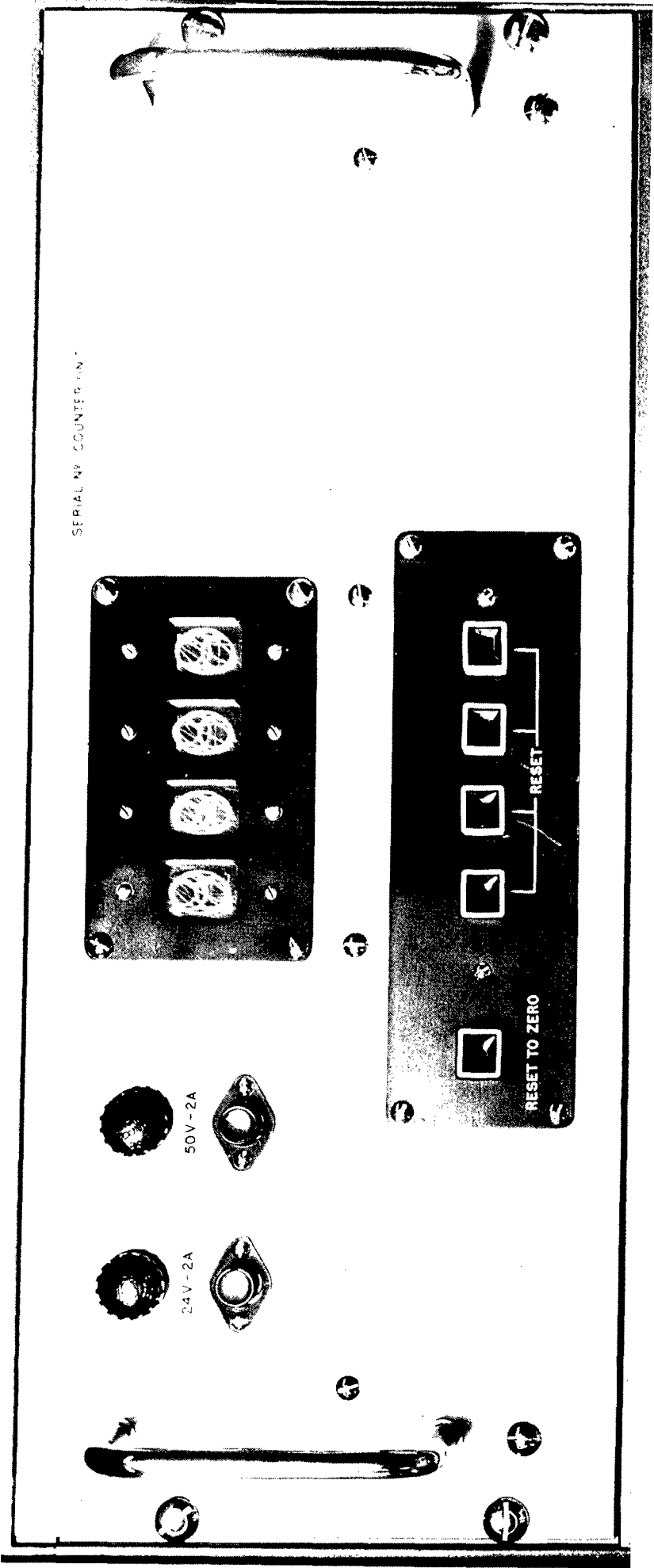
Fig.13. Front panel of serial number counter
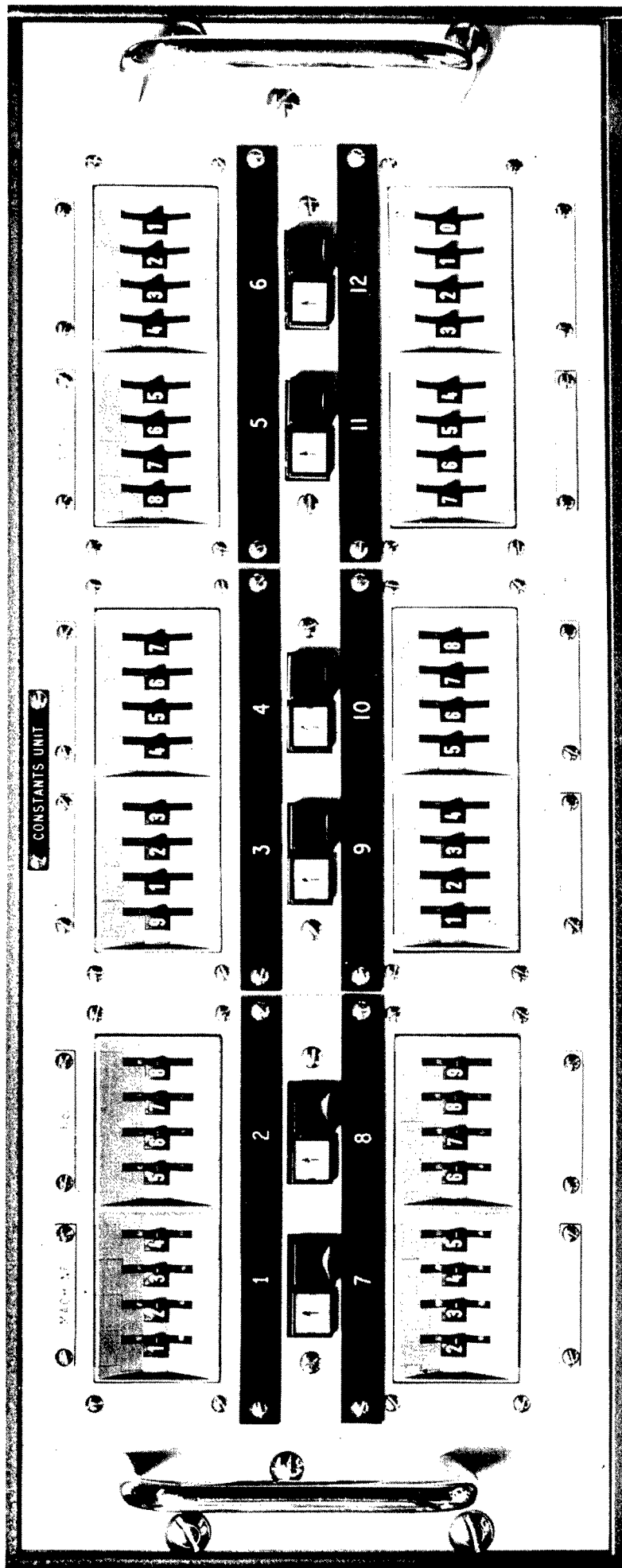
Fig.14

Fig.14. Front panel of constants unit

533.6.071.3 :
533.6.013.42

Leedham, H. C.

A DIGITAL AMPLITUDE AND PHASE MEASURING SYSTEM (DAPHNE)

Royal Aircraft Establishment Technical Report 64070   December 1964

A transportable automatic measuring and recording system has been designed and constructed for experiments concerned with oscillatory derivative measurements in wind tunnels. A "wattmeter" method is used to resolve the input signals in the frequency range 0.05 c/s to 1 kc/s into in-phase and quadrature components referred to the drive or other reference, and accurate measurement of frequency is made by an electronic counter. Results of these measurements together with reference data are automatically read out and printed. A punched-paper tape record is also produced for computation by a digital computer. This Report describes the equipment in a general manner and discusses some of the factors affecting accuracy. The system is adaptable for other work involving the measurement of the relative phases and amplitudes of a number of signals.