Strain Gauge and Blade Motion Recording Systems for Helicopters

By P D MacMahon

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Dr G S Hislop (*Chairman of the Executive Council*) in the Chair

INTRODUCTION BY THE CHAIRMAN

The Chairman, in introducing the Author, expressed great pleasure in welcoming Mr MacMahon to this, the first lecture of the eleventh series of Annual Lectures on the helicopter situation He said that Mr MacMahon was educated at Twickenham Technical Institute During the war, he was with the Admiralty Research Laboratory, working on electronic equipment for anti-submarine warfare development After that, he was engaged on electronic developments with one or two firms and subsequently with the De Havilland Propellor Company as a development engineer engaged mainly on research and development of flight test equipment for high speed aircraft

Mr MacMahon had then joined Saunders-Roe in 1953, and was concerned with design and development of light-weight helicopter strain gauge recording equipment He had now been given a senior appointment in the Helicopter Division of Saunders-Roe, being responsible for design, manufacture and installation of electronic instrumentation for test rigs and other Government contract work

MR P D MacMAHON

> " *When you can measure what you are speaking of, and express it in figures, then you know what you are talking about* "
> —Lord Kelvin

Mr Chairman, Ladies and Gentlemen May I say how honoured I feel to address this Association tonight The scope of the subject is a very wide one and for this reason I hope you will bear with me if some of the more recent facets of electronic recording methods are not fully dealt with Day to day developments in this field make it quite impossible to present a factual picture of new functional equipment and that which only shows promise

As has been shown many times in other fields of helicopter engineering, rotary wing aircraft present quite separate and exacting design requirements for successful operation, this is particularly true of strain gauge recording equipment

The problems of the helicopter instrumentation engineer are considered, and several methods of recording strain gauge and blade motion signals are reviewed

Helicopter instrumentation techniques are based almost entirely on those developed for fixed wing aircraft of the last 2 or 3 decades This means equipment modification and adaptation to a greater or lesser degree, and it is my intention to present that this is not an entirely satisfactory solution to the problem It is essential to recognise that a very different range of problem is met, and whilst the aircraft type of instrumentation can be made to yield answers, these are not often in a convenient form Further, a great deal of uneconomical labour is required to bring into prominence, that data, the provision of which should be the fundamental design task of the instruments in use

It seems a matter of some urgency to provide instrumentation equipment specifically for helicopter work Thereby a 3-fold yield would accrue in simplicity, rapidity and ready availability of relevant data

A 6-Channel equipment, designed and developed by Saunders-Roe is explained in some detail showing its superiority over other types of equipment in current use

THE PROBLEMS SPECIFICALLY ASSOCIATED WITH ROTATING WING AIRCRAFT INSTRUMENTATION

(*a*) Magnitude, nature and distribution of stresses in rotor blades
(*b*) Dynamic geometry of blades about their hinges which require full distribution of typical cycles
(*c*) Stresses in rotating mechanism, for example, control and power distribution linkages
(*d*) Structural vibration
(*e*) Cyclic stresses fed back into pilot's or other control linkages
(*f*) Torsional vibrations associated with rotor drives and other power transmitting shafts

Items (*a*), (*b*) and (*c*) are uniquely helicopter problems, item (*d*) is usually of a totally different order of magnitude to the fixed wing aircraft and item (*e*) rarely arises except in helicopters Item (*f*) is an outstanding problem and requires special treatment

I shall now endeavour to discuss in some detail to show methods in current use and the proposed alternatives and more efficient solutions

STRESS IN ROTOR BLADES

Strain gauges are used exclusively for measuring strain, hence, stress, where no unusual techniques are employed

The gauges may be energised by alternating current or direct current Direct current is to be preferred for two reasons Due to long line lengths alternating current energisation requires fairly careful adjustment of reactive components in the strain bridges Furthermore, where A C energisation is used, it is more usual to ' lose ' the steady components of stress

Whilst these components are highly significant in the general fatigue problems, they are not here considered to lie in the province of a dynamic vibration recording

The problem of recording steady stresses which normally change only with change of flight conditions simultaneously with dynamic stress is particularly difficult in helicopter work This is because the fatigue inducing vibratory stresses are not generally very large compared with the steady stresses Consequently, for any given recording field a choice must be made between accurate recording either of relatively low amplitude high frequency detail or of large amplitude static detail Until recently both could not be satisfactorily described simultaneously

In the case of D C energisation it is simple to reject steady components

In all dynamic strain gauge instrumentation the amplitude and frequency of signals are of primary importance, neither parameters can be controlled by the instrumentation engineer

Signal amplitudes rarely exceed a few millivolts, signal frequency bandwidth is approximately 2 cycles per second to 300 c p s The lower figure corresponds to a once per rev phenomenon at 120 rotor r p m , the higher to possible excitation due to engine vibration harmonic orders at average engine speed However, the problem is not quite so simple as a definition of expected frequency spectrum because the signal may be extremely complex in form and contain many other frequencies which are not necessarily harmonically related

From the foregoing the basic recording requirements for rotor blade investigations may be summarised as follows

(*a*) Amplitude of input signal

(*b*) Frequency of input signal—2—300 c p s with possible extension to 1,000 c p s

(*c*) Number of channels up to 12

(*d*) Recording medium mirror galvanometers to photographic film or paper or, alternatively, magnetic tape

Unless rather drastic curtailment of recording frequency spectrum system sensitivity is accepted, it is not practical to drive the mirror galvanometers directly from strain gauges Electronic amplifications of the signals, is, therefore, necessary The power gained needed from strain gauge to galvanometers is not large, but is somewhat difficult to achieve because of the necessity to record low frequencies

USE OF AMPLIFIERS

The low frequency requirements mean that the transformer as an impedance matching device is inadmissible Therefore, power transfer must be arranged from amplifier valves which are high impedance devices directly to the low impedance galvanometers elements The magnitude of the problem is roughly this—a generator of inherent high internal impedance of the order of several thousand ohms is required to drive a load, which in the most favourable case cannot be increased to much more than 100 ohms Cathode follower connection of the valves is the practical answer, in which case the frequency limitations are important, but a serious degradation of valve efficiency cannot be avoided However, voltage is not difficult to facilitate ahead of the output stage and, furthermore, facilitates linearisation of the amplifiers amplitude/frequency characteristic by means of negative feedback

Clearly the problem of electrical amplification of the strain gauge signals, whilst requiring careful design, is not difficult to achieve The required type of amplifier is not available commercially and requires special development and engineering Insofar as amplifiers are concerned, there are two further alternatives worth considering They are magnetic amplifiers or transconductors and transistorised amplifiers The magnetic amplifier is a useful alternative, chiefly because the frequency spectrum requirements automatically necessitate an excitation frequency supply to the amplifiers of the order of 5/10,000 c p s This makes possible miniaturisation by using " Ferroxcube " magnetic materials with the additional advantage of increased stability and reliability Impedance matching is inherently simple in this type of amplifier and could be arranged for good load matching even to low resistance galvanometers The drawback to this system in the present application is that they are zero frequency amplifiers with a linear response from D C up to approximately one fifth of the energising supply frequency Whether it may be possible to arrange for a finite low frequency cut-off is a question for future investigation If possible, then the use of magnetic amplifiers would considerably simplify the use of this type of amplifier

TRANSISTORS

In the last 18 months transistors and other semi-conductor devices have come into considerable use in all branches of the electronics art

The main advantage of the transistors is that they are great conservers of power They make effective miniaturisation possible and they have inherent electrical characteristics which appear at first sight to have great advantages over the thermionic valve, for instance, they are completely non-microphonic and are alleged to be unaffected by acceleration and vibration

They do have their own inherent disadvantages, however, one being that the transistors are sensitive to incident illumination and care must be taken to ensure that external coatings are not damaged Small amounts of light reaching the interior will make the transistors' efficiency deteriorate rapidly

In conclusion, the stability and noise level present when using these devices compare unfavourably with the thermionic valve

These devices are still being intensively developed It is not difficult to imagine future possible applications of these devices, for instance, a transistorised strain gauge amplifier, in itself an integral unit half the size of a matchbox, working into a frequency modulated system with the bulk of the equipment on the ground

At present, however, until more experience has been gained with transistors, they do not appear entirely satisfactory in this application for helicopter work

ROTOR BLADE MOVEMENTS

The analytical description of blade movements in flight conditions about a convenient reference is clearly a potential source of highly significant data Since all measurements are angular and any changes in angle of relatively low frequency, the ordinary linear potentiometer driven appropriately is applicable as a primary transducer The angular displacements to be measured are these

(*a*) Cyclic pitch changes
(*b*) Flapping sense
(*c*) Drag sense displacements

Displacements (*a*) and (*b*) depending on rotor system design are generally of the order of several degrees The angular resolution obtainable from commercially available toroidal wound potentiometers is normally not much better than $\pm \frac{1}{2}^{\circ}$ Therefore, if unity driven ratio is assumed between displacement and potentiometer shaft, this order of accuracy is probably good enough However, it is quite insufficient to resolve the considerably smaller changes due to drag displacements, for instance, the niggling present at the blade root in a cruising flight condition

Accuracy can readily be improved by step-up gearing in the mechanical linkage of movement to the potentiometer

Care is necessary in design of gearing to avoid any possibility of fundamental resonance excitation in the mechanism since true blade motion requires accurate description of fundamental, plus two or three harmonics

This instrumentation problem presents no special difficulties Recording is quite simply arranged by taking the potentiometer outputs direct to a suitable galvanometer recorder

RECORDING EQUIPMENT

From the foregoing it has been shown that mirror galvanometers are quite adequate to the task of recording There is a number of galvanometer cameras obtainable commercially, including those of Miller, De Havilland and Savage & Parsons These equipments are satisfactory, except for the smaller helicopter where weight and bulk of equipment is of major importance They all use film or paper of the order of 4/6″ in width and because of this they provide good record resolution without serious trace overlap A development of great interest is the Hussenot range of recorders which have been in general use in this country for some years They can be conveniently instrumentated with several types of galvanometers to cover any average frequency spectrum The extraordinary light weight and small size of this recording galvanometer camera opens up the attractive possibility of mounting it co-axially with the rotor shaft on top of the rotor head, thus avoiding slip rings in critical low level measuring circuits This possibility is more fully dealt with later

Great practical importance is attached to any method of avoiding the use of slip rings in low level signal circuits I find that it is not particularly difficult to design successful slip rings, but it is entirely another matter to maintain working efficiency in field conditions They are indeed one of the most prolific sources of troubles in practical tests, mainly because in an endeavour to extract the maximum signal to noise ratio from the strain gauge slip ring system, it is difficult to restrain a natural tendency to run the gauges at the maximum possible energising current This can be a prolific source of drift in the case of steady stress measurements

There remain two further possibilities in the choice of system, they are confluent pulse techniques and telemetering Confluent pulse techniques are exemplified commercially in the Elliott-Yates 10-channel display equipment Briefly, the principle is energising strain gauge bridges by short duration high amplitude pulses and measuring the resultant output from the bridges through a common amplifier and synchronised sampling circuit on to a cathode ray tube display This method is worthy of attention chiefly because slip rings view pulses more favourably than direct current and the equipment is very compact However, the inherent accuracy is not of a high order, in fact, it has no greater use than the display of the order of strains

Telemetry is an exceptionally promising line of attack, particularly when the vast amount of experience now being accumulated in guided weapon establishments becomes more generally available Possible methods have been studied carefully, but the problem of satisfactorily transmitting low level strain gauge information required in helicopter work, with particular regard to the very low frequency fundamentals, seems extremely difficult at present It should also be noted that the equipment's complexity and expense, particularly with the multiplex and matrix system, is of a totally different order of magnitude from those obtaining in any of the systems we have already discussed

Whilst it is true that most of the complexity, bulk and expense is found in the ground equipment, there are still factors of some cogency

Generally speaking, it has been shown that available instrumentation equipments can in part meet the requirements for stress measurement, but the design philosophy of these instruments is not particularly appropriate on three accounts

(*a*) Weight and complexity
(*b*) Frequency spectrum
(*c*) Slip rings in critical measuring circuits cannot be avoided

A suitable choice for instrumentation in helicopters resolves itself into two basic systems, that where the recorder or camera is located and mounted in the hub of the aircraft and that where amplifiers are employed, these amplifiers to be mounted on top of the rotor, the output signals fed through slip rings to a recording system in the cockpit

We may now look in more detail at the direct recording system It is understood that the French " Djinn " helicopter used a direct recording system for an instrumentation programme with some success

There are many advantages to this method, the most obvious being the absence of amplifiers with their attendant drift and phase shift characteristics The signals are fed into the galvanometers direct and, consequently, a requirement for slip rings does not arise The camera, gauges and the battery which performs the dual function of exciting the gauges and driving the camera motor are located suitably in the hub itself Camera motor control is most probably effected by a twin cable through slip rings and a relay operated by the pilot, so dispensing with a flight observer and the weight of bulky equipment

Tests with Saunders-Roe strain gauges suitably treated show a very small amount of drift for temperature change Day to day drift in duralumin, tension, would be in the order of ±15 lb inch^2 stress, steel, torsion, ±100 lb inch^2 stress, when compared with the probable maximum steady stress of 3,000 lb inch^2 stress It would be seen that on paper this method is accurate, and the results are probably easily repeated

The operation of this equipment can be now considered Assuming that a " Sfim " or " Beaudoin A15 " camera is used, a trace width of 59 mm will be available This, it will be shown, is the major limiting factor for the simultaneous recording of more than one, or at the most two, signals The value of such recordings is suspect due to the accuracy required for direct film interpretation For example, a main shaft torque load may be calculated to be 3,000 lb inch^2 stress in duralumin A galvanometer of suitable sensitivity is mounted so that the trace under static conditions is focused at one edge of the recording paper When load is applied a total deflection 59 mm is observed If the stress calculations are correct the trace will not go beyond this Should it in fact be otherwise, the sensitivity of the galvanometer will have to be reduced This in turn will reduce the size of the fluctuating stresses to a point where accurate interpretation will be virtually impossible Should a second galvanometer of higher sensitivity be fitted to facilitate the examination of fluctuating stresses, the same problem will arise, except that the trace will only be visible for a period when the steady load does not exceed the overall deflection of 59 mm

When the addition of more than these two signals is considered, it is seen that the recording paper is saturated with various traces which from time to time may ' leave ' the recording paper altogether and, in fact, is a confused collection of lines, which are very difficult indeed to analyse or interpret If this situation is to be avoided, a lower galvanometer sensitivity must be used when the accurate interpretation of fluctuating and steady stresses becomes impossible

The same arguments for measuring blade motion, *i e*, the application of cyclic pitch or measuring coning angle still apply

From the foregoing it will be appreciated that the absence of instantaneous attenuation, or monitoring facilities, for changing flight conditions, seriously prejudices the use of this equipment for strain gauge or blade motion measurements

A conclusion may be drawn that until a suitably developed camera is available a direct recording system has many disadvantages which are not immediately obvious

In recent years, the performance requirement for helicopters has been drastically increased Accurate stressing and practical measurement of stresses statically and in flight have assumed tremendous importance

A final comment might be that the scope of this equipment is not wide enough to fulfil the exacting requirements of the present day helicopter

MERVYN SYSTEM OF DATA RECORDING AND ANALYSES

The Mervyn system of data recording and analysis represents a new approach to the problem of collection and evaluation of data Any data that can be transduced into electrical terms can be recorded and seven such sets of data can be recorded simultaneously

Magnetic tape is used as the transfer medium in recording For reasons of economy, flexibility and convenience in use, the operations of recording and playback and the presentation of data are separated This has the additional advantage that any multiple of seven sets of information can be recorded simultaneously The recorder takes the form of a very small and compact unit capable of being used in confined spaces

It is the intention of the designers that the playback unit should be installed in an analysis or design office This latter will present the seven channels of information simultaneously across the width of a single track of calibrated paper with timing marks upon an eighth channel, together with marks that provide a direct footage correlation with the magnetic tape for the purpose of editing

The most important feature of this equipment is that built into the playback unit and directly associated with it, is an analyser which will perform an automatic analysis to give the frequency versus amplitude spectrum of any portion of a wave form selected at will from any one of the seven information channels The record for analysis is taken directly from the primary recorded tape, and, therefore, no reading translation or conversion errors are introduced

Patented measures have been taken which have been the result of eliminating from the system all errors due to variations of quality of the tape and of variations in speed of the tape transport mechanism The accuracy of the system is, therefore, very high The recorder may be set up by means of a special calibrator unit supplied without any reference whatever to the playback system The whole recorder system including, if desired, the transducer, may therefore be set up on site and records taken

Such records may be played back in the analysis office without any deterioration whatsoever in the system accuracy, and this has the additional advantage that any number of recorders when set up against the intended calibrator may be fed into or employed to feed the standard play-back unit and analyser As the cost of the recorder is only one tenth of that of the play-back and analyser unit, the working capacity of the system may be doubled by the addition of a mere 10% to the cost To take an example, the ratio that has been found most economic in a large aircraft company has been the use of six or more recorders, in conjunction with one play-back unit and analyser The recorders, which may have different specifications and different frequency ranges, are distributed to various sections, and the time is booked on the play-back unit and analyser to suit the various sections' needs For example those research sections interested in flutter problems and with therefore no interest in frequencies exceeding 100 cycles, can use a recorder giving the desired frequency range, *i e*, 0—100 cycles with a maximum duration of record of two hours, whilst a section interested in engine vibration could employ a recorder with a frequency response 0—3,000 cycles, and duration of record of four minutes Both such recorders can be fed into the same play-back unit and analyser without loss of accuracy providing the necessary multiplication factor is borne in mind

Facilities are also provided on the recorder for direct recording on the tape and one channel may be used for speech and can be played back on the recorder which has a built-in loud speaker and can be used for pilot(s) editing of the record His comments may be noted in conjunction with the footage indicator provided on the play-back tape deck, so that verbal warning of events may be correlated accurately with the presented wave forms Outputs at high level and power are available for feeding any ancillary apparatus that may be required Two such examples are firstly, an automatic amplitude to digital converter—although the use of the built-in automatic analyser largely eliminates the need for such a device—and the second is an analogue device such as a scale model of a helicopter, in which the physical movements of the aircraft in flight are accurately reproduced in the model

Magnetic tape has been selected as the recording medium because of its convenience and small bulk However, whilst magnetic tape is quite satisfactory for entertainment purposes, it shows serious defects when attempts are made to employ it for reliable and accurate recording of data Surface irregularities of the tape cause quite large amplitude errors, the signal sometimes disappearing to zero or below noise, and the mechanical precautions which must be taken to ensure a constant speed of transit of the tape past the recording head are such as to make the recorder bulky, expensive and quite unsuitable for use in small mobile applications, or when subjected to vibration or " G "

To overcome these defects a frequency modulated carrier system has been selected as the medium upon which the information is impressed upon the tape This, with a well designed demodulator, eliminates all errors due to variations of tape quality, other than in the event of a ' drop-out ' Errors due to ' drop-outs ' have also been taken into account in the demodulator by the use of a memory circuit In addition, the need for constant tape speed in the system, has been eliminated by recording one extra channel That is to say, when seven information channels are available, an eighth channel is reserved for a reference signal This channel is used on play-back to cancel those errors introduced in recording, and results in itself in very high system accuracy It has the economic advantage in addition, that the recorder, of which a number will normally be needed, is made comparatively cheap, and such extra cost as is involved in the interest of accuracy is concentrated on the play-back unit which will be required in lesser quantities A servo unit is also incorporated in the play-back unit to eliminate frequency errors

As the field of data that needs to be recorded is very wide, a high degree of flexibility is called for, particularly in respect of maximum frequency response Therefore, a system of time translation is introduced The play-back unit runs at a standard speed of 1″ per second, with a frequency modulated carrier of 700 cycles, and can cope with information frequencies up to 100 cycles which are presented on a bank of pens whose frequency response reaches this figure If 0—100 cycles is the frequency range of interest then the recorder can also run at 1″ per second with the same carrier and the same information frequency However, if for example 0—1,000 cycles is the required frequency range then a recorder can be supplied in which the tape speed is 10″ per second with an F M carrier frequency of 7,000 cycles A frequency range of 0—10,000 cycles would again require a tape speed of 100″ per second, and a carrier of 70,000 cycles Any one of such recorders can clearly be employed with the same play-back unit without difficulty, providing, of course, the multiplication factor is noted

It is not suggested that this equipment in its present form is entirely suitable for helicopter work, but it is eminently suitable for helicopters ot the larger type when modified

A Flight Strain Gauge Equipment Designed Specifically for Helicopters

So far we have dealt in some detail with the problems of helicopter instrumentation and some of the equipment and methods which are available The Saunders-Roe Company Ltd had long been aware of the generally poor facilities available for this work and, consequently, put forward proposals to the Ministry of Supply in 1953 for a light weight 6-channel equipment specifically for helicopters

The projected equipment was revolutionary, catering for all stress measurements required and also making it possible for blade motions to be measured

The company proposed that it should design and develop the equipment for the basic function of measuring structural stresses and blade motion, a design target of 70 lb all-up-weight was set, so that the equipment could be used in the smaller helicopters

Title	*Weight (Lb)*	*Location*	*Overall Dimensions*
1 Pre-Amplifier and Mounting	10 2 ozs	Rotor Head	10 × 10 × 7½
2 Monitor Unit and Pedestal	22 8 ozs	Cockpit Forward	12 × 12 × 11
3 3 Phase Power Unit	9 3 ozs	Cockpit Aft	15 × 10 3
4 24v Power Unit	20 5 ozs	Airframe Aft	9 × 9 × 8½
5 Venner Batteries Box	9 4 ozs	Cockpit Aft	6½ × 8 × 6½
6 SFIM Recorder	4 6 ozs	Cockpit Aft	6½ × 8¾ × 4
TOTAL WEIGHT	76 lb		
Static Use Only 7 Calibrator Unit			

Fig 1 Indicates weights and location of equipment in its fully developed form

To avoid the practical difficulties associated with the use of slip rings at low signal levels, it was proposed that pre-amplifiers should be mounted on the rotor head The relatively high signal output would then be passed through slip rings to a panoramic display unit below in the cockpit

This display unit was to provide a visual assessment of oscillatory stress characteristics, with complete control of signal level by individual attenuatory facilities for each of the six channels The signals would be recorded in a small multi-galvanometer camera

The steady state stresses were to be measured directly by reference to a wide sweep galvanometer mounted in the display unit, the signals feeding this galvanometer being proportional to the unbalance present in the pre-amplifiers which, in turn, would be directly related to the strain gauge bridge or transducer connected to it Attenuating facilities would also be incorporated with this

Power supplies were to be derived from a 3 phase 400 c p s Rotary inverter running off the aircraft 24 volt system, each phase of 115 volts A C being stepped up or down by transformers to provide regulated, unregulated and EHT voltage This power supply system promised to reduce weight and bulk to a minimum

It was proposed to provide excitation for the strain gauge bridges or other transducers and the pre-amplifier heaters with a Venner accumulator, the light weight, small bulk and straight-line discharge characteristics of which were eminently suitable for the purpose

This accumulator was to be housed in the pre-amplifier structure itself, mounted on the hub, to reduce the number of slip rings required

Finally, the whole equipment was to be sufficiently ‘ rugged ’ to withstand all types and levels of vibration, and to remain reasonably foolproof during sustained field operation

A meeting was held at the Ministry of Supply on 20th August, 1953, to decide on acceptable limits of accuracy, sensitivities and other requirements, after which design and development of the equipment was started in the Company’s Electronic Division at Cowes Close co-operation was maintained with the Helicopter Division at Eastleigh, which was later to provide static and flight testing facilities

It was soon appreciated that the pre-amplifier formed the most exacting part of the design The effects of vibration, changes of temperature and the behaviour of the valves when under C F loads all presented problems which were overcome by the careful choice of components, re-design and sustained tests on a spinning rig

The final choice of valve for the pre-amplifier was a ‘ ruggedised ’ VX 7117 This valve is similar to types in current use in guided weapons and will withstand sustained use in unusual circumstances for longer than a normal production valve

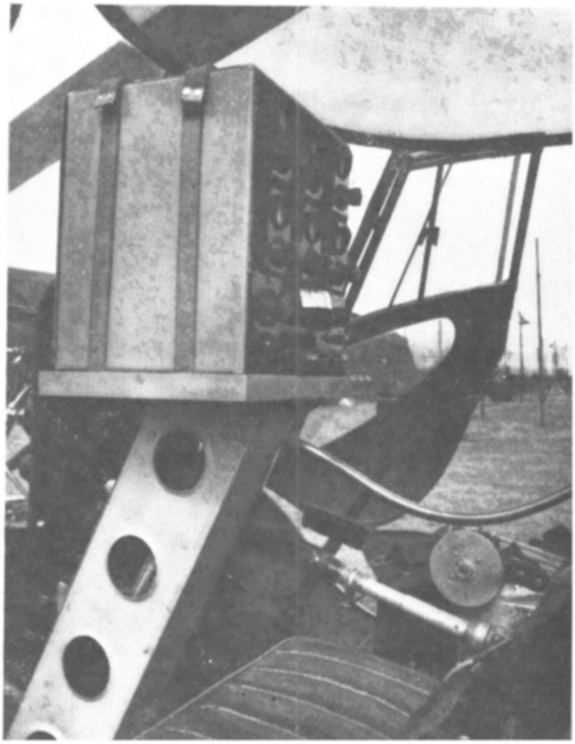


Fig 2 Display Unit Mounted in Skeeter Aircraft

Drift from D C amplifiers is an almost inevitable problem, and a figure of 1 millivolt per half hour was aimed at and eventually achieved This is equivalent to 1,000 lb per sq in stress (dural) when using Saunders-Roe foil strain gauges excited with 12 volts D C

As a certain amount of drift is inevitable in the pre-amplifier, and is indistinguishable from a steady strain, this limit was agreed as acceptable

The remainder of the equipment was by this time complete, and exhaustive laboratory tests were made to establish compliance with the requirements These included such widely-divorced items as wind tunnel evaluation, to observe the individual drift quantities when the equipment was operating in a forward flight condition, careful observations to determine modulation between channels and the noise level in the whole system when operating at maximum sensitivity

While this work was in progress, preparations were made in the Company's Helicopter Division for testing and proving the equipment Special mountings had to be designed and fabricated, so that they could be proved on the rotor test tower in conjunction with the equipment when it became available So did a set of 18-way slip rings

Decisions had to be taken regarding the number of strain gauge stations, the types of blade motions and other factors that would be measured on the Company's rotor test tower Eventually two programmes were planned, as follows

Programme 1 —A minimum of 10 half-hour runs to establish stress levels and the consistency of the equipment in respect of repeatability

Programme 2 —A minimum of 10 half-hour runs to establish mean steady blade angles in conjunction with part of Programme 1

On completion of the laboratory tests in early June, 1954, the equipment was despatched to the Saunders-Roe Helicopter Division at Eastleigh, for full-scale testing on the rotor test tower When it was installed on the tower, a series of static and spinning checks were made prior to the start of the test programme

The schedule of testing was arranged so that as many conditions as possible, representative of normal flight, were simulated It was decided to record sequentially the steady and dynamic loads at eighteen different control settings during all test runs, to ensure optimum usage of the equipment on each run, and to assess the results on a mainly comparative basis

In the course of the tests, it was found that the signals provided by the strain gauge bridges were less than anticipated This was due to the modified hub design used on the test tower, compared with that used for the Skeeter Coupled with the lower torsional vibration level of the rotor tower engine, it gave disappointing results

To provide a stronger signal, strain gauged flexible springs, deflected by the cyclic motion of the flapping links, were installed These proved satisfactory, and the combination of these transducers and the torque gauge on the main drive shaft was retained throughout the testing on the tower The recordings obtained were clear, and even quite small oscillatory and steady stresses were faithfully reproduced

The blade motion recordings were similar in this respect, and it was found possible to resolve zero coning of the main rotor blades at ±15 mins of arc In fact, the attenuating facilities enabled the resolution of much greater angles than this

During the course of these tests, a careful check was kept on drift from each pre-amplifier This and other aspects were recorded, together with a day book and a history of each servicing requirement, and the man-hours required to keep the equipment working

It was thought advisable to make a number of modifications based on the findings of these records before further testing was done The main effect of these modifications was to reduce the absolute drift/stress error to 1 millivolt per half hour, equivalent to 500 lb sq in stress (dural) At the same time, the equipment's overall sensitivity was doubled

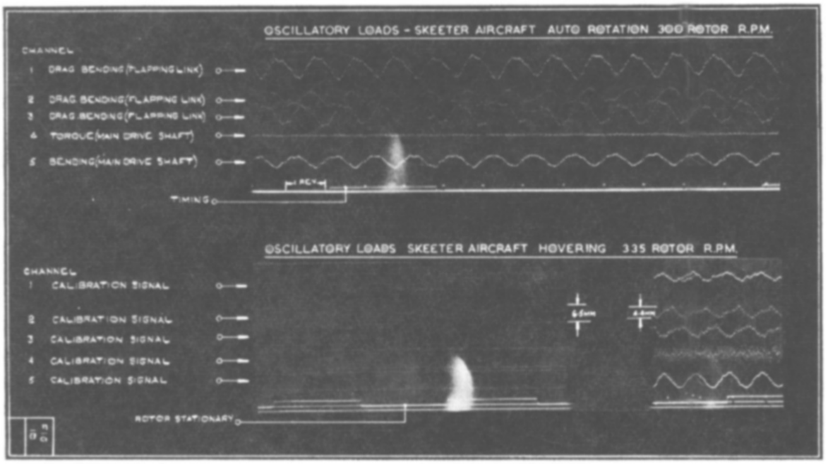


Fig 3

A further series of runs was made with the apparatus in this form, and tests on the rotor tower were completed in late October, 1954

Analysis of the results indicated a satisfactory factor of repeatability for

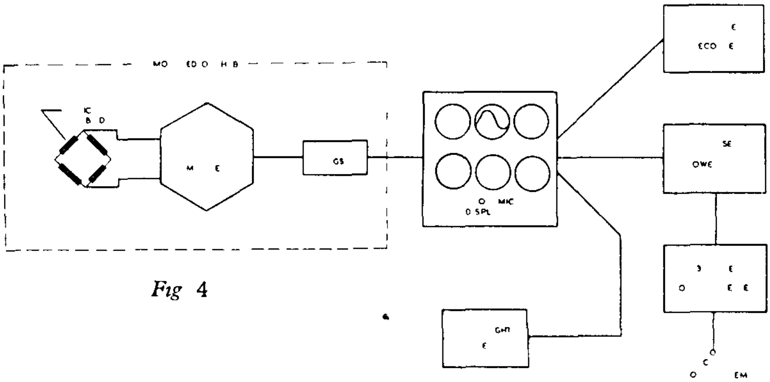


Fig 4

oscillatory and steady stress measurements The blade coning records were of a high quality and were found to be satisfactory in all respects Fig 3 is a typical example

Only the final proving of the equipment on a Mk 5 Skeeter aircraft remained to be done This necessitated the provision of a special set of slip rings, the design of which was the outcome of considerable work, during which many schemes were drawn and discarded The fabrication of the rings was undertaken by the Helicopter Division and necessitated working to watch-makers' tolerances

To facilitate mounting the equipment in the aircraft, it was ' broken down ' into several self-contained units, with multi-way cables connecting the respective circuits This ensured the most efficient use of available space in a small aircraft, and ease of re-deployment of the more weighty items for C G considerations The opportunity was also taken at this time to ' re-style ' the front panel of the monitor unit to ensure maximum ease in operation, and Fig 4 illustrates the layout of the equipment in its present form

The modified equipment and the new slip rings were tested on a specially constructed spinning rig consisting of a Skeeter helicopter secondary gearbox and main drive shaft, driven by a variable speed electric motor

These important components were checked completely before the next phase of tests was undertaken Weighing and C G determinations were carried out, followed by tie-down running to determine initial handling qualities for both equipment and aircraft

Fig 5 shows the pre-amplifier installed on the Skeeter aircraft

The first flight test was made on 1st September, 1955, and eleven 25-min flights were made up to the end of October In this period further modifications were made, the primary one making it possible to re-zero the pre-amplifier datums in flight This operation could be carried out as many times as necessary while the machine was airborne, and made it possible to measure very small steady stress conditions, such as the anti-torque present in the main drive shaft in autorotation This can be observed, because a small load is developed due to friction in the transmission system

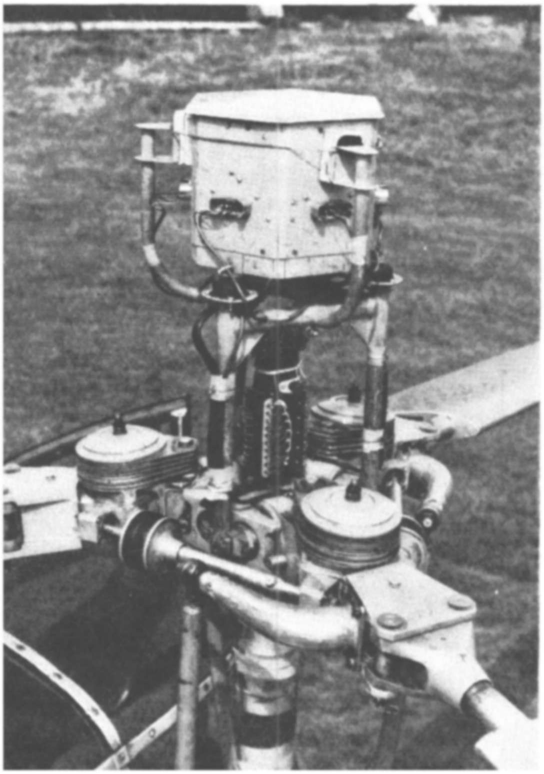


Fig 5 Pre-Amplifier and Slip Rings mounted on Skeeter Hub

With the drift problem finally overcome, the tests went ahead without incident until their completion on 16th December, 1955 A total of 46 flights was made, of which 35 provided full and acceptable stress recordings Fig 6 is a typical example of the oscillatory loads recorded, and the faithful representation of high frequency engine order present in powered flight and the comparatively smooth trace for the autorotative condition should be particularly noted

Following completion of the flight tests, a complete analysis was made and the results carefully studied It was found that the parameters of operation had been considerably improved and the oscillatory load characteristics faithfully reproduced

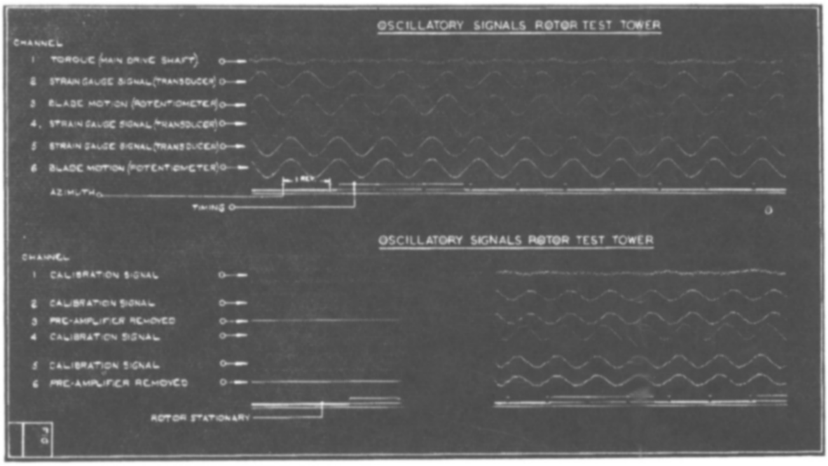


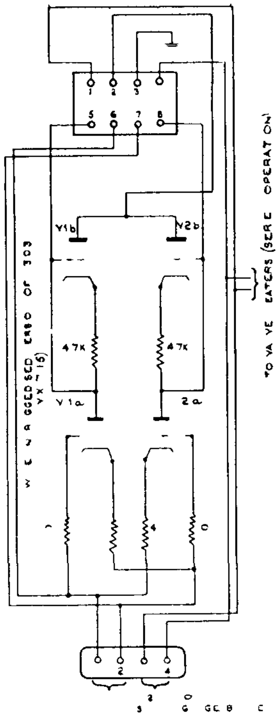
Fig 6

A further series of tests of the now-approved equipment was made on a Mk 6 Skeeter between 3rd and 8th April, 1956, to obtain a direct comparison between the two aircraft Sufficient recordings were made in this period to warrant removing the equipment pending analysis

However, analysis of oscillatory recordings is a lengthy procedure, and it is interesting to note that the test programme was actually completed in little over a week, but that full analysis of the results took approximately six weeks

As a result of full statistical analysis of the results from both aircraft, the Company has obtained clearance in respect of flight strain gauging for the Mk 6 Skeeter Consequently, the future will undoubtedly be busy for this equipment, as it will be required for the sustained testing of the bonded metal rotor blades, both on the rotor test tower and on a Skeeter Mk 6

The foregoing is but a short history of the development of the equipment However, we might now consider some of the interesting parts of the actual design



TYPICAL PREAMPLIFIER UNIT

Fig 7

The pre-amplifier valves used are of the 'wired-in' type, therefore eliminating variation of the valve pin contact potential

They are type VX 7115, this being a ruggedised version of the Brimar 13D3 with flying leads in order to achieve maximum robustness The increased heater consumption of this type as compared with other types of double triode results in a higher cathode temperature and, consequently, less tendency to variations of emission with heater voltage The resistors used are not critical in value, but should be reasonably matched to ensure the compensating action of the circuit (Fig 7)

The connections to the pre-amplifier assembly are made through an 18-way Plessey Mark 4 plug and socket This carries the twelve output signals, the H T +ve and —ve, the 24 volts from the Venner accumulators and the 24 volts to operate the relays An additional 18-way plug and socket is provided for connecting up to the field calibrating unit which is described elsewhere The pre-amplifier outputs and supplies are fed through a set of 20 way slip rings mounted on the main rotor shaft The design of these is dependent on the aircraft involved, but the use of silver rings and silver graphite brushes is strongly recommended

When blade motion measurement is being performed the strain gauges are replaced by high accuracy potentiometers of a type described earlier When using these potentiometers it is unnecessary to use a pre-amplifier and, hence, the equipment has been designed so that the pre-amplifiers can be individually removed and connections from the potentiometers made direct to the turret In this case, the energising voltage for the potentio-meters is obtained from the H T supply to the pre-amplifiers via suitable dropping resistors in either side This ensures that the mean potential of each potentiometer output is approximately the same as the pre-amplifier anode potential

THE BRIDGE BALANCING AND METERING PANEL

In the original scheme it had been proposed to incorporate a cathode follower in each pre-amplifier and switch a microammeter across each output to measure the unbalance With the re-designed circuit this is no longer possible and, hence, a single cathode follower valve with the meter connected permanently between the cathodes has been incorporated in the bridge balancing panel The switching is performed on the grids of this valve by connecting them into any one of the inputs from the pre-amplifiers In order to obtain maximum stability, the heaters of this valve are supplied from the Venner accumulators mounted in the cockpit of the aircraft

As it is not possible to have bridge balancing controls in the input circuits to the pre-amplifiers, these are incorporated in the bridge metering circuit and enable an artificial zero to be obtained on the meter, thereby correcting for any unbalance in the strain gauge or pre-amplifier circuits A second bank of contacts working in conjunction with the channel selector permits an appropriate potentiometer to be connected across the bottom of the cathode load resistors of the cathode follower The slider of this control is earthed and, hence, a variation in the current taken by each half of the cathode follower will result These balance controls would be set with the rotor stationary after a suitable warming up period

The balance meter is of the edgewise pattern and has a 3½″ scale and a 125-0-125 microamp movement A shorting switch normally closed is connected across the meter The reading is such that full scale either side corresponds to 5 millivolts input to the pre-amplifiers, but this is checked by means of the calibrating unit in test work A sensitivity switch is provided giving sensitivities of X1, $X\frac{1}{2}$, $X\frac{1}{3}$ and $X\frac{1}{10}$ It has been established that the sensitivity of the meter is not affected by the position of the balancing potentiometer

In order to amplify further and record the dynamic stress variations, it is necessary to isolate the amplifiers from the metering circuits which are directly coupled to the pre-amplifiers For this purpose a bank of capacitors has been incorporated in the inter-connecting circuitry

THE AMPLIFIER AND MONITOR UNITS

The amplifiers and monitors are built in sub-assemblies which plug into the main frame of the cabinet and are completely interchangeable with one another The facility of individual monitoring for all six channels has been incorporated in the equipment to facilitate rapid operation of the equipment when setting the respective gain levels The amplifiers, each of which has a balanced attenuator across the input giving 33 db total attenuation in 3 db steps, consist of a single balanced stage feeding in parallel a cathode follower and a further stage amplification, the latter supplying the signal at a level suitable for scanning the monitor tubes Negative feedback is taken from the output feeding the monitors to the cathodes of the input stage across which is placed a preset gain control The overall gain is set to about 750 and it is arranged so that full scan on the monitor tubes corresponds to a trace width of about 8 mm peak-to-peak on the film The coils of the galvanometer elements in the recorder, nominally 1,500 ohms apiece, constitute the cathode loads of the cathode follower output stage In this manner, the amplifier is balanced throughout the maximum rejection of hum pick-up and H T voltage fluctuation is ensured

The amplifiers have been designed to have a frequency response flat from 3 c p s up to 1 Kc The phase shift at 3 c p s is not greater than 5° as read on the film or 15° on the monitor tube The monitor tubes have long persistence screens to enable good presentation of the lower frequency phenomena to be obtained Each tube is equipped with individual X and Y shift, brightness and focus controls situated at the rear of the chassis so that they are only accessible when the chassis is removed for functional checking or maintenance purposes The tubes are operated with the positive earthed and the cathodes supplied from a 1,000 volt negative line

The time base has been re-designed and consists of a single pentode connected as a direct coupled transitron   It is a complete sub-assembly

The recording camera is of French manufacture and deserves mention in connection with the amplifiers   The galvanometers, which are of the moving iron type, are connected in the cathodes of the output stage of the amplifier   These galvanometers are mounted in the camera on two bars and arranged to reflect a beam of light direct onto a slit behind which runs the film, in this case, 60 mm recording paper   In addition, three relays are mounted in the camera carrying small mirrors on their pallets which enable them to transmit timing pulses on the film   One of these is normally actuated by a built-in timing device working off the drive motor leaving the other two free for marking azimuth position, the latter being derived from a device in the slip ring housing

BLADE MOTION MEASUREMENT

The measurement of blade motion is best performed with a high accuracy potentiometer coupled to the moving surface in such a way as to follow the angular motion thereof   In order to obtain the required resolution, it is necessary to choose a potentiometer having a large number of turns which inherently entails a winding of fairly high resistance   Since the angular movement of a helicopter blade is of the order of 30° to 45° as a maximum, it is advantageous to use some means of gearing up the movement of the potentiometer wiper to obtain full use of the available winding angle

In the system evolved it has been decided to use potentiometers with a 360° winding, having a centre tap, and employing two wiper arms diametrically opposite   The energisation voltage is applied across the winding and the centre tap, and the output is derived between the wipers   In order to minimise the effects of backlash, a step up ratio of no more than 1 66 1 is employed between the blade and the potentiometer spindle, thus 1° movement of the blade produces 100′ rotation of the spindle   The limit of resolution is the movement of the wiper between one turn of the winding and its neighbour   Hence, to give the necessary resolution, the potentiometer must be wound with 6 turns per degree, or 2,160 turns for the full 360° of winding, as a minimum

Sample potentiometers from two manufacturers have been obtained, having a linearity of 25% and the required resolution   Both are very similar in physical dimensions

As mentioned previously, the potentiometers are supplied from the stabilised H T supply via suitable resistors to ensure the correct sensitivity and mean operating potential   When operating with the six channel equipment, the sensitivity in terms of electrical output will have to be about 150 mV for 2 5° of blade movement, which corresponds to the full scale deflection of the bridge balance meter on its most sensitive range   This means a potential of 7 volts must be applied across each potentiometer

A very important feature of this equipment is the ease with which results may be interpreted

We might first consider interpretation of steady stress results   The calibration voltage from the static calibrator unit is applied to each channel in turn and the overall gain noted   This is usually 1,000 microamps indicated on the galvanometer of the panoramic display for 40 milli volts input at the pre-amplifiers Load is equal to microamps indicated during the tests, multiplied by the slope of the calibration curve

A typical strain gauge calibration curve taken in conjunction with the equipment is shown in Fig 8 The method of slope determination is also shown

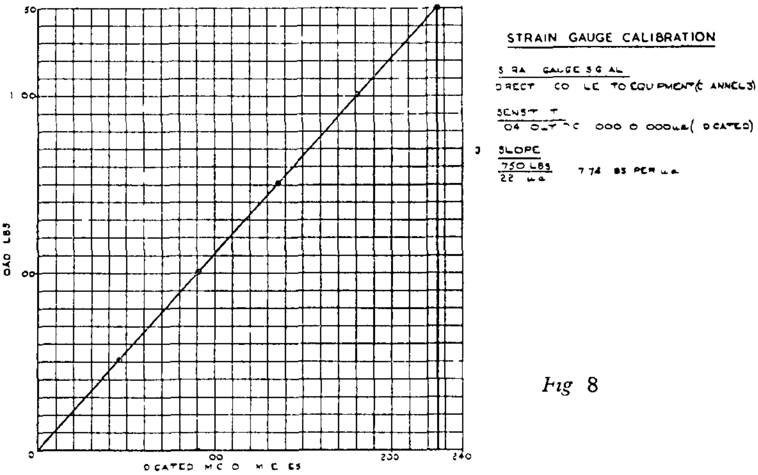


Fig 8

As the calibration bridge voltage is different from the test voltage, the slope must be corrected by the ratio thereof When interpreting fluctuating stresses it must be borne in mind that the amplification of the equipment is determined by calculations and by direct calibration for all attenuator settings

Fig 9 illustrates the peak-to-peak voltages at the pre-amplifier's input for a trace width equal to the calibration trace width

The measured trace width will, therefore, correspond to a voltage at the input equal to that listed at its particular attenuator setting, multiplied by its ratio to the calibration trace, *i e* , if the measured trace width equals d millimeters, if the calibration trace width equals c millimetres and if peak-to-peak voltage at the pre-amplifier input for the appropriate attenuator equals v millivolts settings from the table, then the open circuit voltage from the strain gauge bridge equals $\frac{d}{c} \times v$ millivolts, open circuit at the pre-amplifier input To transform this value into load, the calibration slope used in the steady signals can be modified to give load per millivolt open circuit at the pre-amplifier input This is achieved directly, since the galvanometer deflection is measured for plus or minus 40 millivolts at the pre-amplifier input, the mean of the readings in the two directions being used The deflection is approximately plus or minus 1,000 microamps and, in this event, the slope in load/microamps is multiplied by 25

Attenuator Position Monitor	$\overline{db}$	*Open Circuit Milli-Volts P P at Pre-Amp Input*	*P R Amplitude on Cathode Ray Tube*
11	33	80	1
10	30	56 65	1
9	27	40 15	1
8	24	28 4	1
7	21	20 1	1
6	18	14 23	1
5	15	10 08	1
4	12	7 13	1
3	9	5 05	1
2	6	3 575	1
1	3	2 533	1
0	0	1 795	1

Fig 9

The fluctuating load is, therefore, given as plus or minus

$$\frac{d}{2c} \times v \times 25 \times \text{slope of calibration curve}$$

Example

$$\frac{4\ 4}{13} = 3385 \times 10\ 08 = 3\ 412 \times 25 = 78\ 55 \times 7\ 74 = 607\ 98 \text{ lb load}$$

It would be readily appreciated that both steady and fluctuating stresses can be interpreted from a strain gauge calibration made directly to the equipment This facility avoids unwieldy calculations and conversion factors

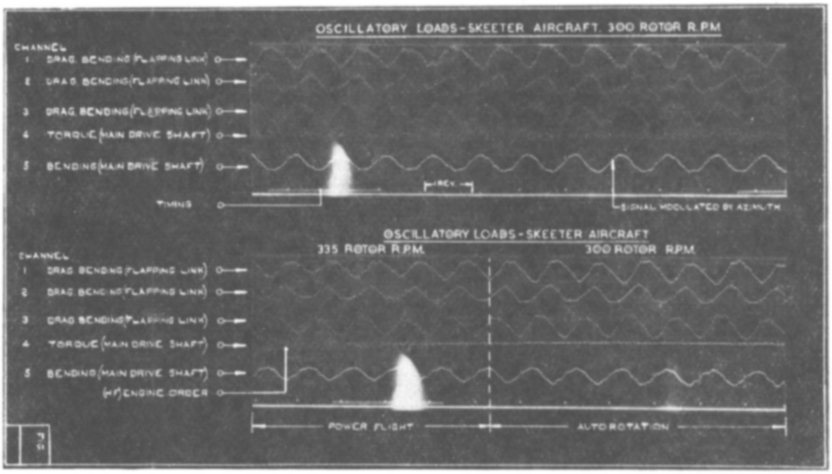


Fig 10

In conclusion, the equipment in its developed form appears to be superior to any other system in use at the present time for accurately assessing oscillatory and steady stresses in rotary wing aircraft

The equipment's relatively small bulk and weight have enabled full scale testing to be carried out successfully in the world's smallest fully articulated helicopter, yet these former considerations have not in any way reduced the scope of measurements or reliability

Due to careful design and development in parallel with flight testing facilities, the requirements of the user have been satisfied, resulting in a flexible and functional set of flight test equipment The individual appraisal in flight of stress levels on the display unit is complementary to relevant attenuating facilities, the advantages of this are considered to be of great importance

The method of amplifying relatively small signals with thermionic valves and passing the amplified signals in a voltage form has proved itself not only practical, but superior to direct recording systems in use in the United Kingdom or the Continent

Maintenance requirements for the equipment are average, bearing in mind its relatively complex nature

The separate unit system makes maintenance much easier The fact that strain gauging blade motion calibrations are made directly dispenses with the hazards of calculation errors and makes analysis of oscillatory and steady stress quantities simpler and quicker

In general, these characteristics are due to the original conception and sound electronic design, married to the experience gained in the field which have led to a major step forward in helicopter stress measuring techniques

I would like to thank the Ministry of Supply for permission to quote certain details relevant to this equipment, I am also indebted to Saunders-Roe Ltd for facilities and permission to present this Paper

I would point out that the opinions quoted herein are not necessarily those of Saunders-Roe Ltd

Discussion

The **Chairman** said it had been a most interesting lecture on a subject which those who were involved in both design and manufacture found it necessary to tolerate! The Author's review of the methods and systems had been most stimulating future the instrument they wanted to use would be a magnetic tape recorder At

The Chairman added that as he was not himself an electronic expert, he would like those most competent to do so to comment and criticise and give their contributions to the discussion

Mr R Trumper (*Test Superintendent*, *Fairey Aviation Co*, *Ltd*), said he had listened with great interest to an excellent summary of instrumentation, because he had been faced with similar problems in the last few years at Fairey's They had had to think of suitable instruments for use on their large helicopter, the Rotodyne, and their ultra-light machine

To his pleasure and surprise, he found that Saunders-Roe and Fairey's had very much the same views on the correct procedure in instrumentation *i e*, that in the future the instrument they wanted to use would be a magnetic tape recorder At the present time the mirror galvanometers, which had been used in propellor testing for many years, were probably the best for large helicopters For small ones the Hussenot recorder, together with some form of amplifier, appeared to be the best