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CURRENT PAPERS

Full-Scale Measurements of Impact Loads on a Large Flying Boat

Part I

Description of Apparatus and Instrument Installation

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Full Scale Measurements of Impact Loads on a Large Flying Boat

Part I

Description of Apparatus and Instrument Installation

by

J.W. McIvor, B.Sc., A.M.I.E.E.

SUMMARY

The variations with time of the tote.1 force and the distribution of water pressures on the hull bottom of a flying boat are related to the horizontal velocity, vertical velocity and keel attitude relative to the mater during tho impact. Methods are described for obtaining, in a form suitable for easy analysis of results, records of these variables, in order to verify impact theories.

The equipment used included transducers for the conversion of physical quantities to electrical signals, multi-channel electronic amplifiers and mirror galvanometer recorders. A shore-based cine camera, synchronised with the internal recorders, provided information on forward speed end rate of descent.

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/Introduction .....

1. Introduction

Information was required on the variations with time of the total force, the stresses in the hull structure and the distribution of water pressures on the hull bottom of a flying boat on alighting. These forces and pressures had to be related to horizontal velocity, vertical velocity and keel attitude, relative to water surface.

Experience from earlier model and full scale experiments of this kind had show that mechanical instruments for measuring total force and local pressures suffered from disadvantages such as inaccurate synchronisation and time-consuming analysis. Many of the disadvantages associated with these instruments can be overcome by the use of electronic equipment, and this note describes the installation and combination of a number of such instruments to give reliable operation, and to provide impact records in a form which would lend itself to the computation of results with least effort.

2. Quantities to be measured

2.1 Impact Parameters

The impact acceleration and hydrodynamic pressures on the hull bottom of a given flying boat have been shown [1,2] to depend on the speed, the flight path angle and the attitude of the aircraft at impact. Verification of these impact laws therefore demands the measurement of horizontal velocity, vertical velocity and keel angle relative to the water surface.

For the Sunderland, horizontal velocity may vary slowly in the range 160 ft/sec to 110 ft/sec during first impact and the subsequent impacts where skipping occurs. The maximum vertical velocity expected is approximately 10 ft/sec. Keel angle may change from horizontal to + 15" during the impact and a range of - 3° to + 17° is necessary to cover normal circuit conditions.

2.2 Acceleration

Measurement of the acceleration normal to the keel of the centre of gravity of a flying boat during impact is complicated by engine vibrations and wing fundamental and first harmonic vibrations. The acceleration/time curve builds up to a maximum in 0.3 to 0.7 seconds and the maximum imposed acceleration expected is 2.0 g.

2.3 Pressure

The hydrodynamic pressures on the hull bottom during impact vary from a sharp peak pressure near the edge of the wetted surface to a comparatively steady value of about half of the peak value, The pressure rises from zero to a maximum of about 35 lb/sq.in. in 0.01 seconds for the sharpest wave fronts. Tha distribution of pressure over the hull bottom during the impact is of considerable importance.

2.4 Strains

The distribution of the load on the hull bottom throughout the structure can be traced by measuring the strains in suitable members. The rate at which strains build up in the structure depends on the location, being about 0.01 second fur bottom plating and 0.2 second in main frames.

2.5 Time of first impact

Zero time in the history of an impact is usually taken as the instant at winch first contact is made with the water. A recorded indication of this event is necessary.

/3. Recording Equipment .....

3. Recording Equipment

3.1 Description

To facilitate analysis and to simplify synchronisation it is desirable to use as few independent recorders as possible. Measurement of the variation of the pressure distribution on the hull bottom during the time of impact demands a relatively large number of recorder channels with a frequency response from 0 to at least 100 c.p.s.

A sixteen channel mirror galvanometer oscillograph, manufactured by the William Miller Corporation, U.S.A., with its associated multi-channel electronic amplifier was at the time the only available equipment suitable for flight use which met these requrements. Two such oscillographs were used making available 32 charnels for internal recording of pressures, accelerations, strains and angles of pitch and roll.

The amplifier unit has fifteen similar channels consisting of a bridge circuit energised by 10 volts, 2000 c.p.s., followed by two stages of amplification at carrier frequency. The galvanometer current is obtained from a phase sensitive demodulator followed by a direct coupled cathode follower output stage. The power supply unit for these amplifiers provides stabilised direct voltages at + 250 v and -150 v and includes a carrier oscillator whose output voltages are maintained at constant amplitude and frequency.

The mirror galvanometers in the recorder are of the D'Arsonval type with a coil of very small dimensions in a common magnet system, Damping forces are provided by the back e.m.f. in the coil and eddy currents in the former. The galvanometers used have a natural frequency of 165 c.p.s. and a response level within 2% up to 100 c.p.s. when suitable individual damping resistors are fitted. The record is made on eight inch wide photographic paper driven by a remotely controlled motor. 6 ins/sec was found to be a convenient speed for impact experiments. The marking of the time base and synchronisation of records will be described later.

3.2 Installation

The recorders, amplifiers and power units were installed in the wardroom of the Sunderland as shown in Figures 1 and 2. The compact arrangement was adopted to enable the equipment to be completely enclosed by plywood panels and covers as shown in Figure 3. It was necessary to devise some form of protection from the humid salt-laden atmosphere as the removal after tests from a moored flying boat of six units weighing up to 90 pounds each was considered to involve too great a risk of damage.

Experience from the first series of tests using this installation showed that the method used was quite satisfactory for summer conditions. Greater precautions to protect the equipment, such as the use of drying agents, may be necessary in adverse weather.

A 12 volt supply consisting of accumulators with a total rated capacity of 480 ampere-hours was provided with local and remote switching for each power unit and recordor. The total connected load for two sets of equipment is 75 amperes at 12 volts. Figure 4 shows the accumulator installation and low voltage switching on the port sido of the wardroom.

The connections for all pick ups and strain gauges were brought to a distribution panel on the aft bulkhead of the wardroom enabling pick-ups to be readily selected for a particular test - Figure 2.

4. Pressure Gauges

4.1 Requirements

Theoretical investigation [2], confirmed by model scale experiments at

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M.A.E.E.[3], has shown that the pressure distribution on a hull bottom during impact has a characteristic peak near the edge of the wetted surface followed by a lower sustained pressure.

In Ref.4, the Wagner pressure distribution was used in the evaluation of a correction factor for pressures measured over a finite area. Within the practical limits of installation in a Sunderland, an instrument with a 1 inch diameter diaphragm requires an area factor varying from 1.07 at the keel to 1.02 at the chine. The correction is small enough to reduce to a negligible amount the effects of errors in area factor due to the limitations of the Wagner distribution theory.

The pressure at the wetted edge has a minimum time to punk of 0.01 second. This demands a pressure gauge with a dynamic response free from errors in amplitude and phase up to at least 100 c.p.s.

The maximum value of the peak pressure expected during heavy landings by a Sunderland flying boat was estimated at 35 lb/sq.in.

Adequate water proofing of the gauges and ease of calibration in situ are of considerable importance.

4.2 Description

Gauges to meet this specification were manufactured at the Royal Aircraft Establishment. The construction is simple and is clearly shown in Figure 5. A German silver diaphragm, 1 inch diameter and 0.004 inches thick is fitted flush with the outer surface of the bottom plating. Diaphragm deflection is transmitted to a beryllium copper cantilever whose bending is measured by strain gauges.

The undamped natural frequency of vibration of the cantilever and diaphragm system was found to be approximately 1500 c.p.s. The damping coefficient is very low, being less than 0.05 of critical for all conditions of diaphragm immersion. The response of the pressure pick up to pressure variations up to 100 c.p.s. is therefore substantially level with a percentage overshoot at 100 c.p.s. of less than 0.5%. Due to the very low damping coefficient and relatively high natural frequency of vibration of the diaphragm-cantilever systemthe effects of phase distortion and consequent displacement of a pressure wave along the time axis can be neglected.

A view of the hull bottom with pressure pick-ups installed is shown in Figure 6.

4.3. Comparison with earlier instruments

In earlier full scale and model scale measurements of impact pressures[5] use was made of a mechanically operated gauge similar, in principle, to the electronic gauge just described, except that the movements of the diaphragm were recorded on a glass or metal slide by a diamond tipped lever. These instruments were inferior to the electronic instrument in that each had its own individual record which had to be measured from a highly magnified projection of the recording slide, thus causing an increase in the time required for analysis. There was, in many cases, some inaccuracy in synchronising the records from various pressure pick-ups.

The results from the latest Sunderland tests confirm that the electronic instruments are more convenient to instal and the records from them are much more easily and accurately analysed. However, in experiments where only one or two pressure gauges are involved and extreme accuracy in synchronisation is not necessary, the mechanical type of gauge may have advantages in simplicity of installation over the electronic types.

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4.4 Calibration

The pressure gauges are calibrated in situ since the pressure/deflection curve for the pick-ups is not quite linear and a change of zero due to slight distortion of the instrument on installation introduces errors.

A calibrating cup was screwed to an outer ring to avoid interference with the pressure gauge, Air pressure applied to the calibrating cup was measured by a dead weight tester.

The calibration of all pressure pick-ups was carried out before and after each series of tests and were found to repeat with a maximum error of 4% of full scale deflection. The greatest anticipated error in peak pressure measurements is estimated to be of the order of 5%.

5. Acceleration Measurement

5.1 Discussion

The measurement of the normal C.G. acceleration of a flying boat on alighting is complicated by the presence of local alternating accelerations. The most important of these vibrations in main structural members at the main step and centre section are engine vibrations and the fundamental and first harmonic vibrations of the wing when excited by a heavy impact.

Troublesome accelerations due to angina vibrations have frequencies greater than 10 c.p.s. and as the impact acceleration has a time to peak of the order of 0.5 second a low pass filter can be used in the amplifier to attenuate the higher frequencies without serious distortion of the impact acceleration wave form.

Frequencies of wing vibration of' significant amplitude are about 3.5 c.p.s. and 8 c.p.s. and, consequently, their effects cannot be eliminated by a frequency discriminating circuit. It has been shown in earlier work on this subject that the addition in correct proportions of the accelerations measured at three points along the wing eliminates the accelerations due to the two predominant modes of vibration and gives a sensibly true measure of the C.G. acceleration. A development of this method is the electrical combination of the signals from three accelerometers whose ssnsitivitics are appropriate to their position.

5.2 Description of method used

There is available for use with the Miller equipment a variable air gap inductance accelerometer whose small size and weight make it suitable for aircraft USC. The Instrument, which is described elsewhere [7] has acceleration' and frequency ranges of ± 12 g and 0-100 c.p.s.

To reduce the effects of engine vibrations the out-off frequency of the amplifier low-pass filter, which normally rejects the carrier, was lowered to attenuate signals above 10 c.p.s. The effects of this relatively severe curtailment of the frequency response were examined by Fourier analysis-of the measured acceleration wave form and was found to cause local changes in wave shape whose magnitude in the worst case measured was less than 2% of peak acceleration. A secondary affect of the low pass filter is the introduction of a phase change of 8°/c.p.s. the result of which is a delay of the acceleration signal by 0.02 sec. This constant delay can be allowed for in analysis of the records.

Inspection of the results of the first series of tests indicates that less severe attenuation of accelerations due to engine vibrations

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can be tolerated as during impact the engine power is small and consequently the level of disturbing signals is low. A higher cut-off frequency will, of course, give an improvement in the accuracy of measurement of the impact acceleration.

To eliminate the effects of wing vibrations, the signals from three accelerometers with sensitivities corresponding to their positions on the wing were combined by applying the parallelled output of three amplifier channels to a single galvanometer. The effect of shunting an amplifier output by the output impedance of two others is appreciable but it can be counteracted by calibrating the accelerometers individually and collectively with circuit conditions as used for measurement.

The accelerometers were mounted on pads clamped at suitable stations to the web of the inverted "T" section which forms the lower member of the main plane front spar.

5.3 Calibration

As accelerometers with a linear acceleration/deflection response were being used to only 10% of their rated frequency range, static calibration over the range ± 1g was considered adequate. The combined accelerometers were calibrated simultaneously after the amplification of the individual channels had been adjusted to give sensitivities appropriate to the position of the accelerometer relative to the nodes of the fundamental and first harmonic vibrations of the wing.

Periodical check calibrations during test flights mere made by recording the inversion of a master accelerometer during straight and level flight and following this by a record of a "1g pull-out" which, of course, applied an equal acceleration to all pick-ups.

Overall error of acceleration measurement is considered to be less than 0.1 g.

A typical acceleration record is illustrated by Figure 7. It shows the third impact in a landing where skipping occurred. Whereas the mid-hull accelerometer shows wing fundamental vibration at 3.5 c.p.s. and the mid-wing accelerometers, situated close to the node of the fundamental vitiation, indicate first harmonic vibration at about 8 c.p.s., both these unwanted signals are effectively eliminated from the record of the combined accelerometers.

6. Strain Gauges

Strain gauges were used to measure the distribution of the impact load on the hull bottom through the hull structure.

Commercially obtainable strain gauges were affixed to selected points on the hull structure with a cold-setting cement and water-proofed by a coating of wax compound, "Dijel" followed by a covering of "Bostic C" cement for mechanical protection. The waterproofing was not entirely satisfactory and further work is required to determine the most suitable method of protection of strain gauges in flying boats.

The strain gauges were calibrated by application of a measured pressure to a limit area of hull bottom by means of a water bag.

7. Angular Movement - Pitch and Roll

7.1 Method

The required range of pitch covered keel angles from -3° to + 17° and roll over ± 15°.

An electrically driven gyroscope of German origin, the Anschütz horizontmutter, was used to provide a reference plane against which the pitch and roll of the aircraft was measured. As the gyroscope was fitted with potentiometer pick-offs a resistance bridge circuit provided voltages for visual indicators and recorder galvanometers. The gyroscope was installed with the gimbal rings completely balanced and with the accelerometer mounted on the inner ring locked. The electrical erection system incorporated a bubble switch and there were also facilities for fast erection when the rotor started from rest.

The installation of the control unit for the gyroscope and the second pilot's indicators are shown in Figures 8 and 9 end the circuit of control unit in Figure 10. A carbon pile voltage regulator provides a constant voltage for the rotary convertor and indicator circuit. A double line switch is necessary to protect the meters from tho transient voltage developed by the convertor on switching off. Further protection from overload during initial erection is given by a thermal delay relay. A remote meter switch cuts out of circuit the pilot's indicators and the recorder galvanometers and trebles the range of the local roll indicator to deal with the angles of bank experienced during flight, To free the gyroscope the erection switch disconnects the erection coils,

During flight the erection mechanism which is, of course, pendulous, is switched on only when no horizontal component of acceleration is applied to the gyroscope and the remote meters are normally disconnected. While on the last leg of the approach the gyroscope is finally erected and the remote meter connect&. Immediately prior to landing the gyroscope is freed. The aircraft is maintained on a straight path to the end of the landing run when a record of the horizontal datum is taken.

7.2 Calibration and assessment of accuracy

Rotating the gyroscope on its mounting and measuring the case angle with an inclinometer enables the complete system to be calibrated. The gyroscope case is then aligned with the keel and the transverse datum line.

A limit to the accuracy of measurement is the angle subtended at the centre of the toroidal wirewound potentiometer by a single turn. This corresponds to approximately 0.2^{o} and the angles are indicated in steps of this magnitude. The maximum error of measurement, including the effects of gyroscope precession during landing, variations of applied voltage and initial calibration errors, is estimated to be 0.5^{o}.

8. Vertical and Horizontal Velocities

8.1 Method

A high speed 35 mm. cine camera running at 100 frames per second was set up on shore to traverse in a horizontal plane and photograph the flying boat descending before impact and during landing, including subsequent impacts whore skipping occurred. The camera was fitted with a 1/50 sec. time marker and was synchronised with the internal recorders.

8.2 Analysis

The aircraft is marked with a series of black crosses at measured intervals on a white background forming a vertical line and a line parallel to the keel. Measurement of the apparent distances between crosses on each frame enables the range and obliquity of the aircraft to be established. Correction of the measured height of the aircraft from a horizontal datum (e.g. the horizon or the edge of the frame if the camera traverses horizontally) gives the true height from the datum line. A height/time curve is obtained by analysis of successive frames and graphical differentiation gives the vertical velocity. Similarly horizontal velocity and keel angle can be

/derived .....

derived although these parameters are more readily measured in the aircraft by a low reading air speed indicator and the Anschutz gyroscope,

8.3 Criticisms of the use of an external camera

The use of an external camera gives rise to a number of disadvantages not the least of which is the time and labour required to analyse the film.

Weather conditions restrict the use of the external camera, both visibility and wind direction being limiting factors. Further, rate of descent is measured relative to a horizontal datum and the method is therefore limited to calm seas with no swell. The presence of a shore based camera complicates the test procedure, requiring in addition to the photographer :-

(a) a communication system, air to camera;

(b) synchronising equipment, as the time of first impact is not sufficiently clearly defined in adverse conditions;

(c) a restricted range of touch down points, adding to the difficulties of a pilot making a controlled heavy landing.

Minor troubles experienced during the first series of tests due to an unsatisfactory horizontal datum line have been remedied by fitting a graticule in the high speed camera and by making an adaptor to fit the camera to a standard F47 camera tripod which has superior levelling facilities.

8.4 Accuracy

The probable error in the measurement of vertical velocity by this means is high, being as great as 1 ft/sec in 10 ft/sec, and is mainly due to innacuracy in differentiating the height/time curve.

9. Time of First Impact

A water contact (Fig.11) is fitted as near to the keel at the main step as possible. The change in its resistance when wetted lights a neon indicator on the second pilot's panel while part of the lamp current is passed through a galvanometer to mark the record, A correction is necessary to allow for the small distance between the contact and the point of the step.

10. Timing and Synchronisation of Records

10.1 Accuracy Required

The most severe demand on the accuracy of time measurement is made by the use of a single initial signal to synchronise the two internal recorders and the external cine camera over the period (say 10 seconds) of successive impacts where skipping occurs. For the internal recorders, alignment of pressure signals to within two milliseconds necessitates a frequency difference between timing systems of less than 2 parts in 10^4. As vertical velocity is a relatively slowly changing parameter before impact, the degree of synchronism required between the external camera and recorders is lower, 0.5% being satisfactory. The absolute accuracy needed from the recorder timing system is not high, 0.1% being more than adequate since a limit is set to the usable accuracy by the difficulty of measuring small time intervals at a paper speed of 6 ins/sec.

10.2 Timing system of Miller recorders

The time base of the Miller oscillograph is derived from a valve maintained 60 c/s tuning fork, driving a synchronous motor through a paraphase

/push-pull .....

push-pull amplifier. As the timing circuit is omitted from the manufacturer's handbook it is included as Figure 12. An occulting disc, with twenty radial slots, the tenth and twentieth being wider than the others, is driven through gearing at 300 r.p.m. Light passing through the disc marks the record at 1/100 second intervals with heavy lines every 1/10 second. A check at room temperature of tuning fork frequency against a sub-standard oscillator indicated that the accuracy was better than 1 in 10^4.

10.3 Timing of External Camera

The timing system of the high speed cine camera consists of a 50 c.p.s. tuning fork which is maintained in oscillation by an electro magnet controlled by a contact on the fork. A similar contact interrupts the primary circuit of an induction coil whose secondary voltage triggers a spark gap; the light from the spark gap marks the edge of the film at 1/50 second intervals. This timing system agreed with that of the Miller recorders to within 3 parts in 10^3.

10.4 Synchronising Signals

The synchronising system is duplicated both radio and light signals being used. An automatic method of originating the signal reduces the possibility of human error and enables a short timing pulse to occur soon after the start of the recorders.

Figure 13 is a schematic circuit of the recorder remote control system and the automatic synchronising unit. The recorders are individually controlled by the remote control units and jointly operated by the second pilot's push-button. Operation of this push-button, normally during the last few seconds of the approach, starts both recorders and initiates the following synchronising sequence. Relay B operates and switches the aircraft's V.H.F. equipment (TR 1430) to transmit. Relay A is slow to make, the 150 m/sec operating time being occupied by the switching and accelerating of the recorder motors and by V.H.F. switching. The contacts on Relay A are adjusted so that when A operates the events listed below occur within 1 m/sec.

(a) A voltage is applied to relay C

(b) A paw of photoflash lamps are fired

(c) 0.25 mA is passed through a galvanometer in each recorder

(d) A relay circuit in the V.H.F. transmitter is closed causing a 1000 c.p.s. note to be transmitted.

Relay C which is also slow to operate, releases A and locks itself in until the push-button is released.

The radio signal system is a simplified version of that used by the Blind Landing Experimental Establishment[8]. The 1000 c.p.s. pulse is received by a TR 1143 at the ground camera and fed to a parallel-T bridge amplifier[9] which controls a relay. This relay interrupts the timing circuit of the high speed camera for the duration of the synchronising pulse. The V.H.F. equipment is also available for voice communication.

Two photoflash lamps are fitted as they frequently fail to operate and there is the possibility of a single lamp being obscured from the camera by a float. A typical view of the flying boat, enlarged from the cine film, shows the light signals - Figure 14.

10.5 Calibration of synchronising signals

Delay in the radio synchronising signal is due to the operating time of the relays in the transmitter and tuned amplifier and to the displacement of the spark gap from the gate in the camera. An overall direct measurement

/of ....

of the time difference was obtained by applying a fraction of the spark gap triggering voltage to an internal recorder. Synchronisstion by this method is to the nearest timing impulse, i.e. not better than 20 mSec.

The only significant delay in the photoflash system is that due to the lamps themselves. By using a photocell to record the light pulse the average delay to 50% of peak light was found to be 7 m Sec, ± 3 m Sec. Synchronising is possible by this method to the nearest frame, i.e. to 1/100 sec.

11. Further Work

Vertical velocity is the parameter which is measured with least accuracy and most computing labour. There is a need for an airborne instrument which will measure vertical velocity directly. A form of low reading radio altimeter appears to be the most promising solution.

The waterproofing of strain gauges in the presence of sea mater is a troublesome problem and the methods recommended by Fitch [10] may well be tried.

12. Conclusions

Electronic equipment is well suited to the measurement of the impact pressures and accelerations experienced during the alighting of a flying boat especially when a number of rapidly changing parameters have to be related on a common time scale.

It is essential, however, that the limitations of the equipment are continually borne in mind and that suitable precautions are taken during the calibration, operation and maintenance of the instruments to keep errors to a minimum.

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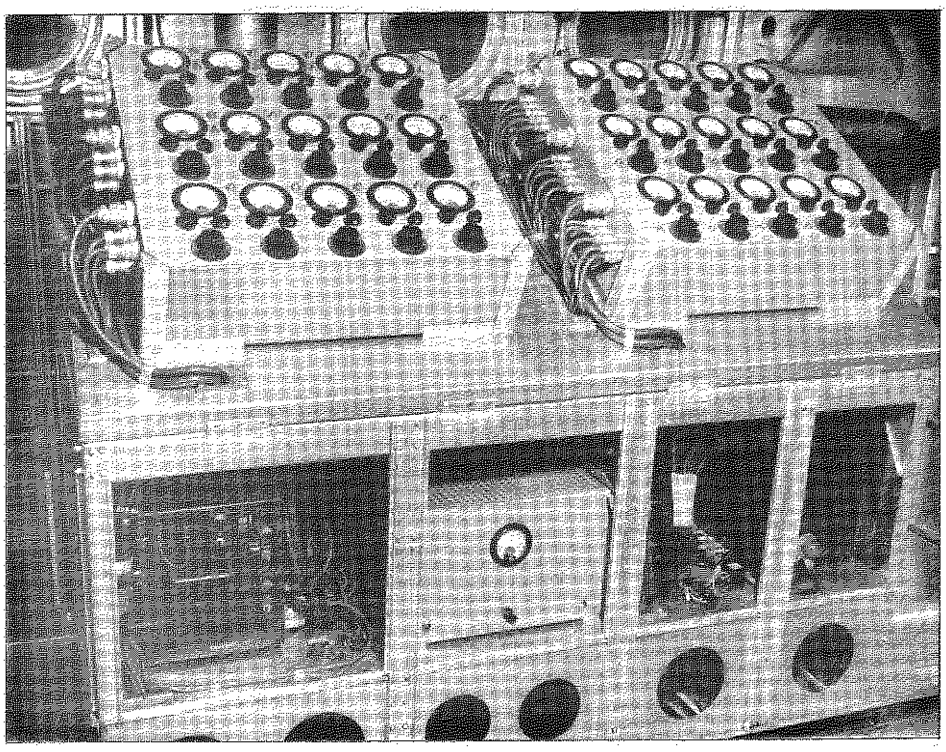
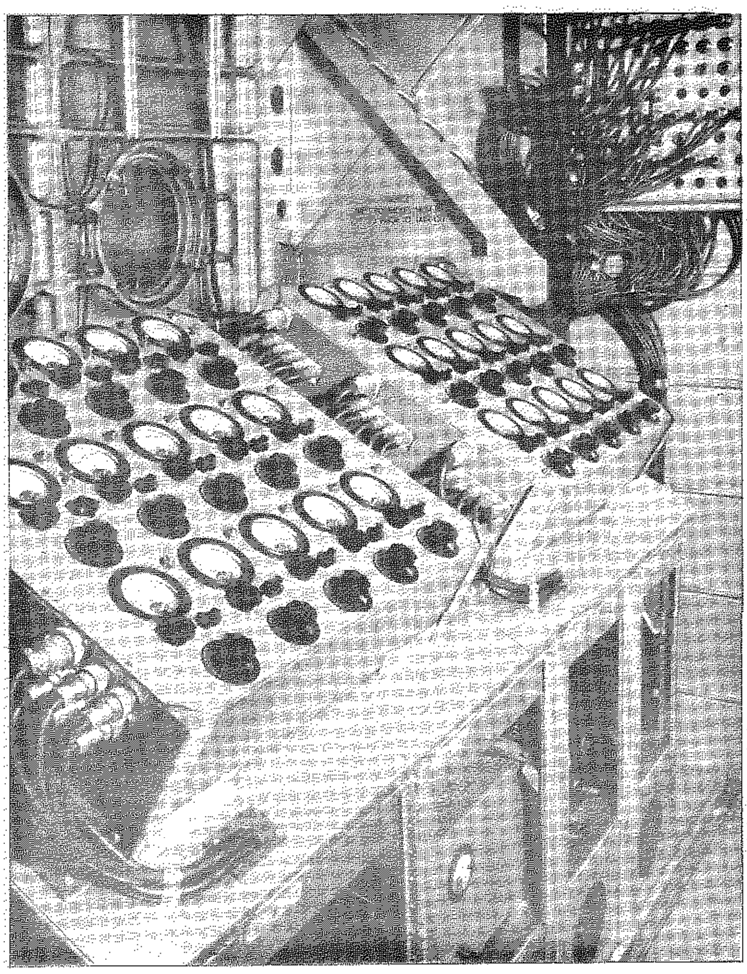
FIG. I.



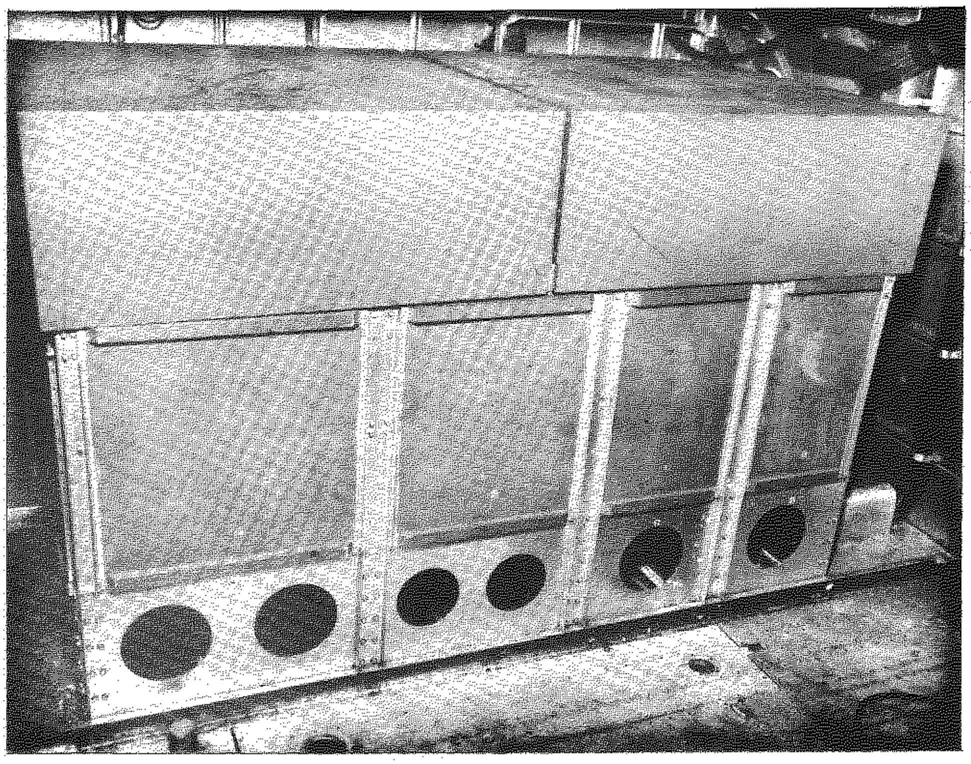
INSTALLATION OF MILLER EQUIPMENT IN WARDROOM

FIG. 2



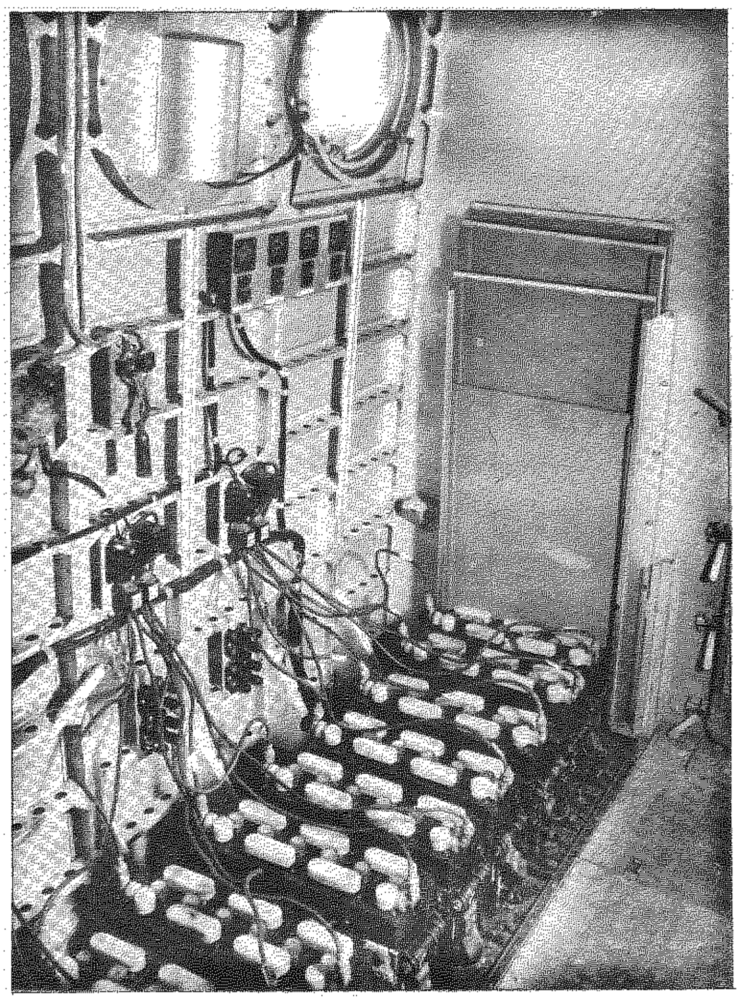
INSTALLATION OF MILLER EQUIPMENT SHOWING PICK-UP JUNCTION PANEL.

FIG. 3.



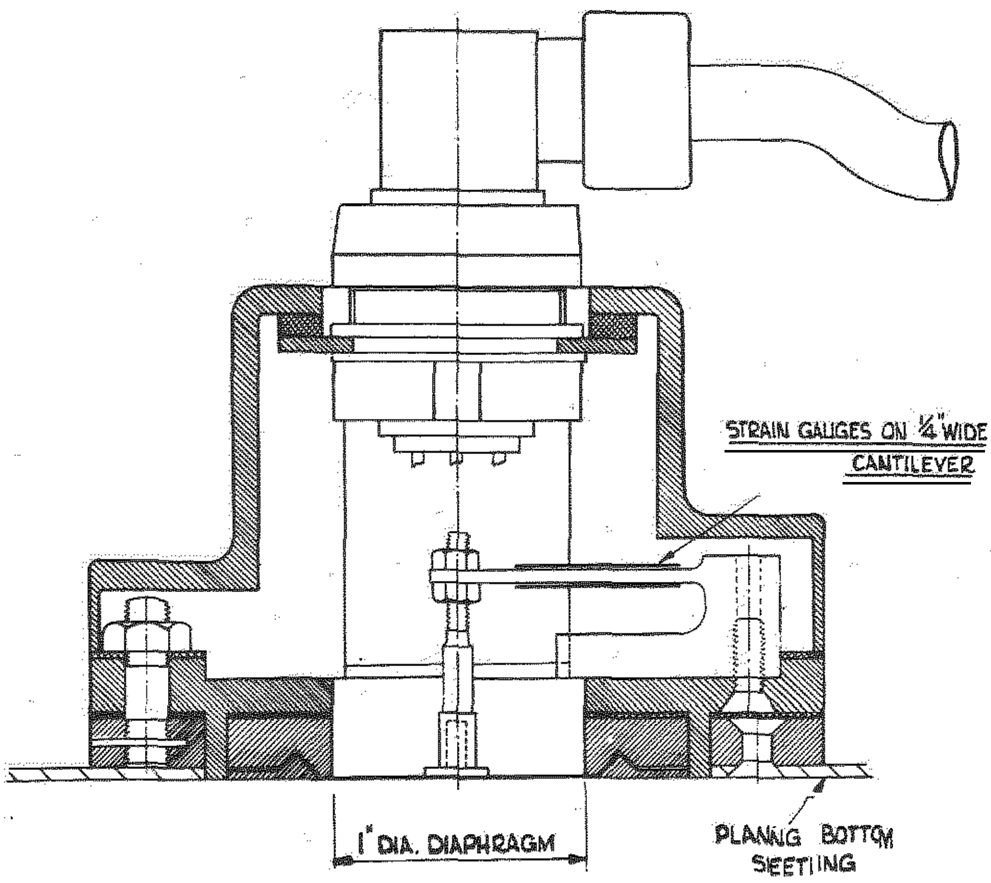
PROTECTIVE COVERS FOR MILLER EQUIPMENT

FIG. 4.



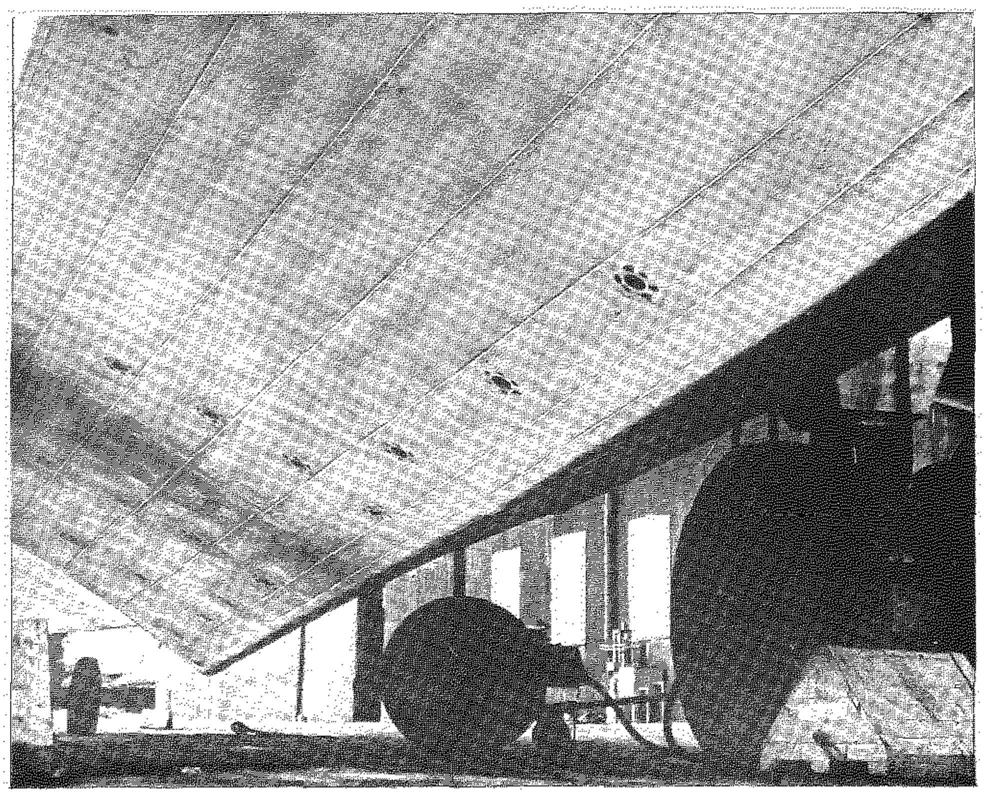
ACCUMULATOR INSTALLATION

FIG.5.

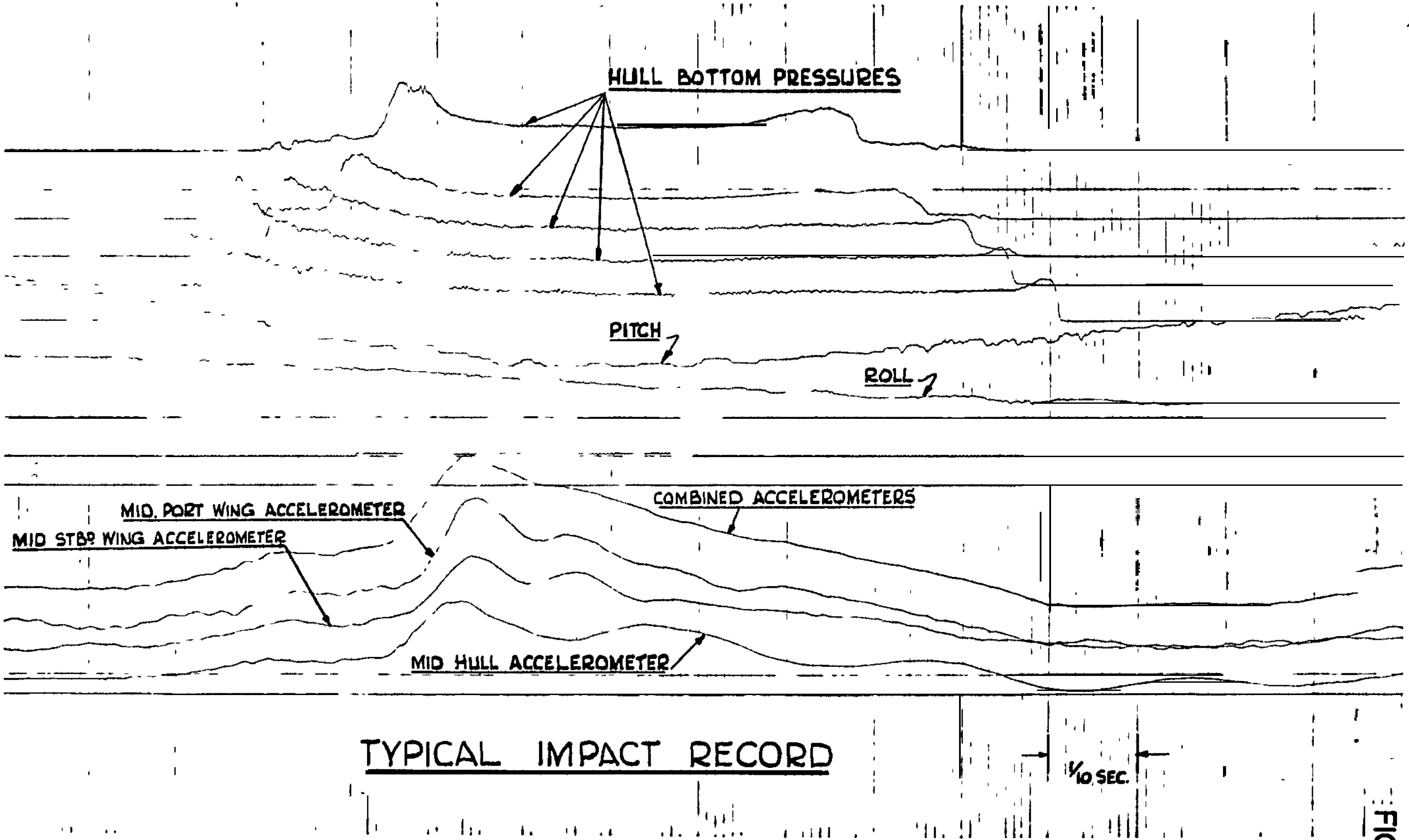


PRESSURE PICK-UP

FIG. 6.



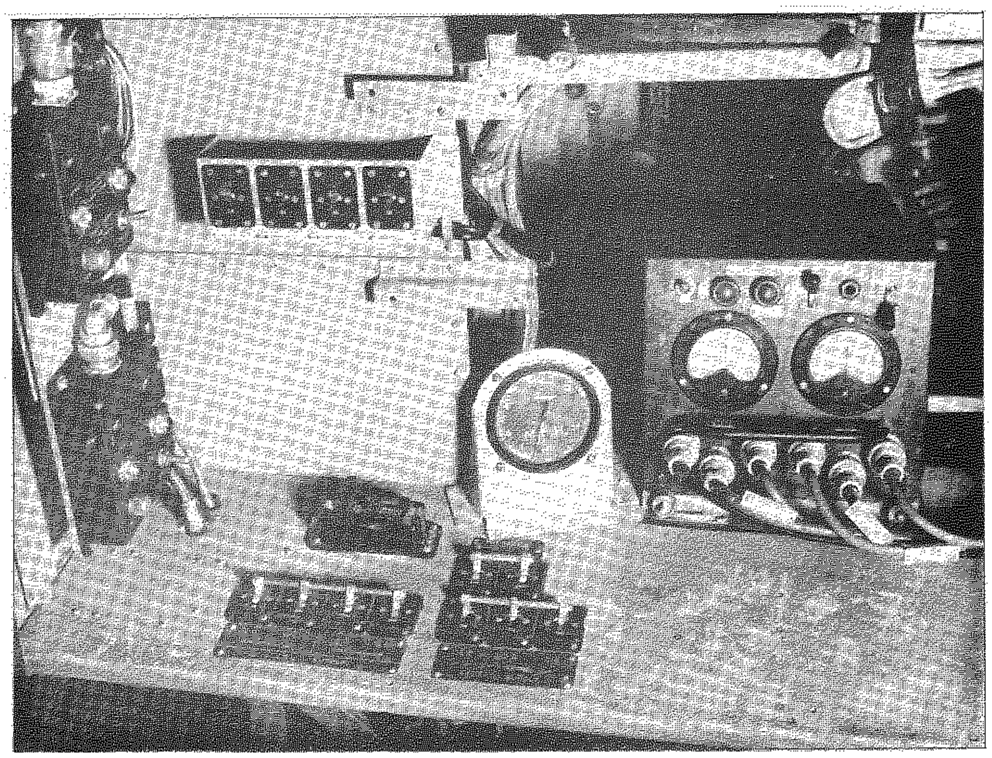
HULL BOTTOM SHOWING PRESSURE PICK-UPS



TYPICAL IMPACT RECORD

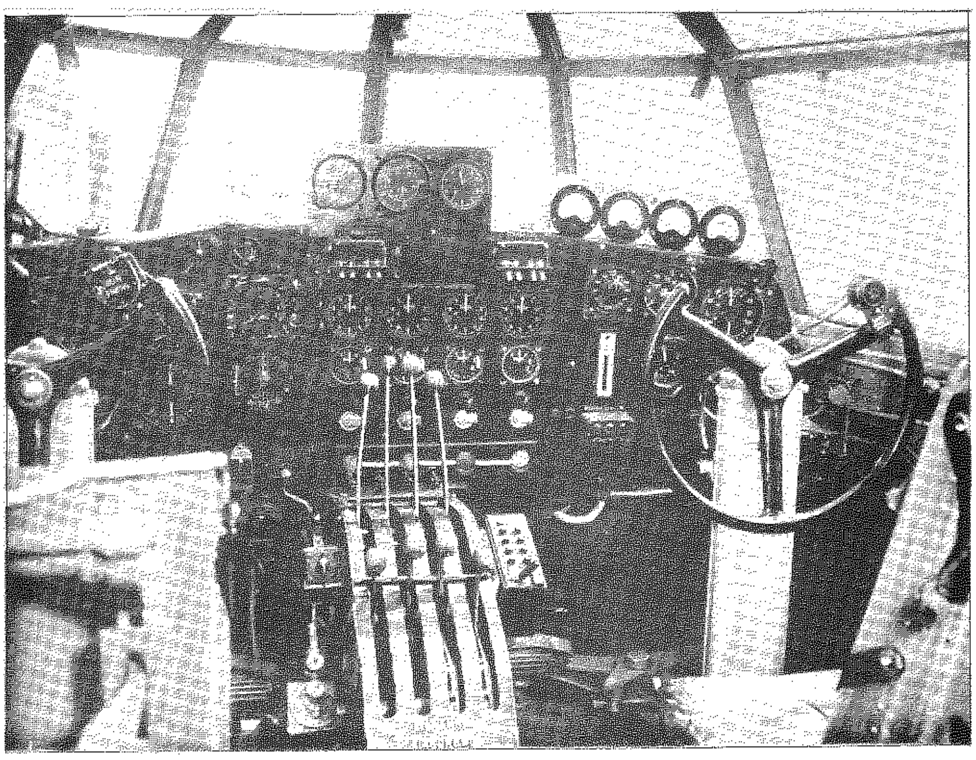
FIG. 7.

FIG. 8

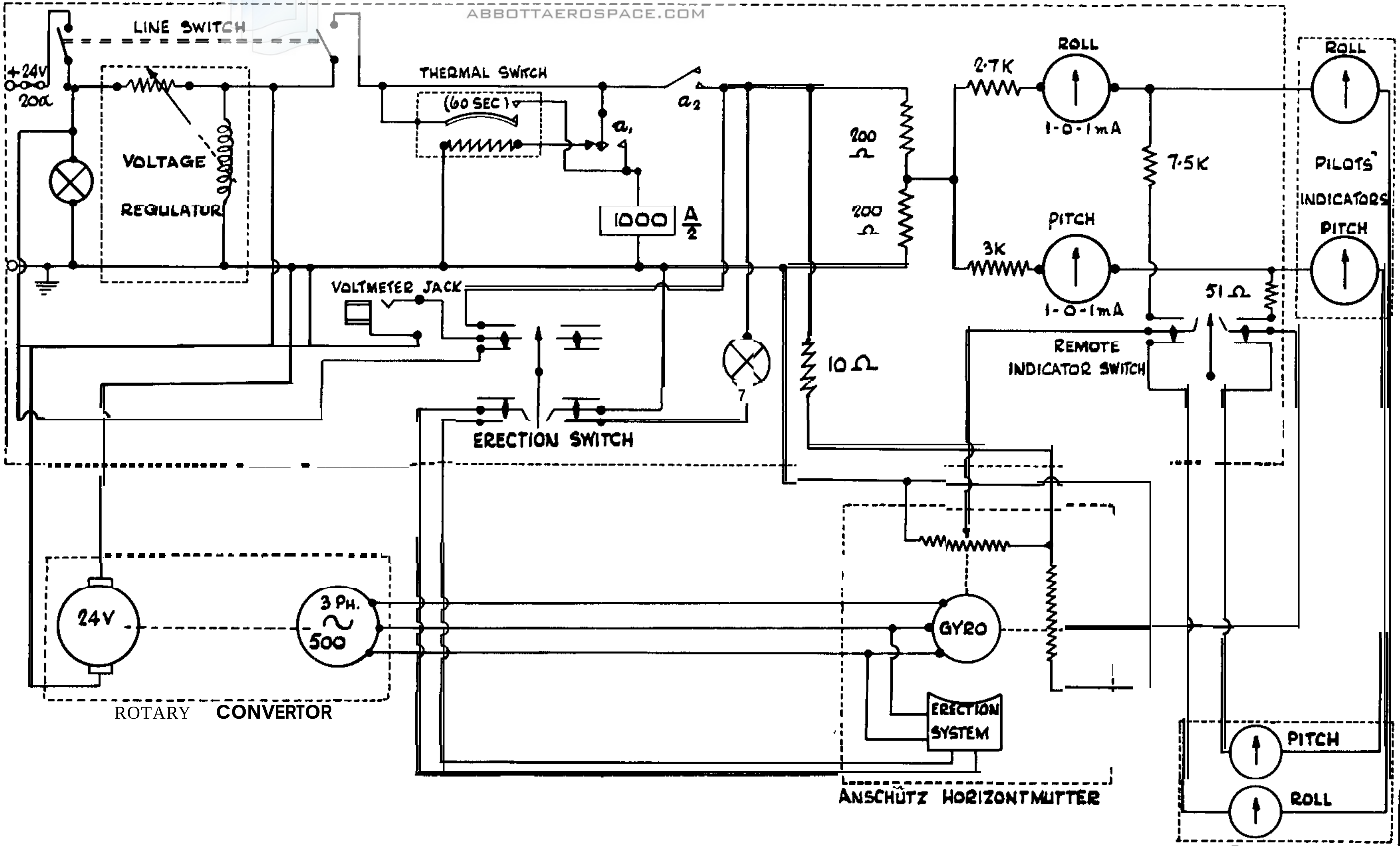


INSTALLATION OF GYROSCOPE CONTROL UNIT AND MILLER REMOTE CONTROLS

FIG. 9



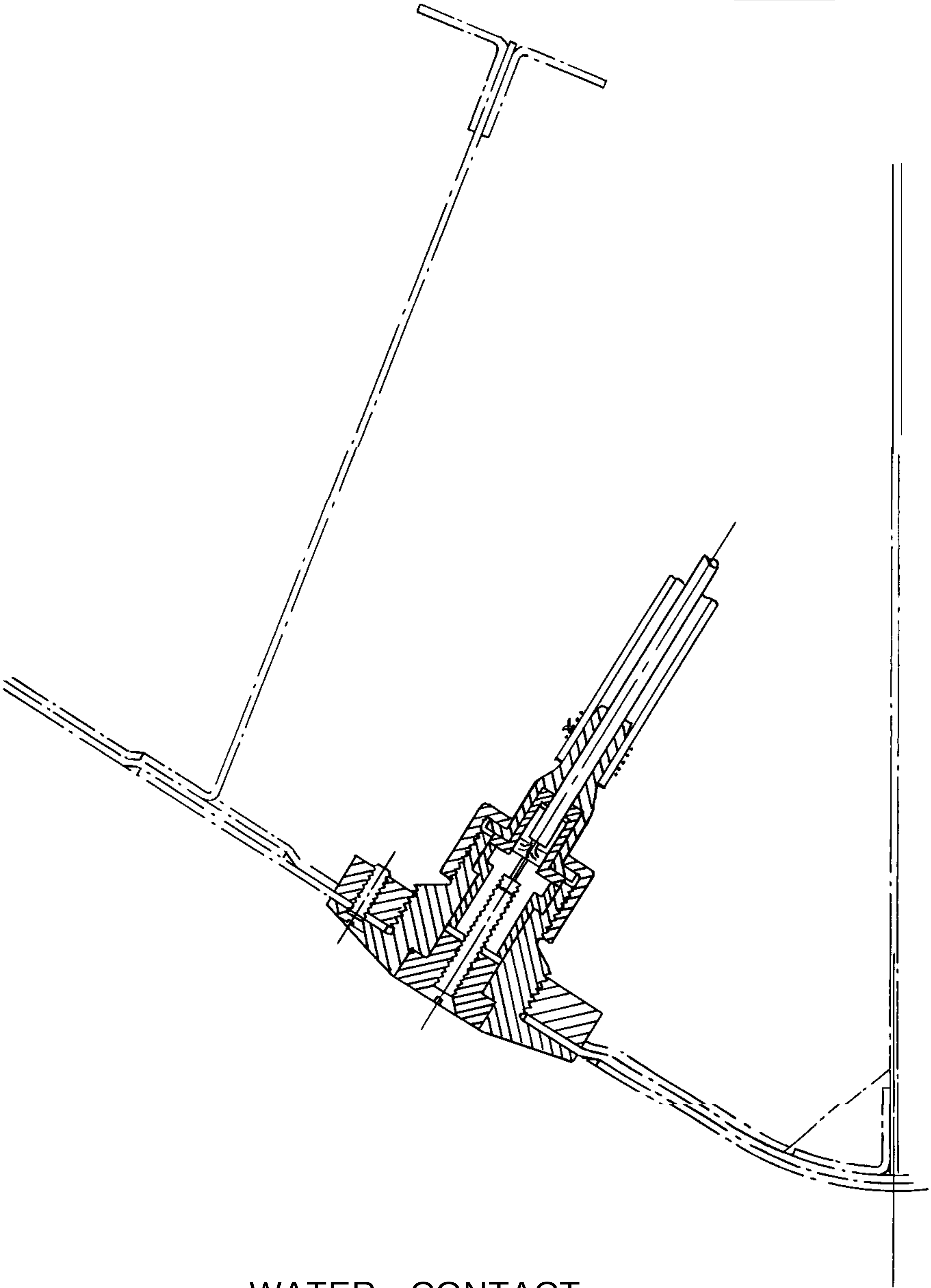
SECOND PILOT'S PITCH AND ROLL INDICATORS



CIRCUIT FOR MEASUREMENT OF PITCH AND ROLL

FIG. 10

FIG. II.



WATER CONTACT.

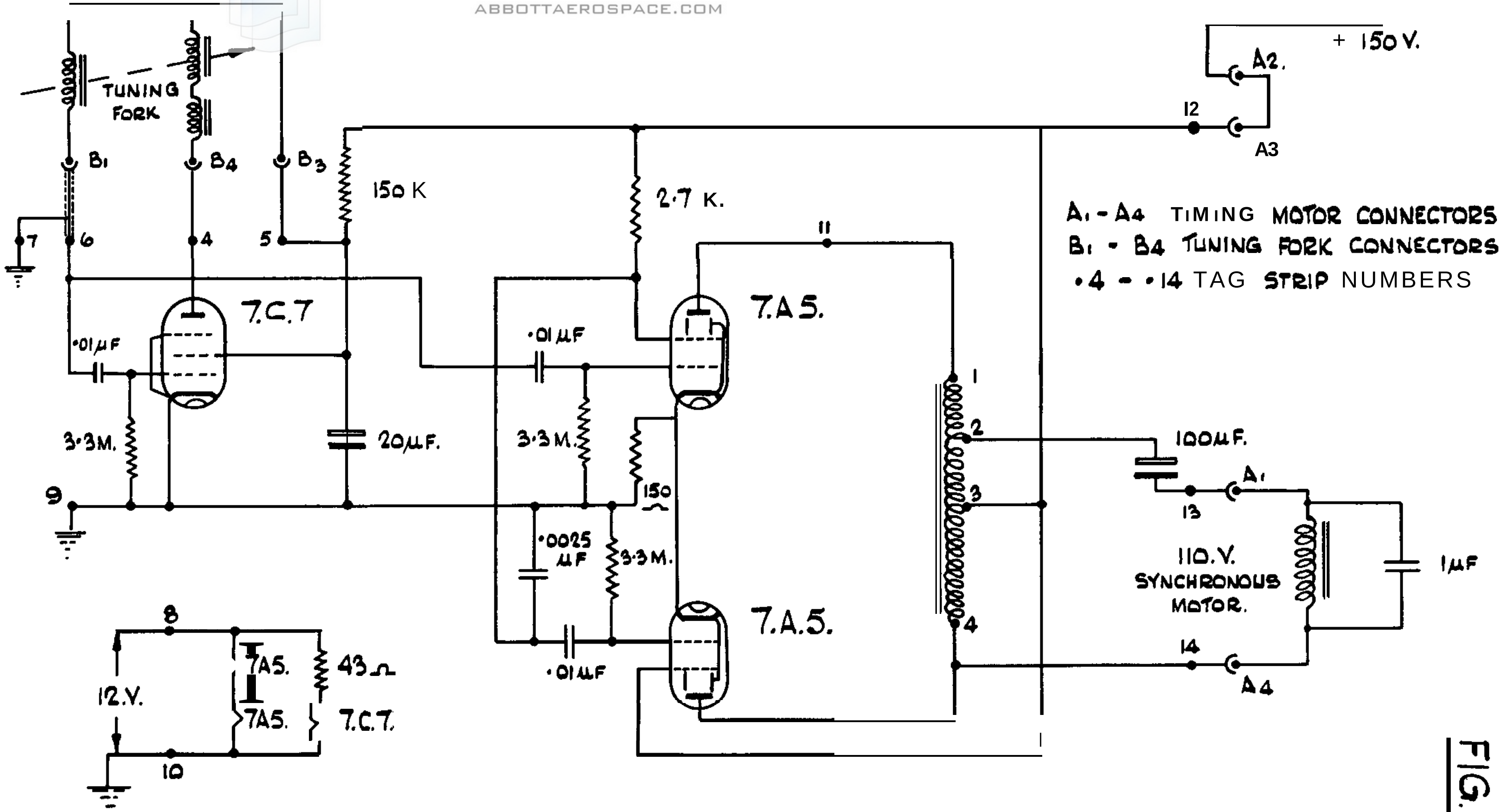
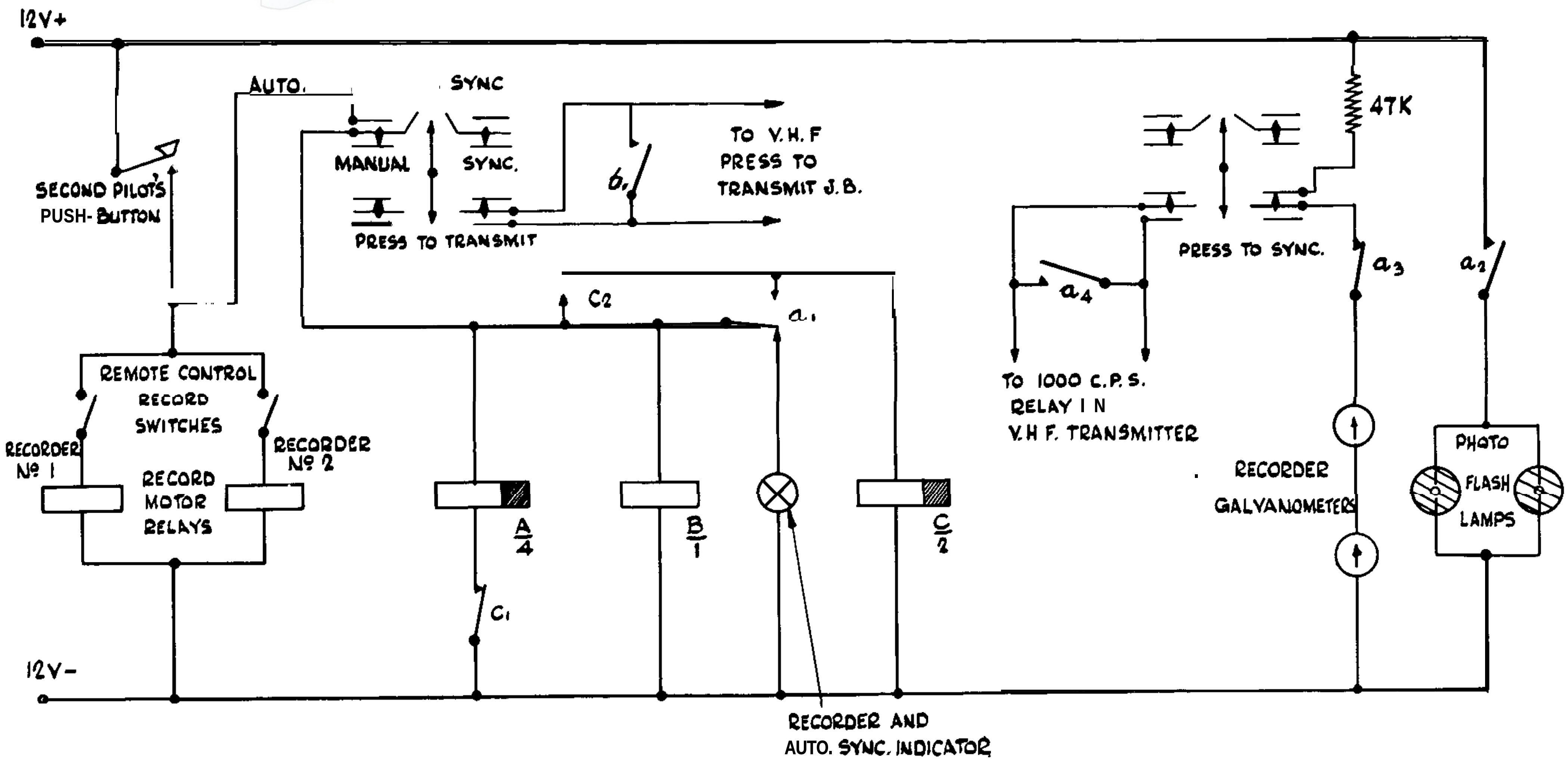


FIG. 12

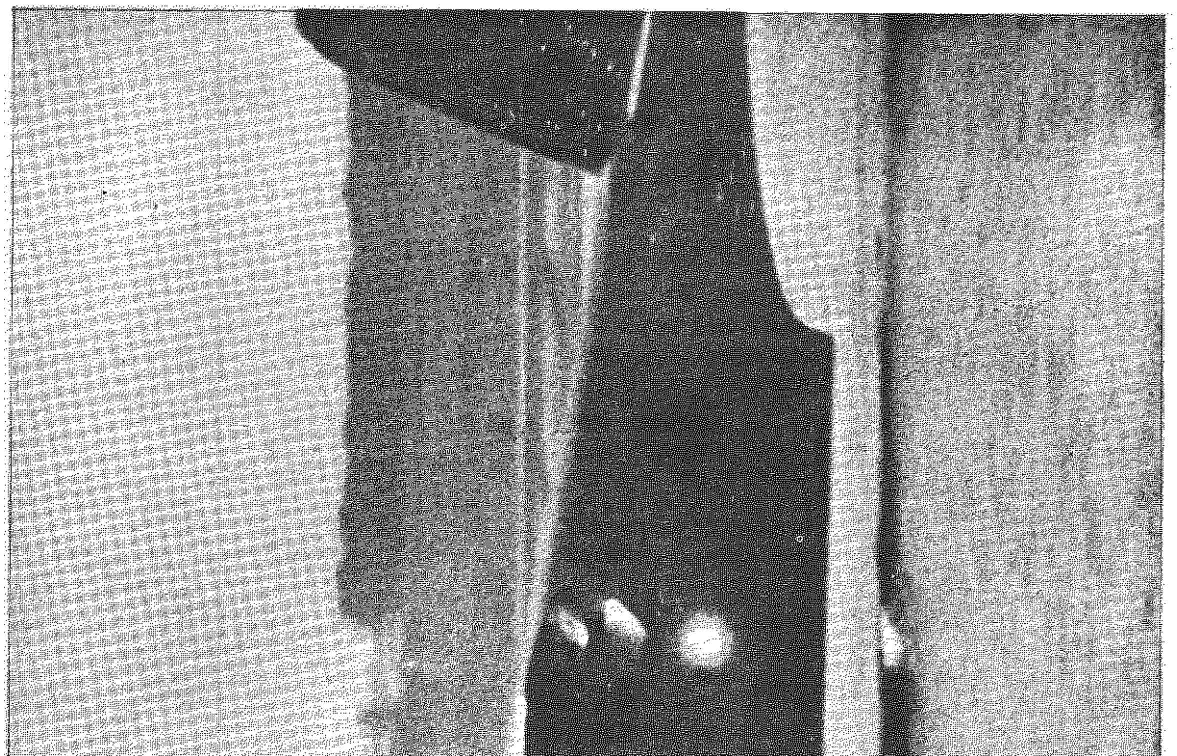
TIMING CIRCUIT- MILLER OSCILLOGRAPH - MODEL W



CIRCUIT OF SYNCHRONISING UNIT.

FIG.13

FIG. 14.



ENLARGEMENT FROM CINE FILM SHOWING LIGHT SIGNALS

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