TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No.18.

THE DYNAMOMETER HUB.

By

W. Stieber.

Translated from
Technische Berichte Vol. III - Sec.6,

by

Technical Staff, N.A.C.A.

September, 1920.

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The Technical Staff of the National Advisory Committee for Aeronautics has translated the following paper in view of its importance in connection with the present development of the design and construction of instruments for directly measuring the torque and thrust of a propeller.

GENERAL CONSIDERATIONS.

Following the earlier reports entitled "Preliminary Results of Free Flight Tests with Dynamometer Hub" and "Propeller Thrust and Measuring Hub," the present report will give a description of the measuring hub actually used.

The instrument takes the place of the propeller hub on the engine shaft and carries the propeller in the usual way. There are two principal moving parts of the measuring hub: one is connected with the engine shaft, the other with the propeller. Between these two parts are inserted dynamometer devices.

For the forces that are to be measured, the dynamometer devices used are the most convenient, because:

1. There is no lag; when the direction of the load changes there are no mutual displacements between the measuring and force-transmitting parts.
2. Have no natural period of oscillation.
3. Can be so built that the forced oscillations (brought about by the crankshaft and propeller) are damped.

These properties are of the greatest importance; because of the highly periodical forces of the motor, which, on account of absence of a flywheel, are transmitted to the hub; and it is those properties that make the measurements possible.

Description of Device.

The propeller dynamometer device of Professor Bendemann is represented in Fig. 1. It consists of a closed ended cylinder, with a tight but very light piston b to which forces can be transmitted by aid of a piston rod c. On the cylinder a pivoted lever d is fixed and guided at the two ends, which are connected with the regulating pistons e and f.

When the rod is loaded, the pistons first go down, the regulating piston f admits at g the liquid under pressure which flows in till the piston b is stopped. In this manner the flow is first throttled down by the regulating piston f and finally stopped when the piston has reached its original position. The pressure under the piston is then (neglecting piston friction) proportional to the loading of the piston and can be measured by a manometer connected with h. The same action takes place when some liquid is lost by the piston's not being completely tight. If the load on the piston decreases, we have at h a flow of liquid under pressure backwards under the piston (all the pressure indicators work with volume variations); the piston rises and the regulating piston e allows liquid to flow from i until the original position of the piston is again reached.

The piston (neglecting sudden changes of the loading) operates through very small displacements that are fixed by the positions of the regulating pistons and lever ratios. These displacements can practically be reduced to zero. The piston will then keep its working position constant. If several similar measuring devices are to be used, then a single regulating system is sufficient, all the pressure chambers being connected with one another.

The above stated properties, full damping and absence of natural oscillations, will be attained when the liquid out-flow is eliminated, which will also give an economy in oil consumption if the oil used contains no air. Lubricating oils under pressure absorb great quantities of air; by tests at 20° C. the following figures have been found:

TABLE I.

Pressure	1	2	3	4	5	6	12	20	27	31 At.
Dissolved air volume as fraction of the volume at 1 At.	30	40	48	52	55	56	59	64	69	71%

These figures show that the oil pressure cannot be obtained by aid of compressed air, but must be generated by a pump and when under pressure must not come into contact with air.

The principal parts of the dynamometer hub,(Figs. 2 and 3) are the cone, the hub, the support of the dynamometer devices and the piston. In addition to the last are the pipes, the recording device, the oil pump, etc. The cone a is fixed at the end of the motor shaft by aid of a screw (in the place of the ordinary propeller hub) and on the cone is fixed a hub b free to move and which carries the propeller. On the cone extension are fixed the measuring devices. For the purpose of securing symmetry, two measuring devices are used for the torque and two for the thrust; the axes of the thrust measuring devices c being parallel to the propeller axis, and the torque measuring devices d being so disposed that their axes are tangent to a circle perpendicular to the shaft and whose center lies on the propeller axis. Thus they can directly measure the torque. The hub b has two lugs e terminating in front of the torque measuring devices and which transmit the torque to the rods f. The thrust is transmitted through the rod g to the hub, b.

The connection between the rotating measuring devices and the fixed pressure indicator (as a recording device) is established by the member h, a kind of long piston, which has a close rotating fit in the long cylinder i. In this cylinder, at equal distances, are made as many grooves as pressure devices used, and in these grooves terminate tubes that connect with pressure indicators. These grooves are thus on one side connected with the measuring devices, and on the other side with the pressure indicators, so that the oil pressure is transmitted by the grooves from the one to the other. As this arrangement demands a free shaft end, it is fixed in front of the measuring devices.

As for the actual dynamometer hub, Figs. 4 to 7 show that for different motors the cone must correspond to the shaft end, and the hub to the propeller; those parts of the cone that support the measuring devices are built in such a way as to be removable and are connected with each other by a special tooth clutch. The measuring devices are the most expensive parts of the dynamometer hub, on account of the close-fitting parts, measuring pistons, regulating devices, etc. Because of the removable cone, the use of the hub is greatly extended and the work of fitting to different engines rendered easier, which largely offsets the price and weight of the additional clutch device.

The cone a, on account of the stress to which it is subjected, and in order that it may have a reasonable size, is made of nickel steel. It is hardened, and, on its cylindrical and conical part, ground. The largest part of the cylindrical surface receives the hub and is provided with lubricating grooves. On the front is disposed the clutch device, and in a recess is placed the hub screw e as well as the pulling ring.

The hub is accurately adjusted on the cone, and, on account of its outside form being irregular, is made of cast steel (see Fig. 8). The dimensions of the hub are fixed by the length and diameter of the central hole in the propeller boss, and the position and size of the propeller hub itself. The diameter of the cylindrical part is limited by the size of the cone. The bearing surface is as usual, lined with white metal.

In the piece h, for the transmission of the torque, special pieces k made out of tempered tool steel are pressed in the holes i, forming seats in which are pivoted silver steel rods or tappets.

The motion between hub and cone is limited in both opposite senses for each force direction; in the sense of the axis by teeth l cast together with the piece h, which act as a stop to the cone (see Fig. 5); in the rotational direction by two stops m, fixed to the seats n of the measuring device . To render easier the exact adjustment of the dynamometer hub special marks s_1 on the rim and s_2 on the lugs h are provided.

The form of the supports of the measuring devices is fixed by the size and position of torque pistons. The last must not only be opposite the stops but must also be so disposed that the centrifugal force on the pistons and on the oil does not affect the measurements.

If, for example, a piston with flat bottom, of radius r and area F rotates around the O axis (Fig. 9) with an angular velocity , and is under the influence of a liquid column of density $_f$ that reaches the axis, then a force $P = c.F. \quad a^2 + b^2 + \frac{r}{2}\ ^2$ is acting on the piston when $c = \frac{^2 \ . \quad _f}{2g}$ and a and b have the signification shown in Fig. 9. If the piston bottom has an excavation of volume V, whose center of mass S_v is at the distance s from the piston bottom, then:

$$P = c \ . \quad F\ (a^2 + b'^2) + \frac{r}{2}\ ^2 \quad + V\ (2\ s - u)$$

where

$$= \frac{V}{F} \text{ and } b' = b - u.$$

Both formulae show that the force P depends upon b or b', that is, upon the position of the piston in the cylinder.

In the center of mass S_k of the piston of weight G_k, there acts in the sense of the piston axis an additional force Z_d, which is a part of the centrifugal force Z of the piston

$$Z_d = G_k \cdot \frac{^2}{g} \ . \ d = G_k \ . \ \frac{^2}{g} \ . \ (b - e)$$

where d and e have the meanings shown in Fig. 9. These two disturbing forces act in opposite senses. If we put P equal to Z_d, we can then find a value for b such that the two disturbing forces will balance one another, and in this way the influence of the centrifugal force will be eliminated. In order to make the force P as small as possible, the open ends of the cylinders of the measuring devices are closed by covers o (see Figs. 5, 6, 10 to 12) and behind the piston filled with oil that reaches the axis through holes q. In order that the stops and piston can act on one another, the covers have special devices just in front of the stops. The balancing of the forces P and Z_d thus has to be made only for the volume change produced by the movement of the covers and the thickness of the piston head. The covers protect the cylinder from dirt and sand. The pistons are made of hardened steel, and are as light as possible. The regulating pistons of the torque measuring devices are connected directly to the piston by threaded rings. As the measuring devices are not provided with out-flow regulation, a regulating lever is unnecessary.

The thrust measuring devices (Fig. 5) have also the back of their cylinders closed with covers, and the space thus formed filled with oil. It is to be noted that their regulating pistons do not get the pressure oil through the pressure oil manifold, but through the hole r, (Fig. 6), from the pressure volume limiting the torque measuring devices; both types of measuring devices are thus connected with one another, which is made possible on account of the fact that the pressure to be measured is less in the thrust measuring devices than in the torque measuring devices.

The disposition of the measuring devices necessitates the complicated form of their supports, which thus have to be cast. They could not be made out of brass, on account of the need for economy in brass during the war, and the difficulty of casting steel brought us to adopt cast iron.

The supports of the measuring devices have inside a special ring body, disposed behind the clutching teeth, and have in front a space for the rotating pressure connection. On this ring body are fixed the cylinders for the moment measuring devices. The most highly stressed section of the measuring device has a T form so disposed that the highest stress is a compression.

The pieces m also serve as abutments for the hub stops n on the cylinders of the torque measuring devices. These pieces act when the torque is negative or the dynamometer hub is closed. The pipes are connected as follows:

t_1 is the pressure oil pipe,
t_2 and t_3 are connected with the measuring pipes,
t_4 and t_5 connect the torque measuring devices, and
t_6 and t_7 connect the thrust measuring devices.

The measuring devices are attached to the cone piece by the cylinder unit, which has an internal flange u through which the stem of the hub screw v passes and is fixed to the hub screw e. The head, which is maintained fixed by the ring w, is adjusted close to the flange and ensures the support of the measuring devices, and also transmits the propeller thrust. The thread of the hub screw is always of finer pitch than that of the motor shaft.

The body of the rotating pressure connection is made of phosphor bronze, and is fastened by a flange and ring screw to the cylinder body of the measuring devices. There is then enclosed a space which is filled with oil. The body has three grooves, from which t_8, t_9, and t_{10} lead to the connection tubes t_1, t_2, and t_3 on the cylinder unit of the measuring devices. The stationary member is made of tool steel, and has four passages, one of which runs the entire length. At the head of this member are fixed four 3-millimeter brass tubes, one of which brings the pressure oil, two others transmit the torque and thrust, and the fourth tube, connected with the through passage leads the oil inside the support of the measuring devices, and thence behind the pistons of the measuring devices and between the cone and the hub.

At the head of the pressure connection there is a security device which prevents, when fully assembled, any part of the dynamometer hub from being deranged, or the propeller from touching anything. For this purpose the copper tubes are disposed in a special casing, supported by ball bearings and guided along a rod to which the casing is fixed. Between this rod and the casing a special wire is stretched, which will be broken by a load of 70 to 80 kg., but which under ordinary conditions will more than sustain the friction moment at the bearing. As soon as the friction moment exceeds a certain quantity, the wires break, the copper tubes are twisted apart in the casing, and the casing is left free to rotate on its ball bearings.

As the pressure connection is a new mechanical detail, it has been tested under working conditions for friction, security, pressure transmission and tightness. The friction moment varies from 0.10 to 0.25 kg.-m. The pressure transmission is perfect, and the oil loss by lack of complete tightness was ordinarily 25 c.c. per hour, with oil of 40 degrees viscosity. The total oil consumption of the dynamometer hub was found to be

Thrust meters	60	c.c. per hour
Torque meters	100	" " "
Indicator	10	" " "
Pressure connection	50	" " "
Manifold	30	" " "
Total	250	

From the pressure connection rod the tubes are brought to the observers place. The parts necessary for this purpose are different for different motors and airplanes. In general the tubes are inclosed in a case made of tubing with thin walls, and lead over the propeller to the motor and then to the observer (see Fig. 13). The additional devices, such as the pump, pressure tank, oil tank, oil divider, recording device, and indicator are disposed on a small special table (Fig. 14), which can easily be placed in the fuselage.

Tests with the Dynamometer Hub.

The dynamometer hub was first tried on a propeller testing stand which is operated by an electric motor and suspended on a pendulum frame. The pendulum frame has a friction of about 0.5 kg.-m., which for small powers is relatively high. But for greater powers this friction, because of the greater vibration for higher revolutions, is both relatively and absolutely decreased, and in the range of torques from 60 to 80 kg.-m. is so small that in ordinary conditions it has no appreciable influence. The torque of the electric motor is controlled by varying the magnetic field. As the balanced frame oscillates nearly all the time a sensitive adjustment is obtained.

For the thrust measurements the largest error was ± 5 kg. For the calibration of the dynamometer hub the torque was by steps of 10 kg.-m. increased from 30 kg.-m. to 80 kg.-m., the revolutions of the motor being adjusted in proportion, and starting from 50 kg.-m. the thrust was measured, because for smaller torques the error is too great. The diagrams of this calibration (Fig. 15) are mutually displaced 34.5 mm. because of the recording arrangement. In order not to increase unnecessarily the length of the diagram, the recording was stopped during the adjustments. The figures on the diagram and in Table II correspond to each other. The mean error is 0.5% for the torque and 1.3% for the thrust. As in the dynamometer hub there are no reasons for a less accurate measurement of the thrust than of the torque, the greater error in thrust measurement must be attributed to a less sensitive measuring of the thrust of the propeller stand. The error in the torque measurement ought also to be less; but this error extends through the propeller stand, dynamometer hub, and recording device.

TABLE II.

Calibration of the Dynamometer Hub.
Nov. 11, 1917. - At 13°C. and 765 mm.

No.	Electrical Test			Dynamometer hub diagram.					
	R.P.M.	Torque	Thrust	Torque Diagram height	spring scale 3 mm.=3.95 kg. Torque	Error %	Thrust Diagram height	spring scale 4 mm.=25.2 kg. Thrust	Error %
1	851	30	175	23	30	+0			
2	972	40	225	31	40.5	+1.25			
3	1085	50	285	38.5	50.5	+1	45	284	-0.35
4	1181	60	335	45.5	60	+0	53	334	-0.29
5	1257	70	380	53.5	70.5	+0.7	61	384	+1
6	1324	80	405	60.5	80	+0	65.5	413	+1.9
7	1319	80	405	60.5	80	+0	65.5	413	+1.9
8	1252	70	380	53.5	70.5	+0.7	60.5	381	+0.26
9	1176	60	330	45.5	60	+0	54	340	+3.0
10	1083	50	280	38	50	+0	45.5	286	+2
11	941	40	230	31	40.5	+1.25			
12	860	30	175	25.5	30	+0			

Afterwards the dynamometer hub was put on an aviation motor testing stand with a pendulum frame. The last is not very convenient for a calibration, but the dynamometer hub had to work on an aviation motor under the same conditions as on an airplane. In spite of the greater stressing of the different parts, the dynamometer hub worked as well as on the electric testing stand. Fig. 16 gives a complete diagram. The motor gave a torque of 80 kg.-m. The thrust record shows fluctuations which are to be attributed to the fact that the tests were made in the open air and in the neighborhood of other testing stands, so that the wind and artificial air currents acted on the propeller. At a and b the recording devices, by aid of their three-way cocks, were suddenly disconnected and connected again, which produced the sudden apparent fluctuation from zero to full load. At c the motor was quickly throttled, at d slowly throttled. At e quick variations of the load follow. The inertia of the propeller appears very clearly under this condition.

After the dynamometer hub had worked here without trouble, it was placed on an airplane and observed in flight. Special care was taken that no new vibrations could occur as a consequence of the disposition of the hub.

Testing Results.

The greatest stressing of the dynamometer hub occurred on the aviation motor stand. Large vibrations took place, which did not influence the measurements but so strongly vibrated the manifold connections between the pressure connection and the supports of the measuring devices and between the measuring devices themselves, that they broke after from 20 to 60 minutes of work. The tubes were on this account made stronger, in order to reduce their period of natural vibration, and were connected with each other and attached more strongly. The cone and hub pieces worked without difficulty. The pressure connection heated slightly. The safety device operated once because the pressure connection was too closely adjusted, but prevented any breaking damage to the connection parts, so that it was possible to disassemble the connection by hand. Since then each connection was tested for torque resistance, before being put in use.

For sudden changes of the load, the diagram showed that the thrust stays behind the torque and does not increase as rapidly as the torque. This is a result of the inertia of the propeller and hub, for the acceleration of which a part of the motor power has to be employed. For studying the shape of the diagram we must take into account the time that elapses, after a disturbance of steady conditions, until new steady conditions are reached. For the determination of this transition time T_u we need to know the moment of inertia of the rotating masses, that is, of the propeller and the hub, because the torque is measured between hub and cone. By the well known pendulum method it was found for a 160 H.P. hub and "Eta" propeller $J = 0.49$ kg.-m. sec.^{2}. As the moment of inertia of the rotating motor parts, including part of the connecting rods, is around 0.008 kg.-m. sec.^{2}, that is 1.5% of the moment of inertia of the propeller, the following calculation may also hold for motors with thick hubs.

For an air propeller we can with sufficient accuracy put $M_1 = m \cdot \omega_1^2$ where M_1 is the torque at the angular velocity ω_1 and m the torque as determined by experiment for angular velocity equal to unity. If the torque increases to M_2, with corresponding increase of angular velocity to ω_2, then, as we pass from ω_1 to ω_2, for any intermediate value ω and a corresponding torque M the surplus torque is equal to

$$M_u = M_2 - M = m \cdot (\omega_2^2 - \omega^2)$$

The angular acceleration at that moment is equal to

$$\frac{d\omega}{dt} = \frac{M_u}{J} = \frac{m}{J} \cdot (\omega_2^2 - \omega^2)$$

From this, by integration between the limits ω_1 and ω'_2 we obtain the transition time,

$$T_u = \frac{J}{2\,m \cdot \omega_2} \left[\log_e \frac{\omega_2 + \omega}{\omega_2 - \omega}\right]_{\omega_1}^{\omega'_2}$$

as a logarithmic function that for $\omega'_2 = \omega_2$ gives $T_u = \infty$
To assist in evaluating this equation, it is usual to introduce the degree of steadiness $\epsilon = \frac{\omega_2 - \omega'_2}{\omega_2}$, that in no case needs to be less than the degree of irregularity of the motor. Afterwards introducing. $\delta = \frac{\omega_2 - \omega_1}{\omega_2}$ as the relative variation of the angular velocity or r.p.m. we get

$$T_u = \frac{J\,\omega_2}{2 \cdot M_2} \cdot \log_e \frac{\delta\,(2 - \epsilon)}{\epsilon\,(2 - \delta)}$$

For ϵ = 0.005 and ϵ = 0.001 we obtain the following values

ϵ = 0.005,	ϵ = 0.001,
δ = 0.05, 0.10, 0.50, 1.00,	δ = 0.05, 0.10, 0.50, 1.00,
T_u = 0.9, 1.2, 2.0, 2.5 sec.	T_u = 1.6, 1.9, 2.7, 3.2 sec.

δ = 1 corresponds to the time of the start. ϵ = 0.005 represents the approximate degree of irregularity of an aviation motor. A reduction of this value to 1/5 increases T_u by approximately 0.7 sec., and conversely. An exact knowledge of these values, which express the degree of irregularity of the motor, is thus seen to be unnecessary. The values of T_u ranging from 1 to 3 seconds, explain the retardation of the thrust relative to the torque; because where torque variations occur in less time than T_u, the full thrust corresponding to the angular velocity cannot be reached.

Free Flight Tests.

Following the above described preliminary tests, the first dynamometer hub was tried on a Rumpler C-2 airplane. Fig. 14 shows the general arrangement, with the exception that a recording device with a paper speed of 10 mm./sec. and two indicators with a mutual displacement of 34.5 mm. and recording height of 30 mm. were used.

The first flight took place November 7, 1916, in clear calm weather, and was of 15 minutes' duration, a height of 800 m. being reached. Fig. 17 represents this best without the scale reducing that took place while calibrating. During the test the indicator traced the torque line rather thick, because it reproduced to some extent the torque shocks of the motor. Before the flight, (a), a trial was made at 1000 r.p.m. and also at full load. Thereupon the motor was throttled and the dynamometer hub locked; the torque record rose to the highest limit of the indicator. At the moment of the start of the flight (b) the device was freed and the two indicators began to record. The torque rose, and having reached its high value, kept it. The thrust first rose, but immediately dropped with the increase of speed of the airplane. With increase of altitude both quantities dropped. The stopping of the motor for a glide (c) brought a sudden drop of both quantities. Close to the ground the throttle was once more opened and the motor allowed to run. This is clearly shown in the diagram. Fig. 18 represents a flight made April 3, 1917, in gusty weather. The air speed is here recorded as a third quantity, by aid of a pressure plate.* The diagram shows the influence of the different gusts on the thrust. It may be seen how important it is to record the air speed at the same time.

Summary. The construction of the dynamometer hub is illustrated and explained, and its electrical and aviation motor tests, as well as those in free flight, described.

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* Hoff. New Forces, Measuring Devices, and Determination of the Forces in the Wires in Flight, Zeitschrift fur Flugtechnik und Jahrgang 1914, pp. 21 and 149.

Motorluftschiffahrt

Load balancing device of Prof. Bendemann.

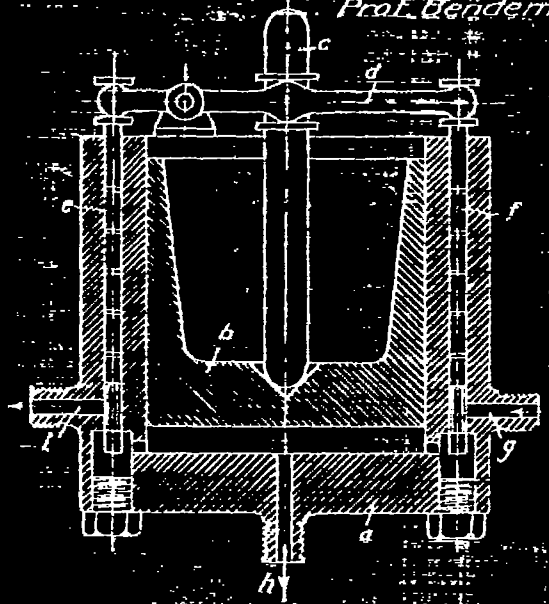


Fig. 1.

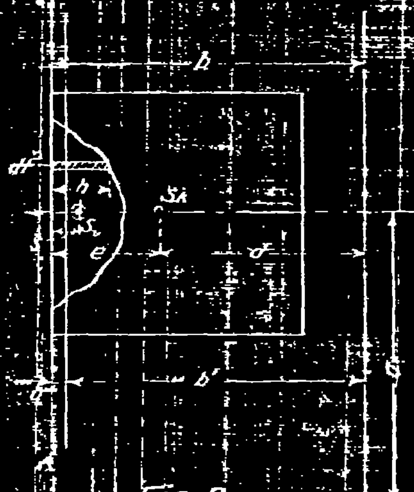
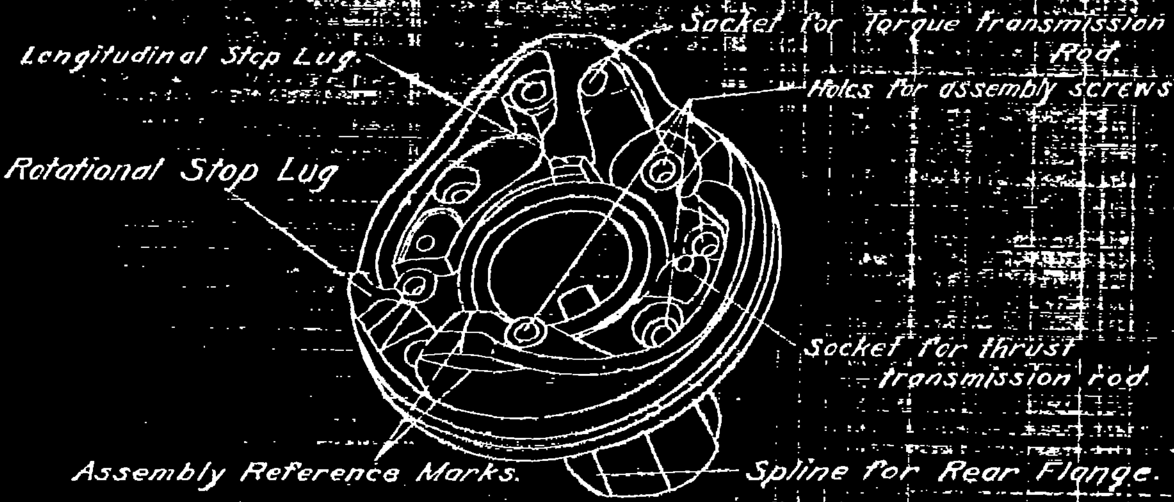


Fig. 9.



Complete Hub Piece.

Fig. 8.

Figs. 1-8-&9.

CHIEF ELEMENTS OF THE DYNAMOMETER HUB.

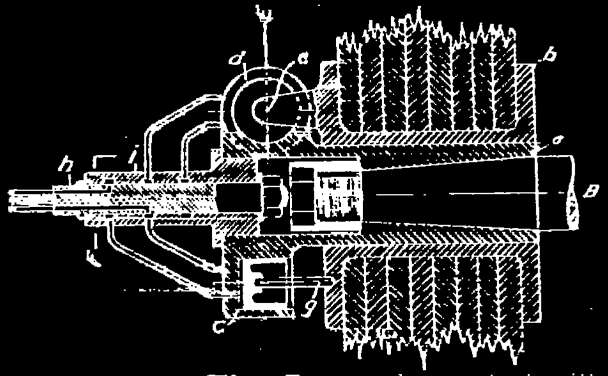


Fig. 2.

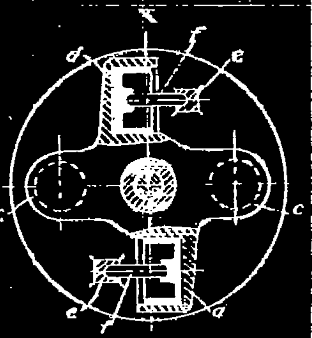


Fig. 3.

ASSEMBLY DRAWING OF THE DYNAMOMETER HUB.

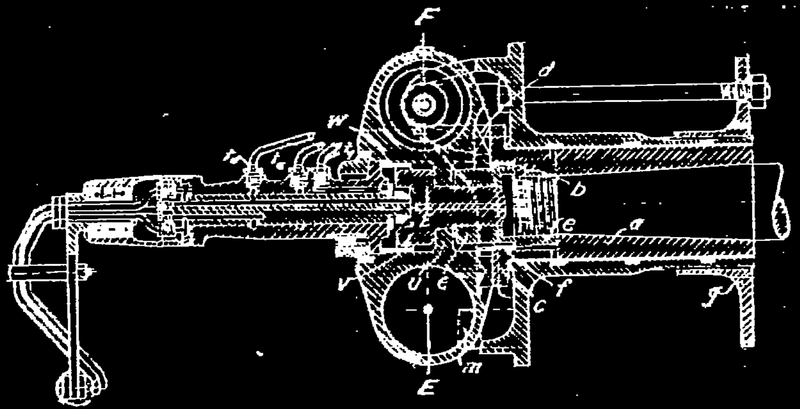


Fig. 4. Section A-B.

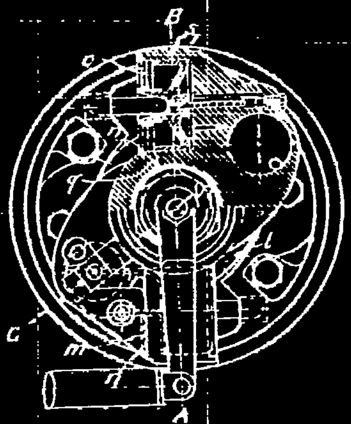


Fig. 6 Section E-F.

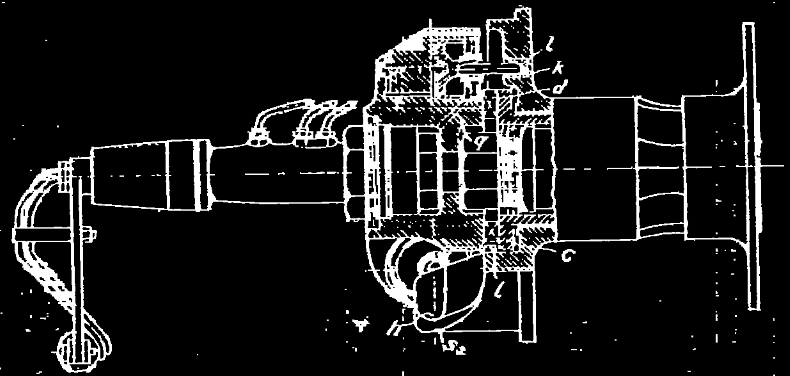


Fig. 5. Section C-D.

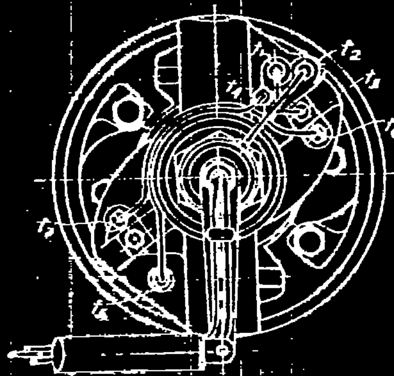


Fig. 7.

Figs. 2.-3:-4-5.-6-& 7.

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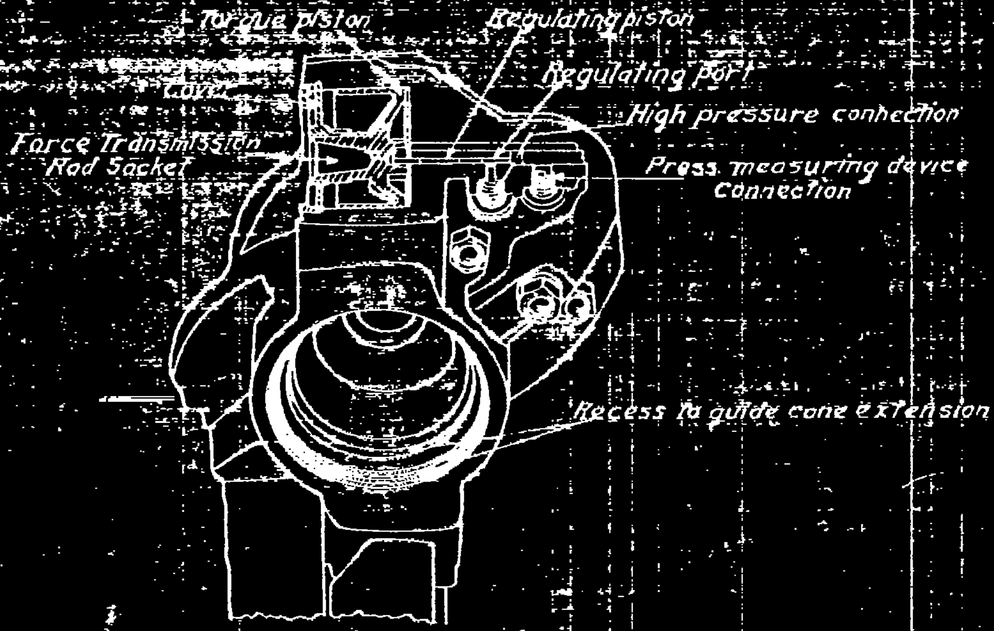

Fig. 10.

Section thru Torque Measuring Device showing regulating parts.

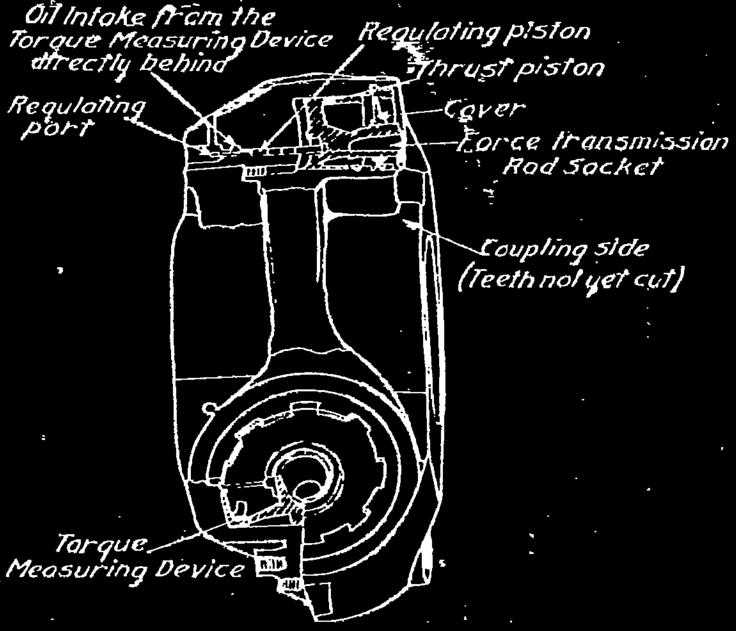

Fig. 11.

Section thru Thrust Measuring Device showing regulating parts.

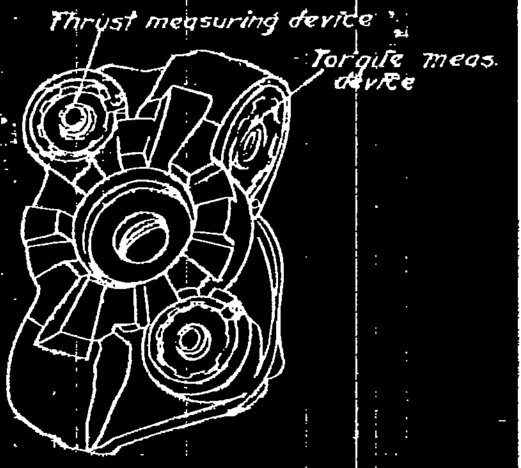

Fig. 12.

Coupling Side

DYNAMOMETER DEVICE SUPPORT

Figs. 10, 11 & 12.

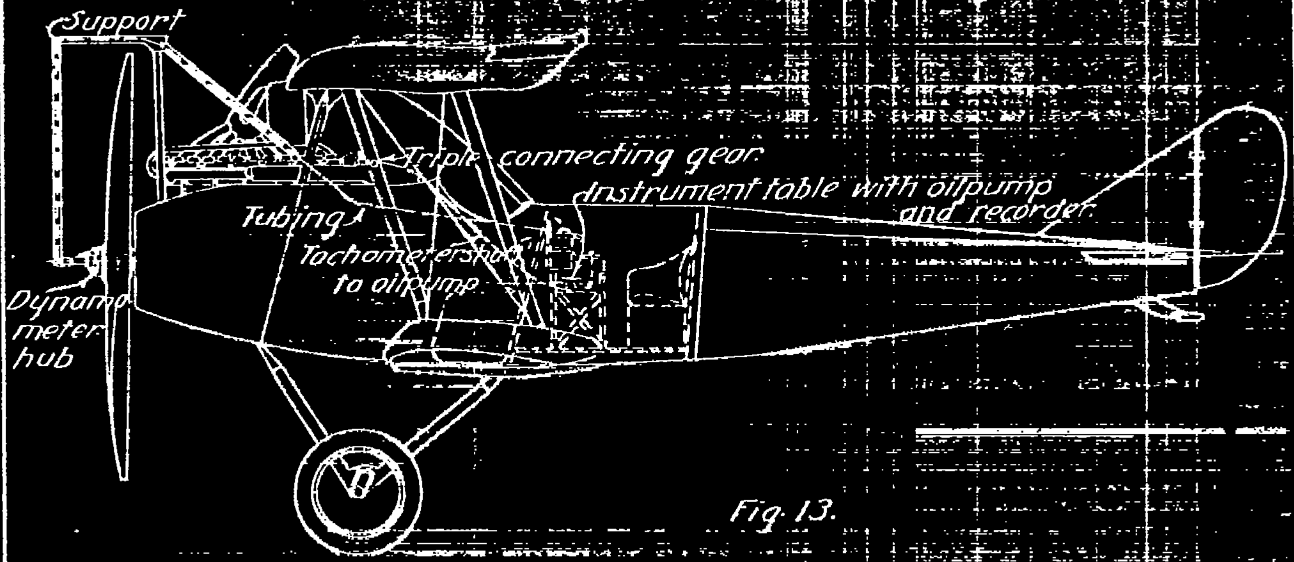

Fig. 13.

Assembly of apparatus showing connection for dynamometer hub.

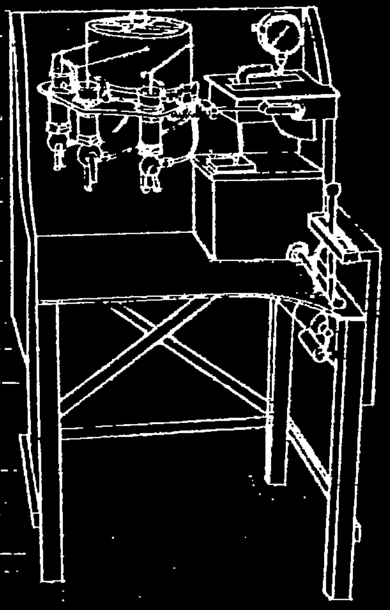

Fig 14.

Instrument table.

Figs. 13 and 14.

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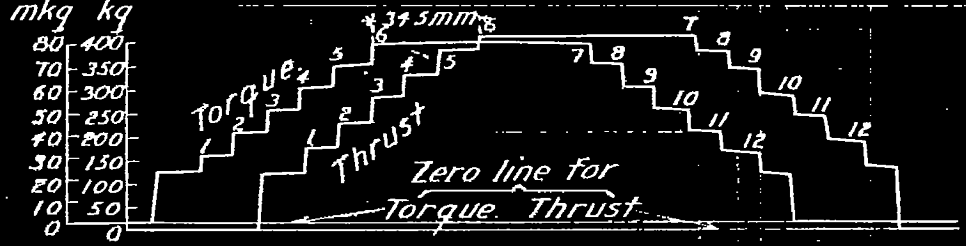
Fig. 15.



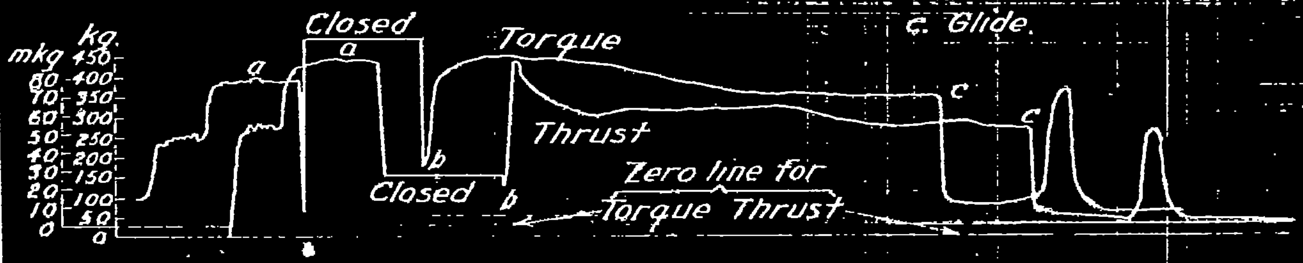
Calibration of the Dynamometer Hub

Fig. 16.

Full load diagram of the Dynamometer Hub.

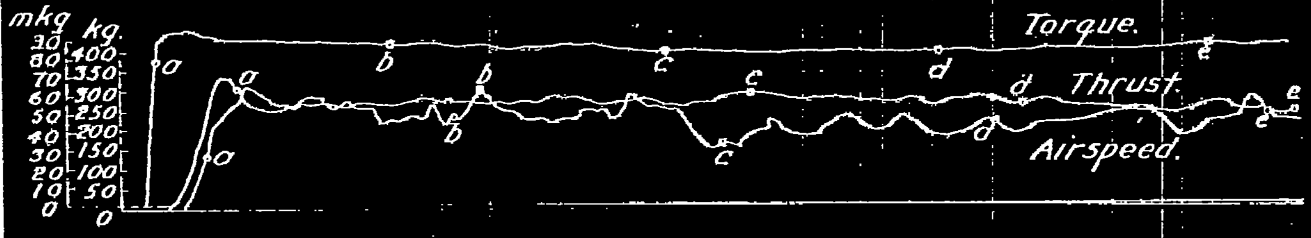
a. Static test with full load.
b. Start.
c. Glide.

Fig. 17.



Record of the first flight.

Fig. 18.



Free flight test in gusty weather.

Figs:- 15-16-17-18.