TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 168

AIR REACTIONS TO OBJECTS MOVING AT RATES ABOVE THE VELOCITY OF SOUND WITH APPLICATION TO THE AIR PROPELLER

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Washington
November, 1922

AIR REACTIONS TO OBJECTS MOVING AT RATES ABOVE THE VELOCITY OF SOUND WITH APPLICATION TO THE AIR PROPELLER.

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In the course of experiments conducted during the year 1916, regarding acoustic pitch of high frequency, it was found necessary to use an apparatus with arms radiating from a hub and rotating at a very high rate of speed. In an effort to reduce air resistance it was discovered that the arms could be made quite thin and sharp at the edges and still have sufficient strength to withstand centrifugal force. It was further observed that, through centrifugal force, the arms possessed sufficient rigidity to resist stresses which existed tangential to the circles described by the tips of the blades. This naturally led to the consideration, whether a twist (warping) or inclination (pitch) of the arm-blade from the radial plane could be maintained, the arms then acting as blades of a propeller. It developed that with the proper shape and proportion a twist or warp could be maintained with reasonable constancy making it evident that I had perhaps discovered an elementary air screw or propeller adapted to very high speeds. Investigations pertaining to the usual type of propeller disclosed that tip speeds seldom exceed 900 feet per second and that the only recorded attempts to explore the higher speeds appeared in a paper issued by the British Advisory Committee for Aeronautics, March, 1919. At this time a tip speed of 1180 feet per second was reached with a two-blade nine-foot propeller, the observations revealing that, "as the tip speed approached the velocity of sound the usual air flow breaks down entirely, the slip-stream rapidly diminishes and ultimately disappears; the air apparently being sucked in on both sides of the disc and exhausted at or close behind the periphery when the velocity of sound is reached."

There has been a tradition general among aeronautical engineers that a critical point exists for tip speeds at or near the velocity of sound, indicating a physical limit in the use of propellers at higher tip speeds; the idea being that something would occur analogous to what is known in marine propellers as cavitation. Being unable to find a verification of this tradition or a record of other experiments along this line, other than the British paper quoted, it appeared that this field had been practically unexplored. With the new type of blade, described in this paper, it is evident that other and more extensive experiments are possible and that the validity of the existing belief can be tested. It also appeared, in reference to the air resistance of projectiles, that there was supposed to exist a critical point in the plotted curve of speed and resistance at velocities between 1100 and 1200 feet per second.* In the examination of the physics pertaining to both propellers and projectiles moving at or above 1100 feet per second, the conclusion was reached by me that there is no reason for the existence of such a critical point and that, if it had been noted by observers it was not inherent in the phenomena revealed, but rather due to a particular shape or proportion of the projectile and that, with properly proportioned sections, it would not exist.

* Berthol. Guns and Gunnery.

Experiments were then begun with thin flat blades of aluminum constructed with sharp edges and set at various angles of twist or pitch up to 45 degrees, and with tip speeds from 700 to 1550 ft/sec.

Series 1. This series was tested in the author's laboratory with a 10 HP electric motor at 1150 r.p.m. geared to propeller shaft in ratio of 12.25 to 1, producing a shaft speed of 14088 r.p.m. or 235 r.p.s. Aluminum propellers of two blades measuring two feet from tip to tip were used, with provision for measuring speed, thrust and torque.

Series 2. were made and tested under the author's directions by the engineers of the Curtiss Aeroplane and Motor Corporation at their factory in Garden City, L.I., N.Y. A 100 HP aircraft engine at 1500 r.p.m., capable of running at 1800 r.p.m. was used. The gear ratio was 4 to 1, producing a propeller speed of 100 r.p.s. Aluminum propellers measuring four feet from tip to tip of blade were used, propellers having two, four and six blades of various shapes and proportions, all blades being so thin as to make them devoid of sufficient structural or inherent rigidity to withstand more than a fraction of the stresses of operation, relying mainly upon the virtual or kinetic rigidity due to centrifugal force.

Series 3. Propellers installed on standard well-known types of airplanes and subjected to rigid tests under actual flight conditions.

Discussion.

From the well-known formula for centrifugal force it is easily ascertained that, with a velocity of 1500 feet per second, the radial tension at the tips, in this case, is increased about 32000 times, i.e. one ounce at the tip produces a radial tension of one ton. With a deflecting force on the whole blade of not over 100 lbs., parallel to the shaft, there would be but a slight flexure, thereby permitting the use of thin blades with sharp edges and a minimum contour, without the danger of rupture. Furthermore, as a matter of convenience and simplicity in manufacturing for testing purposes, the boss can be made very plainly quite unlike the helical shape of the regulation propeller as will be seen further on.

Numerous mechanical devices were designed to meet the rather unusual requirements of enormous rotational speed, high power, and the necessity of obtaining accurate measurements of thrust and torque. In order to relieve the propeller shaft of almost every strain except torsion, the shaft, with its pinion, was mounted so as to be free to move in either direction parallel to thrust, as shown in Fig. 3, avoiding the usual device of a sliding or clutch joint, which necessarily causes some degree of binding and an interference with thrust variation readings. The geared transmission avoids this binding in that the teeth are rapidly engaged and disengaged, thereby affording intervals, although extremely brief, during which the thrust variations take place.

The longitudinal play in the propeller shaft was about a half inch. The shaft was equipped with a flange which operated against ball bearings, the latter running in a concave receptacle attached to a hinged lever. The free end of this lever was connected to a spring scale, thereby providing a means by which the thrust was measured as shown in Fig. 5.

The thrust bearing requirements presented problems far beyond the scope of customary ball-bearing practice. In Series I, it was necessary to make provisions for a maximum thrust of 50 lbs. at 235 r.p.s., and in Series 2, for a maximum thrust of 500 lbs. at 100 r.p.s. To meet these unusual conditions three sets of ball-bearings were employed and arranged in tandem, thereby reducing their speeds by the ratio of the number of sets used, as shown in Fig. 3. This proved to be a complete success.

In order to ascertain the torque stresses in the countershafts intervening between the motor and propeller, measurements were made by the use of an extended arm in accordance with the principle of the well-known transmission dynamometer, Fig. 4. The torque of the frame or box, carrying those countershafts, had a certain fixed ratio to the HP being transmitted making it possible to get a very accurate reading.

The apparatus used in making experiments in Series 1 and likewise in Series 2, is shown in Figs. 3, 4 and 5. Fig. 7 shows the results in Series 1 with the 22- and 17-inch propellers given in Fig. 6, the 17-inch being simply a 22-inch propeller with the blades cut off 2 1/2 inches. Fig. 8 presents the difference between thrust and torque at the same r.p.s. due to the 2 1/2 inch difference in blade length, avoiding the complication of including the characteristics of the more slowly-moving portions of the blades.

The results obtained in experiments with a two-blade, 4-foot propeller of series 2, are given in Fig. 9.

It is quite apparent from these results, that the ratio of thrust to tip speed undergoes no appreciable variation when exceeding the velocity of sound or even to an excess of 50% in velocity, and that the physics in the problem reveals nothing that would deter the operation of propellers at tip speeds far greater than those heretofore considered possible. The failure of the British experiment, previously referred to, was due no doubt to the air turbulence and other disturbing factors resulting from the use of blades not adapted to high speeds.

In the problem of projectiles, valuable data may be derived from this method, by eliminating the angle of attack or pitch with the consequent thrust, and by measuring the rotational air resistance only, the blades generally having an approximate "boat shape" section - a term applied to certain types of rifle bullets. No previous use apparently has been made of this method, in which it is possible to get very accurate and reliable observations. This is due probably to the mechanical difficulties previously described, which will always be experienced when very high velocities are used, approaching and exceeding that of sound.

From observations of projectiles in flight it is known that the usual velocity of a rifle bullet is 2100 to 2700 f.t.p.s. and the pistol bullet below 1000 ft.p.s.

The results from a series of experiments in the region of velocities from 700 to 1400 ft.p.s. with the 22- and 17-inch propellers at 0° pitch, are given in Fig. 12. It will be noted that there appears to be no critical point or sudden turn in the plotted curve at or near the velocity of sound.

As to the rate of rotation to velocity, the frequency of the air impulses from one blade of a two-bladed propeller at 100 r.p.s. is about equal to that of the 3rd F, reaching the middle octaves of a piano. The tone emitted by the 2- and 4-foot propellers when absorbing 100 HP is clear, sharply definite as to pitch, and of great intensity, being audible for several miles. The tone is very similar to that of a powerful steam siren and has none of the confused and distressing violence claimed in the British experiment.

The standard two-blade propeller, of the usual character, when mounted on an aircraft engine with the customary speed of 1500 r.p.m., gives rise to air impulses reaching the ear at about 40 per second, no greater than the lowest bass note of a piano and is therefore generally not clearly perceptible, as a definite musical tone, mainly because of its depth of pitch. It is also of the same frequency as that of the tone of an 8-cylinder exhaust, but the latter, being more powerful, remains the predominating sound.

Very high speed propellers have an unusual note of great penetration, quite distinct from the roar of the exhaust. Important usage has been made of this tone in experiments, by which it was possible to determine speed and a verification of tachometer readings.

The success of these experiments is due largely to the effici ency with which the profiles were designed in order to get stability of pitch, stability against fluttering and also against segmental vibration under the action of enormous centrifugal force. In these designs the resultant of axial, radial, tangential and torsional stresses on the blade at full speed gave a close uniformity of load distribution, the blades therefore not vibrating either as a whole or segmentally. If such vibrations do occur, due to an improper form, the thrust diminishes perceptibly, as seems to have been the case in the British experiments, the absorption of power may increase rapidly and become excessive while the sound emitted may be of a most disagreeable character.

With the proper form the thrust and speed progress steadily and in a constant ratio, and the sound emitted is a clear, definite, simple note, the pitch being easily determined by comparison with a suitable tuning instrument.

In order to ascertain the performance of a propeller in actual flight, and owing to the diameter of the propeller making it too large for the wind tunnel, the Curtiss Aeroplane & Motor Corporation anchored an airplane immediately in front of the propeller erected for test. The airplane propeller was driven by its own engine and delivered a slip stream parallel to the slip stream of the propeller under test - the wind being controlled to some extent by screens - at an average velocity of 41.9 miles per hour as indicated by a Pitot tube. The results obtained from this method, although reasonably substantial, are not considered as having the accuracy of those of wind tunnel tests.

The comparative results of thrusts and velocities of a four-blade, 4-foot propeller from tests in a wind, similar to that just described with those of a wind tunnel are given in Fig. 13.

Referring to Series 3, the practical test, nine different propellers were made and used on airplanes in flight: one, the D-4 on a Curtiss J.N., O.X.5, 75 HP engine, Fig. 1; another, first on a Curtiss Standard K-6, 150 HP engine, and afterward on a Curtiss Oriole, 160 HP engine, Fig. 2; two others on Curtiss Orioles, and one on an Air Mail 400 HP Liberty engine. In the first four cases the Reed propeller proved the more efficient when compared with a wood propeller while with the Liberty engine, the pitch being purposely too low for full speed, the flight was made with engine throttled, the propeller turning at about 1900.

The D-1 and D-2 were tested statically at McCook Field and proved a success. D-1 had been flown several times on a 160 HP engine and also endured a 30-hour test successfully. The D-6 was flown a number of times, twice with a passenger, attaining an air speed of between 106 to 108 m.p.h., the usual wood propeller accomplishing a speed of 96 m.p.h. It was again flown on an Oriole, in a race during the spring meet at the Curtiss Field and won easily against several competitors. It was then given to Amundsen for an Oriole taken on the Arctic Expedition. Another propeller, D-8, was tested to destruction at McCook Field in order to determine the maximum blade width in the tip region which a blade of certain root thickness can sustain without oscillation of pitch, or fluttering under the stresses for which the propeller is designed.

Tests were also made with a 50% additional overload as required in government tests. The speed was increased until the pitch broke down, causing violent fluttering which eventually resulted in fracture. With the data thus obtained the maximum power absorption can be determined and when the propeller, so designed, is subjected to test and found to maintain its pitch steadily, it can be relied upon as proof against fracture in service.

The D-26 propeller, 7-foot 9-inches in diameter, with a 9-foot 6-inch pitch, designed for the Curtiss Army Racer for the Pulitzer trophy, was tested statically at McCook Field in October, 1922, to over 2300 r.p.m., absorbing 639 HP without flutter and without deformation.

In the proportioning of stresses exerted on the blades, in order to maintain the required pitch, there are involved calculations and formulas which differ in some degree from those used for wood propellers, necessitating a departure from established precedents. There is no doubt, however, but that propellers of this type can be adapted for use up to the highest powers and speeds; in fact, at the present time, they are probably superior in efficiency to any other. Being made of solid duralumin, or an alloy with similar physical properties, and in a single piece, it has no hollow spaces, weldings or rivets. Its weight is almost the same as that of a wood propeller of the same area; and while the advantages of metal over wood are generally accepted, its superior aerodynamic properties are still the prominent and essential factor. This latter feature is due to the thinness of the blades, the use of which without deformation under conditions of service, has been made possible in the Reed propeller.

This propeller may be classed as semi-flexible. It is made of rolled sheet metal 5/8" to 1" thick, annealed, and cut to the desired shape. The tapering in thickness is begun a short distance from the hub-center and is continued straight to the tips, at which point the thickness is from 1/10" to 3/16". The back surface of the tapered portion is cambered, producing an approved airfoil section, at least, from the 30" station out, with lower surface flat and upper surface cambered. The blades are twisted to the proper pitch and heat-treated, after which they are drilled to admit the propeller shaft and then mounted, either on one of the regular wood propeller steel hubs by means of a filler block, or on a specially shaped steel hub as shown in Figs. 10 and 11. The propeller is then rigid at the center and progressively flexible toward the tips.

In order to further present the theory of this propeller, attention may be given to Fig. 14, in which the approximate profiles of a typical wood propeller and that of the Reed propeller at the same radii, are given, the peripheral speeds in feet per second for an 1800 r.p.m. being :

Radii:	6"	12"	18"	24"	30"	36"	42"	48"	54"	60"
F.P.S.:	94.2,	188.4,	282.6,	376.8,	471,	565.2,	659.4,	753.6,	847.8,	942

The performance of airfoils is generally assumed to agree with the results obtained in wind tunnel experiments which have been made up to 250 ft.p.s. only, with interpolations for greater speeds up to 900 ft.p.s., the latter being accepted without question, although based upon assumption. In considering speeds which approach the velocity of sound there is reason, however, for not relying upon interpolation, the indications from results for speeds approaching 1100 ft.p.s. being that there is no longer only the increase in pressure on the rear surface and a diminution on the front surface, both contributing to a useful thrust, but also a compression wave which accumulates around and on both sides of the leading edge and a similar rarefaction wave at the trailing edge.

These pressure waves spread forwardly as well as aft in relation to the course of the airplane, and, therefore, not contributing to thrust, absorb and waste power. As affecting the velocity of bullets, Professor Boys' photographs of bullets in flight, made first in 1893, and described in "Nature," March, 1893, and also in Smithsonian Institution reports of 1893 (similar photographs are now being made by Major Wheelock at the Frankfurt Arsenal) throw much light on this subject, demonstrating that slowly-moving bullets, having a speed of not over 800 ft.p.s., may have quite a blunt nose without creating a compression wave (Fig. 15); but as the velocity approaches and exceeds 1100 ft.p.s., the compression waves become the chief consideration, and are reduced only by the use of a sharp nose, or a small angle, and a cut-away tail (Figs. 15 and 16). In the Reed propeller the blade sections up to approximately 36" from the hub-center, travelling at about 600 ft.p.s., could, therefore, have reasonably thick sections with blunt edges, but beyond this station the thinness of profile and sharpness of edges becomes a very material factor; and in the eight or ten inches of the tip, a portion which contributes largely to thrust, it is a matter of serious importance whether or not the leading edge is blunt or sharp, and with a low angle of edge.

Another advantage, by no means negligible, is afforded in the Reed propeller, in the thrust created by the profiles toward the root of the blades. Although comparatively small, this portion contributes to thrust and also produces a cooling blast of air against the nose of the fuselage, which is very serviceable when a radiator is used at that point. The profiles in this portion of a wood propeller, as shown in Fig. 14, are thick and poorly-shaped serving more in the capacity of strength, and do not create enough thrust to carry even their own weight. It may, therefore, be theoretically concluded that the higher efficiency of ~~the~~ Reed propeller is due somewhat to the structure at this point, the determinations, based upon experiments, indicating that the net average advantage gained is at least 6%. Considering radial tension as existing specifically in the Reed propellers on account of centrifugal force; calculations reveal that under a speed of 2000 r.p.m. the tension does not exceed 8000 lbs. per square inch of section,-and moreover, under 3000 r.p.m. the tension does not exceed 60% of the breaking strain claimed for the material. In the matter of pitch constancy when properly proportioned the propeller will maintain its pitch under a power absorption of 50% in excess of that for which it is designed. Other features of value, not contained in the usual wood propeller, will be readily appreciated, i.e. the pitch is adjustable, and on account of the ductility of the material, the blades can be twisted back and forth a number of times without injury to the material until the desired pitch is obtained. Furthermore, in the case of accidents, causing a moderate deformation, it is possible that the original shape may be completely restored. Still another feature, made possible by the thinness and flatness of the blades at the root, is that by crossing a two-blade propeller, a four- or six-blade propeller is easily provided, or if preferred, two or more can be mounted in tandem.

Fig. 1- Reed duralumin propeller D-4 mounted on a Curtiss JN with OX5 engine.

Fig.2 - Reed duralumin propeller D-6 mounted on a Curtiss Oriole.

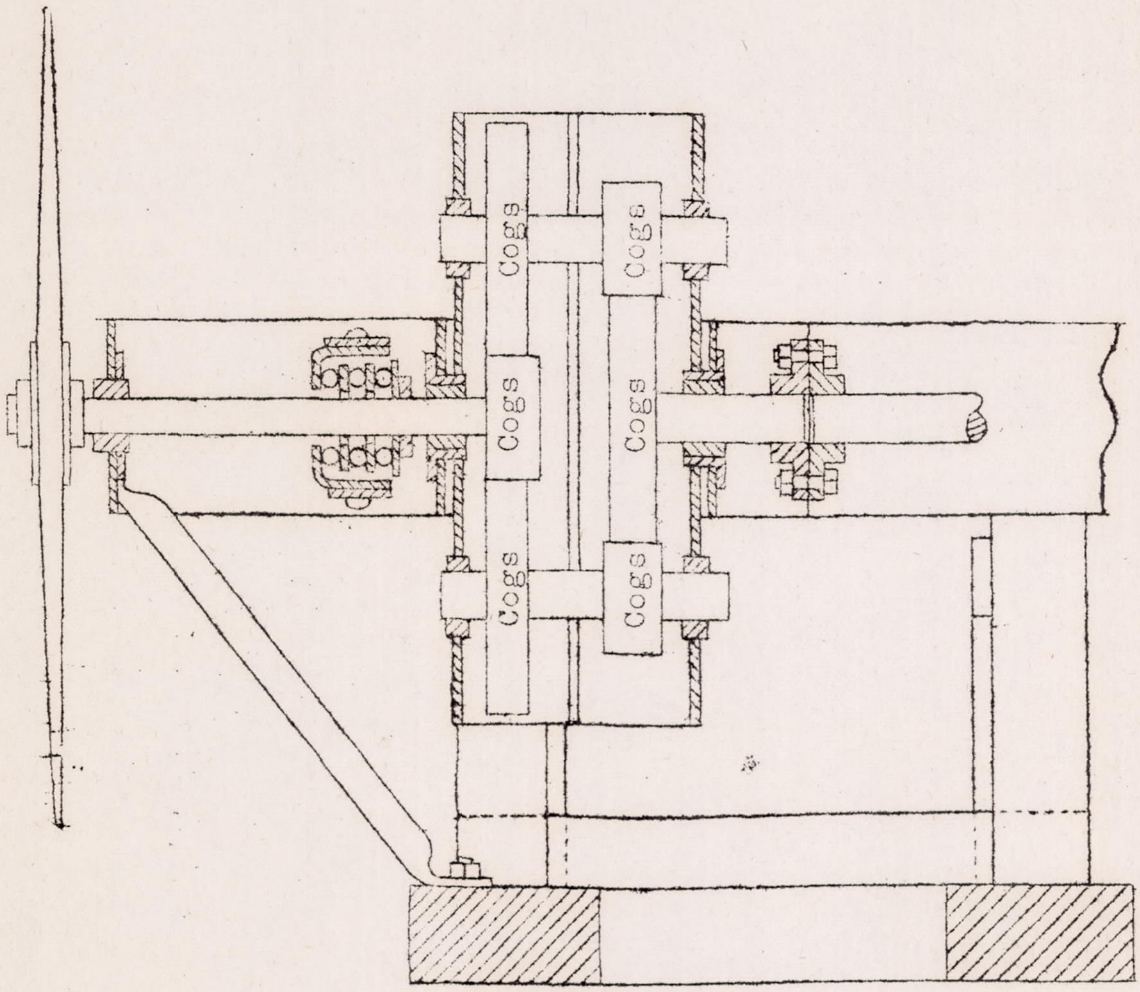

Fig. 3

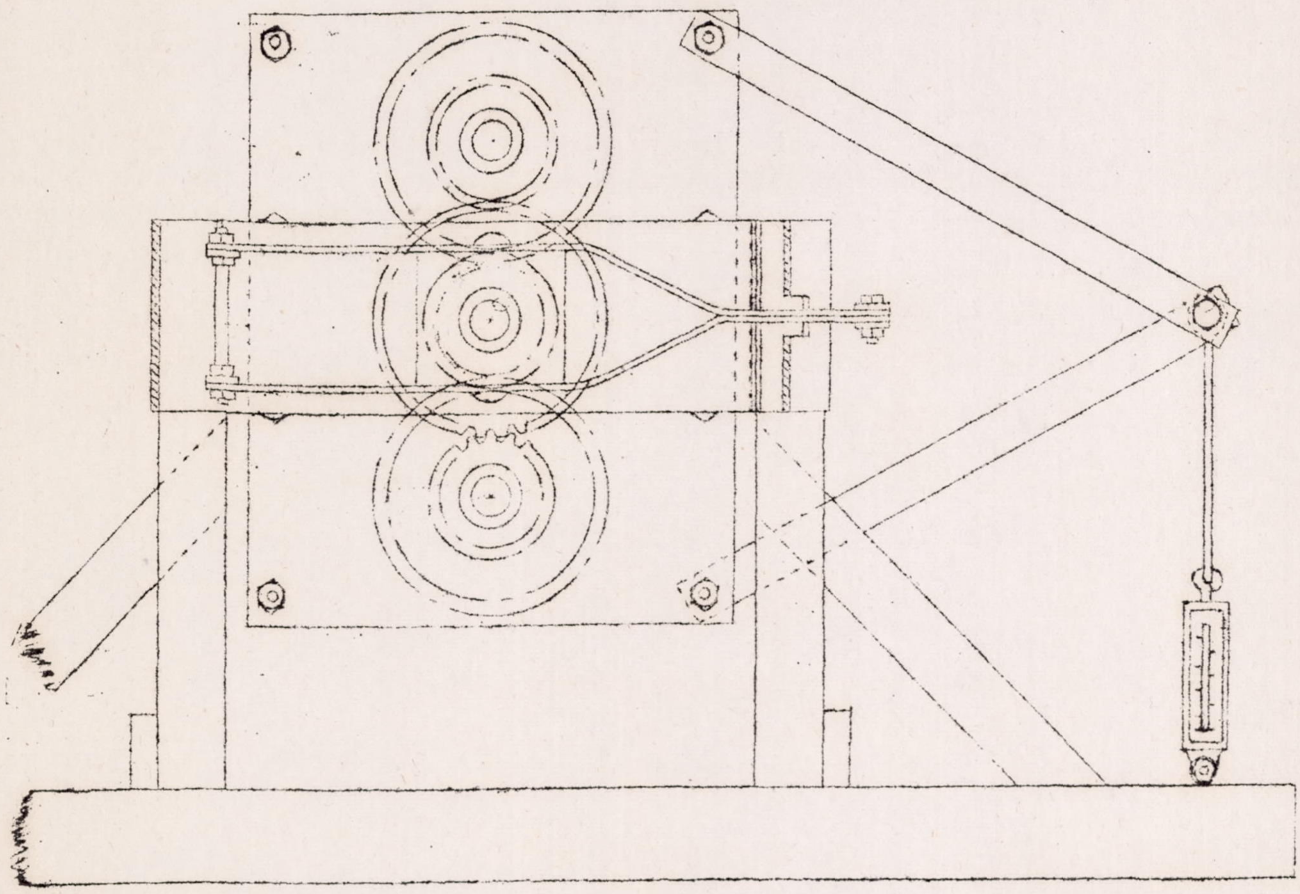

Fig. 4.

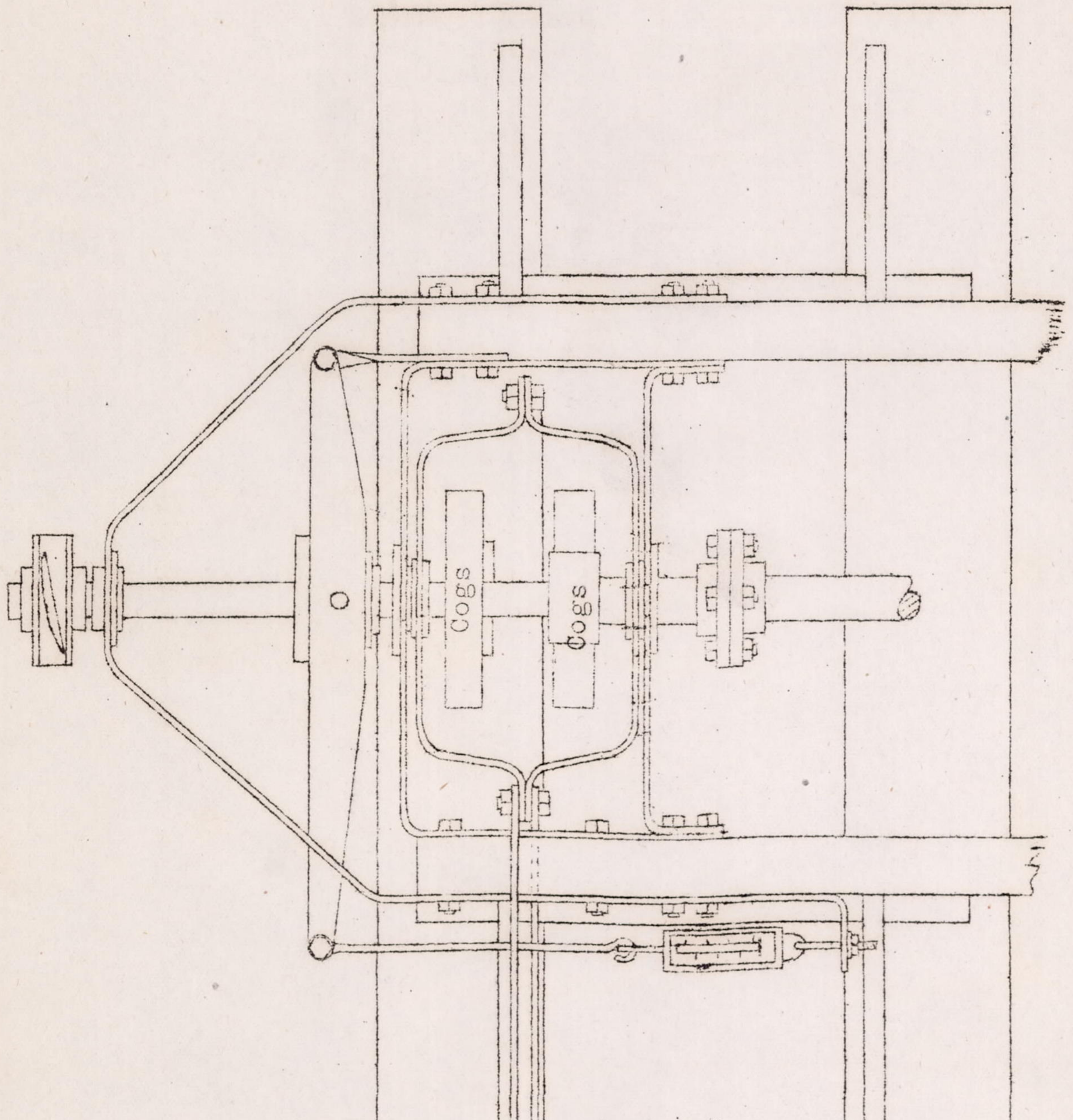

Fig. 5.

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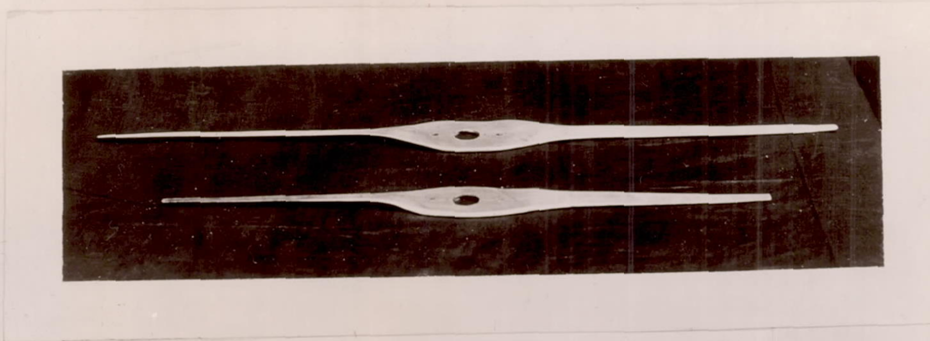

Fig. 6 - Propellers, 22 and 17 inches long.

Fig.10 - Reed 8'7" duralumin propeller 5/8" thick at hub section; 1/8" at tip section; made of a single piece of sheet metal 5/8" thick. Pitch 5 feet.

Fig. 11 - Reed duralumin propeller with twisted flange hub.

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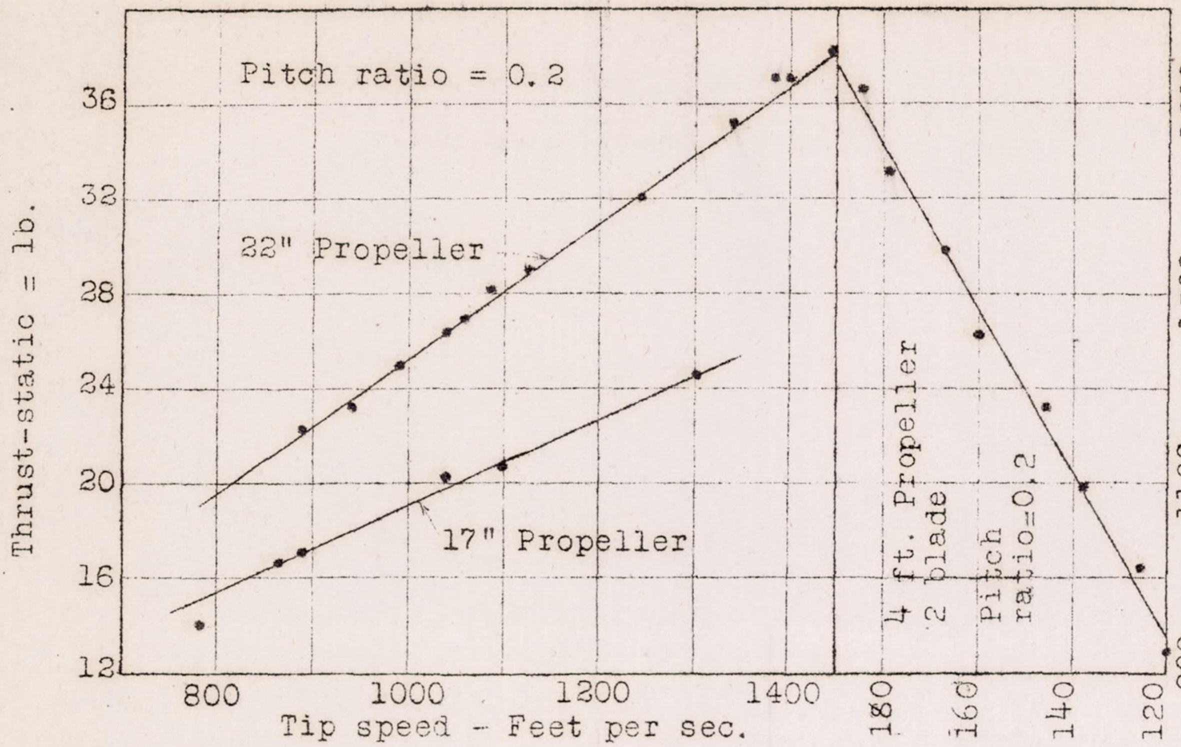


Fig. 7. Comparing 22" & 17" propellers.

Fig. 9. Test at Curtiss A & M Corp.

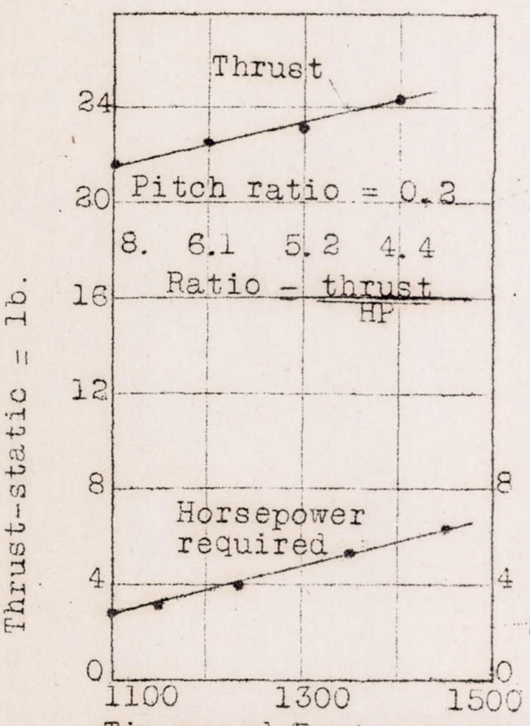


Fig. 8. Thrust & HPrequired for outer $2\frac{1}{2}$" of the 22" propeller.

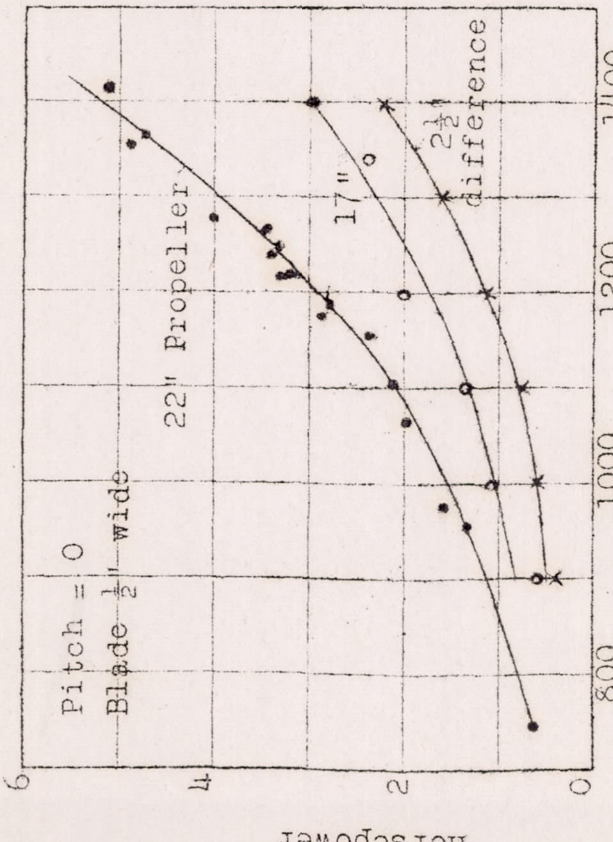


Fig. 12. Gross HP. for Prop. Net HP. for outer $2\frac{1}{2}$".

Figs. 7-8-9-12

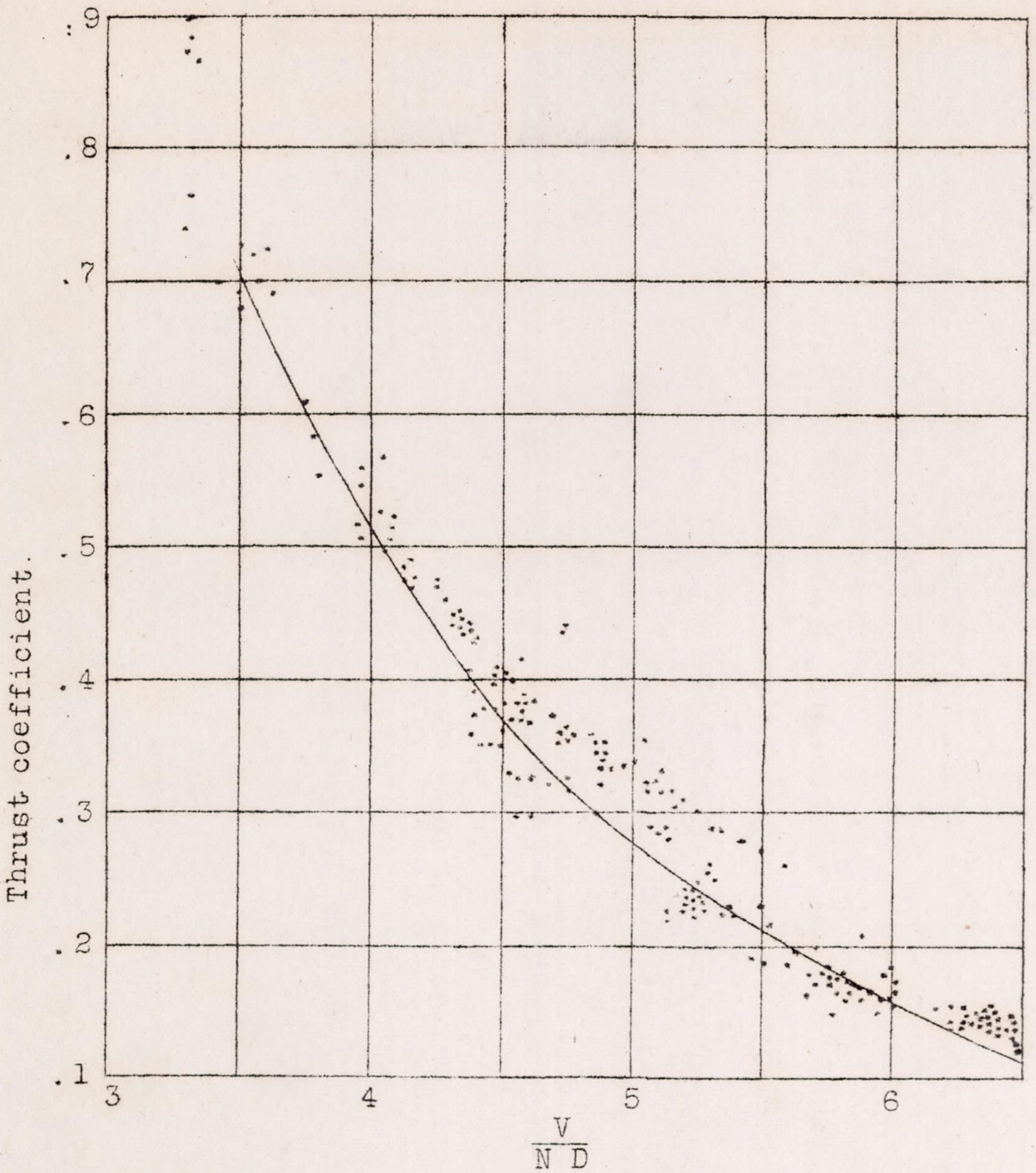
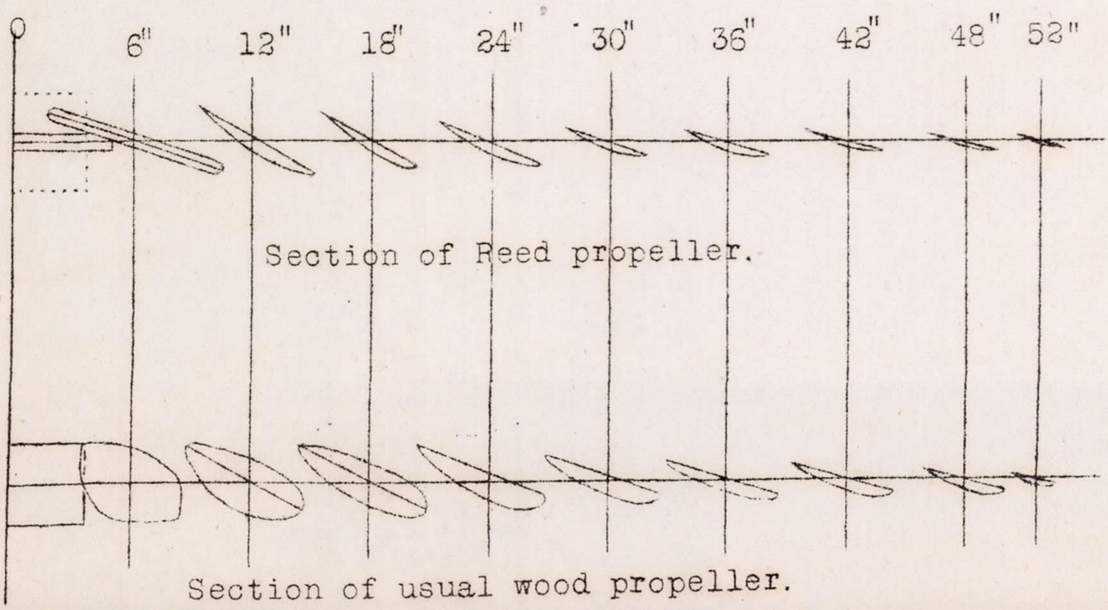
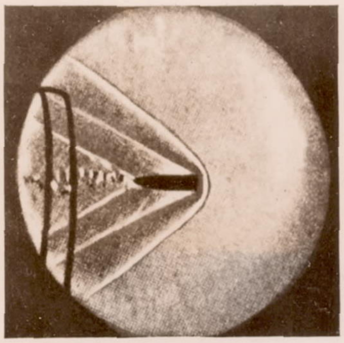


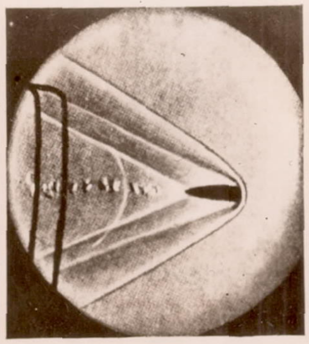
Fig. 13



Section of Reed propeller.

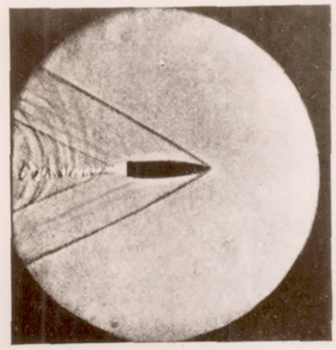
Section of usual wood propeller.





BULLETS FIRED BASE FIRST

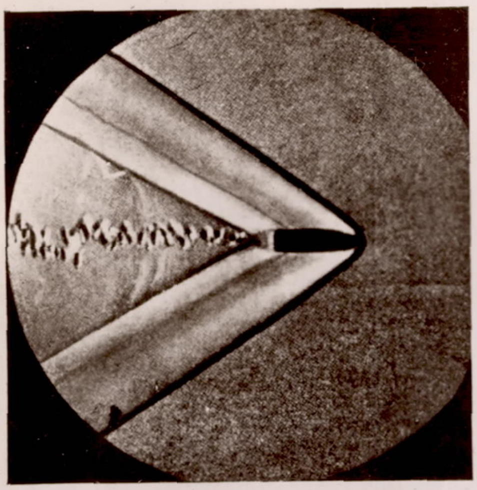
In the case of bullets fired base first there is a very strong pushing out of the head wave of compression, and only a small rarefied air space and formation of whirls behind. It is not to be supposed from this that bullets with pointed bases would be an advantage. As a matter of fact, they are very unstable. The rarefied air space and whirls would seem to indicate steadying as well as retarding influences



FRENCH "BALLE D" IN FLIGHT

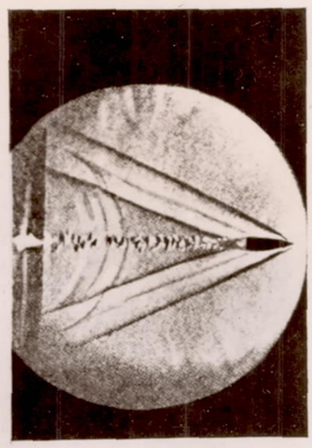
The French "Balle D" has a slightly tapered base which they claim has helped in the production of a projectile of high ballistic qualities

Fig. 15



1. AN OGIVAL-HEADED PROJECTILE IN FLIGHT

The lines flowing from the bullet at an angle are lines of different air density. From the nose of the bullet comes the "head wave" or wave of compression. From the base there is the tail wave. Immediately behind the base of the bullet is a rarefied air space, and in the rear of it a track of air whirls. Between the head and tail waves are the compression waves caused by the rotation of the projectile. This projectile is the Italian service bullet



2. A POINTED BULLET IN FLIGHT

In this photograph the sharper angle of the lines from the nose and tail indicate a higher velocity. It will be noticed that the point of the bullet projects through the head wave. In other respects the phenomena to be observed in the two photographs are similar. There are the head and tail waves, the rarefied air area, the track of whirls, and the compression lines caused by rotation. This bullet is the German "S"

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Fig. 16