AIRCRAFT PROPELLERS

by

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In analysing the manner in which an aircraft propeller performs the work of converting the power of the engine into thrust, we can examine it in two ways. Either we regard the propeller as a rotating wing, or we regard it as a device for accelerating a large mass of air rearward, the reaction thus produced moving the propeller (and the aircraft !), in the opposite direction ; a sort of " cold jet," deriving its thrust from a large mass flow and a relatively small change of velocity.

The two are, of course, closely analogous but we must focus our attention on the former and rather more involved viewpoint if the behaviour of the propeller, and more particularly its practical limitations, are to be fully appreciated.

It is, in truth, a rotating wing and behaves in an almost identical manner to the mainplanes. Just as the best lift-drag coefficient for a wing is obtaining at an angle of attack to the incoming air of about four degrees, so is this also true for the aerofoil section of the propeller blades. It follows that to obtain maximum thrust from the propeller with the available engine power when the aircraft is at rest, the ideal blade angle should be about 4°, but to absorb, say, 2,000 B.H.P. with such a small blade angle, the propeller would probably have to be some 25 feet in diameter. To avoid this a far coarser angle has to be tolerated in order to absorb the power with a propeller of reasonable diameter.

Blade Stall

Logically, however, a point will be reached when the blade section is hopelessly stalled, and the thrust developed by the propeller will be far below that expected from the engine power which is required to rotate it.

This condition, in its most pronounced form, may be readily observed when an aircraft is being " run up " on the ground and the constant speed (c.s.) propeller control is tested. When the governor unit is controlling at high r.p.m., the blades are operating at a relatively small angle ; they are not stalled and the airflow, though possessed of a very appreciable rotational component is, none the less, largely axial. As a result, an observer stationed at the leading edge of the aircraft wing will feel little or no air disturbance, even when standing within a few feet of the propeller.

When the c.s. control lever is moved rearward to a reduced r.p.m. position, however, the blades, coarsening to absorb the torque at low r.p.m., will stall, the axial airflow will diminish sharply, and the observer will immediately feel the swirling rotational disturbance about him as the blades throw air radially outwards, somewhat after the manner of a centrifugal compressor rotor.

The only way to combat this stalling limitation is to increase the blade area and there are several possible ways of doing this. Perhaps the obvious way is simply to use a larger propeller but, as already inferred, one cannot pursue this line indefinitely. In the first place one cannot have an aircraft with a ground angle of about 45°, or a tricycle undercarriage resembling stilts, expressly to enable an enormous propeller to clear the ground ; incidentally, such long undercarriage legs would lead to weakening of the structure (or at best, increased structure weight) in allowing additional space for their retraction.

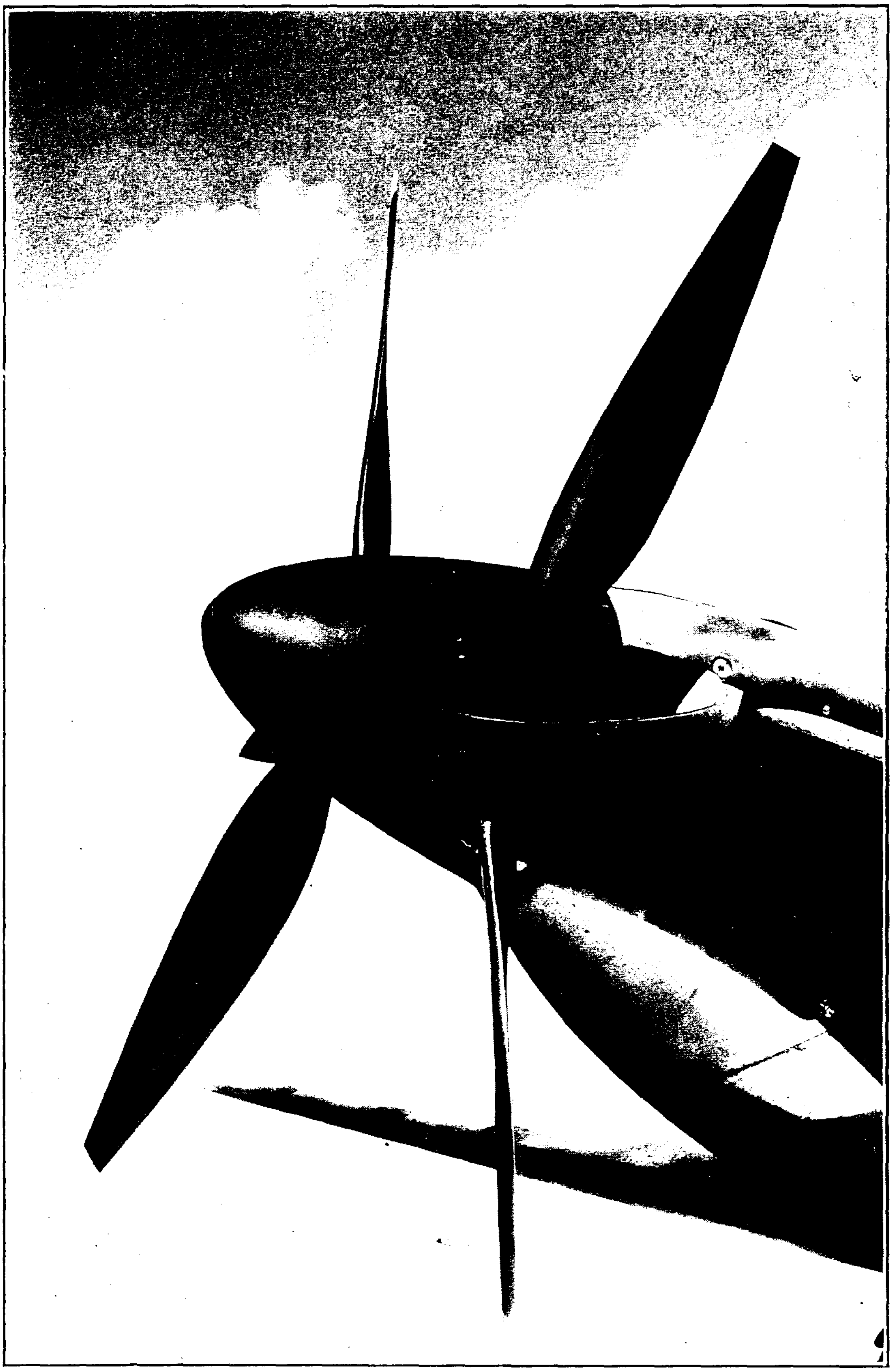

Fig. 1.—D.H. Contra-Rotating Propeller fitted to "Spitfire"

Compressibility

There is, also, the ever present bogey of "compressibility." It is not practicable to rotate a propeller at a speed higher than that which will produce a tip speed of some 75% of the speed of sound at sea level without incurring *shock waves* at the tips, and the resultant sharp increase in drag or engine power absorbed. This figure will vary according to the forward speed and operational altitude of the aircraft.

If *compressibility* does not occur at take-off, it does not necessarily follow that it will not occur in flight. In flight, a point on the propeller is following a helical path. On a constant speed governed propeller, the pitch of the helix, and thus the distance travelled by a given point, increases with forward speed. Add to this the fact that the speed of sound decreases with the temperature drop at altitude ($V_s = 65.9\sqrt{T^\circ K}$), and it will be appreciated that compressibility at take-off must be avoided by a substantial margin, if the condition is to be avoided in high speed and/or high altitude flight.

For example, a propeller having a constant *rotational* tip speed of 726 feet per second is, at zero forward speed at sea level, operating at a Mach number (ratio ; in this instance, tip speed to speed of sound at altitude obtaining) of 0.64, which is well within limits. At a forward speed of 450 m.p.h., however, the *helical* tip speed has become 982 feet per second giving, at sea level, a Mach number of 0.86, rising to 0.91 at 10,000 feet, and to 1.01 at 40,000 feet when compressibility is occurring.

Certainly then the problem will not be fully solved by increasing the blade area by recourse to increased diameter alone, *i.e.*, just a larger propeller. Same diameter, more blades ? Yes, a far better way out and, of course, we have seen this policy pursued. In the 1930's two blades (and even one and a mass balance !), then three, four, and finally five on one hub in an effort to absorb with reasonable diameter and, thus, tip speeds, the ever increasing engine torque.

At the present time five blades appear to be the maximum number it has proved practicable to mount on a single hub. Experimental work has been carried out with six and more though not, apparently, to advantage. Aerodynamic interference between the blades, a factor which, in conjunction with increasing hub diameter, probably compels a limit in this direction to be observed.

However, the latest types of five bladed propellers represent a big advance in piston engine aircraft propulsion, and are able successfully to absorb horsepowers of over 2,000 with propeller diameters of around 13 feet, and to propel single engined fighter aircraft at speeds in excess of 450 m.p.h.

Blade Section

It is at such extremely high forward speeds that the problem of blade section and shape assumes the greatest importance. There are numerous aircraft wing sections in use to cover various requirements ; from the low speed, high lift sections with high thickness chord ratio, to the thin laminar flow wings of the modern high speed fighter. As might be expected, the first gives the best lift/drag characteristics at low speeds, and the other at high speeds. Incidentally, a fortune awaits the designer who can effectively combine the two, and give the 500 m.p.h. fighter the stalling speed of a trainer.

Now we have suggested that there is a marked similarity between the behaviour of the propeller blades and the mainplanes. The comparison becomes particularly apparent with the propeller for high speed aircraft, for a moment's thought will show that with sections operating at various radii, there will arise the two extreme, or near extreme requirements, on the same blade section. While it is in no way unique for a designer to change the section along the length of a mainplane (usually to promote a progressive stall), the

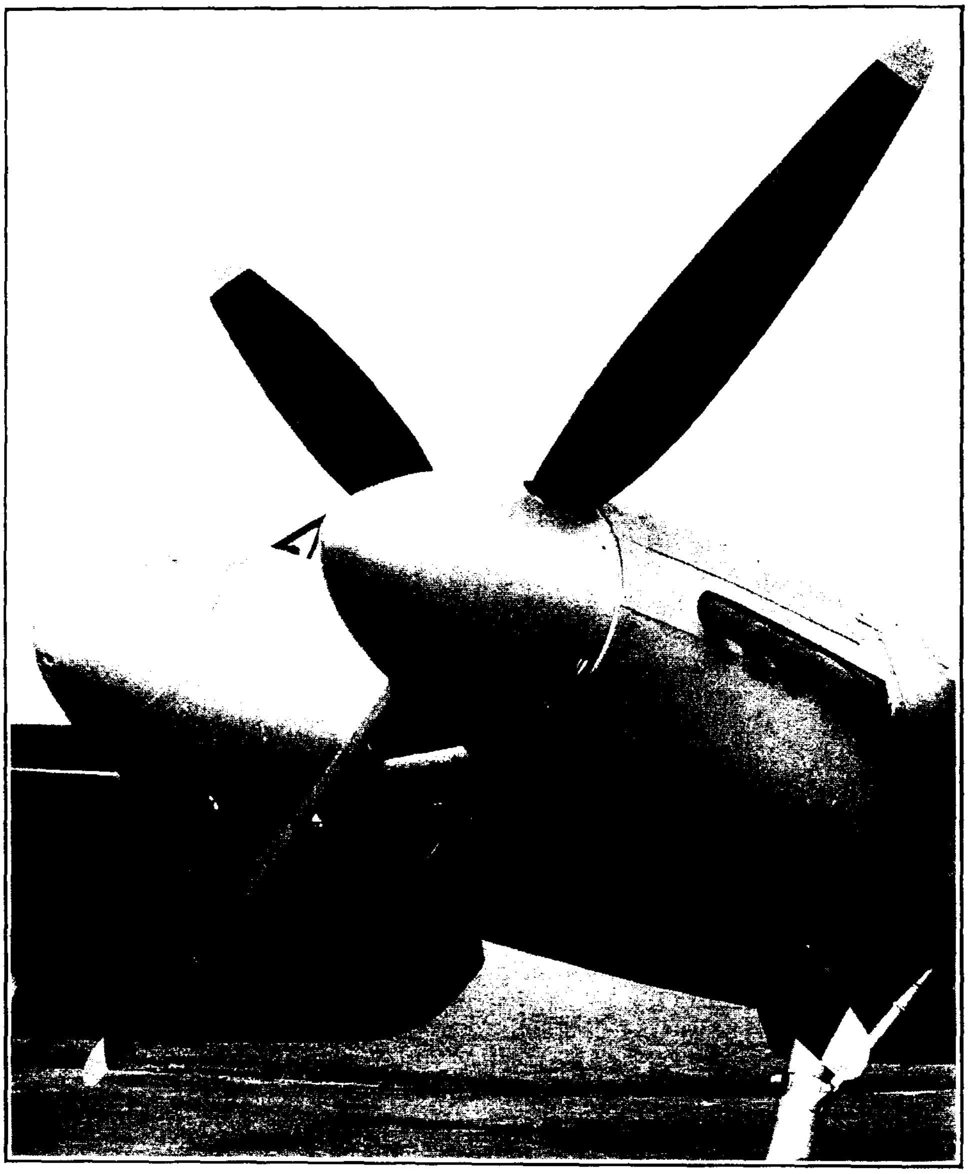

FIG. 2.—D.H. 4-BLADED PROPELLER FITTED TO "SEA HORNET"

change is never so marked as in the high speed propeller blade for, unlike the propeller, all sections of the wing will, it is hoped, travel at the same speed !

At the root, a low speed high lift section is used, partially from aerodynamic considerations and partially from structural, since the root of a blade is extremely highly stressed and must be robust to avoid blade flutter. It is for this reason that, rather surprisingly perhaps, compressibility at the root can frequently occur almost simultaneously with that at the tip. In spite of the far lower rotational speed of a root section, the increase in the velocity of air flow over it is far more marked than over the thinner sections at greater radii, and local shock stalling can occur.

Hence, the modern tendency is towards reduction of thickness at the root as well as the tip, though recourse to this essential development certainly tends to affect adversely the lower speed characteristics of the propeller ; *e.g.*, at take-off and during climb. It will, also, ultimately lead to the rejection of wood as a suitable material for propeller blades ; a reliable authority has stated that metal has the advantage over wood at speeds in excess of 450 m.p.h.

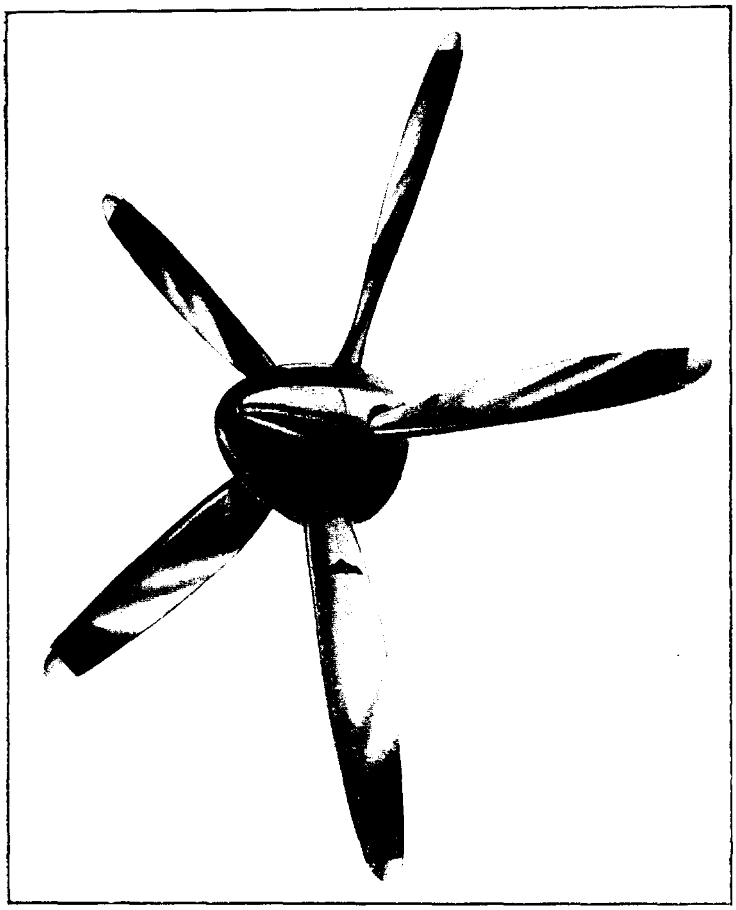

FIG. 3.—MESSRS. ROTOL'S 5-BLADED PROPELLER

Indeed, if propellers are to be the means of traction at speeds in excess of 500 m.p.h., the current solid forged duralumin and the hollow steel blades, may give way to an extremely thin, high speed section blade of solid steel. It would seem inevitable that take-off and climb performance will suffer materially with such a choice, unless our designers are able to develop some section which is a compromise of extremes to a degree at present unattained.

Two-speed Reduction Gear

In the meantime, and possibly ultimately, in conjunction with the contra-rotating propeller, another interesting expedient is being developed, viz., the two-speed reduction gear.

It seems possible that when the propeller is called upon to absorb full torque at take-off, and the blades of even multi-bladed propellers take on a stalled or near-stalled angle to achieve it, a thrust improvement may be attained by using a higher reduction gear ratio. With the resultant lower torque, the propeller will " fine-off " to well within the stalled angle, and so deliver a greater thrust, although a proportion of the outer sections of the blades may be in the compressibility zone.

Development along these lines may well lead to improved take-off characteristics on existing types of propeller aircraft in the 2,500 to 3,000 B.H.P. category.

Another factor which has long assumed important proportions in single engined aircraft of this power category, particularly when carrier operated, is that of swing at take-off which is the product of a lateral force on the fin and rudder due to the rotating slipstream, and of the high torque reaction from engine to airframe, tending to rotate the aircraft about its longitudinal axis against propeller rotation. The magnitude of the former force is difficult to assess, but with a propeller absorbing 2,500 B.H.P. at 1,200 r.p.m., we have the very high figure of nearly 10,500 foot-lb. which has to be resisted if propeller and airframe are not to share the r.p.m. between them !

At high forward speeds, when there is a substantial airflow over the entire aircraft, these forces can be combated aerodynamically at the expense of additional drag. At low forward speeds and maximum power they present an extremely tricky exercise in aircraft handling, especially during a carrier take-off, where the pilot has little choice of direction if the aircraft is to become airborne and remain so in the required fashion.

Contra-rotating Propellers

It is largely due to these factors, though it offers other advantages, that the contra-rotating propeller is coming into increasingly wide use on aircraft of this type. The slipstream from these propellers is very nearly axial, thus eliminating the lateral force on the fin and rudder. Assuming that the two components of the propeller are absorbing equal torque, the reaction is neutralised. The contra-prop approaches the basic ideal of propeller propulsion : it exerts a force to pull the aircraft through the air without the hitherto inevitable rotary component, and its wake is virtually axial which does not adversely influence airframe and control surfaces.

Its other advantages include reduced diameter for a given power ; ability to absorb (*via* the medium of its increased blade area) power at a smaller blade angle, thus avoiding blade stalling at take-off ; smoother absorption of power ; and increased efficiency at high altitude. Its disadvantages : weight, cost, and alteration of the C of G when replacing an existing single propeller.

In order that both components shall absorb equal torque it is necessary to run the rear component at a somewhat finer angle than the front (as it is operating in a flow which is already rotating against it) ; this difference is in the order of 1½ degrees. It is interesting to note that while this difference is critical from the point of view of eliminating torque reaction, the figure may be varied as much as two degrees without otherwise influencing the performance of the propeller.

The ideal difference is not a constant over the working range, though while the American designers have thought fit to tolerate the complication necessary to cater for this variation, in this country it is considered adequate to decide on an optimum difference of angle, and to maintain it through the range by coupling both sets of blades to a common operating cylinder.

The propellers run at equal speeds so that the radial " white lines," caused by the stroboscopic effect in the passage of the blades past each other, remain stationary and less disturbing to the pilot.

As regards the limit in the number of blades that may be thus employed, while the " double-three " is the type in general use at present, there appears to be no aerodynamic or structural obstacle in the way of an increase to a " double four " or to a " double five " as increasing engine powers dictate. On the matter of diameter, earlier observations on the same problem with the single propeller are, of course, still applicable.

And so we come to what is, without rash prophecy, apparently the ultimate in aircraft propulsion by propeller, and effectual to forward speeds of 500 or possibly 550 m.p.h., beyond which with propeller efficiency fast decreasing, jet propulsion takes over, and goes forward with increasing efficiency to speeds which to attempt to foretell would be rash prophecy indeed.