Speed*

By Prof. B. Melvill Jones

THE reason why a real fluid can leave the surface is now well understood, but the calculation of the precise point at which it will do so is still a matter of great difficulty, over which we are only just beginning to obtain the mastery. It is still true, in the main, to say that the question whether or not a given body will give a good streamline flow can be determined only by experiment, and it is entirely for this reason that it has been found worth while, in the countries interested in aeronautical development, to spend large sums of money on the construction of huge wind tunnels, within which the necessary experiments can be made. Even in these tunnels the question cannot be settled with absolute certainty, and research workers are turning more and more to face the difficult technique of experimenting in actual flight, to determine how nearly the flow about actual aeroplanes approaches the ideal streamline form.

It is, of course, no easy matter to design and make what may be described as streamline aeroplanes. It is necessary first to eliminate such an obvious obstruction to the air as the undercarriage, by pulling it up into the body or wings when in flight. This involves designing a light and strong mechanism which will return the wheels to the landing position and lock them there with wellnigh absolute certainty. The importance of this point strikes one with added force when landing for the first time upon a collapsible undercarriage which cannot be seen from inside the aeroplane. Next, there is the still more difficult problem of cooling the engines without exposing unstreamline objects to the air stream. The problem is especially difficult with the air-cooled engine which is so convenient in other respects: it has been partly overcome by devices known as the N.A.C.A. cowling and the Townend ring, which are placed around the engine to prevent it from deflecting the air stream away from the surface of the body behind it. Then again the pilot must be able to see forward comfortably through a window which does not spoil the streamline form of the body. This is rather easier when there is no engine in the nose of the body, for the pilot can then be placed well forward in a position where there is less danger of his window causing the stream to separate from the body. Finally, it is necessary to ensure that the junctions between the body and the wings and tail are not such as to lead to unstreamline flow, even though these parts separately would behave in a perfectly streamline manner. It is only recently that reliable information on this point has become available and led to designs in which the wings are carefully moulded into the body.

Until two or three years ago, these difficulties were altogether too much for designers and constructors, with the result that the resistance of the average aeroplane at high speeds was many times greater than it would have been with correct streamlining, and speeds of 100 miles per hour or slightly more were all that could be obtained from the power—one horse-power to about 12–15 lb. weight—usually supplied for transport purposes. During the past few years, the speed of the most advanced forms of civil aerial transport has risen from something less than 100 miles per hour to the neighbourhood of 170 miles per hour—the top speeds of the best aeroplanes have, as everyone knows, risen to more than 200 miles per hour, but I am referring to the actual travelling speed. This increase has been primarily due to improvements in streamlining. Secondary developments, such as that of the variable pitch screw and the split-flap wing, have been necessary to enable advantage to be taken of the reduced head resistance without adversely affecting the problem of landing and taking off, but these of themselves could have achieved but little upon the older unstreamline aeroplane.

In the epoch of the imperfectly streamline aeroplane, from which we are only now beginning to emerge, the skin friction on the exposed surfaces contributed so small a fraction to the whole resistance that, even if it could have been eliminated altogether, the speeds would not have increased to any important extent, but, now that it is becoming possible to approach the perfect streamline shape, skin friction provides the dominating contribution to the resistance, and its study with the view of possible reduction of head resistance is transformed from a matter of mainly academic interest to one of supreme practical importance. Here again that curious and insistent urge, which causes the unpractical man of science to study problems for their own sake, without reference to their immediate practical application, has stood us in good stead; for now that skin friction has suddenly taken the foremost place in the

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search for still greater speed, we find ourselves already in possession of much useful information about it, although there is still a long way to go before we shall understand its action completely. It is to the consideration of what we already know about skin friction that we must now turn.

A real fluid, such as air, cannot slip over a solid surface ; the layers in immediate contact with the surface having no appreciable motion over it. This, of course, is in direct contrast to the ideal fluid of the mathematicians, which is assumed to slip with perfect ease. When one examines the flow of air close to a solid surface, one finds that the velocity parallel to the surface increases very rapidly from zero at the surface to the full velocity of the main stream at a point not far from the surface. The thin sheet of fluid in which this rapid change occurs is called the *boundary layer*. When the flow within this boundary layer is smooth, in the sense that sheets of fluid slip over one another without mixing—like the cards of a pack which is thrown down on a table—we say that the boundary layer is *laminar*, and it is found that when a body, such as a wing, has a smooth surface and a rounded leading edge the boundary layer is smooth—or laminar—for some distance along the surface back from the leading edge. Sooner or later, however, at some point behind the leading edge, this laminar condition breaks down and the flow within the boundary layer becomes *turbulent*, so that the separate sheets of air no longer slip as a whole over one another, but are thoroughly mixed together by the formation of little eddies and erratic movements of small portions of air to and from the surface. Anyone who has looked down over the side of a ship in motion will have seen the effect of this turbulence extending, on a large ship, for a foot or more from the side.

The distance from the leading edge of the wing or the bow of a ship at which the flow within the boundary layer passes from the smooth to the turbulent form is controlled by a number of factors such as the speed of the main flow, the shape and roughness of the solid surface and the turbulence, if any, already in the fluid before it reaches the wing. Speaking roughly, the greater the speed, the greater the roughness, or the greater the initial turbulence of the fluid, the sooner does the transition take place, and although we have a great deal of experimental evidence on the matter, we have, as yet, no means of calculating the distance from the leading edge at which the transition will occur, or even of placing any theoretical limit upon this distance if the surface were perfectly smooth and the main stream perfectly steady.

Experiments made in wind tunnels suggest that at speeds now in contemplation for civil aircraft—say 200 miles per hour—the transition to turbulent flow would be expected to occur within a few inches from the leading edge of the wings and front of the body, so that almost the whole of the surface of the wings and body would be covered by a turbulent boundary layer. But unfortunately there are no large high-speed tunnels yet in existence in which the air stream is as free from turbulence as the open air through which aeroplanes fly ; consequently it is to experiments on actual aeroplanes in flight that we must look for a final reliable estimate on this matter. There is as yet very little evidence of this kind available, but the necessary work is in hand.

The practical importance of discovering how far back it is possible to coax the boundary layer to remain smooth will be appreciated from the fact that the skin-friction force exerted by the smooth layer on a high-speed aeroplane would be about one-eighth that of the turbulent layer, so that anything which would increase the area covered by the smooth layer would have a powerful effect in raising the ultimate limit of speed. Assuming, however, for the moment, that it will not be feasible in the near future to retain the smooth form of the boundary layer over more than a small portion of the total exposed surface of an aeroplane, we have to consider the magnitude of skin-friction applied by the turbulent layer.

We have already a considerable knowledge of the skin-friction forces on thin smooth flat plates advancing edgewise into air or water, and we know that on such a plate, as large as the wings of a large aeroplane, the mean skin-friction resistance applied by the turbulent boundary at a speed of 200 miles per hour would be about one-third of a pound per square foot of exposed surface. But, in order to obtain this low figure the exposed surfaces would have to be very smooth. Recent work by Profs. Prandtl and von Kármán has suggested that roughness corresponding to small grains of sand larger than one-thousandth of an inch in diameter, thickly spread over the surface, would appreciably influence the results. Grains, for example, of the order one-hundredth of an inch in diameter would, it is estimated, raise the friction by as much as sixty per cent.

These estimates, it is true, were based only upon experiments made in long pipes with roughened surfaces, and the results were applied to flat pieces of finite length, after elaborate calculations based on unverified assumptions, but, for my part, I believe that the estimates will be found to be substantially correct when checked by direct measurement on wings of various roughnesses. Such experimental checks should shortly become available from experiments in the compressed air tunnel at the National Physical Laboratory, and from some experiments which we are making at Cambridge to find the resistance of parts of the wings of actual aeroplanes in flight.

As to how far the skin friction on the curved surfaces of a wing or an aeroplane will be the same as that on a flat surface, we are still very much in the dark. The curvature of the wing causes the pressure to change from point to point on its surface, and these pressure changes, or gradients as they are called, influence the flow in the boundary layer and the intensity of the friction applied by it. They also appear to influence the point of transition from smooth to turbulent flow, in the sense that the flow seems more likely to become turbulent when pressure is increasing in the direction of flow. It has long been known that a too rapid pressure rise in the direction of flow reverses the flow in the boundary layer, and is the cause of the separation of flow from the surface of unstreamline bodies ; and it now seems that pressure gradients, much smaller than are necessary to cause separation, may still adversely affect speed by encouraging the boundary layer to take on the turbulent form with its inevitably increased resistance. It may be that the impossibility of avoiding such rising pressure gradients over some parts of the surface of an aeroplane will place a final bar upon efforts to extend the laminar boundary layer over the whole exposed surface, but it is as yet too early to make any definite prediction on this question.

We are now in a position to take stock of the situation in respect of the attainment of high speeds by the civil transport aeroplanes of the near future. The most efficient aeroplanes of the present day have travelled a long way towards perfect streamlining, and achieve cruising speeds of a little less than two hundred miles per hour. It has been estimated that if perfect streamlining were to reduce their head resistance to that of a smooth flat plate of the same exposed area with turbulent boundary layer, they would travel some 20 per cent faster than at present on the same power. Hence there is some improvement, though not much, still to be achieved by perfect streamlining.

Now, however, that skin friction has been promoted from the minor role which it played in the pre-streamline epoch to the principal part which it will henceforth play amongst the factors which limit speed, it is no longer accurate enough to assume that it can be represented by the turbulent layer skin friction on a flat plate, and a great vista of research is opened up, of which the object will be to determine accurately the skin friction on the actual curved surfaces of the aeroplane, and to reduce it so far as possible towards the figure appropriate to the laminar boundary layer. Complete success along these lines might result in a further eightfold reduction of direct head resistance, which might correspond to a nearly twofold increase of speed with the same power. One cannot say yet what part, if any, of this great reduction will ever be achieved, for the difficulties in the way of extending the laminar layer appreciably may be very great, and they may prove to be insurmountable. One can only note the reward to be gained if success were complete, and observe that to achieve a relatively small fraction of this reward would be worth a very great effort.

An alternative to the reduction of head resistance would be an increase of power for weight, and no one can predict what new developments of the power units may occur. But to increase speed greatly by this method alone is a difficult matter, for even if the power were to be doubled, by giving to civil aeroplanes powers comparable to those given to-day to war aeroplanes, speed would be increased only by some 25–30 per cent. Personally, I do not look for much increase along these lines in the near future.

There is one other foreseeable way of evading the restrictions on speed, which is much discussed at present, but which has not yet been exploited. This is to fly very high, using totally enclosed aeroplanes within which pressure and temperature can be maintained at a comfortable level for the occupants. By this means, the direct resistance to motion might be decreased almost indefinitely, at the expense of some increase in what I have called the track-laying power, which, as I have shown, places no final limit on speed. Many very difficult practical problems must be overcome before much can be made of this method, and it is too early to give any estimate of the increases in economical speed which might result from this line of attack. Possibly the ultimate limiting factor here will be the difficulty of cooling the engine at these high altitudes.

For my own part, I feel reasonably confident that stratospheric flying, as this high flying is called, with its as yet unpredictable limits to speed, will eventually provide the principal means of long-distance transport over the earth. For I cannot believe that man will fail to take advantage of the arrangement, so conveniently provided by Nature, whereby the air is thick where he has to land and take off, and thin a little way above, where he can travel at high speed with small resistance and without inconveniencing those who remain on the ground.