Some ways of obtaining an Integrated Aircraft

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Professor J A J Bennett (*Chairman, Lecture Committee) occupying the Chair*

The Chairman, in introducing the Author, said that Dr Kuchemann had been a member of the scientific staff at the R A E , Farnborough, since 1946, and was now head of the Supersonics Division of the Aerodynamics Department From 1930 to 1936 he studied at the Universities of Munich and Gottingen, where he obtained the degree of Dr rer nat , and from 1936 to 1946 he had worked in the Aerodynamics Research Establishment at Gottingen under Professor Betz He was, perhaps, best known on both sides of the Atlantic for his classic textbook with J Weber " Aerodynamics of Propulsion "

The integration of the aerodynamics of a propulsive system with the aerodynamics of a lifting system as achieved in the helicopter was of fundamental significance in aeronautics and promised to become much more so in the future The Author had undertaken to discuss the generalised subject of an integrated aircraft, and it would be difficult to find anyone better qualified to present a paper of this nature

SUMMARY

The question considered in a general way in this paper is whether there is the possibility that other general types of aircraft exist, which differ in their aerodynamic aspects from and are more integrated than the existing types of aircraft Of these, there are considered to be only two, namely, the conventional aircraft combining a separate fuselage, tail unit, and propulsion unit with a wing of moderate or large aspect ratio , and the helicopter It is thought to be profitable in this context to briefly consider how nature solved these problems with the flying animals and whether some of their schemes can be adapted and translated into technical terms Another possible line of development, involving the use of jets and thus essentially engineering methods, is also briefly outlined Altogether, it would appear that the development of flight has by no means come to an end and that new types of aircraft are still to come

(1) INTRODUCTION

The rather sweeping title chosen for this paper needs to be qualified. I should say that emphasis will be on aerodynamic means of achieving the aim of integration, and that I shall not consider definite layouts of actual aircraft, but rather the more fundamental aspects of the problem. What is meant by " integration " will, I hope, become clearer in the course of the paper, and I shall not attempt a rigorous definition at this stage. Conventional aircraft as we know them now are not integrated. The units for producing the necessary propulsive and lifting forces are quite separate, and room for stowage is again usually found by adding a separate fuselage. Although such non-integrated aircraft have been acceptable for a long time, more and more thought is given to the problem and possibilities of integration.

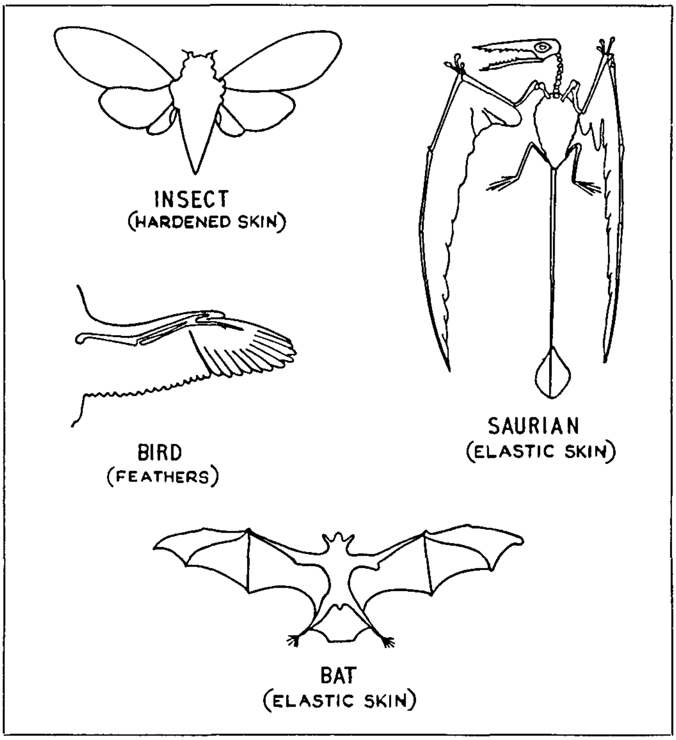

Fig. 1. The four types of flying organisms developed by nature

Engine-airframe integration in particular has recently been considered in detail by Nicholson[1]. He concluded that the advantages of integration are often marginal especially if it leads to such specialization that each aircraft demands its individual engine design and also throws up a profusion of structural and aerodynamic problems, peculiar to the particular design. On the other hand, flight at very high speeds and at very low speeds makes integration essential and he recommends that this should be a sort of integration where, starting with common building bricks, each design is built up to do its job in the full knowledge of their interactions with one another

Nicholson considered some specific layouts, in particular flight up to Mach numbers of about 5, and specific purposes Here, we want to consider and discuss the more general aspects, that is, we begin at some stage before a scheme crystallizes into an aircraft In the present company, we naturally want to keep in mind the possibilities of vertical take-off and landing, such as a helicopter is capable of

If we want to start at the beginning, we could not start any earlier than looking at the flying animals , they are always integrated in many respects The question is, how do they do it, and how can their schemes be adapted and translated into technical terms Further, we want to know whether there are any technical means beyond the capacity of flying animals

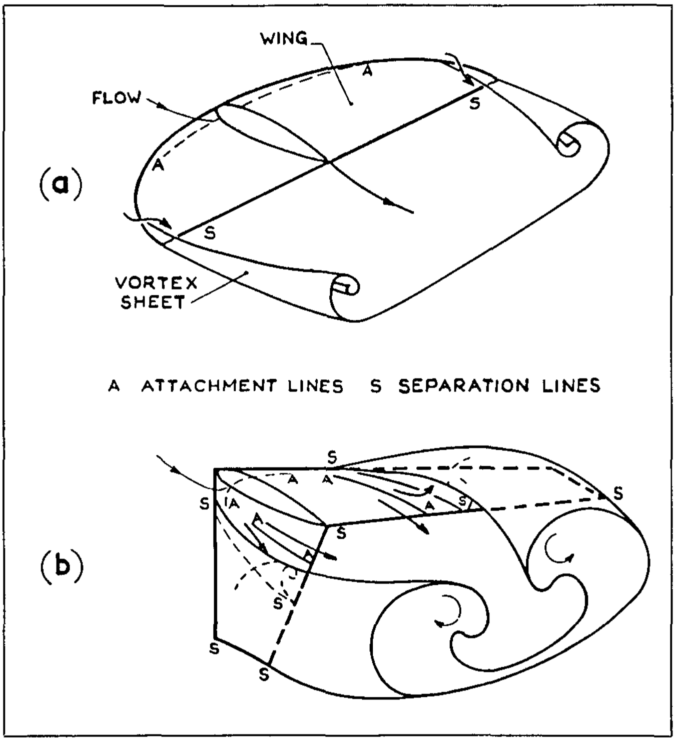

Fig 2 Types of flow with vortex sheets and with bubbles

(2) A Brief Consideration of Flying Animals

According to the zoologist[2], the art of flying has been invented independently four times by different kinds of animals at different stages of evolution, namely, by the insects, the saurians, the birds, and the bats Typical examples of these four are shown in Fig 1 In the course of millions of years they have found out about and adapted themselves to the laws of aerodynamics A closer study[2,3] of animal flight shows that many of the methods and principles of aeronautical engineering are used by the animals, too We know that some birds can preserve laminar flow for the sake of low drag , we know that a great variety of high lift devices are used by birds such as slotted wings and flaps , we know that they use even similar means of " instrumentation " and Haskell[4] has described how some of the mechanisms on which insects rely are analogous with aircraft instruments In certain cases, their ability to navigate also depends on methods resembling those which human pilots use This is an interesting and fruitful field for research In our context, we are interested in a more aerodynamic aspect, namely, which type of flow they use

For our purpose it is sufficient to distinguish between two types of flow, namely one with solid surfaces and vortex sheets only and another involving bubbles, which contain air that is not part of the main stream Both are defined by a system of attachment and separation lines on the solid surface, as described by Maskell[5] Fig 2 gives an example of each of these types (*a*) being a type of flow with an attachment line just underneath the leading edge of the wing and with a separation line along the trailing edge, a vortex sheet being left behind , (*b*) being a type which contains two bubbles in the regions of the wing tips joined by some kind of vortex sheet In the latter case, part of the leading edge is also a separation line and secondary separation lines appear on the upper surface of the wing accompanied by another set of attachment lines The separation lines are obviously not fixed in position and significant changes occur with the various flight conditions On the whole, this type of flow is undesirable and one would not like to build it into a good engineering design On the other hand, the first type of flow involving fixed separation lines and no changes with flight conditions could be called a good engineering type of flow It seems that the flying animals invariably use this type of flow

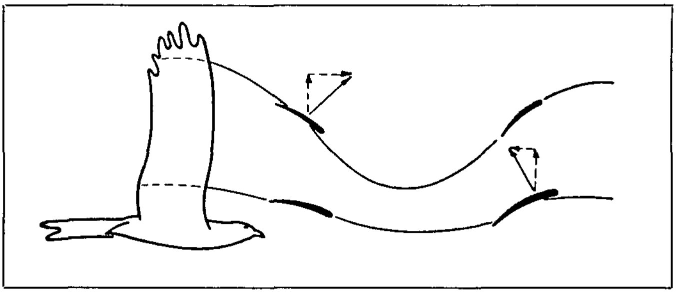

Fig 3 Possible paths of wing tip and wing root of a bird

We know, for instance, that the larger birds possess aerofoil sections which are very similar to those used in aircraft In fact, this is one of the few cases where aeronautical engineering definitely learned from the example of the birds With these wing sections, the birds usually employ the forces nearly normal to the relative wind direction, which act on lifting surfaces at small angles of incidence and are generally known as Kutta-Joukowsky lift Now we come to a first and typical example of integration, in that the birds use their wings to generate lift and thrust simultaneously In principle, air forces other than pure lift always result if the wing moves relative to the general direction of flight For instance, if a wing moves vertically downwards relative to the body, which itself is moving in a horizontal direction, then the airflow relative to the wing is inclined upwards The resultant air force, being nearly normal to the wind direction, is inclined forward Relative to the body the resultant air force then has a vertical component, the lift, and a horizontal component which is a thrust in the present case The flying animals have to perform such a movement of the wing relative to the body periodically and many different oscillatory motions are possible Fig 3 gives an example where the outer wing moves in such a way as to produce primarily thrust forces whereas the inner wing is mainly responsible for producing the necessary lift We note that the motion of the wing relative to the body takes place in a plane which is nearly normal to the direction of flight

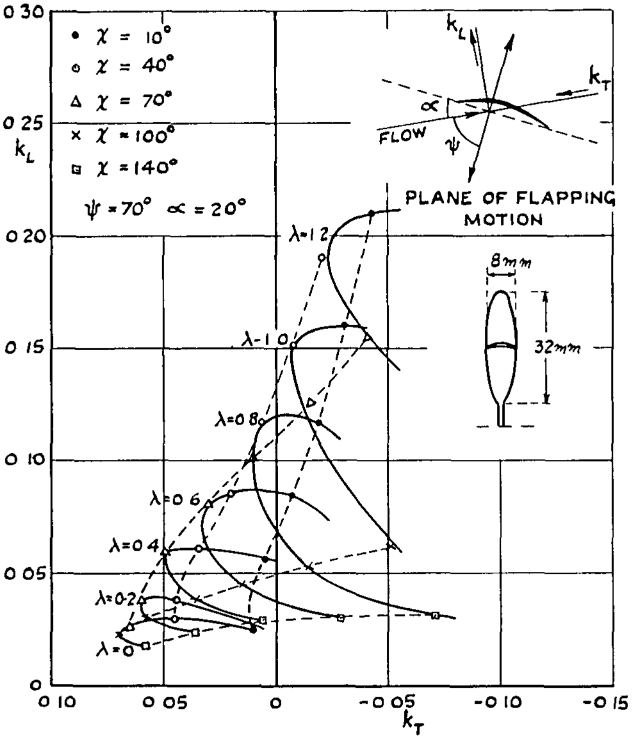

Fig 4 Experimental thrust and lift coefficients of a small oscillating wing Von Holst (1943)

Some of the flying animals might be expected to find it very difficult to effectively use Kutta-Joukowsky lift forces The small scale of some of the insects, for example, necessarily implies very low Reynolds numbers To study the efficiency of oscillating wings at these low Reynolds numbers (below 1,000), some experiments have been carried out by Von Holst[6] and some of his results are shown in Figs 4 and 5 The wing of nearly elliptic planform and just over 1″ semi-span was made to perform pitching and plunging oscillations and the mean angle of incidence as well as the inclination of the plane of the plunging oscillations were varied. The lift and thrust forces* in Fig. 4 demonstrate that a considerable variety of resultant forces can be produced and the propulsive efficiencies in Fig. 5 are reasonably good, considering the small Reynolds numbers of the test and the fact that the insects will be able to improve on it by using counter-oscillating wing systems. In particular, Fig. 4 shows that the direction of flight can be chosen within wide limits. For example, if a climb under 45° is required then the position of the k_T axis should be inclined by 45° to the horizontal and it will be seen that the resultant forces, which should then be vertical if we consider only the weight of the insect, can take a fairly wide range of values. A pitching amplitude of about 70° combined with a rate of advance

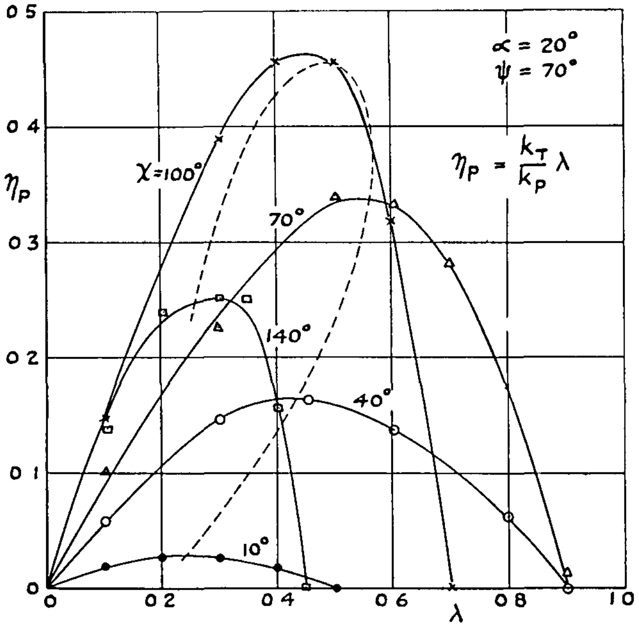

Fig. 5. Experimental propulsive efficiencies of a small oscillating wing. Von Holst (1943)

of about 0·35 will lead to the greatest resultant force in the present case of 45° climb.

To see the actual motion of the wing in relation to the flight path Fig. 6 has been prepared for the case of a vertical climb and a climb under 35°

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* In these tests, the wing performed a plunging oscillation with 68° amplitude, sweeping a sector of a circle of area S, the amplitude χ of the pitching oscillation was varied, as were the mean angle of incidence, α, of the wing and the inclination, ψ, of the plane of the plunging oscillation to the mainstream direction (see Fig. 4). $k_L = L/(\frac{1}{2}\rho u^2 S)$ and $k_T = T/(\frac{1}{2}\rho u^2 S)$ are lift and thrust coefficients, respectively, normal to and against the direction of the mainstream, u being the mean circumferential velocity. The rate of advance is defined as $\lambda = V_O/u$, with V_O as the velocity of the mainstream, and $k_P = P/(\frac{1}{2}\rho u^3 S)$ is the power coefficient.

In both cases values of the various parameters have been chosen so that the propulsive efficiency is at its maximum It will be seen that in each case the actual angle of incidence to the relative wind direction at any instant is always small and of the order of 20° We may, therefore, infer that the greatest efficiency is obtained when Kutta-Joukowsky lift forces are used Thus it is the type of flow with vortex sheets only and not the type of flow with bubbles (which would obtain at higher angles of incidence) which is the most efficient and which is the one that the insects are most likely to use

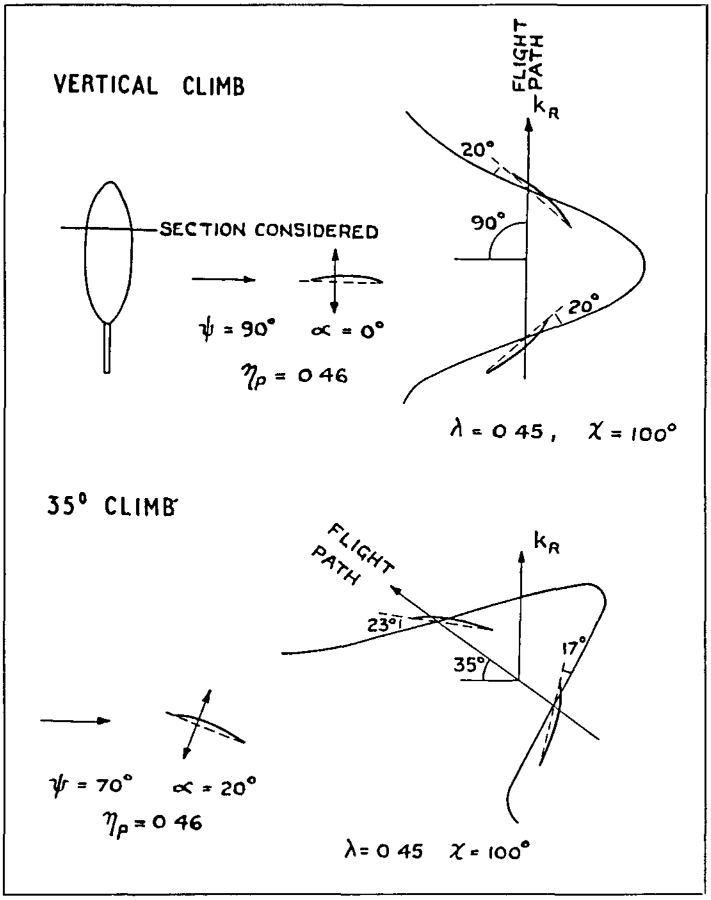

Fig 6 Two possible flight paths from experiment on small oscillating wing Von Holst (1953)

We note again that the oscillation in these cases takes place in a plane which is nearly normal to the direction of flight

It is another matter how insects succeed in achieving this type of flow at these low Reynolds numbers We may remind ourselves in this context that their particular wing sections may be useful in this respect and that quite possibly serrated leading edges, hairs and other excrescences, which many insects have, may conceivably be useful, too, and operate as vortex generators

(3) ONE POSSIBLE LINE OF TECHNICAL ADAPTATION

There is little doubt that the object of aeronautical engineering is not just to imitate the flying animals For example, we may assume for the time being that there is no intrinsic virtue in the oscillatory motion as such and if this were replaced by the much simpler rotation of the wing about some axis, none of the essential aerodynamic characteristics and advantages would be lost Similarly, the animals can only supply mechanical energy to the air in order to produce the required forces, whereas technical engineering can also supply heat energy as in jet engines Thus the two main features which distinguish aeronautical engineering from what nature can provide are the rotation and the jet The question then arises how to preserve the main features of the modes of flight found in nature and at the same time to adapt them to engineering purposes

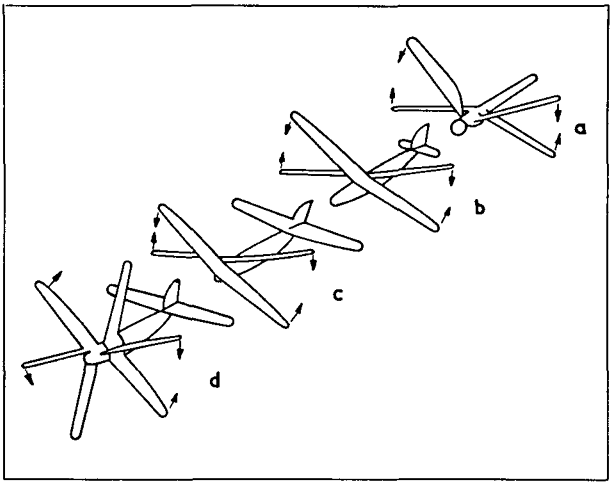

Fig 7 Possible line of development from Dragonfly (a) to thrustwing (b)

As an example of a technical adaptation, let us consider the case of the dragonfly which, being part of this Society's badge, should be of particular interest Various stages in the development of this scheme are listed in Fig 7 According to Von Holst[7], beginning with the dragonfly, the first step would be to make the wings rigid and to add a tailplane, replacing the long body which is otherwise needed to counteract the large alternations in pitching moment caused by the periodic changes of the lift forces on the two wings The next step indicated in Fig 7 would automatically eliminate the pitching moment variations, but only the final transition to counter-rotating wings is of real engineering significance

Now, this scheme has received some attention, although no aircraft has yet been built A detailed design has been made by Multhopp who further suggested the use of ramjets to drive each blade individually and make it possible to dispose of the second system of blades without introducing a reaction moment about the fuselage This is a particularly suitable application of the ramjet principle since its velocity can be kept constant and it can always work at the design point with the optimum efficiency Such a " thrust wing " as the final stage in Fig 7 may be called, may then look like the sketch shown in Fig 8 Such an aircraft would take off with its axis vertical, resembling a helicopter but, unlike the helicopter, it would not keep its axis vertical, but turn over gradually until in high-speed flight it would be almost horizontal The well-known speed limitations of the helicopter would thereby be overcome Thus this type of aircraft could take-off and land vertically and at the same time be designed for efficient operation at high speeds including flight at supersonic Mach numbers since the rotation might then well be stopped altogether, the lift being produced as on conventional aircraft and the thrust being produced by the ramjet engines However, this type of aircraft will of necessity be a tailsitter A short film sequence of the flight of a model of a " thrust wing," made by von Holst, will be shown later

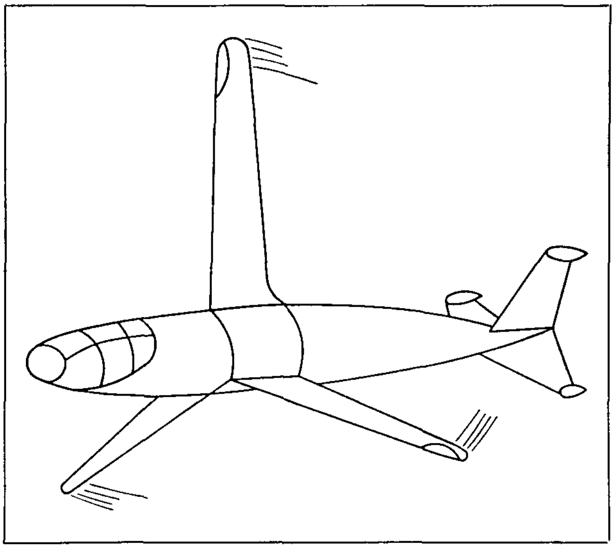

Fig 8 Thrust-wing scheme of Von Holst

This is a particularly simple adaptation of the flight of an animal where the resulting aircraft is largely integrated and preserves as its main feature the motion of wings in a plane which is nearly normal to the direction of flight The process of technicalization can be carried still further For example, the diameter of the rotating wings could be reduced if the blades were surrounded by an annular fairing This would then take part of the lifting and propulsive forces, but otherwise the method of flight is exactly the same as that of the " thrust wing " Aircraft of this type have been proposed by several people and the best-known is the Coleopter of von Zborowsky[8]

The design of these aircraft is still largely within well-known engineering principles In particular, aerofoil theory can be applied and some results are available, but an actual aircraft does not seem to fly yet

(4) ANOTHER LINE ON DEVELOPMENT, INVOLVING THE JET-FLAP SCHEME

The ducted propeller of the Coleopter could be regarded as a kind of jet engine which also produces lifting forces In continuing along that line we may deform the fairing so as to make it more suitable to carry lifting forces We may thus arrive at a flat fairing, in fact, a hollow wing, where air is taken in near the leading edge and ejected in the form of a jet sheet near the trailing edge In this case the supply of energy to the internal airstream need not be mechanical We might now also consider the possibility of adding heat energy directly to the airstream This would then be a combination of the ramjet engine with a wing producing lift forces In this case, the fairing is an essential part of the production of thrust also , supplying heat energy to an airstream does not produce a thrust, but only heats up the air , it is the fairing which modifies the flow so that a thrust is produced and it does itself carry thrust forces This " jet wing " is again a promising scheme for future development Obviously, it is closely related to a jet-flap scheme as proposed by Davidson[9] Since the jet flap is a means of producing extraordinarily high lift forces, such an aircraft could, in principle, again combine exceptional take-off and landing performance with high efficiency in level flight It is a typical sign of the great variety of types of aircraft which become evident as soon as one leaves the conventional type that the jet-wing principle can, of course, be combined with that of the thrust wing In this case, the blades of the thrust wing would be wholly or partly hollow and the jet emerging from somewhere near the trailing edge

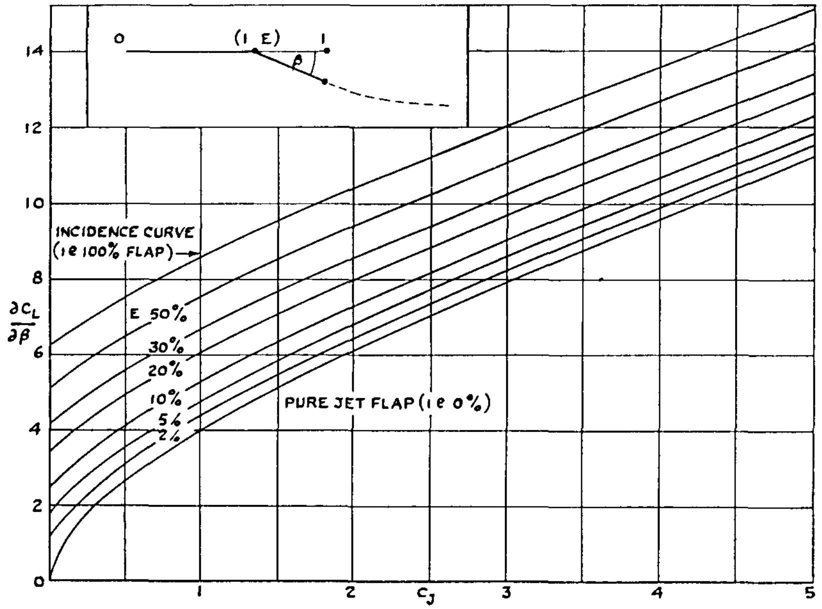

Fig 9 $\frac{\delta C_L}{\delta p}$ *For thin wings with blown flaps* SPENCE (1956) could be used to produce lift forces or thrust forces at the moment of rotation

The jet-flap scheme itself goes beyond the Kutta-Joukowsky principle Two vortex sheets with a high-energy jet in between are left behind and, apart from direct reaction forces, lift is induced also on the main wing and its circulation changed from the Kutta-Joukowsky value The theory of the jet flap in two dimensions as well as in three dimensions is now well advanced, mainly due to Maskell, Gates and Spence (10, 11, 12 13) To demonstrate its potentialities, Fig 9 is reproduced from Spence's work to show the lift obtained on a two-dimensional aerofoil with or without flap deflection when a jet emerges at the trailing edge It will be seen that the lift increments are quite considerable and one of the main features is that lift is produced not by incidence alone It would seem that these lift increments are obtainable in a real flow and do exist not only on paper The main reason for this must be seen in the fact that the lift is so distributed along the chord

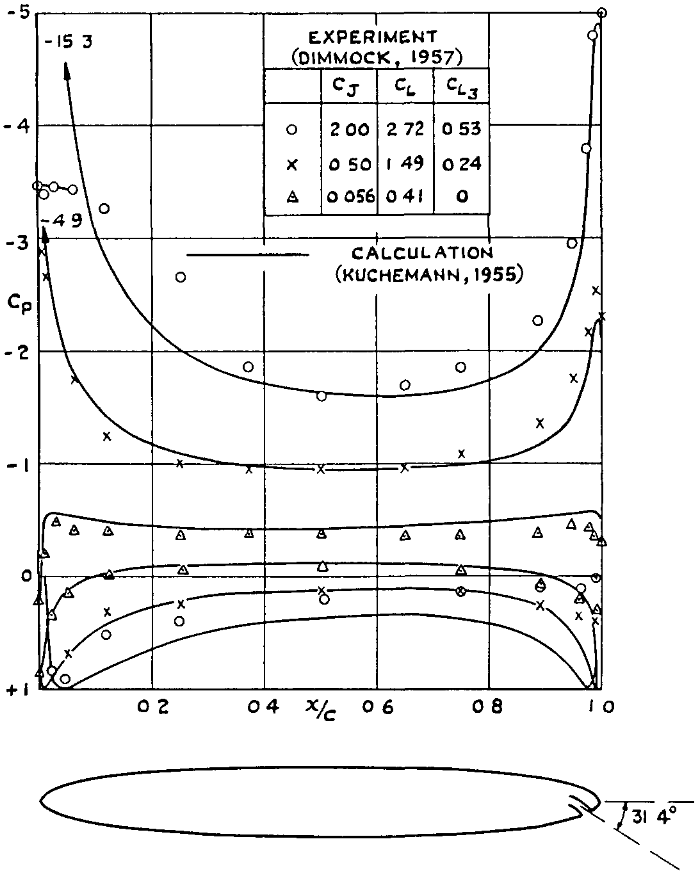

Fig 10 Pressure distribution on two dimensional jet-flap aerofoil

of the aerofoil that flow separations at the leading edge may more easily be avoided Fig 10 shows the chordwise loadings on a wing of elliptic section, as measured by Dimmock[14], together with calculated distributions[15] The main characteristic of this loading is that it is no longer concentrated near the leading edge, as on an aerofoil at incidence, but that it is of a saddleback shape and hence more uniform Roughly, the jet-flap aerofoil can carry twice as much lift as the corresponding aerofoil at incidence before the flow separates In the case of the highest jet momentum shown in Fig 10, the flow actually separates near the leading edge, forming a bubble, but the flow soon re-attaches on to the wing surface and, therefore, no appreciable loss of lift occurs The reattachment is helped considerably by the fact that the downstream pressure gradient tends to be favourable Altogether the application of the jet-flap scheme offers many possibilities of integrated aircraft which have not yet been fully exploited

(5) CONCLUSIONS

It will be clear from the few examples given that we are faced with a large number of possible approaches These range from the technical adaptation of animal flight to something which constitutes essentially aeronautical engineering If we look at the matter from this point of view, the present type of aircraft would appear to be very special indeed , so far, we seem to have followed just one or two particular lines Thus, we may do well to remind ourselves that the development of flight has by no means come to an end On the contrary, many new types of aircraft are still to come

To enlarge on this point, we may state that, in the stricter sense, only two general types of aircraft have so far been developed and cultivated One is basically a combination of a fuselage, a tail unit, a propulsion unit, with an unswept wing of moderate or large aspect ratio, making use of a good engineering type of flow with a trailing-edge separation only and producing vortex sheets and Kutta Joukowsky lift , swept wings should still be regarded as belonging to this category, and they have proved troublesome only when the basic type of flow was not realised, possibly by default The other type of aircraft is the helicopter, about which no more need be said here It is only now that we begin to look into a third type of aircraft, namely the integrated slender wing with separation from all edges leading to largely non-linear air forces As this will have to be thoroughly investigated first before its most suitable range of application can be assessed, so any other type of aircraft requires first of all research work rather than specific project studies It is as yet far too early to consider well-defined projects and layouts and it may well be dangerous and misleading to do this at too early a stage and so dismiss possibilities as unprofitable when the knowledge is still insufficient The foundations must be properly laid first, and this research work should be interesting enough in all its aspects Later, one hopes to find this work to have been profitable, too, and to lead to aircraft which are superior to the existing ones with regard to their economy, safety and performance One would be content, too, if new types of aircraft would emerge, complete and sound, of their own kind and justifiable in their own right

LIST OF SYMBOLS

c — wing chord
S — wing area , or sector area swept by oscillating wing
α — angle of incidence
β — flap deflection angle
χ — amplitude of pitching oscillation
ψ — angle between plane of plunging oscillation and direction of mainstream
ρ — density of air
V_o — mainstream velocity
u — mean circumferential velocity
λ — rate of advance $(= V_o/u)$
L — lift, or mean lift force of oscillating wing
T — mean thrust force of oscillating wing
C_L — lift coefficient $(= L/\frac{1}{2}\rho V_o^2 S)$
k_L — lift coefficient of oscillating wing $(\quad L/\frac{1}{2}\rho u^2 S)$
k_T — thrust coefficient of oscillating wing $(\quad T/\frac{1}{2}\rho u \ S)$
P — mean power expended
k_P — power coefficient $(- P/\frac{1}{2}\rho u^3 S)$
η_P — propulsive efficiency $(\quad \lambda k_T/k_P)$
J — jet momentum
C_J — jet momentum coefficient $(- J/\frac{1}{2}\rho V_o^2 c)$

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