



# **Aerodynamic Theory**

**A General Review of Progress**  
Under a Grant of the Guggenheim Fund  
for the Promotion of Aeronautics

**William Frederick Durand**  
Editor-in-Chief

## **Volume VI**

Div. P · Airplane as a Whole · W. F. Durand  
Div. Q · Aerodynamics of Airships · Max M. Munk  
Div. R · Performance of Airships · K. Arnstein and W. Klemperer  
Div. S · Hydrodynamics of Boats and Floats · E. G. Barrillon  
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With 127 Figures  
and 2 Plates



**Berlin · Julius Springer · 1936**

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## NOTATION

The following table comprises a list of the principal notations employed in the present Volume. Notations not listed are either so well understood as to render mention unnecessary, or are only rarely employed and are explained as introduced. Where occasionally a symbol is employed with more than one meaning, the local context will make the significance clear.

### DIVISION Q

<i>a</i>	Semi-longitudinal axis
<i>b</i>	Semi-transverse axis
$\gamma$	Radius of curvature
<i>x</i>	Length along longitudinal axis
<i>S</i>	Area or surface, usually area of section
$\alpha$	Angle between axis and direction of motion—angle of attack
$\varphi$	Angle of yaw, 9
<i>U</i>	Axial velocity
<i>V</i>	Velocity in general
<i>v</i>	Lateral component velocity
<i>W</i>	Resultant velocity, 6
$\omega$	Angular velocity, 10
<i>F</i>	Force
<i>L</i>	Lift
<i>M</i>	Moment
<i>P</i>	Pressure on surface
$c_1, c_2, c_3$	Special correction factors, 7
$k_1$	Inertia factor for axial motion
$k_2$	Inertia factor for lateral motion
$k'$	Inertia factor for rotation
$\eta$	Special inertia factor, 2, 8

### DIVISION R

<i>x</i>	Distance along longitudinal axis
<i>b</i>	Transverse force breadth III 2
<i>h</i>	Change in metacentric height
<i>R</i>	Radius of circular path
<i>A<sub>D</sub></i>	Drag area II 5
<i>S</i>	Area, usually of cross section
<i>Q</i>	Volume
$\alpha$	Angle of attack
$\epsilon$	Slope of ships path III 1
<i>V</i>	Speed
<i>L</i>	Lift
<i>D</i>	Drag
<i>F</i>	Lateral air force on ship
<i>M</i>	Mass
<i>P</i>	Power
<i>C<sub>L</sub></i>	Coefficient of lift

DIVISION P  
AIRPLANE AS A WHOLE  
GENERAL VIEW OF MUTUAL INTERACTIONS<sup>1</sup>  
AMONG CONSTITUENT SYSTEMS

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PREFACE

The Editor regrets most sincerely to announce that the other engagements of Professor Panetti of the R. Scuola die Ingegneria di Torino, Turin, Italy, have not permitted him the time to prepare the manuscript for the present Division, as was originally planned. Pressed near the close of the period of publication by the need of some treatment of this topic, and in order to fill out the original schedule of Divisions and of subject matter to be treated, the Editor has undertaken to give a brief treatment of the subject which, it is hoped, however, may aid the reader in gaining a more comprehensive view of the airplane as a whole and of its performance as the resultant of a very considerable manifold of actions, interactions and reactions.

In the present Division, the airplane is viewed as a complex of four interacting systems—the lifting system, the non-lifting system, the propulsive system and the control system. These four systems may and do interact mutually, thus modifying in various ways the basic effect or purpose of each of these systems considered as isolated from the others. In all there are twelve such interactions, some of which, however, are of small or negligible importance.

Several of these interactions have been discussed in mathematical terms in other Divisions of this Series and it is the purpose in the present Division to give rather in a descriptive and non-mathematical way, a general view of this entire manifold of interactions, with suitable reference to other Divisions for more complete discussion of the more important in mathematical terms.

Such a bird's eye view, as it were, of these various actions and reactions seems desirable in a series of monographs of the character of the present series, and the Editor only regrets the need of any departure from the original plan regarding the authorship.

<sup>1</sup> See Journées Scientifiques et Techniques de Mécanique des Fluides, Vol. 1, p. 189, Paris 1935.

Also with special reference to sections 4, 5, 9, 11 see Division O, pp. 37—41.

**Introductory.** We may view the airplane as a complex of four systems as follows:

- 1) The lifting system.
- 2) The non-lifting system.
- 3) The propulsive system.
- 4) The control system.

The basic aerodynamic effect or purpose of each one of these systems will be in some measure influenced or modified by each one of the other systems. There will be, therefore, twelve such effects or influences as we may choose to call them. Not all of these effects are of equal importance, but it will be of interest to list them all, in order that they may be viewed as a whole and examined, each with reference to its place in the picture of an airplane as performing under the aggregate of this complex of disturbing actions and reactions.

These disturbing influences are, therefore, as follows:

- 1) Influence of the lifting system on the non-lifting system.
- 2) Influence of the non-lifting system on the lifting system.
- 3) Influence of the lifting system on the propulsive system.
- 4) Influence of the propulsive system on the lifting system.
- 5) Influence of the lifting system on the control system.
- 6) Influence of the control system on the lifting system.
- 7) Influence of the non-lifting system on the propulsive system.
- 8) Influence of the propulsive system on the non-lifting system.
- 9) Influence of the non-lifting system on the control system.
- 10) Influence of the control system on the non-lifting system.
- 11) Influence of the propulsive system on the control system.
- 12) Influence of the control system on the propulsive system.

We proceed, then, with the examination of these in order.

**1. Influence of the Lifting System on the Non-Lifting System.** The lifting system is represented by the wings and the non-lifting system primarily by the fuselage, to which may be added such items as the landing gear (when not retractable), engine nacelles in multi-engined planes, struts, guy wires, etc. The fuselage also may and usually does contribute something to the lift and the stabilizer likewise contributes vertical forces, though often opposed to wing lift for purposes of longitudinal stability. However, for our present purpose it will be sufficient to consider the influence of the wings on the fuselage.

The purpose of the fuselage is, of course, to house a power plant, operating personnel, passengers and useful load, and to make connection between the wings and the empennage or otherwise to furnish a mounting for the latter. None of these is directly aerodynamic in character and the chief aerodynamic result of the presence of the fuselage is the production of so-called parasitic resistance or drag. At the same time, as noted above, the fuselage may, and at large angles of attack will, give

an element of lift, functioning as a poorly formed airfoil of aspect ratio much less than unity. However our major interest in the present inquiry will relate to the influence of the wings on the production of fuselage drag.

The lift produced by the wings is associated with a circulation about them, with the trailing vortices streaming down the wake and producing the well known induced "downwash" or downward component in the resultant airflow over the plane and changing the geometrical angle of attack  $\alpha$  by the so-called induced angle  $\varphi$  or  $\alpha_i$  (see Division E I 12 and III, Part C).

The circulation about the wing itself will furthermore introduce another factor, especially influential at the leading edge where it tends to produce an upward component in the line of the airflow to the wing. The general character of the lines of airflow in approaching a wing as shown by photography and as indicated by diagram may be seen by referencé to Division E I, Figs. 7, 10, 12.

The extent to which the airflow over the wings as influenced by circulation and downwash will influence the airflow to the fuselage, especially in respect to direction, will naturally depend on the location of the fuselage relative to the wings. In the general case, however, some degree of such influence may be expected and, to the extent to which it exists, it will enter as a more or less influential factor in modifying the effect of obliquity due to the attitude of the plane under the conditions of flight controlling at the moment.

Thus, in actual flight, at any one loading, there will be only one speed and one attitude of plane at which the axis of the fuselage will lie strictly in the line of flight. At all other speeds, the attitude will be such as to make some angle of obliquity between this axis and the line of flight.

The combination of these obliquities, of flow and of attitude, will in general, result in an obliquity of airflow relative to the direction for minimum fuselage drag, with increase in the size of the turbulent wake and with the result of an increase of drag, more or less pronounced as the resulting angle of obliquity is large or small. The same obliquity relative to the airflow will likewise influence such lift as the fuselage may give—in general, an increase of fuselage lift with increasing angle of wing attack, up to some angle presumably approaching the burble point for the wings.

In addition to these more or less obvious forms of reaction, there will result on the body of the airplane a positive lift resulting from the development of a positive circulation about the body due to the existence of the circulation about the wings. Where the wing extends continuously across from tip to tip over the airplane body, the wing circulation must in part extend around the body itself with the result

of a positive lift. Where the wing is discontinuous, this action will be less pronounced, but even here there may be some lateral extension of the wing circulation in such a way as to at least partially inclose the body of the plane.

We have thus, in summary, first an attitude of the plane relative to the line of flight, dependent on the wings in that such attitude is necessary to enable the wings to realize the lift under the actual conditions of load; second, some modification of the resulting lines of airflow to the fuselage, due to the influence of the downwash and circulation about the wings; and third, some actual increase in the circulation about the fuselage, representing, in a sense, an extension of that about the wings. The combination of obliquities will, as noted, produce some increase in the fuselage drag while the increment of circulation will produce an increment of fuselage lift.

The amount of the increase in drag will be small unless the obliquity of the axis of the fuselage to the line of flight becomes large, in which case it may become serious. The increment of lift due to wing circulation will be relatively small, depending on the arrangement of wings and fuselage.

**2. Influence of the Non-Lifting System on the Lifting System.** For our present purposes, the non-lifting system may be represented by the fuselage, to which may be added such structures as engine nacelles in the case of multi-engined planes. On the other hand the lifting system is represented by the wings, so that the present question reduces primarily to the influence of the fuselage on the wings.

We may first refer to Division K III, wherein this subject is approached from the mathematical standpoint and results are given based on two methods of treatment as follows:

(1) Representation of the fuselage by an indefinitely long cylindrical body with wings attached.

(2) Treatment of the combination of wings and fuselage (or wings and nacelles) as a generalized form of wing with abrupt change of profile at the location of the fuselage or engine nacelles. The distribution of lift over the span is then developed by suitable mathematical procedures.

Method 1 admits of a certain simplification in the theoretical treatment and furnishes results of definite interest and significance. In general it is shown that there is produced what is called an "additional stream flow", conditioned by the body, and which will produce a downward component of velocity on the wing. It thus results that the body will cause a change in the effective angle of incidence of the wing and likewise a supplementary drag for the same, the character and value of which will depend on the relative locations of body and wing. Division K should be referred to for further details.

Method 2 permits of treatment by several different mathematical procedures of which three are given in brief abstract. This mode of approach to the problem shows, as might be anticipated, an abrupt decrease in lift over that part of the span represented by the body or by engine nacelles. It shows also what may be termed the spread of this influence over the rest of the wing, resulting in a general decrease of lift as compared with that for a wing alone of the same total span (see Fig. 1<sup>1</sup>). This departure of the lift distribution from that for the wing alone causes also an increase in the induced drag, the magnitude of which is, however, relatively small. See Division K, Fig. 45. Attention may be called to the considerable amount of experimental information on this subject, especially as regards the results of fillets between body and wings and the best relative location of engine nacelles and wings<sup>2</sup>.

It may be desirable to give some further discussion of this general topic from a slightly different viewpoint and without direct reference to mathematical procedures. This will permit the development of a somewhat more complete picture of the subject as a whole, reaching however, the same general conclusions as above.

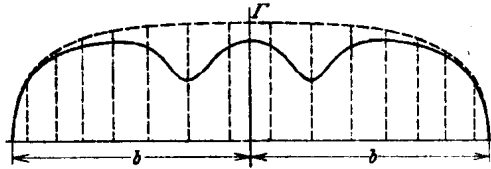


Fig. 1. Effect of nacelles on distribution of lift.

To this end we shall find it convenient to consider the question in two parts, depending on whether the wing is continuous across the span from tip to tip or is interrupted by the fuselage. In the latter case it may be considered either as a continuous wing structure with an extreme and abrupt change of form in the central portion, or as two half wings, with attachment at one end to the fuselage and with the other end free.

We take first the case of a continuous wing extending across the span above the fuselage, and recall that such a wing realizes lift by reason of its translation through the air combined with a circulation flow around the wing section. These two types of flow give a resultant

<sup>1</sup> Repeated from Division K, Fig. 44.

<sup>2</sup> Ergebnisse der Aerodynamischen Versuchsanstalt zu Göttingen, I. Lief., p. 118, 1925.

MUTTRAY, H., Untersuchungen über die Beeinflussung des Tragflügels eines Tiefdeckers durch den Rumpf. Luftfahrtforschung, Bd. 2, Heft 2, 1928.

GOUGH, M. N., The Effect of Fillets Between Wings and Fuselage on the Drag and Propulsive Efficiency of an Airplane, U.S. N.A.C.A. Technical Note No. 299.

KLEIN, A. L., Effect of Fillets on Wing-Fuselage Interference, Transactions Am. Soc. Mech. Engrs., 1934.

WOOD, DONALD, H., Tests of Nacelle-Propeller Combinations I, II, III, U.S. N.A.C.A. Technical Reports Nos. 415, 436, 462; 1932, 1933.

air flow about the wing and we have now to inquire as to the extent to which such flow will be influenced or modified by the presence of the fuselage lying below its middle portion and of breadth some five to ten per cent of the wing span.

Stated in this way it is clear that this influence should not be of serious amount. Its major effect will be confined to a small part of the span near the center, and with usual dimensions, this effect will be relatively small in magnitude. There will be a tendency toward a slight compression of the flow between the fuselage and the central part of the wing, combined with a tendency for the flow to spread obliquely as the air travels along the under side of the wing from the leading to the trailing edge. Compression of the lines of flow will result in higher velocities, the result of which will depend on the form and attitude of the under surface of the wing. Insofar as the velocity is increased, the pressure will be reduced (Bernoulli's law) but to the extent the flow is deflected downward, the upward dynamic reaction will be increased. We have here two opposing effects, the resultant of which will depend on the special circumstances of the case and no general conclusion can be drawn. Obliquely spreading flow may likewise cause a disturbance over a width somewhat greater than that of the fuselage itself, and of a character to reduce the over pressure which would otherwise result from an uninterrupted flow. Viewed otherwise, it would appear that the effect of this crowding of the lines of flow may have the effect of decreasing the circulation velocity below the wing and to the extent to which this might result and for the parts so affected, the lift would be correspondingly reduced.

On the whole, however, with normal dimensions, it is clear that this influence, compared with the lift of the wing as a whole, will be small though perhaps not of vanishing importance.

With certain types of design however, notably with some of the high wing monoplane types, the wing is structurally continuous but with a much reduced if not vanishing clearance between it and the fuselage. In such cases these effects will be much more pronounced and may seriously affect the lift of the under surface of that part of the wing nearest the fuselage. On the other hand, the upper surface of the wing will still be effective, so that the result as a whole may not involve a serious loss in the total lift.

It is clear, therefore, that in any case, viewed in comparison with a continuous wing with unimpeded flow, the near presence of a body such as the fuselage will result in some distortion and change of flow, all of which will react unfavorably on the lift of the wing as a whole; and that the magnitude of such influence will depend in primary degree on the amount of clearance between the wing and the fuselage body.

At the same time such disturbances to the flow over the wing may likewise affect the drag, both form and induced; the first by an increase in the turbulent wake and the energy carried away in it, and the second as a result of relatively abrupt changes in lift distribution and in the resulting system of trailing vortices.

Turning now to the case of a wing interrupted by the fuselage and comparing it with a single wing of the extreme span from tip to tip, it is shown in Division K III 2, as indeed may naturally be expected, that at normal angles of attack the abrupt change in virtual wing form at the center will result in a loss in lift over this part of the span, and furthermore, that this general disturbance will cause a measurable loss over the remainder of the span. At the same time the abrupt change in lift distribution will also cause an increase in the induced drag as noted above. On the other hand it may be noted that at high angles of attack and with special fuselage forms, the combined lift of wings and fuselage may be more than for an uninterrupted wing of the same over all span. In this connection special attention should be given to the influence of the geometrical form at the abrupt transition from wing to fuselage. Such a transition of form, if relatively sharp angled, will result in the formation of turbulence in the angle, spreading outward on the wing and creating generally a disturbance in the normal flow over the wing in this vicinity. The consequences here depend further in marked degree on the character of the flow through the angle between the wing and the fuselage—whether divergent or convergent. In the former case there will be high probability of separation of flow with increase in drag; in the latter case this condition should not develop and this particular increment of drag will be avoided. Naturally the low wing monoplane will be more subject to the consequences of a divergent flow than will the high wing type. The results of such conditions will be, in general, a decrease of lift and an increase in drag.

However, generous and carefully designed fillet forms connecting wings and fuselage are found to reduce in marked degree the prejudicial results due to these conditions<sup>1</sup>.

If now we view the lifting system as consisting of two half wings, one projecting on either side of the fuselage, we have a pair of wings, of which one end is free and the other shielded by the fuselage side. We shall therefore have, for each wing, the normal spilling of the air around the free end, while the fuselage form will act in some degree as a shield for the inner or root end of each wing.

In addition, there will be, as discussed above, turbulence and general disturbance to the flow about the root of each wing due to the more or less abrupt transition in form from wing to fuselage.

<sup>1</sup> See references on p. 5.

We now ask, with what form or porportion of wing shall we compare these two half wings in order to discuss the question of the influence of the fuselage on the lift of such a wing system. It will be of interest to consider two such ideal wing forms: (1) A continuous wing of span equal to the combined span of the two wings excluding the fuselage. (2) Two wings of span each equal to the span of the wing structure on one side of the fuselage, but with free ends. This will be, in effect, two wings each of half the span in (1) and hence with half the aspect ratio.

Taking these in order, we shall have, with the actual structure, and excluding the fuselage entirely, a close approach to (1) except for the turbulence and disturbance to the flow at and near the root of each half wing. The shielding due to the fuselage side should much reduce the loss due to spilling or in other words it should give, over the root of the wing, a close approach to two-dimensional flow. There remains, however, the loss due to turbulence and disturbance of flow as already noted. In addition we must remember that, as we have already seen, the disturbance to the flow caused by the presence of the fuselage will extend in some degree over the entire wing span and the present picture is, therefore, the same as that presented by Fig. 1, except that we now exclude from consideration the marked loss in the center over that part of the total span represented by the fuselage itself. There remains then the loss over the actual wings proper plus that due to turbulence caused at the roots of the wings. The latter, as noted, can be much reduced by careful filleting, but the former will persist, and over all, as compared with a single wing of combined wing span, there will result a definite loss in lift together with some increase in drag.

Taking now the second ideal, we have to compare on each side of the plane, two half wings, one of which has both ends free while the other has one end shielded by the fuselage side, with the resultant turbulence formation. The shielding considered by itself, compelling as it will a close approach to two-dimensional flow near the root of the wing, will be favorable to the lift. It will give, in effect, a lift distribution holding up to a considerable value at the wing root, instead of falling to zero as in the case of a free wing tip. There will be, however, some general decrease of lift over the wing due to what may be termed the "spread" in the effect of the fuselage; see Fig. 1.

There will be likewise some further loss in lift and increase in drag due to turbulence at the root of the wing as already discussed. Definite experimental measure seems to be lacking regarding the values of these effects, favorable and unfavorable, but with a well filleted wing junction with the fuselage, the beneficial effect should definitely outweigh the loss due to turbulence, and with a wing structure of this character, the lift should be definitely greater than for two separate wings, each of the span of the half-wing on one side of the fuselage, and with free

ends. This would mean in effect, two wings each of approximately half the aspect ratio of the single wing as a whole.

Again, to the lift of the two half-wings as here considered, must be added the lift due to the fuselage, whatever it may be, usually small at low angles of wing incidence, but larger with increase of this angle.

On the whole, therefore, it appears that if the wing be considered as extending across the entire span from wing tip to wing tip, the presence of the fuselage, for small angles of attack, will result in a loss of lift, while for large angles, the combined lift of wings and fuselage may be greater than for a single wing of the same over all span. Likewise if we consider the wing as composed of the two half structures on either side of the fuselage, and compare this with a single wing of the same aggregate span, there will likewise result a loss in lift. But if we compare this latter structure with two wings with free ends, each of the span of the half-wing of the actual plane, the result will involve effects favorable and unfavorable, but with the balance, in any normal case of a well filleted junction, definitely on the favorable side.

In this connection attention may be called to the fact that other things the same, the two wings of half span would have double the induced drag of the single wing, thus giving a further advantage to the actual construction in comparison with this particular combination.

**3. Influence of the Lifting System on the Propulsive System.** The propulsive system in the simple case is represented by the propeller located at the nose of the fuselage. Propeller performance as based on the simpler theory and as estimated from the results of model or even full scale tests in aerodynamic laboratories, is considered relative to the case of motion in the direction of the shaft. That is, propeller traction (thrust) is considered as acting along the line of the shaft, and the relative motion of propeller and air is assumed to lie along the same line. It is shown, however, in Division L<sup>1</sup> that obliquity of flow of the air to the propeller has the effect of producing lateral forces on the propeller as well as other marked effects on its performance. The production of lateral forces on the propeller and hence on the shaft will have the effect of giving a resultant propeller force oblique to the line of the shaft and likewise in general, oblique to the direction of flight.

<sup>1</sup> See VIII 7 and XII 5; also:

CLARKE, T. W. K., Effect of Side Wind on a Propeller, Br. A.R.C. R. and M. 80, 1913.

BRANWELL, F. H., RELF, E. F., and BRYANT, L. W., Experiments to Determine the Lateral Force on a Propeller in a Side Wind, Br. A.R.C. R. and M. 123, 1914.

HARRIS, R. G., Forces on a Propeller Due to Sideslip, Br. A.R.C. R. and M. 427, 1918.

MISZTAL, FRANZ, Zur Frage der schräg angeblasenen Propeller, Abhandlungen aus dem Aerodynamischen Institut an der Technischen Hochschule Aachen, Heft 11, p. 5, 1932.

In the case of the actual propeller in flight we have four directions to consider; (1) the direction of flight, (2) the direction of the shaft of the propeller, (3) the direction of the flow of air to the propeller, and (4) the direction of the resultant force on the propeller shaft and hence on the plane. In the general case, neither (2), (3) nor (4) will be the same as (1). The direction of the shaft will vary with every change in the angle of attack (quite aside from the rapid changes in maneuvers) and this will mean generally that with every change of speed the line of the shaft will change relative to the line of flight.

Regarding the line of airflow to the propeller, we remember that, due to the action of the wings on the direction of the airflow over the plane (see 1) the lines of flow to the propeller will suffer more or less deflection (normally upward) as compared with the line of flight. This deflection will vary, furthermore, with the attitude of the plane, greater as the angle of attack is greater. We shall thus have, in general, a variable angle between the line of airflow to the propeller and the line of flight. This combined with the variation in the angle between the shaft and the line of flight will result in an angle between the shaft and the line of airflow to the propeller, subject to more or less irregular variation, and in the general case differing from zero.

This complex of obliquities may, therefore, be considered as due to the fact that the lifting system, in order to maintain a lift  $L$  equal to the weight  $W$  at varying speeds, must assume varying attitudes in flight; and in this sense these various consequences on the propulsive system may be considered as due to the characteristics of the lifting system.

It must, therefore, be accepted that the propeller normally does not find itself in the simple condition of operation usually assumed, and in particular that it must in general accept a flow of air with some degree of obliquity relative both to the line of its shaft and to the direction of flight. This will result, as we have seen, in the production of lateral forces on the shaft and in a line of action of the total force on the propeller oblique to the line of flight. The obliquity of the flow to the propeller will itself result in some loss of efficiency and the obliquity of the total resultant propeller force to the line of flight will cause a further loss in propulsive effect. Adequate experimental data bearing on these losses do not seem to be available, but it may be safely assumed that such loss will not be serious until the angles of obliquity approach values larger than those in usual practice. However in the case of a plane making long flights, in particular for those periods of time for which the angle of attack may be relatively high, these sources of propulsive loss will be operative in some degree and corresponding allowance should be made for them.

In addition to these influences traceable primarily to obliquity of airflow and shaft direction, there may be, especially with wing mounted