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A.R.C. Technical Report

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Report of the Definitions Panel on Definitions to be Used in the Description and Analysis on Drag

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Report of the Definitions Panel on Definitions to be used in the Description and Analysis of Drag

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17th May, 1957

SUMMARY

Terms used in the description and analysis of the external drag of a body (with or without internal flow) are considered, and definitions suggested for the various components of the drag. Care has been taken to ensure that the proposed terms are consistent with those used in the Panel's report on thrust[2].

1. Introduction

With the attainment of supersonic flight, the speed range through which the drag of an aircraft must be measured or estimated has increased considerably. Terms in common use for describing low-speed characteristics have had their use extended to supersonic flight speeds, and sometimes confusion and ambiguity have resulted. In its present form the British Standard Glossary of Aeronautical Terms[1] does not resolve the difficulties satisfactorily and the ever-increasing demand for data on drag at high speeds has emphasized the need for a set of precise terms, of wide application, which would enable a logical analysis of the drag to be made.

Early attempts to meet this need were made by Warren in two unpublished papers. These were discussed by the Performance Sub-Committee of the Aeronautical Research Council in 1953, when it was agreed that the subject required further consideration. At the Sub-Committee's request the Definitions Panel was set up to consider the definitions of terms used in describing and analysing external drag, and also the problems which occur in defining the thrust and internal drag of a ducted body. A Report[2] by the Panel on the latter subject appeared in May, 1954; the present Report deals with the terms used in the description and analysis of external drag. Both these reports refer only to the case where the thrust acts in the direction of the undisturbed stream, i.e., along the line of flight.

The Panel, which first met in May, 1953, was composed of the following members who were nominated by two Sub-Committees of the Aeronautical Research Council.

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Nominated by the Engine Aerodynamics Sub-Committee

Mr. S. Gray	(M.O.S.)
Mr. H. Pearson	(S.B.A.C.)
Dr. J. Seddon	(R.A.E.)

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2. Statement of the Problem

In the present Report the body, which may possess an internal duct, is assumed to be immersed in a steady uniform stream of fluid which is both viscous and compressible; gravitational forces are ignored. Drag is positive if it acts in a downstream direction.

The fluid may conveniently be divided into that part which flows outside the body (External Flow)+ and that which flows through the body (Internal Flow). The surfaces bounding the internal and external flows will be called the Internal and External Surfaces, and the drags associated with the internal and external flows, the internal and external drags*. It should be noted that the internal and external drags are not necessarily manifested as stresses which appear only on the corresponding surfaces of the body but are related to the internal and external flows.

In order to analyse the external drag, it is necessary to assume that no mixing takes place between the internal and external flows, both ahead of and behind the body. Thus ahead of the body the flows are considered to be separated from each other by the surface of the Pre-Entry Streamtube. Behind the body, where turbulent mixing between the internal and external flows would normally take place, it is convenient to postulate the existence of a similar dividing stream-surface, the Equivalent Post-Exit Streamtube. It is further assumed that no shearing stress occurs between the internal and external flows along these streamtubes.

Whilst the analysis requires the assumption that the internal and external flows do not mix, there is no restriction on mixing within the external flow itself; indeed it is in general only because of mixing that at large distances downstream from the body the static pressure approaches that of the undisturbed stream. Thus to correspond with the definition of thrust given in Reference 2, the Total Drag associated with the external flow is given by the rate of decrease of momentum of the external flow in a direction parallel to the undisturbed stream, this decrease being calculated between stations at infinite distances upstream and downstream of the body.

The most convenient method of analysing the total drag is to some extent dependent on the type of problem being considered. In general, two systems of analysis are required. The first is made in terms of what have been called 'drag concepts' in the present Report; these are the components of drag obtained by considering how the drag forces arise and are experienced by the fluid boundaries. The second analysis is made in terms useful for the estimation of drag.

3. Drag Concepts

It is convenient to resolve the force acting on an element of the body surface into two components, normal and tangential to the surface. The normal and tangential forces may in turn be resolved to give components in the downstream direction; the resulting drag forces can be called Normal-Pressure Drag and Surface-Friction Drag respectively. Should shorter names be required, the use of Pressure Drag and Friction Drag is recommended. The sum of the Normal-Pressure and Surface-Friction Drags is the Total Drag.

For/

+Terms which are underlined are defined in the Appendix.

*Internal drag (which is discussed in Ref. 2) may become negative if heat is added to the internal flow and the definitions set out in this Reference are then appropriate.

For a body with no trailing vorticity, in an ideal fluid and in the absence of shock waves, the normal-pressure drag is zero (d'Alembert's paradox). For a real fluid, however, because of energy dissipation within the boundary layer, a drag force is experienced by the body and this may be called Boundary-Layer Drag. Boundary-layer drag is experienced by the body partly as surface friction and partly as a change in the distribution of normal pressure; the latter may be called the Boundary-Layer Normal-Pressure Drag. Further, when shock waves are present, an additional component of drag arises from the energy dissipated in the shock waves; this component may be called Wave Drag.

The generation of lift by either the whole body or some part of it will, in general, alter the magnitudes of the boundary-layer normal-pressure drag and wave drag and in addition will give rise to a trailing-vortex system. The kinetic energy that is being continually added to the trailing-vortex system is derived from work done against Trailing-Vortex Drag+, which appears on the body as the third component of the normal-pressure drag. If a shorter name is required, the term Vortex Drag is suggested for this quantity.

It should be emphasised that these drag concepts are not independent of one another. Thus, for example, the change of pressure distribution caused by the presence of the boundary layer leads to a change in the shock-wave system, so that a part of the boundary-layer normal-pressure drag may appear as a contribution to the wave drag. Again, the energy dissipation associated with regions of interaction between shock waves and boundary layers cannot be separated into wave drag and boundary-layer drag except in an arbitrary way. It must also be noted that a change in any one drag component due to some flow change (e.g., a movement of the transition point) will, in general, be accompanied by changes in the other drag components.

The transfer of heat between the body and the external flow will lead to a change of total temperature within a narrow layer of fluid adjacent to the body surface (the thermal boundary layer) and there will in general be a corresponding change in external drag. Indeed in certain circumstances the total drag may become negative, i.e., there may be a thrust, since the transfer of heat between the body and fluid may constitute a form of heat engine. Quite apart from this, the heat flow between the body and the fluid may have large effects on the stability of the boundary layer, causing changes in drag. However no new drag concepts are required in such cases as the associated drag changes appear as changes in the various drag components already described.

When the drag concepts discussed above are applied to a ducted body, special consideration of the normal-pressure drag is required. From the definition of total drag given in Section 2 it is found that this consists not only of the force component parallel to the stream arising from the pressure and friction forces acting on the external surfaces of the duct, but also of the components arising from the pressures on the outsides of the pre-entry and equivalent post-exit streamtubes. These drag forces on the outsides of the pre-entry and equivalent post-exit streamtubes are, of course, equal and opposite to the pre-entry and post-exit thrusts discussed in Ref. 2. They are not drags in the dissipative sense and are not associated with any

increase/

+This quantity is frequently referred to as the 'induced drag', particularly for low-speed flows, but it is recommended that the term 'induced drag' should be avoided as it is at present used with more than one meaning. (See also the discussion of Lift-Dependent Drag on page 5.)

increase of entropy; they arise solely from the division of the forces on the ducted body into components due to the internal and external flows. The normal-pressure drag of a ducted body can therefore be regarded as a drag component arising from the normal pressures on the fluid boundary extending from infinity upstream to infinity downstream, part of which is the actual surface of the body.

It is realised that this extension of the term 'normal-pressure drag' to the case of a body with a duct is novel and that the normal-pressure drag associated only with the external surfaces of the body is at present that commonly called 'normal-pressure drag'. The Panel feels however that the proposed definition for this quantity is logical and consistent with the terminology of Ref. 2 and to illustrate this point, the relation between the thrust and drag analyses is shown diagrammatically in Fig. 1(a), and is discussed further below.

4. Terms Useful in Drag Estimation

The drag components listed in Section 3, though useful in illustrating the nature of the drag, are often unsuitable for use in estimating drag. It has already been mentioned that when calculating the drag of a ducted body it is desirable to introduce fictitious drag components obtained from considering the forces on the surfaces of the pre-entry and post-exit streamtubes; these can be called the Pre-Entry Drag and the Post-Exit Drag and are indicated by broken lines in Fig. 1(a). It may be convenient however to have a name for the drag associated with the pressure distribution actually observed or estimated on the body's external surfaces and by analogy[2] with the corresponding thrust component, it may be called Intrinsic Normal-Pressure Drag. The sums of this and the pre-entry and post-exit drags will be equal to the normal-pressure drag for the ducted body, as defined in this Report. In Ref. 2 the Intrinsic thrust includes the surface friction on the internal surface of the ducted body; the analogous quantity for the external drag, if required, could be called Intrinsic Drag and would be the sum of the intrinsic normal-pressure drag and the surface-friction drag (see Fig. 1(a)).

Since the drag associated with the internal flow will in general vary with the flow into the body, it is necessary to specify a datum value for this (Datum Intake Flow), defined as the flow obtained when the boundary of the pre-entry streamtube is unaffected by the presence of the intake. (It may however be affected by the presence of other parts of the aircraft as for example with side intakes, see Fig. 2.) Thus for a pitot-type nose intake operating at datum intake flow, the cross-sectional area of the pre-entry streamtube at infinity upstream is equal to the intake entry area measured normal to the undisturbed stream. For a pitot-type intake at the side of a body, the Mach number at the entry will be different from the free-stream value because of the presence of the body; for this case only there exists a Pre-Entry Drag at Datum Flow+.

Spillage occurs when the intake operates at a mass flow other than the datum intake flow. When the change of mass flow is caused by the presence of a pre-entry compression body in the intake, Full Intake Flow is said to occur if the pre-entry streamtube, although modified by the pre-entry body, is unaffected by the cowl (Fig. 2). Full intake flow is less than datum intake flow by an amount called the Basic Spillage. For an

intake/

+Some care is required in analysing the flow into a side intake since presumably the pressure and friction forces on the body surfaces upstream of the entry are associated with the internal and not the external flow. (See Also Appendix IV of Ref. 2.)

intake without a pre-entry compression body the basic spillage is zero, the full intake flow being identical with the datum intake flow. When the actual flow is smaller than the full intake flow, the difference between these two quantities is called the Incremental Spillage.

Spillage of the air approaching the intake causes an alteration of the normal-pressure distribution and surface friction on the body's external surfaces. Thus associated with the three conditions of spillage are the terms Spillage Drag, Basic Spillage Drag and Incremental Spillage Drag. These terms are formally defined in the Appendix.

Thus changes in total drag caused by alterations in the internal flow can be allowed for in terms of spillage; similarly drag changes caused by changes in the lift of the body from some Datum Lift Coefficient can be regarded as Lift-Dependent Drag. In the most general case, the spillage drag will vary with the lift coefficient, and the lift-dependent drag will depend on the internal flow. However, it is usually assumed that the spillage drag and lift-dependent drag are in fact independent of one another, and that lift-dependent drag is measured at datum intake flow. The Datum Drag may be defined as the value obtained at both datum intake flow and datum lift coefficient.

The value chosen for the datum lift coefficient is to some extent arbitrary, but it is recommended that it is defined as the lift coefficient at which for given Mach and Reynolds numbers, the drag coefficient is a minimum. Thus if the body is asymmetric the datum lift coefficient is not, in general, zero. In the past, the drag at zero lift has often been called 'profile drag', though this term has also been used to describe the total drag of a two-dimensional aerofoil, or the drag due to the wing of an aircraft at either the minimum drag or zero-lift condition. In order to avoid such ambiguity, the Panel feels that the term 'profile drag' should be avoided and that in future the concept of datum drag should be used instead. The drag increment which accompanies an increase in the lift of the body has often been called 'induced drag'. Unfortunately, this term also has alternative meanings, such as the increase in drag from the zero-lift condition, or the drag due solely to the trailing-vortex system. Because of this ambiguity, the Panel recommends that the name 'induced drag' should not now be used and the term lift-dependent drag$^+$ should be employed.

It is also often convenient to assume that the drag due to viscous effects is independent of both the internal flow through the body and the lift. Thus the Boundary-Layer Drag may be regarded as one component of the datum drag, which also includes the Drag due to Incidence, Camber and Twist at Datum Lift Coefficient and the Wave drag due to Thickness.

The foregoing analysis is shown diagrammatically in Fig. 1(b).

The/

$^+$It will be often convenient to assume a relation of the form

$$C_{D_L} = k(C_L - C_{L_0})^n$$

where C_{D_L} is the lift-dependent drag coefficient, C_{L_0} and C_L are the datum and actual lift coefficients and k and n are constants (usually $n = 2$). Strictly C_{D_L} depends on an increment of lift from the datum value C_{L_0} and not on the total lift, and hence ought to be called the 'lift-increment dependent drag'. The Panel feels, however, that it may be more convenient to use the shorter term 'lift dependent drag' for this quantity.

The Panel appreciates that there exist other and perhaps equally acceptable analyses of drag which are useful in certain aspects of performance estimation; it is felt, however, that the one presented here is of wide application and merits consideration.

5. Concluding Remarks

In the foregoing analyses of the external drag of a body which may have an internal duct, terms have been introduced which are generally applicable for both subsonic and supersonic speeds; the terms are defined precisely in the Appendix.

It is realised by the Panel that alternative systems could be devised which would lead to drag components different from those discussed in this Report. It is felt though that the methods of analysis presented here are similar, in the main, to those commonly used in aerodynamics. Some of the drag components are also in common use and where possible the Panel has used the accepted name for these items; in a few cases where a widely used term may be ambiguous (e.g., induced drag), alternative names have been suggested.

References

No.	Author(s)	Title, etc.
1	-	British Standard Glossary of Aeronautical Terms. B.S. 185: Part I: 1950.
2	-	C.P. 190, 20th May, 1954. J.R.Ae.Soc., Vol. 59, pp. 517-526, August, 1955.

APPENDIX

Definitions of Certain Terms used in the Description and Analysis of Drag

In using these definitions, reference should be made to the discussion in the appropriate part of the Report

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A. Drag Concepts and Associated Terms

1. External Flow. The flow of fluid which passes around the body.

2. Internal Flow. The flow of fluid which passes through a duct in the body.

3. External Surface. A surface forming a boundary of the external flow.

4. Internal Surface. A surface forming a boundary of the internal flow.

5. Pre-Entry Streamtube. The streamtube, extending to the body from infinity upstream, that separates the internal flow from the external flow.

6. Equivalent Post-Exit Streamtube. The streamtube, extending from the body to infinity downstream, that is assumed to separate the internal flow from the external flow in the absence of mixing.

7. Total Drag. The force corresponding to the rate of decrease of momentum, in a direction parallel to the undisturbed stream, of the external flow around the body, this decrease being calculated between stations at infinite distances upstream and downstream of the body.

8. Normal-Pressure Drag (or Pressure Drag). Drag arising from the resolved components of the normal pressure on the boundary under consideration (see p. 3).

9. Trailing-Vortex Drag (or Vortex Drag). Drag associated with the trailing vortices. The product of the trailing-vortex drag of a body and its velocity is equal to the work done per unit time in extending the trailing vortices, and is also equal to the rate of production of kinetic energy within the system.

10. Wave Drag. Drag associated with the shock waves.

11. Boundary-Layer Normal-Pressure Drag (or Boundary-Layer Pressure Drag). The difference between the boundary-layer drag and the surface-friction drag.

12. Surface-Friction Drag (or Friction Drag). Drag arising from the resolved components of the tangential stresses on the surface of the body.

13. Boundary-Layer Drag. Drag associated with losses in total pressure and total temperature in the boundary layers. It is the sum of the boundary-layer normal-pressure drag and the surface-friction drag.

B. Terms useful in Drag Estimation

1. Pre-Entry Drag. The normal-pressure drag on the outside of the pre-entry streamtube.

2. Post-Exit Drag. The normal-pressure drag on the outside of the equivalent post-exit streamtube.

3. Intrinsic Normal-Pressure Drag (or Intrinsic Pressure Drag). The drag arising from the components of the normal pressure on the external surfaces of a ducted body.

4. Datum Intake Flow. The intake flow that occurs when the boundary of the pre-entry streamtube is unaffected by the presence of the intake.

5. Full Intake Flow. The intake flow that occurs, when with a pre-entry compression body in position, the boundary of the pre-entry streamtube is unaffected by the presence of the cowl. If there is no pre-entry compression body then full intake flow is the same as datum intake flow.

6. Pre-Entry Drag at Datum Flow. The pre-entry drag that arises when a side intake is operating at datum flow. This drag is zero for a nose intake.

7. Spillage. The amount by which the intake flow is less than the datum intake flow.

8. Basic Spillage. The amount by which full intake flow is less than datum intake flow.

9. Incremental Spillage. The amount by which the intake flow is less than full intake flow.

10. Spillage Drag. The difference between the drag at a given intake flow and the drag at datum intake flow.

11. Basic Spillage Drag. The difference between the drag at full intake flow and the drag at datum intake flow.

12. Incremental Spillage Drag. The difference between the drag at a given intake flow and the drag at full intake flow.

13. Datum Lift Coefficient. The lift coefficient at which, for given Reynolds and Mach numbers, the external drag coefficient is a minimum.

14. Datum Drag. The drag at datum lift coefficient and datum intake flow.

15. Drag due to Incidence, Camber and Twist at Datum Lift Coefficient. That part of the drag associated with the incidence and with the distribution of camber and twist at datum lift coefficient.

16. Wave Drag due to Thickness. The part of the wave drag associated with the thickness distribution.

17. Drag due to Incidence, Camber and Twist. That part of the drag associated with the incidence and with the distribution of camber and twist.

18. Lift-Dependent Drag. The difference between the drag at a given lift coefficient and the drag at datum lift coefficient.

FIG. 1a.

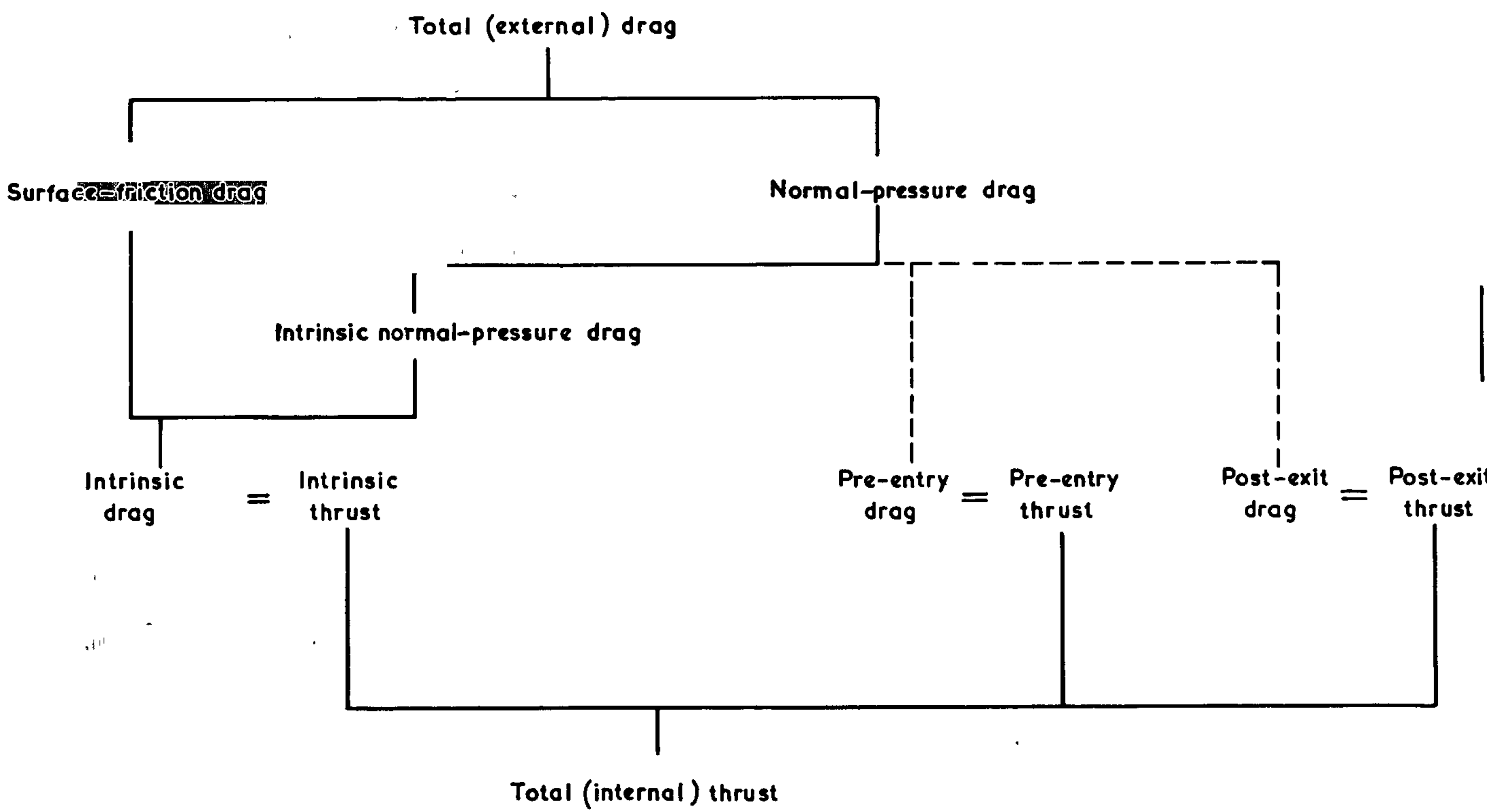
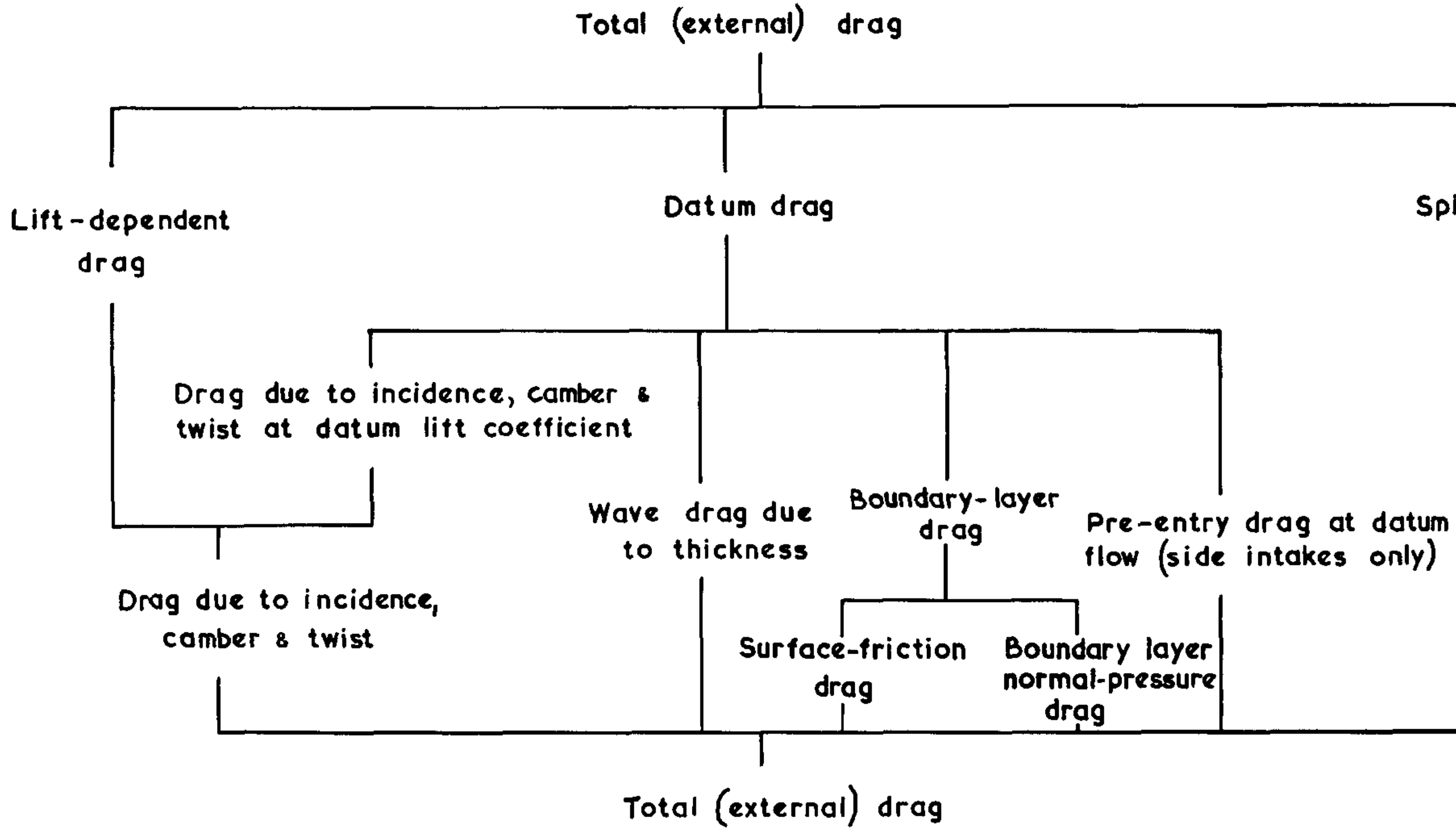


Diagram showing balance between thrust and drag for a ducted body in level flight with zero acceleration



Analysis of total drag in terms useful in drag estimation
(assuming independence of spillage drag, lift-dependent drag & boundary-layer drag)

FIG 1b.

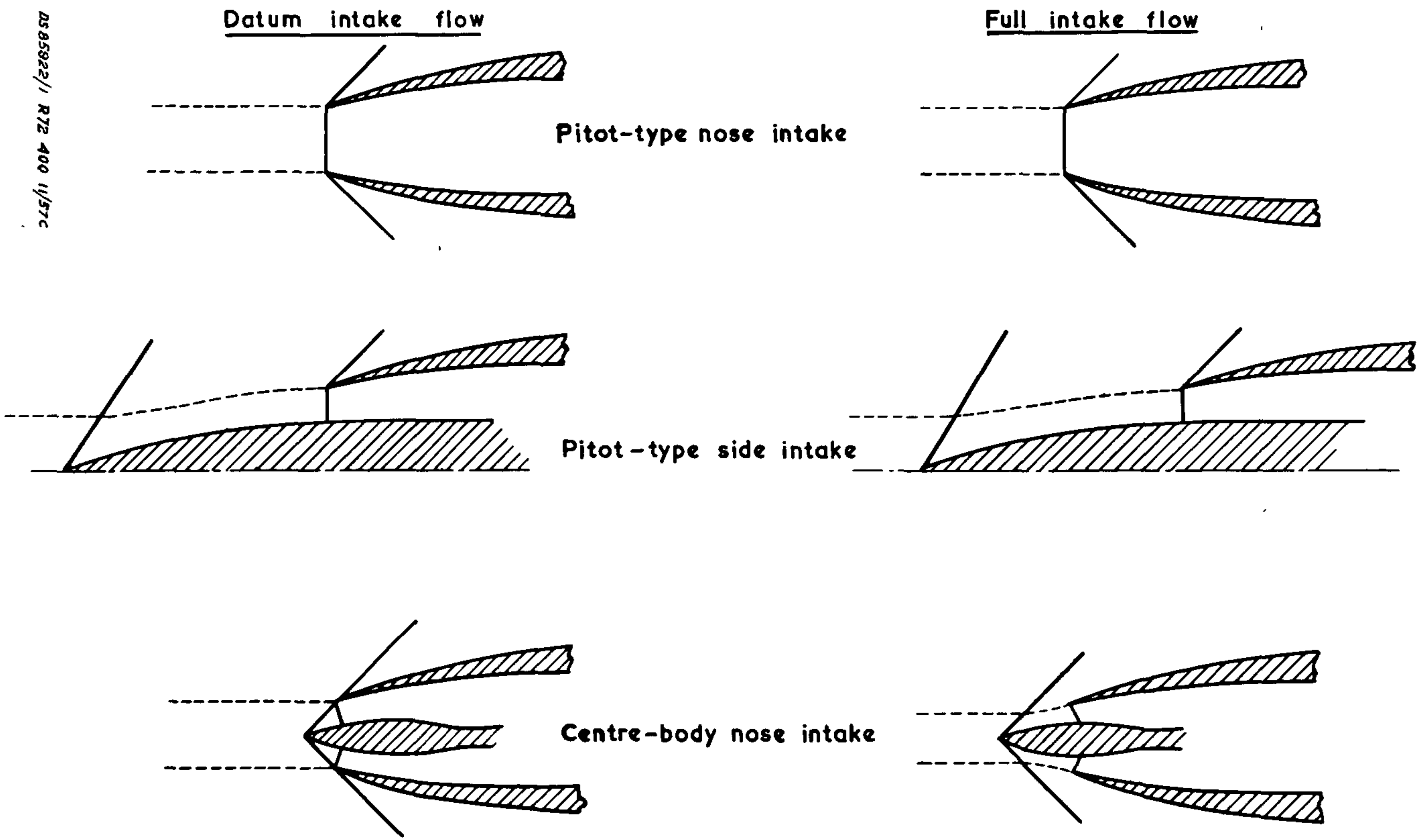


FIG. 2.

Diagrams of datum intake flow and full intake flow for various types of intake

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