1. INTRODUCTION

The search for improved weapon performance whether guided, unguided, powered or unpowered often leads to proposals where the weapon is required to operate at extreme angles of incidence. In addition, disturbances of various kinds in flight may cause a weapon to inadvertently reach a high incidence angle. In all these situations it is essential to be able to estimate the aerodynamic characteristics to a fair level of engineering accuracy before embarking on expensive programmes of tests.

The flow around bodies and wings at large incidences becomes very complex due to large areas of separated flow, and the theoretical problems are as yet unsolved. Some years ago however a systematic series of low speed wind tunnel tests on a combination of a double diameter body with various sets of lifting surfaces, have been performed at the British Aircraft Corporation, Bristol, as a preliminary to the development of a test vehicle. These results provided a set of systematic data on the component contributions as well as for the overall aerodynamic forces; it proved possible therefore to gain an improved understanding of the physical flow model and hence derive an "engineering" method of evaluating force and moment in the total incidence plane. The analysis was done by BAC under contract to the U.K. Ministry of Technology and monitored by RAE Farnborough. The method takes into account the features of the real flow, but relies on empiricsm to supply appropriate constants and factors in the equations. The technique is applicable over the whole incidence range from 0 to 90°, and the equations follow the same framework as the one we employ for wing-body - fin combinations, that is the forces are calculated for the body and sets of surfaces in isolation and then put together with appropriate interference factors. The method is therefore consistent with the more usual techniques for low to moderate incidences.

In addition to the force in the plane of total incidence the tests revealed the existence of a large force acting in a plane normal to the total incidence plane. A detailed research study into this topic has been performed at Bristol University. The study was done on a single diameter body in isolation and has helped to improve our understanding of the underlying flow mechanisms.

These notes discuss high incidence flow aspects and outline the method used for predicting forces in the incidence plane. Some results of the wind tunnel tests on the basis of which the technique was compiled are shown. These notes are concluded by presenting a short synopsis of the work done on the out of plane force at Bristol University.

2. FLOW FIELD ASPECTS AND AERODYNAMIC FORCES

The diagram in Figure 1 illustrates the principle aerodynamic forces generated by a uniform flow field having a velocity U and a large angle of incidence α, that is, an "in plane" force, coefficient C_N, and an "out of plane" force, coefficient C_Y. The sketches below illustrate important features of the flow field and some basic assumptions in the theoretical flow model. The flow over the body is characterised by separation on the lee side, and at moderate incidences, the separated flow rolls up into a symmetrical pair of vortices, originating at a point close to the nose and increasing in strength as they trail downstream. At larger incidences the symmetrical pair of vortices gives way to a series of asymmetric vortices and hence a very complex flow field, and this flow field resembles the familiar vortex street behind a circular cylinder inclined at 90° to the free stream. This topic is discussed further in Section 4.2 on out of plane force. In the flow model however the concept of a symmetric pair of vortices is retained, throughout the whole incidence range, this is justifiable since the vortices shed further forward tend to be the strongest, and their effect at larger incidences on lifting surfaces tends to become small.

It should finally be noted that lifting surfaces are subjected to incidences well beyond the stall, and it is necessary therefore to predict their stalling characteristics.

3. PREDICTION METHOD ZERO ROLL ANGLE

3.1. Body alone

It is thought that a plausible means of deriving the force C_N is to assume some combination of a linear function and a non linear function. The linear term to take account of lift on expanding sections e.g. the nose and the non linear term to account for lee side separation. At smaller incidences this equation usually takes the form

$$C_N = A\alpha + B\alpha^2 \qquad \ldots\ldots (1)$$

However in order to achieve a plausible relationship applicable over the whole incidence range 0 to 90° then a more correct form is considered to be

$$C_N \quad = \quad A \sin\alpha \cos\alpha + B \sin^2\alpha \qquad .....(2)$$

The effect of varying the ratio A/B on the shape of the curve is shown in Figure 2. In order to match the available experimental data it was found appropriate to assume a value for $A = 1.7$, compared with a slender body value of 2, and values of B which differ on the front and rear portions of the body. The relationship of the cross flow drag coefficient B relative to that on a two dimensional circular cylinder at the same Reynolds Number will tend to become exact as $\alpha \rightarrow 10^\circ$, however for intermediate incidences, this should not be overstressed in view of the different flow conditions, including the effect of the axial flow component $V \cos\alpha$.

It proved preferable to use pitching moment data rather than normal force data. The estimated values were derived by assuming that the centre of pressure of the linear force acts at points on the nose or frustrum, these being evaluated from slender body theory. The non linear components are assumed to be uniformly distributed over their respective cylindrical parts with a linear fairing over the frustrum. It also proved necessary to assume different values of B over different incidences, the relationships arrived at were therefore, for the fore and aft cylinders respectively

$$0 \leq \alpha \leq 20^\circ \qquad B = 0.69 \text{ and } 0.45$$

$$\alpha \geq 40^\circ \qquad B = 0.81 \text{ and } 0.35$$

The resulting fit to the experimental data for is illustrated in Figure 3; this was completed by fairing the derived curves over the incidence range $20^\circ < \alpha < 40^\circ$.

3.2. Normal force on wings in isolation

The next step was to find a suitable technique for predicting the forces C_{N_W} on any of the surfaces in isolation (2 panels joined together). The method of Reference 1 was employed. This is based on the equation

$$C_{N_W} = C_{N_\alpha} \frac{\sin 2\alpha}{2} + C_{N_{\alpha\alpha}} \sin^2\alpha \qquad .... (3)$$

in which the first term takes into account the characteristic linear lift curve at low incidence while in the second term, the parameter $C_{N_{\alpha\alpha}}$ is a cross flow drag coefficient. This coefficient is derived in reference 1 from an empirical correlation of experimental data that takes into account aerofoil stall characteristics. Figure 4 shows some comparisons of this method with experimental data taken from reference 2.

3.3. Wing on Body interference factors

In this flow model it is assumed that interference due to upwash and body carry over is in essence similar in form to that at low incidence that is

$$C_{N_{W(B)}} = (K_B + K_W)\ C_{N_W} \qquad \ldots.(4)$$

Theoretical ideas suggest that K_W, the interference term due to body upwash should decrease to unity as $\alpha \rightarrow 90^\circ$. However the resultant velocity at the wing increases above the free stream value as $\alpha \rightarrow 90^\circ$ and this tends to offset the reduction in K_W. A constant value of K_W, and also for K_B was used, except for surfaces at the body base, where a simple rule was made up to allow for this. Apart from this empirical rule the values used were based on slender body theory of reference 3.

3.4. Vortex interference terms and overall normal force

The interference on rear positioned surfaces due to the downwash field of the forward surfaces was evaluated by assuming a simplified vortex flow model as sketched in Figure 5. A strip theory method, reference 3, was used to evaluate the vortex interference terms. The effect of the forebody vortices was also taken into account, using Spahr but for the forward surface only. At incidences above 40° or thereabouts the significance of the vortex interference terms diminishes rapidly. The contributions as outlined in Sections 3.1-3.4 were then summed to obtain an estimate of the overall normal force.

3.5. Comparisons with experimental data

Typical comparisons are illustrated in Figures 6 and 7, these serve to illustrate that the method is capable of achieving an acceptable degree of accuracy. Figures 8 and 9 illustrate a satisfactory estimate for a difference configuration.