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Technical Evaluation Report on AGARD Specialists' Meeting on

Aerodynamic Interference

by

D. J. Peake

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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TECHNICAL EVALUATION REPORT ON AGARD SPECIALISTS' MEETING ON "AERODYNAMIC INTERFERENCE"

by

David J.Peake

CONTENTS

This report contains a review of the information presented in both the formal papers and the Round Table Discussion which are already published as AGARD Conference Proceedings No.71-71, January 1971

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1. INTRODUCTION

The AGARD Fluid Dynamics Panel organised a three-day Specialists' Meeting on "Aerodynamic Interference" that was held at the U.S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland, USA, from 28th to 30th September, 1970. The Programme Committee was chaired by Dr. D. Zonars, and was composed of Monsieur P. Carrière (France), Professor K. Gersten (Germany), Dr. U. Sacerdote (Italy), Dr. J. Seddon (U.K.), Dr. J.A. Steketee (Netherlands), and Dr. R.E. Wilson (USA), the last six gentlemen also accepting the duties of Session Chairmen. During the course of the meeting, the author of this report was invited by the Chairman of the Fluid Dynamics Panel, Professor W.R. Sears, to prepare a critique of the topics discussed, and as a direct consequence, the present commentary includes the constructive criticisms of Professor Sears, Dr. D. Küchemann and Mr. R.J. Templin. The author must emphasise, however, that the editing is his own and as such, he accepts full responsibility for all of the opinions expressed in the following paragraphs.

The meeting was intended to provide a forum for the discussion of theories and experiments to explain the existing comprehension of aerodynamic interference; and to provide some guidelines and design rules to improve the flight characteristics of military and commercial aircraft and weapons. The speed régimes were restricted to subsonic, transonic and supersonic Mach numbers.

The objective of this report, therefore, is to assess the current state-of-the-art of the analytical and test techniques concerned with junction flows (in terms of that which was preached and that which should have been recited, perhaps), to outline their advantages and disadvantages and to indicate any relevant omissions. In particular, it should strive to show the practical applications of the work presented with the view of immediate help to the aircraft designer. It was considered that the report should be candid and forthright to stimulate discussion, accepting, of course, that an element of the author's personal bias would be involved.

There were six sessions at the meeting. Sessions I and II dealt with wing-body and wing-body-tail interference, Sessions III and IV with the flow fields about propulsion components and Sessions V and VI exclusively with the flows about airframe stores. A total of thirty-five papers was presented, where it was noted that the major emphasis inclined towards configuration studies of lift, drag, pitching moment and stability, and the optimisation of configuration geometry to provide the least drag.

The order of the oral presentations was changed from that of the written versions in the Conference Proceedings' Preprint to facilitate a more systematic arrangement of associated topics. The titles of the papers at the end of the text are thus sequenced according to the oral list while additional references have been included in a second list to augment this discussion. The evaluation will conclude with comments from a Round Table finale, around which some recommendations for future work will be hung.

As an alternative to the usual oral presentation time of twenty minutes plus an additional ten minutes of questions, Dr. J. Seddon re-organised the morning of the second day, to permit a short period of questioning after each paper, which then broadened into a further discussion after a group of three papers had been presented. This enabled the ideas of the three papers to be viewed collectively by both the authors and the audience and produced an improved participation; evidently the approach, because of its success here, might well be considered at future meetings of AGARD Specialists.

A disturbing feature at most scientific gatherings is that many authors copy the figures in their written reports directly on to photographic film for visual support of their oral presentations, with the consequence that the lettering cannot be read. At this meeting, however, the NOL is to be congratulated on possessing such a large screen coupled with variable intensity projection equipment, that even the poorest of slides was legible. The projectionist also deserves a vote of thanks for the exemplary way in which he delivered the visual material.

The report is split essentially into three parts: following a synopsis, an attempt is made to give a constructive review of the papers presented, subsequent to which some clear-cut conclusions are drawn.

2. SYNOPSIS

On re-reading Küchemann's erudite evaluation[37] of an earlier AGARD meeting, it is remarkable how many of his comments can be applied directly to the present context, exchanging only the words "aerodynamic interference" for those of "transonic aerodynamics". We were reminded there that such a meeting of specialists should be concerned with research aimed at providing good principles of design, rather than the reporting of interest motivated research, or that associated with tangential aspects of a particular discipline. As Shaw stated so succinctly, in posing the designer's dilemma for design criteria, one was often presented with the aircraft requirements of range, manoeuvrability, cruise Mach number and landing run .. and how did one progress in a logical fashion from there to an aerodynamically efficient, practical aeroplane? Obviously, there is a great deal of empiricism and intelligent guesswork still involved in the evolution of a basic aerodynamic shape to suit a proposed mission after which the configuration assessment methods described in the present meeting might then be applied to refine the design. It is evident, therefore, that the power of most of the calculation procedures involving digital computers (such as that generated by A.M.O. Smith and his team[38], for instance,

where the surfaces of a prescribed configuration are divided into finite elemental areas to solve the Neumann boundary value problem) is in their assessment of a particular design; rather than the development of a rational design procedure, based on an appropriate physical flow model. This overall design problem was treated inadequately at the meeting. Only Küchemann's paper[1] on swept wing/body interference, Loeve's paper[11] utilising a finite element procedure to treat a vortex sheet leaving the trailing-edge of a wing/body combination at subcritical speeds, Lock's paper[5] dealing with the wing/body flow at low supersonic speeds, and Middleton's paper[3] on supersonic aeroplane design, offering constructive approaches to the wing-body and wing-body-tail inviscid flow design problem. On the propulsion side, Neale and Armstrong's review[19] was restricted to the design of two-dimensional Mach 2 air intakes based upon a wealth of experimental testing associated with Concorde.

The other most striking deficiency of the meeting, was the almost uniform lack of recognition (and in some cases, denial!) of the gross effects of the three-dimensional viscous regions* that exist in all junctions, and which may be broadly classified into flows about slender or bluff protuberances. The examination of three-dimensional viscous flows with respect to power-plant installation was particularly disappointing. That these three-dimensional viscous flows were only given superficial and perfunctory consideration in the U.S. for example, was not dispelled by Zonars, who admitted during the course of the meeting that few of the aircraft in the USAF inventory had escaped from embarrassing three-dimensional viscous flow problems. Although the fundamentals of skewed boundary layers and three-dimensional separations were reported almost twenty years ago, it is perhaps opportune to reflect upon the physical aspects of three-dimensional separations, particularly as the author was requested to provide an interpretation of such flows in a question after paper 14. The problem appears to be the grasping of a suitable general concept of flow separation, rather than the insistence on thinking in terms of two-dimensional criteria. Ideas based on two-dimensional flow where separation lines must be perpendicular to the external flow direction are of limited value in synthesising flow separations in three dimensions. For the sake of simplicity, the calculation of boundary layers has tended to exclude the third space dimension, leading to overt emphasis by experimenters on flows with similar two-dimensional restrictions in order to allow comparison with theory.

Considering the subject of three-dimensional viscous flows in its historical context, Sears in 1948, utilised the very important concept of "limiting streamlines" in a paper[39] discussing the laminar boundary layer on a yawed cylinder. Each streamline near the surface, in the inner collinear part of the boundary layer, is one of a continuous pattern of streamlines that approaches the surface at an attachment point or line and leaves the surface at some point or line of separation. (Note that an aerofoil with attached flow over its surface still suffers separation at a cusped trailing-edge.) Clearly, if the distance of the streamline above the surface is infinitesimal, its direction is everywhere tangential to the vanishing fluid velocity as the surface is approached. It is then identifiable as a limiting streamline, or, in other words, it possesses the same direction as a skin friction line or surface shear stress trajectory. These limiting streamlines at the base of the boundary layer must not be confused with the streamlines of the external inviscid flow over the surface, and they will in general follow paths that are different in direction to those of the external (inviscid) streamlines.

Sears, moreover, included a sketch[39] which showed the convergence of limiting streamlines towards a three-dimensional separation line (and from either side of it), although he did not call it by name; and later, Wild[40] substantiated Sears' physical interpretation of separation, in his investigation of the laminar boundary layer on yawed 'infinite' wings. In subscribing to the Cornell University work, Eichelbrenner and Oudart[41,42] proposed that a line of three-dimensional separation was the envelope of the limiting streamlines (conversely, a line of attachment is the divergence of same) and this was also supported by Susan Brown[43] in a mathematical treatise of the Royal Society. Lighthill[44], on the other hand, disputed the term 'envelope', in spite of flow visualisation experiments supporting the previous authors. Coalescence of the limiting streamlines is perhaps an acceptable description to avoid argument.

It remained for Maskell[45], however, to lay the ground rules for the precise interpretation of the physical composition of three-dimensional viscous flows (including the effects after the flow leaves the surface) by demonstrating that the limiting streamlines provide a "three-dimensional skeleton structure of the viscous flow". Provided a flow visualisation indicator is very thin on a wind tunnel model, for example, it has been shown[46] that the direction indicated by the streaks on the surface is very close to the direction of surface shear and the limiting direction of the velocity when the indicator is absent. Thus the many surface flow visualisation techniques yield a powerful means of diagnosing the qualitative features of three-dimensional viscous flows.

Two types of separation were conceived by Maskell[45]: a bubble type and a free shear layer type, both of which may exist together. The latter would appear to be the more common, however. Fluid accumulating at a three-dimensional separation line, which in general is set obliquely to the direction of the external and essentially inviscid flow field, leaves the separation line as a free shear layer and rolls up in the process of passing downstream. The shear stress is usually finite along such a three-dimensional separation line, although it may be zero at a singular point. High local suction

*the term viscous region or viscous flow is used instead of boundary layer, because both the separated and unseparated flows may be discussed in a single context.

pressures are frequently induced on the surface beneath the vortices, close to which are noted inflexion points in the limiting streamline patterns. Examples here are the delta wing flow (the ONERA and RAE work being the most extensive - see the subject list in reference 47) and cones[47,48,49], the flows on long pointed slender bodies at incidence, those about upswept fuselages[50], and those about bluff protuberances[47]. The scale of the rolled-up flow with respect to the oncoming boundary layer thickness may be large or small. In the bluff protuberance case, for example, which applies to most junction problems, the rolled-up shear layer departing from a horse-shoe shaped separation line occurs within the depth of the oncoming boundary layer, but the changes to the pressure distribution are still significant[1]. A review of NAE work on three-dimensional separations is published in Reference 47 and a more up-to-date paper is to be presented soon[51]. For those interested in three-dimensional boundary layers (prior to separation) Cooke & Hall's review[52] is instructive, while the more recent work of Bradshaw[53] and Nash[54] indicate the importance of considering the boundary layer history by means of the turbulent energy equation. Nash and Patel[55] have recently compiled a monograph on the subject which is to be printed during 1971.

Particular neglect of three-dimensional viscous flows (or their attempted interpretation in a two-dimensional sense) may be seen in some of the contributions to the meeting. Moreover, little use seemed to have been made of flow visualisation techniques, which if utilised, would surely have provided a safer foundation for any modelling of the flow in a computer programme. In addition, it was surprising that several authors appeared to lack in background reading of their subject specialisation, as indicated, in a few instances, by no references appearing in their texts. Another noticeable and general feature,was that many authors were conversant only with work progress in their own countries - at least, one would surmise this from the reference lists. Has the circulation of documents between the scientific communities of the NATO countries been reduced, or are some research workers deficient in reviewing publications from abroad?

Specifically, only Küchemann[1], Winkelmann[12], Peake[14], Grosche[2] and Taisseire[29] paid attention to the effects of three-dimensional separations. Taisseire should be congratulated for providing an excellent film near the meeting's end, of a water tunnel flow illustrating qualitatively the overall three-dimensional boundary layers and separations generated on and about a store mounted beneath a wing. The film summarised in a nutshell and telescoped effectively the comments that were made by the audience during the course of the meeting, on the necessity to realise the limitations of inviscid flow theories, and the reasons why some of the inviscid flow field predictions failed.

3. THE SESSIONS

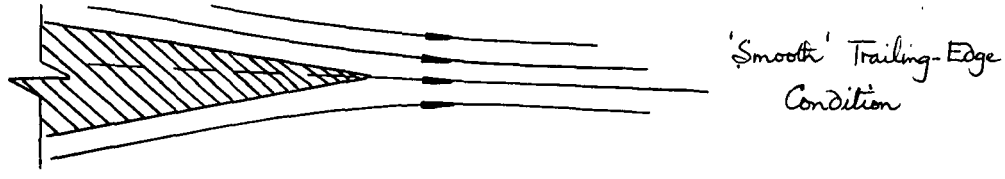
3.1 WING/BODY AND WING/BODY/TAIL FLOWS

Küchemann[1] commenced the session on wing-body flows by proposing that the essential aim of a good theory was to predict the flow in the junction correctly, as there, the three-dimensional interference between the wing and fuselage was largest. The basic model contemplated to identify the physical nature of the interference was a circular cross-section fuselage of infinite extent, to which was attached a wing of large span, all immersed in subcritical inviscid flow that was attached and shock free. Thus aware of the severe restrictions of these impositions, two interference effects were nevertheless clearly identified: the reflection effect associated with the mirror image in a plane wall of the half wing outside the fuselage, that depended mainly on sweep and dihedral angle, and secondly, a body interference effect that was found at all sweep and dihedral angles. The method of singularities was applied to compute the inviscid flow field. Some experimental results, however, demonstrated that there were large effects of the viscous flow in the junction (bluff protuberance type separations - explained in supersonic flow by Winkelmann[12]) which caused the wing suction pressure to decrease as the junction was approached. The suction pressure fell still further with progression around the fuselage from the junction.

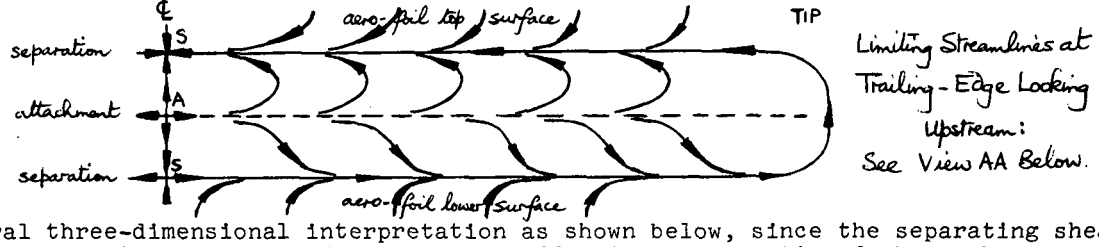
Grosche[2] followed with some well executed yawmeter explorations of the three-dimensional vortex wake emanating from a slender pointed, ogive cylinder, of slenderness ratio L/D = 15. The tests were conducted at subsonic speed ($M_\infty \doteq 0.12$) at a Reynolds number based on body diameter of 0.5 million, and at angles of incidence up to 20°. Unfortunately, no surface measurements of static pressure or flow visualisation had yet been attempted to identify the three-dimensional separation line positions emanating from the ogive apex. The attachment of straight or delta wings to the body in the horizontal plane reduced the circulatory strength of the body vortices, caused them to move farther (in the vertical plane) from the body near the wing, after which the wing downwash field rapidly altered their direction yet again. Other experiments[51] have shown differences in the normal force/incidence slope with change of nose geometry and Mach number. In partial support of this observation, Grosche commented that some additional experiments he had made with conical noses did indicate changes in the structure of the vortex wake, which would imply changes on the body. The position of boundary layer transition was unknown in Grosche's experiments, while the incidence range was sufficiently low for no vortex bursting phenomena to be witnessed.

Loeve[11] described the numerical solution of the Neumann problem for three-dimensional compressible, subcritical flow, but this time with circulation. This technique is an important extension of A.M.O. Smith's finite element inviscid flow method[38] (some additional examples of which, employing principles of superposition were

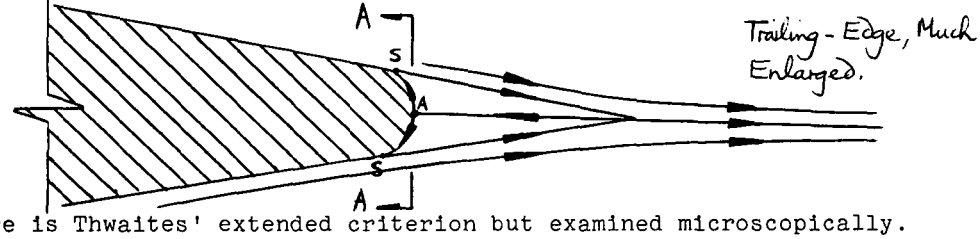
advanced by J. Hess[24]), for now, lifting configurations can be treated. The wing camber surface and its extension through the fuselage were composed of horse-shoe vortices, while a rigid vortex sheet was considered to leave the wing along the bisector of the trailing-edge angle. It was shown, for example, that the local lift near mid semi-span of a mildly swept wing was more sensitive to the distance from the trailing-edge of the control point on the wing surface, if the vortex sheet was tangential to the upper surface. Lock commented that if the trailing-edge were not cusped, that the $\Delta p = 0$ condition at a swept trailing-edge could not be satisfied unless the velocity vector were made parallel to either the upper or lower surface at the trailing-edge. A cusped trailing-edge obviously causes no problem, but does a boundary layer produce an effective cusp? We may begin to answer this question by referencing Thwaites[56], who discusses the Kutta-Joukowski condition in the inviscid and viscous flow contexts for two-dimensional aerofoil sections. The first inviscid approximation utilises a simple condition that the velocity is finite and non-zero at the trailing-edge. This condition is violated when boundary layers are present for the velocity must be zero at all points along the aerofoil surface. An extended Kutta-Joukowski hypothesis proposes that a rear dividing streamline leaves the aerofoil trailing-edge, its tangent there passing through the interior of the aerofoil in a manner similar to that of Loeve[11]. This proposal contrasts at first sight



with the suggestion of Lighthill[44] whose interpretation of the trailing-edge flow for a three-dimensional wing is directly linked with our concepts of three-dimensional separation. He indicates that a separation line issues from a 'saddle point of separation' on the lower surface at the wing centre-line, which travels outward to the tip and returns to disappear into a nodal separation point on the top surface at the wing centre. A nodal point of attachment exists between the two separation points (see page 80 of L. Rosenhead[44]). The two-dimensional 'extended condition' may be formulated from this



more general three-dimensional interpretation as shown below, since the separating shear layers at the trailing-edge could provide the effective cusp mentioned above, by means of another 'saddle point' formed in the flow external to the aerofoil. In fact,



Lighthill's picture is Thwaites' extended criterion but examined microscopically.

Loeve's calculated pressure distributions[11] on a swept wing/waisted body configuration at Mach 0.8 and $\alpha \doteq 5°$ showed reasonable agreement with experiment although it was clear here, as well as with the results for a typical subsonic transport aircraft configuration, that the practical three-dimensional viscous flows caused a reduction of lift in all cases, of approximately 15 per cent on spanwise lift distribution, for instance.

Lock[5] then presented theoretical and experimental results on 55° warped, swept wing/body combinations at Mach 0.9 to 1.4 with application to sonic bang-free jet transports flying at low supersonic cruise Mach numbers. The tests were conducted with half-models at Reynolds numbers based on mean chord of approximately 1.2 million, with transition fixed by roughness, and were performed in a perforated wind tunnel with no sidewall boundary layer control. He demonstrated that the correct shaping of the body waisting, wing leading-edge radius and wing root can lead to drag reductions at transonic and low supersonic speeds. 'Peaky' type pressure distributions obtained with relatively blunt leading-edge sections (and well known for their application in high subsonic speed wing section design) improved the performance of swept wings at off-design as well as at design conditions. Moreover, as an alternative to body waisting, the corresponding thickening and reshaping of the inboard regions of the wing may be used to maintain a satisfactory low drag wing pressure distribution. Some of the interesting slides supporting Lock's paper[5] are not in the preprint, including one showing isobars on the wing top surface at a Mach 1.2 condition and a figure explaining the interesting philosophy of the trade-off involved in changing the wing near the body, that produces an increased wing drag but a reduced body drag.

Carmichael[4] followed Lock in an unfortunately all too brief review of the finite element numerical procedures currently in use and under development at NASA Ames, showing no quantitative examples. His paper in Reference 57 does, however, illustrate some configuration calculations. The power of the finite element procedure, of course, is that inviscid flow solutions may be generated for flow situations where complex surface geometries exist. In the NASA methods, a wing-body combination is set up with a collection of line sources and doublets, in association with surface panels to represent thickness and lift (and described by Woodward[58]). This use of different types of element distinguishes the NASA method from most other finite element procedures. Very recent developments appear to allow the simulation of an actual aircraft geometry in subsonic and supersonic flow. Deficiencies do remain, however, for one reason or another, in the treatment of, a trailing vortex sheet, bodies with varying diameter or non-circular cross-section, the wing root junctions, where sideslip exists, and in the estimation of induced drag. One surprise was the author's comment that a Kutta-Joukowski condition was not needed at the wing trailing-edge, because the number of control points was the same as the number of elements. An explicit Kutta condition appeared not to be required, because there were control points on the top and bottom surfaces near the trailing-edge, and hence the Kutta condition was implicitly applied. An additional query was raised by Nielsen to the effect that the 'trailing vortices' from the force elements should not appear in the flow, and should remain in the surface as far back as the rearmost element.

The final paper in the wing-body session was presented by Bannink[6] on half-cone/delta wing flow fields, in which he emphasised that "the numerical accuracy of slender body theory is not very great ... and where the effect of base drag, skin friction and (three dimensional) flow separation has been ignored." In spite of these restrictions, it was hoped that the results indicated the correct trends on lift/drag ratio when configuration geometry was altered, and a high wing configuration was proposed as possibly the most desirable. The method examined a subsonic leading-edge in a supersonic oncoming flow.

The second session, on wing-body-tail interference, was commenced by Middleton[3], who introduced rational empiricisms into the discussion of supersonic aerodynamic interference, in contrast to the methods discussed during the first session. The flow was typically at Mach 2.7 and the interference was that existing between a wing and a body, or bodies adjacent to a wing (a current example being the Boeing supersonic transport aircraft). In this paper, some comparisons were shown between increments in total drag of attaching a pod to a wing, that were demonstrated to be substantially less than the isolated skin friction drag of the pod. The positioning of the nacelle at about 0.6 of the chord on the underside of a delta wing appeared to yield minimum nacelle drag, but there was no discussion of the effects of the adverse pressure fields on the underwing boundary layers.

Gregoriou[7], considering swept cruciform wings attached to missiles at incidence and yaw, worked with a simplified vortex sheet model for the wing flow, that traversed through the wing at the one quarter chord point. The downwash that he calculated, demonstrated reasonable agreement with experiment, and hence provided the ability to compute forces and moments on several examples of cruciform tail at $M_\infty = 0.1$. No account was taken of the body vortices that were investigated by Grosche[2], however. The latter paper showed that the shear layers separating from the leeside of bodies of revolution induced a downwash aft of the wing, larger than would be predicted from considerations of the wing alone. Consistent with Grosche, although not explained, Gregoriou's test results appeared to show that the body vortices increased the downwash at the tail over that calculated, but that the additional body flow effects were reduced as the distance between the tail and the wing trailing-edge was made smaller.

Shrout[8] described a method used at NASA Langley to calculate the supersonic friction drag, wave drag and induced drag, to result in trim drag polars of an aircraft. The tail or canard was planar with the wing in the model used for drag due to lift. The method was applied to the integrated aircraft configuration rather than summing up the characteristics of the component parts, and gave good agreement with experiment on the scale of the plotted graphs. Enselme[9] then presented a neat analysis based on an electrical analogue of wing-body or wing-pod interactions in steady supersonic flow, as well as the computation of an arbitrary planform wing in unsteady flow.

There is an important class of three-dimensional viscous flows in which the oncoming two-dimensional or axisymmetric boundary layer suddenly encounters a steep, adverse pressure gradient, due to the blockage effect of a protuberance. If the protuberance is sufficiently bluff, there will exist a three-dimensional separation close to and about the junction of the protuberance with the surface. Typical examples of bluff protuberances include some boundary layer diverters and the wing leading-edges at wing root/fuselage junctions. In supersonic flow the pressure generated by the bow shock wave of the obstruction causes the three-dimensional separation, and this is the flow case that Winkelmann[12] described enthusiastically. In his experiment, a bluff fin protuberance was partially immersed in a turbulent boundary layer at Mach 5, and a Reynolds number based on fin thickness of about 0.3 million. A plausible physical flow model was constructed from surface flow and schlieren/shadowgraph observations but all of the three-dimensional separation lines in the junction itself were not immediately evident in the flow visualisation records, from which, of course, the corner vortices emanated. The importance of such protuberance flows cannot be over emphasised as high rates of heat transfer exist in the regions downstream of separation, where reattachment occurs, leading to the possibility of skin burn-off in a practical installation at high Mach number.

3.2 AIRFRAME/PROPULSION INTERACTIONS

The session on airframe/propulsion interaction with particular reference to military aircraft opened with three papers, two of which dealt with the external flow field about an intake while the third described an analytical investigation of the effects of a distorted approach flow on a compressor stage.

Peake's[14] paper emphasised the necessity of considering the strong three-dimensional interactions that exist between the shock system of a half-cone intake mounted adjacent to a fuselage, and the approaching fuselage boundary layer. It is unfortunate that in almost all of the previously reported literature[14] on half-cone intakes and the associated boundary layer bleed and diversion systems described, that the three-dimensionality of the viscous flow was overlooked. In the present paper, the inviscid pressure field of an isolated half-cone at Mach 1.6 of the same geometry as the intake was calculated by Jones' numerical method[59]. This pressure field, when impressed upon a fuselage wall, yielded a pressure gradient sufficiently adverse to cause three-dimensional separation of the oncoming boundary layer. The ensuing roll-up of the free shear layers from the separation lines emanating from the cone apex (shown by oil flow) and situated obliquely to the external flow direction caused the upstream boundary layer to be diverted around the intake bleed system, and to be dumped into the flow about the fuselage.

The external stream approaching an intake that is adjacent to a wing or fuselage, is non-uniform, and this was the subject of a paper by L. King[18] who described some analytical and experimental flow field surveys using a shoulder-wing military aircraft configuration. The numerical procedure followed that of Walitt, Trulio and King[60], which is a technique founded upon a time-dependent, two-dimensional numerical solution of the Navier-Stokes' equations. By using the equivalence principle to relate the time dependence to the axial position along the body, the method provided an approximation to the steady, three-dimensional, supersonic flow about a body of arbitrary cross-section at angle of attack. Axial viscous effects were neglected in this procedure although viscous terms were included in the cross-flow calculations. A typical example at Mach 2.5 and $\alpha = 15°$ showed reasonable agreement between the flow fields of theory and wind tunnel tests, where the flow angularity was measured with conical yawmeters at $R \doteq 10$ million based on model length. The windward side naturally demonstrated better agreement between calculation and test because of the thin boundary layer development around the fuselage in the nominally favourable surface pressure gradient commencing at the windward generator. Differences were noticeable between the canopy shock wave locations in the cross-flow and the flow field adjacent to the canopy, presumably as a result in the wind tunnel case of three-dimensional separations. No inlet was provided in the aircraft geometry, and the question arises as to how much this item would in turn affect the flow field. The results of paper 14 would suggest the effect of the inlet to be large.

In a recent discussion on altitude testing of turbojet engines in the Aeronautical Journal[61], large scale turbulence generated by vortices emanating from separations on the intake sidewalls and shock boundary layer interactions, were proposed as two reasons for spatial and time dependent variations in the flow at the engine (subsonic) compressor face. The flow studies in papers 14 and 18 thus provided a suitable background to the paper by Goethert[17] on the unsteady aerodynamics of compressor rotor blades under oscillating and distorted incompressible flow conditions. Two calculations were described. The first dealt with the lag associated with a spacer volume between two stages, where for a sinusoidal input, the stage output pressure was shown to lag. The second calculation was involved with a sinusoidal disturbance that was convected by the mainstream to impose <u>in-phase</u> perturbations on all members of a blade row. Blade flutter investigators have previously worked with the in-phase and 180° out-of-phase cases, while the modern work of Mani[62-66] and Kaji and Okazaki[67-69] provides for arbitrary phase and propagation speed in a compressible flow. On two figures[17] showing the amplitude of the normalised lift coefficient in oscillatory flow as a function of cascade stagger angle and solidity (Figures 13 and 14), the single-aerofoil curve should presumably be the "Sears function"[70], and in fact does seem to be an approximation to that well-known result; just as the corresponding curve of Figure 14 behaves as "Theodorsen's function"[71].

Napolitano raised the query of whether a stochastic approach to the problem of aircraft inlet flow fluctuations could be used: if the fluctuating input frequency spectra were continuous rather than showing discrete frequencies, the system response characteristic could still be linear.

The problem of interference between jet exhausts and the wing was considered in transonic and subsonic flow by Mikkelson[13] and Kutney[16] respectively. The transonic work concerned some wind tunnel and full scale flight tests on an F-106 aircraft to which underwing nacelles were attached. The favourable effect of underwing position reduced nacelle boat-tail drag, but as no overall configuration drag data were shown, it might be misleading to assume that the total drag had indeed been reduced. The effect of the diversion of the wing boundary layer about each nacelle pylon was not mentioned specifically, and any three-dimensional separations generated there could have an effect on the viscous flow on the external surfaces of the nacelle.

The interference effect of the nacelle and pylon was favourable on the wing pressure field upstream of the intake but largely unfavourable downstream of the inlet

capture area, leading (presumably) to pitch-up. It should be possible to tailor the wing section design using supercritical aerofoil sections, for example, to yield an improvement in positive pressure coefficient all along the wing underside, but not steep enough in gradient to cause boundary layer separation.

Corresponding wind tunnel and flight tests with cold and hot jets demonstrated large differences in nozzle gross thrust coefficients plotted against flight Mach number[13]. The necessity to simulate nacelle flows correctly was thereby introduced and Kutney[16] and Aldrige[23] hammered home this point throughout the meeting. If the wind tunnel flow field about a 'fan engined' nacelle and wing was to simulate effectively the full scale counterpart, Kutney showed that it was necessary to set up the correct pressure ratios in the fan and turbine effluxes. A small gas turbine engine simulator (where the turbine was driven by an external source of compressed air) was shown to advantage over through-flow nacelles or induction type devices, particularly with respect to the under wing pressure field. The inlet flow was still not matched correctly, however, so that the upwash close to the wing leading-edge was inexact.

Runckel[15] presented a large number of wind tunnel test results to examine aircraft afterbody and engine nozzle interference at subsonic, transonic and supersonic speeds, in terms of the gross thrust minus nozzle drag, ratioed to isentropic thrust. The care that must be taken in treating the boat-tail angles, base areas and approaching viscous flows was evident, but although most of the results were for a common forebody, one was left in doubt whether the same results would be obtained once a complete airframe were added.

Airframe propulsion from the point of view of the civil aeroplane was discussed first of all by Armstrong[19], who presented an up-to-date NGTE design analysis of two-dimensional supersonic intakes similar in most respects to those fitted to Concorde, but did not comment on the effects of the underwing flow field about such an installation. Reference 72, in fact, provides some of these interesting details: viewed in plan, the intake nacelles possess a banana-like curvature to take account of the underwing sidewash. The optimising of the drag of the bicusped-type boundary layer diverter between the intake and the wing was also discussed[72]; it was shown that it was only necessary to divert about 70 per cent of the undisturbed boundary layer depth, leaving the outer boundary layer to progress along the intake ramps to be controlled at the intake throat.

Paper 19 presented how the external drag of the intake was assessed at both supersonic and subsonic cruise Mach numbers. The supersonic drag was split into pre-entry drag caused by the loss in momentum between the freestream and the intake capture plane, and the drag associated with the pressure on the external forward facing cowl surface. In the event of no substantial side spillage, either schlieren observation or measurements of the intake mass flow coupled with ramp static pressures enabled the pre-entry drag to be computed, while pressure measurements on the cowl surface allowed the drag associated with the latter to be deduced.

Depending on the method of assessment, the sum of the pre-entry plus cowl drag at about Mach 2 for the four intakes could be measured to an accuracy of about 5 drag counts near critical mass flow operation (based on Concorde wing area). This accuracy is important to keep in mind when a 1% increase of aircraft drag at supersonic speeds is equivalent to a 4½% reduction in payload[72]. Finally, an excellent feature of the written paper 19 was an acknowledgement of the effects of viscous flows, particularly the internal three-dimensional boundary layers on the intake sidewalls, and the improvements in intake and subsonic diffuser performance with testing at representative flight Reynolds numbers.

The arguments concerning the choice between two-dimensional and axisymmetric intakes, have been resolved as far as Boeing is concerned, in favour of the axisymmetric type on their Mach 2.7 supersonic transport aircraft. The paper by van Duine[20] sought to explain the flow in the vicinity of the underwing engine nacelles, and the elemental drags associated either with a dual engine two-dimensional pod, or two separate single engine axisymmetric pods. The final summation indicated that the two-dimensional engined aeroplane would yield a reduction in range over the axisymmetric podded type of almost 2% at Mach 2.7.

The disturbing feature of this otherwise very informative paper was the poor description of the underwing boundary layer flows, which were not identified as three-dimensional. In addition, the three-dimensional separations generated by the conical inlet/boundary layer diversion shock systems interacting with the wing boundary layer (and which were shown on a surface oil flow photograph) were discussed only in terms of "the general extent of pod-induced pressure fields...". The interpretation of the unstarted intake shock/boundary layer interaction flow was another cause for concern, for the context of three-dimensional viscous flows was again omitted altogether, all of this being surprising in view of the correspondence of Reference 73. As the inlet shock/wing boundary layer interactions of the axisymmetric pod type flows would appear to be worse than with a suitable two-dimensional intake installation (such as on Concorde), would the drag associated with the three-dimensional separations therefore dispute the answer on range performance that was in favour of the axisymmetric inlet?

The mounting of powerplants adjacent to a rear fuselage on a high subsonic speed transport aircraft was next introduced, with specific reference to the BAC VC-10 and 1-11 aircraft. Williams[22] presented the reasonable agreement between wind tunnel and flight measurements that was obtained between the supercritical pressure distributions on the fuselage close to the engine support strut, where shock waves and viscous flow separations were in evidence. The effects of changing the fuselage length, nacelle

setting and shape of the rear fuselage were also discussed, where it was decided that at lower Mach numbers it was of more benefit to carry lift on the wing rather than on the nacelles and rear fuselage; however, as the Mach number was increased, some of the wing lift should be transferred to the nacelles and rear fuselage. One point of query immediately arises with reference to the discussion of Kutney[16] and Aldrige[23]. The nacelles in paper 22 appeared to be of the throughflow type - rather than the type with engine 'simulators'. Would an improved nacelle flow simulation have significantly changed any of the conclusions of paper 22?

Aldrige's paper[23] provided an interesting comparison with the previous work, for he reported the results of wind tunnel testing a high bypass ratio turbofan engine attached to a wing via a pylon, using the engine simulator previously introduced by Kutney[16]. The presence of the nacelle had no measurable effect either on the wing upper surface pressure distribution or around the leading-edge. At a typical $\alpha = 6°$, Mach 0.6 flow condition, however, the attachment of the nacelle produced gross changes in the underwing flow field, along the fan nacelle and turbine cowl and along the pylon, when compared with separate component tests. The acceleration of the flow caused by the passage area convergence between the nacelle and the wing increased the negativeness of the underwing pressure distributions, and increased the chord-wise adverse pressure gradient downstream of the suction peak. Increasing the power of the engine simulator decreased the interference drag increment at a given lift coefficient, although the effects of power were diminished as Mach number increased from 0.6 to 0.725. The fan nozzle pressure ratio was less than for choking at the lower Mach number but was choked at Mach 0.725. There appears to be one difficulty with powered engine simulators, and that is one of data precision. If a single balance is being used to assess the forces on the wing, pod and nacelle together, it is being loaded toward a null condition as thrust is increased. Balances, enabling the force components to be measured on individual configuration elements, would presumably be a solution, but at the expense of additional complexity.

If an aircraft tailplane is situated in the jet efflux emanating from a wing-mounted pod, Wulf[21], using a model of the European airbus, demonstrated that there was a large destabilising influence at the tailplane due to the additional downwash field created by the jet. Movement of the engine outboard along the wing remedied the situation.

3.3 AIRFRAME/STORES INTERFERENCE

The high cost of today's military aircraft demands that an airframe be capable of carrying a pot-pourri of external stores and weapons usually to be mounted beneath the wings. Substantial penalties in aircraft performance are often incurred as a result, notable among which are a decrease in longitudinal stability and an increase in drag, the latter materialising as a quid pro quo reduction in range. Conspicuously lacking in the papers, however, was any discussion on the mutual interferences between several stores adjacent to one another beneath a wing, all of the papers dealing essentially with a single unit hanging from a pylon. Pylon design itself received little attention, while Taisseire[29] was the only author who deliberately demonstrated (on film) the overall three-dimensional viscous flows around and downstream of the store's proximity to the wing. Moreover, since the interference effects posed by a store and an engine nacelle are not dissimilar, it was surprising that both problems were not viewed in the same light.

To place the drag problem of store attachment in perspective, it is instructive to first of all refer to a paper written by K. King[31], because it encompasses most of the topics raised in the remaining papers on airframe stores. King's contribution described selected flight tests to determine the drag of jettisonable stores - without the requirement of knowing engine thrust, itself a difficult measurement. Essentially the method was to evaluate the store drag from the change in aircraft acceleration along the flight path at the time of and subsequent to the dropping of the store. Due to the sudden change of mass at store separation, the aircraft incidence, pitch rate, attitude, and accelerations longitudinal and normal to the flight path all changed, so that the aircraft drag also changed.

Using sensitive instrumentation to measure the variations in aircraft attitude, the change of aircraft drag was assessed from the flight path force equation. The drag penalty due to the external stores, consisting of the drag acting on the store itself plus the drag induced on the aircraft by the store's presence, showed no systematic variation with either Mach number (up to Mach 0.66) or lift coefficient, C_L. Nevertheless, the second element of this drag penalty did vary linearly with C_L^2. One should note at this juncture, that the term 'interference drag' is conventionally used to mean the difference between the <u>total installed drag</u> of the store on the airframe and the drag of the <u>isolated store in a uniform oncoming flow</u>. This context will be implied in the succeeding remarks, rather than the 'drag penalty' defined above.

Assuming zero lift on the store, the RAE work[31] demonstrated good agreement between calculation and flight test of the early development of the store trajectory in proximity to the airframe.

The inviscid flow field beneath the swept wing of a conventional fighter-bomber is three-dimensional by design, so that the sidewash and upwash distributions generated by the 'clean airframe' at the <u>location where the store would be hung</u> formed essential constituents of the three calculation procedures proposed individually by Grose[28], Fernandes[33] and Nielsen[26]. Grose[28] using Woodward's compressible, linear theory (for wing-body combinations), wherein line and distributed singularities were utilised to

simulate both lift and thickness effects of components, calculated the strong outboard sidewash at aircraft angle of attack in subsonic and supersonic flow. The prediction of pitching moment on a store, either isolated or adjacent to the airframe, showed better agreement with test than did the calculation of normal force, where non-linearities were presumably attributable to three-dimensional viscous flows on the store.

The effect of pylon thickness, omitted in Grose's programme, was judged to be particularly important by Taisseire[29] and Fernandes[33]. Paper 29 exposed the decrease in longitudinal stability that was caused by the wake of the pylon and the store interfering with the tailplane of the aircraft (compare with the nacelle efflux decreasing the longitudinal stability in paper 21). The particular culprit was assessed as the vortex wake from the pylon trailing-edge and the junction three-dimensional separations, as a result of the pylon's effective incidence in the wing sidewash field. At low C_L, a low mounted tail indicated a larger loss in longitudinal stability with store on than did a high mounted tail. However, this trend reversed as C_L increased, because now the high tail was blanketed by the wing wake. One remedy was to move the store outboard, as in the case of the engine nacelle[21].

Fernandes[33] proposed what appeared to be a more sophisticated subsonic, compressible, linear theory, where the pylon thickness envelope was included. The aircraft propulsion inlet situated on the fuselage was also inserted, but no spillage was allowed. The effects of the fuselage forebody and wing/fuselage junction were assessed as insignificant and ignored in computing the inviscid flow field at the underwing store location. Virtually the same aircraft planforms were assessed by Grose[28] and Fernandes[33]. As the store traversed forward along its (20-ft) rail, the large changes in aircraft pitching and yawing moments that were observed, varying from negative to positive, were predicted by the analysis. Canu[25] also reported the same pitching moment changes but showed, moreover, that the pitching moment also depended strongly on Mach number.

The components contributing to the flowfield in Nielsen's analysis[26] were synthesised from fuselage volume; fuselage angle of incidence; wing angle of attack, camber, twist and thickness; wing/fuselage interference and external store volume. The fuselage volume effect was handled by placing point sources along the body axis, whose strengths were forced to satisfy the boundary condition on the body surface, while the additional flowfield due to incidence was treated with slender body theory. A vortex lattice simulated the wing.

Generally good agreement between experiment and analysis was achieved for local angle of attack and sidewash at semi-span underwing locations, with the store and pylon removed ('simplified method'). The prediction of normal force and pitching moment on the external store in this non-uniform flowfield was moderately successful by comparison with experiment but would presumably have been improved if the true effects of three-dimensional separations could have been provided. The treatment of wing/store/pylon interference ('improved method') was discussed but was not compared with experiment. The integration of the equations of motion, using the forces and moments obtained above with the 'simplified method' then determined the store trajectory satisfactorily.

The experimental measurement of the underwing sidewash field approaching a representative store mounted beneath a swept wing was also discussed by Berry[27], with particular regard to the side force on the store and pylon, and their drag increments. The forces on a single store in sidewash were calculated using empirical methods developed by ARA, Bedford, and were found in good agreement with experiment when the store was about 0.8 of the local wing chord length. As the store length increased, the agreement deteriorated. Drag divergence of an aircraft plus a pair of stores occurred at a Mach number typically 0.15 lower than for the clean aircraft.

Furey[34] sought to promote the use of unconventional half-stores mounted with their flat surfaces flush with a fuselage underside, at subsonic and supersonic Mach numbers. According to the author, the halving of a store already mounted close to the airframe (without pylon) and the flush mounting of the half-stores thus obtained, yielded a drag decrease "as the result of immersing a larger percentage of the store in the low energy fuselage boundary layer". Totally absent in this paper was any interpretation of the three-dimensionality of the fuselage boundary layer, or in fact, its separation from three-dimensional separation lines. A more satisfactory explanation is, that by comparison with the whole store, the half-body induces a less severe adverse pressure gradient on the oncoming fuselage boundary layer because of its increased slenderness. The severity of the protuberance three-dimensional separation region is thereby reduced, and as a direct consequence, the drag is lower. Some sample oil flow visualisation tests in the wind tunnel would have provided the necessary skeleton around which to have built an appropriate flow model.

No evidence[34] was provided to prove that half bodies would make good bombs or missiles, although the author "found it reasonable to assume" that fins could be designed for adequate control. The reliance on the longitudinal characteristics of the relatively low slenderness ratio lifting body shapes as representative of the very slender half stores would appear to be unjustified.

The danger of collision with the airframe or with the stores themselves in the jettisoning of external and internal stores[30] formed the subjects of papers by Kalivretenos[35] and Holloway[30]. The latter author provided a thoroughly entertaining thirty minutes on the stacking distribution of bombs in a bomb bay, to provide the minimum of dispersion at a target. If the top of one bomb just released was not just below the

bottom of an adjacent bomb (when the latter in turn left the guide rails) the mutual suction pressure fields between the bombs caused them to collide, and set off a chain-reaction of further collisions. The rear bombs in particular were affected by the upwash in the bomb bay.

The devastating effectiveness of concentrated bombing was vividly displayed on film. If two-dimensional concepts of boundary layer separation could be annihilated as easily with respect to junction and most configuration problems, then an improved physical understanding of the three-dimensional flow fields would assuredly result.

4. ROUND TABLE DISCUSSION

The third and final day of the conference ended with a Round Table discussion whose purpose was to summarise the formal and informal presentations and offer recommendations for work in the future.

Gersten commenced the discussion by outlining the sequence of calculations that one would hopefully apply to a wing-body combination or a complete configuration in incompressible flow. The treatment of the inviscid flow could be accomplished by means of a discrete element method, several techniques of which appear promising (see A.M.O. Smith[38], Carmichael[4] or Loeve[11]) but taking particular care to include the Kutta-Joukowski condition at all sharp edges. Once the outer solution were known, and with the possession of a three-dimensional turbulent boundary layer calculation scheme (perhaps a modified form of Nash's turbulent energy method with longitudinal and transverse curvature included) the viscous flow could be predicted up to a three-dimensional separation line. The free shear layers emanating from the three-dimensional separations should then be considered and their effects upon the remainder of the configuration downstream. Knowing the displacement surfaces, and with an appropriate inviscid model of the rolled-up shear layers (not currently available for an arbitrary three-dimensional flow) the inviscid flow calculation could then be repeated. Loeve commented that because the control points on the surface elements were always set at a certain distance away from sharp corners, the singularity at the corners provided no difficulty. Numerical experiments had been attempted at NLR which proved that the source density approached zero as the corner was approached, implying that the finite element solutions were physically meaningful. In general, a complex aircraft shape that would require many hundreds of discrete surface elements for its description, still cannot be dealt with because of insufficient computer storage even with today's advanced computers. The potential of the finite element methods, with the appropriate refinements mentioned above, is probably greater than the pursuing of sophisticated approximate methods.

Küchemann agreed in principle, but was convinced that approximate methods, based firmly on good physical models, would always yield quicker solutions. He picked on two main features of the conference: the overwhelming use of computers to provide answers, and the design problem. The former had produced a confusing "fuzz" surrounding the problems of Kutta-Joukowski "conditions" and aerodynamic interference, the remedy for which was perhaps a water tunnel to be delivered with every large computer, so that a reliable physical flow model could be developed on which to finally base a computer programme! There was nothing more practical than a good theory of design, few of which had been forwarded at the meeting, and which could be used in practice and applied by industry. It was of no particular benefit to indulge in the computation of the flow about ad hoc aircraft geometries for they might all yield a disappointing performance.

With respect to propulsion matters, the design of an isolated intake is tuned to the greatest detail, but when placed adjacent to an airframe, is expected to perform by just managing the diversion of the local oncoming boundary layers. Insufficient attention is paid to the local three-dimensional inviscid and viscous flows. Hence during any forthcoming rational design procedure, the immediate flow environment to the fuselage forebody, wing and tail, plus the propulsion nacelles, should be considered overall as an integrated problem.

Young questioned whether an inviscid flow model which would even approximate a lifting wing/body combination that generates a trailing and curved vortex wake - these undoubtedly deriving from the three-dimensional boundary layers - could be approximated with adequate accuracy for the purposes of engineering design. He felt that there was a long way to go before a correct flow model would be available and therefore a case upon which our numerical equipment could begin to work to yield results that were meaningful and in which some confidence could be placed.

It was recalled that the Stanford meeting, in its assessment of two-dimensional incompressible turbulent boundary layer computation schemes, showed what appeared to be the relative merits of the latest calculations compared against the same set of experimental results. Should we then, in the light of that successful experience, plan in two or three years time to compare the various methods of calculating junction flows against a good set of accurate test results? Or would it be preferable to try a simpler flow case, an ellipsoid at incidence, for example, to test the various theories? It did appear that certain of the methods demonstrated at the meeting tended to "fudge" the answers, and contributed to the "fuzz" about which Küchemann complained.

Shaw commented that theoreticians will produce appropriate methods that may be developed into design tools; but that the aircraft project people deliver to him the aircraft requirements. From these, according to some mystical process, he is supposed

to extricate the most desirable isobar plot on the wing and in the root coupled with the thickness distribution and leading edge contour, that yields the correct peak pressure distributions, ... and the rest of the answers! Some effort in parallel to the development of design methods should proceed, therefore, to outline criteria for design.

Pavelka admitted in the main, that the designer resorted to wind tunnel testing as an indication of the design criteria required in a given job. Because of testing under low Reynolds numbers, the viscous flows in the junctions were frequently not simulated correctly, and the wrong results were produced. The effects of wake and efflux flows on the configuration were important and were not discussed in much detail at the conference. Kutney continued on this theme, and recommended that the integrated configuration must be assessed rather than the components in isolation. Nielsen countered that the same remarks were applicable to stores. For example, as Küchemann insisted, if the propulsion nacelle affected the flow field near it, surveys of flow fields without the inlet may not be useful. The most relevant means of propulsion simulation must be used, and 'power on' measurements must be conceived in wind tunnel testing if the correct thrust minus drag answers are to be obtained. Wind tunnel programmes involving propulsion simulators appear to yield drag and thrust data to an accuracy of one per cent as against three per cent in flight, so that the simulator shows that the 'flight answer' can be obtained in the wind tunnel.

The engine/airframe integration problem was not just one of hardware integration as Williams saw it. It was often an 'off design' problem as the major offenders against realising predicted performance were usually extensive regions of separated flow.

Nielsen leant towards the use of approximate methods to realise good engineering answers to the problems of wing/body and store interference. The use of modern aerodynamic theory coupled with digital computers for rapid execution of the arithmetic can enhance the understanding of interfering flow fields. Such methods were required for it was obviously uneconomic to test all possible permutations and combinations of a design in a wind tunnel. It was, moreover, not unexpected that the range and maximum performance of a particular aircraft would deteriorate substantially when "garbage" was hung on the airframe, because in the design of the aircraft, the integration of stores with the airframe was not usually considered. Nielsen was against a contest between the calculation procedures as advanced because the state of the art was not highly developed. When it was, it probably would then not be important because the better calculation methods would all give solutions sufficient for engineering accuracy. Küchemann agreed, pointing out that for some laminar boundary layer cases, exact solutions can be provided against which to check approximate methods. And this might still be feasible for two dimensional aerofoil sections, whose solutions are known. But no exact solutions were available for an arbitrary three-dimensional aircraft configuration, and hence international competition amongst calculation schemes was not warranted. More analytical work should be concentrated upon the destabilising effect of stores, and the interference problems in transonic flow. But from the overall design point of view, adequate attention should be paid to the integration of the airframe, stores and power plants.

Seddon disagreed with some previous speakers, querying the dangers inherent in the application of airframe integration procedures, for one was then deprived of the versatility of attaching new weapons to an old airframe. Once integrated, the adaptability to carry an alternative store was lost. The same remark might be set against a too highly integrated propulsion system as well. The higher the degree of integration to absolve the system from interference problems, the less the development potential remained in the resulting configuration. Seddon agreed with Nielsen that a balanced approach to the problems under discussion was essential, as apart from the building of appropriate overall theories, parallel approaches along experimental lines, and empirical methods, were still invaluable. He was disappointed that a picture had not emerged from the meeting in respect to where the major problems were in the whole panorama of interference effects. Where should the experimental efforts be concentrated - for with experiments, the three-dimensional viscous and compressible flows with shock waves may be dealt with immediately.

In summary, Zonars wondered whether from a joint standpoint, a specific configuration could be identified and the various analytical techniques be applied to it. Could there then be a critique of results prior to experiment? He considered that blended aircraft/store configurations would probably never be used, and insisted that more attention be paid to the physical aspects of the flow, particularly the three-dimensional viscous flows.

5. CONCLUSIONS AND RECOMMENDATIONS

In greater part, the meeting should be considered successful, especially as good attendance and participation was provided by members from both the United States and European aircraft industries - although little in the way of new design methods was revealed either by industry or research establishments.

The meeting demonstrated the lack of comprehension by many, of the physical aspects of three-dimensional boundary layers and separations, yet these contribute significantly to the flows in those regions where components of a configuration are joined. More support is necessary for work on three-dimensional inviscid and viscous flows, whether at design or off-design, and particularly in the transonic régime. At the same time, the search should proceed for rational design methods, design criteria, and the continued development of the finite element calculation methods, with the

Kutta-Joukowski condition included realistically at all sharp edges.

The major advance at the meeting was probably the treatment by Loeve of a lifting wing/body combination, where for the first time, a sheet of trailing vorticity from a wing was coupled with the finite element method of A.M.O. Smith.

If there was one recommendation, it was to the effect that a calibration model of a wing-body combination be chosen, against which to check the various computation schemes available. Concurrently, some high Reynolds number wind tunnel tests should be conducted to provide details of the junction pressure distributions and the three-dimensional boundary layers and wakes.

Lest the reader feel that a saturation bombing technique has been applied to emphasise three-dimensional viscous flow effects, a comment of Nonweiler[74] is perhaps appropriate in this, the closing paragraph: "in case I've trodden on any corns, let me say that I know my prejudice is inexcusable. In aircraft design, we have in the past, specialised too much - we mind our own business and let others mind theirs. The aerodynamacist supplies the C_L, and the propulsion expert the C_T, while the design man hangs the two together. Ultimately, design must be simplified into an amalgam of lift, thrust and strength ...", but we should always remain aware of the three-dimensionalities involved.

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1	D. Küchemann	Some Remarks on the Interference between a Swept Wing and a Fuselage
2	F.R. Grosche	Wind Tunnel Investigation of the Vortex System near an Inclined Body of Revolution with and without Wings
11	T.E. Labrujere, W. Loeve, J.W. Sloof	An Approximate Method for the Calculation of the Pressure Distribution on Wing-Body Combinations at Subcritical Speeds
5	J. Bridgewater, R.C. Lock, G.F. Lee	Theoretical and Experimental Investigations of Wing Body Configurations at Low Supersonic Speeds
4	R. Carmichael	Recent Experience in Using Finite Element Methods for the Solution of Problems in Aerodynamic Interference
6	W.J. Bannink, J.W. Reyn	Lift and Drag Characteristics of Delta-Wing-Half-Cone Configurations with Subsonic Leading Edges, Using Slender-Body Theory

SESSION II - WING-BODY-TAIL;- Chairman: Mr. P. Carrière

3	E.J. Kane, W.D. Middleton	Considerations of Aerodynamic Interference in Supersonic Airplane Design
7	G. Gregoriou, J. Laude	Downwash Investigations on Tails of Missiles
8	B.L. Shrout	Extension of a Numerical Solution for the Aerodynamic Characteristics of a Wing to Include a Canard or Horizontal Tail
9	M. Enselme, J.P. Boisseau, A. Guillois	Calcul d'Interactions Aérodynamiques entre les éléments Portants d'un Avion en Ecoulement Supersonique Stationnaire ou instationnaire
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12	A.E. Winkelmann	Aerodynamic Interaction Phenomena Produced by a Fin Protuberance Partially Immersed in a Turbulent Boundary Layer at Mach 5

SESSION III - AIRFRAME PROPULSION (Military Aircraft);- Chairman: Dr. J. Seddon

14	D.J. Peake, D.J. Jones, W.J. Rainbird	The Half-Cone Pressure Field and its Significance to Side-Mounted Intakes
18	L. King, T.W. Schmidt	Studies of Aircraft Flow Fields at Inlet Locations
17	B.H. Goethert, K.C. Reddy	Unsteady Aerodynamics of Rotor Blades of a Compressor under Distorted Flow Conditions
15	J.F. Runckel	Aerodynamic Interference between Exhaust System and Airframe

13	D.C. Mikkelson, B.J. Blaha	Flight and Wind Tunnel Investigation of Installation Effects on Underwing Supersonic Cruise Exhaust Nozzles at Transonic Speeds
16	J.T. Kutney	Airframe/Propulsion System Integration Analysis Using the Propulsion Simulator Technique

SESSION IV - AIRFRAME PROPULSION (Transport Aeroplanes);- Chairman: Dr. U. Sacerdote

19	M. Neale, F. Armstrong	Some Recent Research on Supersonic Intakes at NGTE
20	A.A. Van Duine, W.W. Rhoades, W.C. Swan	Configuration Aspects of Propulsion Installation on Supersonic Transports
22	P.R.G. Williams, D.J. Stewart	The Complex Aerodynamic Interference Pattern due to Rear Fuselage Mounted Power Plants
23	S.E. Aldrige, J.L. Nye	Experimental Results of High Bypass Ratio Turbofan and Wing Aerodynamic Interference
21	W. Geissler, R. Wulf	Jet Simulation and Jet Interference Effects on Tailplane
24	J.L. Hess, S.M. Faulkner	Determination of Low Speed Interference Effects by Superposition

SESSION V - AIRFRAME STORES I;- Chairman: Prof. J.A. Steketee

25	J. Christophe, J. Coste	Etude en Soufflerie des Interactions Aérodynamiques dues aux Charges Largables
27	J. Berry	Examples of Airframe-Store Interference
33	F.D. Fernandes	A Method for Predicting Interference Forces and Moments on Aircraft Stores at Subsonic Speeds
28	G.G. Grose, D.R. Bristow	Evaluation of the Prediction of Airplane/Store Interference by Linear Theory
29	R. Taisseire	Analyse de l'Influence de Charges Externes Fixées sous la Voilure d'un Appareil à Aile en Flèche sur la Stabilité Longitudinale de cet Avion
31	K. King	Flight Investigation of a Technique for the Measurement of the Total and Interference Drag of External Stores

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26	J. Nielsen, F. Goodwin, M.F.E. Dillenius	A Calculative Method for Predicting Store Separation Trajectories at Speeds up to the Critical Speed
35	C. Kalivretenos	Aircraft/Store Interference
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