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12. FUTURE NECESSARY WORK

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> ***„They're difficult things, wind tunnels, aren't they!"***
> ***Pat Ashill, 17 January, 1995***

12.1 INTRODUCTION

The subject of wall interference dates back over 75 years. Developments in understanding and in methodology of applying wall corrections have more or less kept pace with progress in developmental testing of aircraft to the point that wind tunnel test programs, in general, have not come to grief for want of a better method. The future is changing and, as competition heightens the need for higher quality data to reduce uncertainty (e.g., in predicted performance), we discover more and more that wind tunnels are indeed *difficult things*. This is particularly true when testing models of large size either at highly loaded conditions or high subsonic speeds. Assessing and correcting test results from these large models for wall interference effects to provide a data accuracy commensurate with the objectives of the test is particularly challenging. Validation of any method of correction to be used is always of consideration. Measurement accuracy, numerical accuracy and accuracy in capturing the essential physics of the flow are concerns. Linear-theory based corrections, although highly useful, are increasingly becoming insufficient as are Euler methods, even when coupled with integral boundary layer representations of viscous effects. Further, the need to include details of the tunnel empty flow field, the tunnel geometry (especially the down-stream features), and a representation of the wall boundary conditions that is sufficient to capture the essential viscous features is becoming more apparent. The foregoing chapters of this report have provided the reader with an excellent reference source concerning current wall interference technology as well as a systematic approach to selecting an application. The question as to What Next? naturally arises. The following discussion is an attempt to address some of the issues which have come to light in this regard.

12.1.1 NEAR TERM OBJECTIVES

Near term objectives are considered as those objectives that are achievable now with current capability and that provide a measurable improvement in wall interference prediction and control. Therefore, by definition, these objectives are the ones that should be worked now. The need to continue working wall correction issues is self-evident to those working this discipline. It is not always self-evident to others who should be aware (e.g., test engineers, managers, etc.). To help put the need to develop and use wall-corrections in proper focus for all affected parties, it is suggested that an activity be undertaken to develop a measure of benefits to be derived from wall interference technology. Such benefits should be presented in customer-important terms such as reduced uncertainty in global quantities (Mach number and angle of attack), distributed distortions (induced velocity vector), and a measure of impact on force coefficients (historical results for specific cases tested). Failure to properly appraise the potential customer has an impact of the ability of work the discipline of wall corrections. For instance, to develop wall correction technology requires a funding source which either must come from some form of general overhead, or be a direct charge to each test in addition to the cost of utilisation of wall correction capability. Thus, in the case of direct charges, the customer who will be the recipient of the corrections will be presented with a range of cost choices depending on what corrections, if any, are utilised. Unless the customer becomes accustomed to supporting these costs and understands the accrued benefits, the services will be under-utilised. In consequence, the budget allocation for wall interference development work is jeopardised. These cost considerations argue for a method of demonstrating that the benefits of having and applying wall corrections outweigh their cost. Mounting economic pressures on institutional activities which seem to be globally typical within the testing community indicate that being able to show benefits against costs is an urgent near-term need.

The preceding chapters of this report serve to bring the reader up-to-date on the technology of wall corrections. They also indicate how complicated wall corrections can be. And, as detailed in Section 12.2, there can be unresolved issues, even in classical methods. A particular example concerns drag increments due to tunnel-induced gradients. A new formulation has been applied successfully to bluff bodies (see Hackett [15] and Chapter 6) yet it conflicts with the classical result of AGARDograph 109 and with the result given in Chapter 1. Since Hackett's derivation is general and produces similar results to the accepted treatment of Maskell, this creates an issue for resolution in the validation for use of the methods in question. The topic is discussed further in Section 12.2.

Testing and user organisations have very few people who have conversant knowledge of data corrections in general and wall corrections in particular. Consequently, there is a community need to instill expertise in wall correction methodology in new personnel. An advocacy position is needed as well as a structured approach to becoming conversant in the wall correction methodology. The preferred media would be some form of "expert system" that employs "computer-aided" techniques for one to become self-taught along with access to a collection of "user-friendly codes" and data bases for computing or estimating wall corrections. Further, such media should have a means for growth to rapidly and efficiently incorporate new information. A simple form of the implementation of this concept is an electronic version of this report utilising an appropriate introduction, including terminology and a summary of benefits indicated above. The references contained herein along with the general discussion can then direct the user to specific sources for further consideration.

Regarding correction methodology, economic considerations call for corrections that are fast to produce and cost-effective. The implication according to Lynch, et al, is "... a collection of methods and techniques with various amounts of empiricism specialised for certain types of tests and specific kinds of wind tunnel walls and testing ranges." Having such a "collection" implies a method for cataloguing as well as a means for adding to the collection. The view taken here is that such a collection would not just be a compendium of various schemes with an assessment for each scheme, but would also include either reference to a specific code or data base or access to the actual code and/or data base as well. It is proposed that in the near-term, a standard means of assessing the range of applicability (model and tunnel configuration, Mach number, attitude, Re, etc.) be developed for verifying wall correction methods and data bases and, where permissible, the originator of the method (including any code) and custodian of the data base make the information commercially available. Notification of the method or any data base information should be accomplished through appropriate media (AGARD, GARTEUR, STA, SATA, AIAA, ASME, etc.)

Global competition for new aircraft forces the designer to work all technology areas that could contribute to higher quality performance predictions There are numerous error sources affecting high quality predictions.

Many of those error sources were discussed in AGARD AR-304 [1]. This document is focused on only one of those error sources, wall interference, which can be a major contributor to data uncertainty. A better understanding of wall interference is very desirable, particularly as model and model support sizes are increased to maximise Reynolds numbers for a given test facility and as testing speeds are increased toward sonic conditions. It is particularly important to be able to make a trade-off decision between model size for increased test Reynolds number and accompanying increased wall interference. Work is required in the near-term to quantify the gains in Reynolds number benefits versus the losses due to increased wall interference. The "indefinitely-postponed" US National Wind Tunnel Complex (NWTC) program is a recent example where emphasis was placed on maximum model size.

A key thrust of the NWTC program was to provide new test capacity for aircraft development that would include high Reynolds number, high data quality, high productivity at data costs consistent with today's costs and high through-put (tests per year). Originally, the NWTC program was to provide a complex of two wind tunnel facilities that would cover both low speed and transonic speeds up to Mach number 1.5. One of the NWTC constraints was to be able to test models up to 80% of the applicable test section dimension so as to maximise Reynolds number for a given stagnation pressure and temperature. Owing to the goal of high data quality, strong consideration was given to the design of the test section for minimising wall interference as well as correcting for wall effects. Cost and productivity considerations constrained the design to a passive slotted test section with segmented throttle segments for each slot as opposed to a fully adaptive configuration. Sickles and Steinle [30], using a linear porous wall boundary condition for a large MD-11 type model in the proposed NWTC test section sized to this criteria at Mach number 0.85 test conditions, showed that, depending on the method for correcting the test results and establishing the wall setting (porosity distribution and side-wall divergence angle), the lift, drag, and pitching moment corrections as well as global corrections to Mach number and angle of attack could be very small. This result, although promising, is not conclusive since an Euler method was involved. Viscous effects can significantly change the magnitude of corrections. To properly evaluate the net increase in quality of test results through higher test Reynolds numbers achieved by increased model size, the accompanying losses in quality associated with increased wall interference effects should be assessed with a method that includes viscous effects.

As the maximum size of the model and its support system grows with respect to the tunnel, the details of the flow-field between the model and the wall and both the upstream and downstream boundary conditions become more important for proper prediction of the wall corrections. Further, both wall geometry and tunnel operational mode affect the flow about the model. Prior work of modelling wall boundary conditions is a good start. However, there is opportunity for improvement in the near term as will be discussed in section 12.2.

Many facilities today are undergoing upgrades to improve flow quality; but, little is being done to reduce the magnitude of wall interference in those facilities. Considerable activity has been going on for over a decade aimed at developing adaptive wall capability that theoretically offers the best technical solution for reducing wall interference. However, issues of productivity and maintainability are detractors. Other forms of variable walls that are limited in adaptive capability such as global-adaptation and passive-adaptation (pre-settable or controllable cross-flow resistance) offer less complex solutions that are not technically as good as fully adaptive walls, but are superior economically (capitalisation and productivity-driven.) For any form of adaptive walls used, a simplified method of computing wall settings in advance of the test will greatly ameliorate productivity issues. Regardless, near-term improvements or developments aimed at these more modest productivity issues. Regardless, near-term improvements or developments aimed at these more modest goals will lay the foundation for even the more ambitious far-term goals. Both computational and experimental work aimed at the next generation large-scale, highly-productive test section, is sorely needed.

12.1.2 Far-Term Objectives

No end is seen to the competitive forces that have provided the impetus for wall-correction work. Economic pressures for "cheaper, faster, and better" are fully expected to result in far term (say, 20 to 25 years from now) objectives closely resembling near-term objectives in most respects. However, in the far term we will see technological improvements that will enhance the testing process and data quality that can affect both adaptive and passive wall tunnels. The capability of the computational resources is expected to improve dramatically: grid generation - substantially; code efficiency - significantly; and fluid-mechanics models (e.g., turbulence model, shock/boundary-layer interaction model, shear layer mixing, boundary-layer separation criteria) somewhat. With sufficient increase in computing power, Euler solutions with coupled integral boundary layer solutions may well be done on a desk-top size computer in seconds. Navier-Stokes equations may be computed in minutes. Further, we will have the benefit of the work in the near-term in areas such as model geometry definition, in-tunnel measurements (model and flow field parameters), wall correction methodology, basic CFD, etc.

Assuming the above technological advances and probably a moving test data quality target that will only be stopped if computational capability is ever fast enough, accurate enough, and affordable enough to obviate the need for wind tunnel testing, what should we plan for the far-term? The general idea is to keep on with continuous improvement consistent with experimental and computational capability (as long as they are cost-effective) until such time that the residual data uncertainty after wall corrections is negligible. Whenever an improvement in a solver, or a computer system is realised, the wall correction methodology that is affected should be verified. Planning should be initiated for what changes would be made in methodology for, say, each order of magnitude improvement in computational capability and then move in that direction when it occurs.

The role of the wind tunnel is expected to change with time. One view is the wind tunnel will only be required for code validation. Another view is it will still be required for product development and basic research as well as code validation; but, there will be substantial changes to what is tested and what measurements are required. Regardless of the change, the desire for high quality test results points toward elimination of wall interference to the maximum extent practical and correction of any residual wall effects. There is no change here from what is desired today. However, to be able to achieve this goal in a highly productive fashion probably resides in the far term. The far-term goal that is suggested is to strive for the capability to either compute real-time wall corrections with confidence or to support highly-productive fully-adaptive wall capability (e.g., two seconds per data point). How much growth in computational capability might be required for this to happen? It seems like between three and four orders of magnitude increase in computing power may be required for this to be a reality by direct computational means. Can such growth be reached? Optimistically, yes. Even if the answer is no, highly-productive capability could still become a reality, depending on the ability to characterise and store wall settings versus gross details of the model, support system, and flow condition. With this approach, although the ability to perform CFD calculations may not measure up to real-time productivity requirements, real-time productivity could still be achieved by accessing a pre-computed data base, real-time measurements of wall boundary conditions and model loading.

Emphasis should be placed on three paths: making efficient direct computations in real-time during a test, developing a pre-computational approach to couple with real-time test measurements, and developing highly productive fully adaptive capability. In so doing, improvements in productivity and quality of wall interference computations can also be realised.

12.2 AREAS FOR EMPHASIS, VERSUS EXPECTATIONS

There are three basic requirements for dealing with wind tunnel wall interference effects regardless of the type of test section or kind of model. They are: "Ability to accurately establish maximum allowable model size for a specific test. Ability to reduce, or correct wall effects in any test in which the maximum allowable model size is not exceeded. Ability to estimate the uncertainty or accuracy of the corrections applied", Lynch, et. al [22]. These abilities are required for a wide range of wind tunnel testing. Commercial and tactical aircraft, space vehicles, as well as the automotive and trucking industry all have their requirements for improved data accuracy. The following discussion will address some specific areas pertaining to these requirements that warrant emphasis, included expectations for outcome of future work.

12.2.1 BETTER UNDERSTANDING OF APPLICATION OF WALL INTERFERENCE

Accurate, practical, wall interference correction techniques are needed for a wide variety of wind tunnel testing scenarios. These include:

- Cruise performance in ventilated (perforated, slotted, and porous-slotted) test sections
- High lift in solid wall, ventilated wall, and open-jet test sections
- Sting & distortion or support tare & interference testing for all wall types
- Stability and control for all wall types
- Power effects (jets, turbine simulators, rotors, propellers)
- Buffet and unsteady aerodynamics - all wall types
- Incremental testing, all types
- Advanced airfoil development,
- Bluff body tests (including automobile and truck)

Understanding of limitations on the accuracy of methods is required. Chapter 11 addresses issues related to the sources of uncertainties in wall correction methodologies and approaches to resolving those uncertainties. The finer points of underlying assumptions in determining drag increments due to model-image induce effects that led to the conflict noted in section 12.1 is an atypical example of the problem of understanding of limitations on methods. This is atypical because we have methods producing conflicting results that have the same basic underlying small disturbance, incompressible flow assumptions.

Nevertheless, it is worthy of note because the conflict does serve to illustrate that any method should be called into question if we are to work toward a full understanding of limitations. Briefly, the expression for low speed, model-image induced drag increment, developed by Taylor as Equation 1.3 is $\delta C_D = -C_D\epsilon$, where ϵ is the normalised sum of solid and wake image-induced velocities, ϵ_s and ϵ_w. In Section 1.3, Taylor assumes ϵ_w to be small and obtains the classical result, $\delta C_D = - C_D \epsilon_s$, as in AGARDograph 109, pp 109 -111. However, the derivation of Hackett [15], gives , $\delta C_D = - C_D\epsilon_w$. This works well in application to normal flat plates and gives corrections that agree closely with those of Maskell. If this is true in general, then application of Equation 1.3 would overcorrect by an amount, $- C_D \epsilon_s$. As seen in Chapter 1.3, the difference between the two representations is small, but could be significant. Consequently, further theoretical and experimental work is required to resolve this issue. Perhaps a sufficient means of resolution could be achieved by a numerical experiment which captures the physics of the flow about a body with a large wake.

Little has been done toward establishing accuracy requirements for wall corrections, or providing for the systematic validation of various techniques. However, Steinle & Stanewsky [31] state that, wall "... correction methods should be able to assess (1) relative changes in the free-stream flow conditions and (2) changes in local flow conditions at the wing location and along the model axis caused by configuration changes..." to the model. Required accuracy was given in flow inclination and Mach number as 0.010 degrees and 0.001 respectively. These criteria were intended to apply for Mach numbers from 0.5 to 0.85 at transport cruise lift conditions. These accuracy requirements were based on the ability to resolve drag coefficient to 0.0001 (one drag count). Krenz [19] repeats the need for 1 drag count accuracy at high speed; but, notes that an equivalent accuracy for typical take-off and landing conditions (Airbus) would be 5 drag counts. The NWTC project's Customer Requirements and Operations team established wall interference magnitudes not to be exceeded <u>prior to correction</u> for a base-line transport configuration that would span 80% of the applicable test section dimension (CR&O Release 11.0, Vol. 1) . Those requirements are repeated herein:

	Mach Number 0.3	Mach Number 0.85
Delta Mach	± .006	± .003
Delta Alpha @ C_N =1.0	± .150	±.150
Delta CN body	± .01	±.005
Delta CA body	±.0006	±.0003
Delta CM	± .02	±.01

These requirements for uncorrected magnitude of wall corrections were established with the hope that by the time the NWTC would have been operational, a verified wall correction methodology could provide corrections with sufficiently low uncertainty residual that with sufficient quality in the measurements (e.g., forces, angle-of attack, reference conditions), the target values established by Steinle & Stanewsky [31] could be attained. Euler code calculations by Sickles & Steinle [30] indicate, with suitable control over wall resistive properties and wall divergence, all of the above criteria could probably be achieved for the reference transport configuration. The most difficult target to achieve is for pitching moment since, without a fully adaptive wall to provide inflow or outflow when wall pressure coefficient would result in the opposite effect, flow curvature effects will tend to dominate. Reduction in axial force coefficient to the above target value does require some form of active wall control (real-time scheduling of side wall-divergence angle was planned for the NWTC) to minimise buoyancy.

The NWTC project did not develop requirements for other types of tests. Such requirements would be useful since applying cruise transport wall interference criteria to other types of tests (e.g. manoeuvring fighter aircraft) could be overly restrictive. For each type of test, careful consideration needs to be given to test requirements, and allowable error in performance factors should be translated into test data uncertainty requirements. Of course, wall corrections represent only one potential error source among many. Therefore, allocating error magnitudes to wall corrections should be done in conjunction with an overall assessment of error sources and their magnitudes. Even if precisely defined uncertainty requirements were available for each type of test, there would still be a serious deficiency in establishing the uncertainty of wall corrections themselves. Computing wall corrections is not like measuring pressure. There is no readily available calibration standard from which to define "truth". Tunnel-to-tunnel comparisons can be very helpful in indicating general validity. However, wall corrections are just one of many factors which enter into wind tunnel data correlation studies and it would be difficult, time consuming, and expensive to establish absolute uncertainty from such efforts. Analytical approaches to estimating wall interference uncertainty are even more difficult. Error propagation from measured data can be tracked, but the relative validity of explicit and implicit assumptions contained in all correction schemes are difficult to assess. Despite all of the difficulties, the need still exists to pursue development of methods to assess the uncertainty of wall corrections for typical applications. Chapter 11 addresses methodology for this assessment.

Two obvious approaches to arriving at a calibration standard ("truth") from which to form a basis for validating wall interference methodology are seen. One is experimental and the other is strictly numerical. Both are artificial definitions of "truth" since boundary conditions and flow uniformity contaminate the experimental "truth" and limitations in modelling of fundamental flow physics and model shape affect the numerical "truth".

Traditionally, an experimental definition of "truth" has been taken as either the results from a very low blockage model at conditions assumed to be essentially interference free, or the corrected results from a model tested in a tunnel whose boundary conditions were assumed known (closed wall). In the former, adjustment to free air conditions is accomplished by applying a wall correction assumed sufficiently certain. Of these two experimental approaches, the low blockage approach is to be preferred since the goal is to validate wall correction methods and use of the other approach involves a correction to validate a correction. However, to improve the process, the test section used to provide the reference data should have exceptional flow quality and its upstream, downstream, and wall boundary conditions measured to provide a basis for future adjustment of the low interference results. Here, an adaptive wall test section, with validated methodology, is expected to be superior. From this point, there are two experimental choices. The first is to test the same reference model in a tunnel that will produce typical magnitudes of wall interference, measure the boundary conditions, correct the test results by the method in question and validate against the defined "truth". The second approach is to build a large model to the "same" scaled dimensions as the low blockage model (within tolerances consistent with allowable variation in computed pressure coefficients) and test as before. For all experimental activities, identical test techniques (including instrumentation, if possible, and data reduction programs) should be employed and the results corrected for every identifiable error source. Consideration of matching Reynolds number and model distortion effects leads to testing the same model in a smaller tunnel with both tests conducted at the same total pressure. For a relatively low loading condition with a high-stiffness model (non-lifting body) testing with scaled models in variable density tunnels to match Reynolds number should not lead to any significant uncertainty due to model distortion. However, other error sources would be present and must be accounted.

The basis for a numerical definition of "truth" is simply a shape whose surface flow conditions in free air can be represented by a computational method to a low enough uncertainty as to serve as the free air reference for validation of a wall correction method. This definition of truth would include say, a body of revolution for which a Navier Stokes representation could be computed with confidence. Representation of the installation in the tunnel to the degree necessary to capture the fundamental physics and flow non-uniformity's is required. Test results would include measurement of those parameters necessary to validate the basic physics model. Variation of parameters to tune the computation to match the essential features of the measured flow-field is required. From this work, the influence of the entire installation can be studied (upstream and down-stream boundary conditions as well as wall boundary representation). Extension to a lifting case requires other considerations such as aero-elastic distortion and potential separation. Sensitivity studies concerning the choice of turbulence model in any CFD calculations may be required as well as uncertainties in model geometry. Technically, this process can be implemented now. The effect of improvements in computational methods and better representation of tunnel boundary conditions will lead to a newer version of truth for each calibration configuration. Use of this method should not end with testing of a model that can be computed. Extreme cases are the ultimate goal and those can't be computed with sufficient certainty. Hence, the goal for validation of wall correction methods should include the previously mentioned experimental definition of truth.

Both the experimental and computational approaches to the definition of truth warrant careful consideration. It is anticipated that results of greatest value will emerge from a dual approach that employs both. Experimentally, the most difficult part is the determination of the boundary conditions (upstream, down-stream, and equivalent inviscid wall boundary) and the sensing of the model shape and orientation. Numerically, the representation of the model wake (including model - support system interaction) is expected to create the most challenge. A collection of standardised approaches with an uncertainty assessment for each for validating wall correction methodology would benefit the entire testing community.

Development of a standardised validation methodology is in keeping with the charter of the AGARD FOP and it is recommended for consideration of sponsorship.

12.2.1.1 INCREMENTAL CORRECTIONS VS ABSOLUTE CORRECTIONS

Strictly speaking, all wall interference corrections are incremental since they are applied to an experimental result. However, one thinks of an absolute value of a wall correction as correcting an experimental result to a condition of free air. An absolute value of wall correction is always desirable, even when comparing the results for an incremental configuration change. On the other hand, it is suggested that in many cases an incremental assessment may be sufficient. Clearly, en linear theory would suffice for determining the pressure loading on a model, an incremental wall interference correction due to a change in model geometry and/or loading would be sufficient for correction of a comparison of the effects of the change. Further, if the comparison was made between two configurations at the same total loading, the required wall correction incremental corrections are further reduced (e.g., no net change to measured angle of attack) although not necessarily eliminated (e.g., pitching moment and buoyancy). When the description of the model loading requires more than linear theory, a test condition correction (as in global corrections to Mach number and angle-of-attack) may still be required.

When a test condition correction is insufficient, even when testing for the effects of incremental configuration changes, integrated corrections to the measured data must be applied to both the base-line and the increment to the base line configuration. Establishment of the limits for applying an incremental wall correction to incremental test results has not been demonstrated. Incremental corrections can also apply to the baseline configuration since a change in angle-of-attack is an incremental change as well. Thus, for conventional testing, an incremental approach may serve to bridge the gap between computed absolute corrections sufficiently well as to minimise the extent of computations required. Accordingly, since the range of usefulness and application of incremental wall corrections is not established, work in this area is needed.

12.2.2 DEFINITION AND MEASUREMENT OF BOUNDARY CONDITIONS

Regardless of the solver used to estimate wall corrections, the result will be influenced by the representation of the boundary condition. The need to characterise the boundary condition with an accuracy consistent with the accuracy of the wall correction method to be employed has been long recognised. There is more to be done to improve the characterisation. Troublesome areas include the upstream and downstream boundary conditions, treatment of wall-divergence, growth of the tunnel wall boundary layer, auxiliary suction and wall pressure effects on cross-flow, localised effects versus homogenous representation for ventilated walls, amplification of wall cross-flow due to boundary layer effects, and modelling of jet (downwash) impingement effects.

12.2.2.1 FORM TO USE FOR WALL BOUNDARY CONDITION

Classical work has, of necessity, used linear homogenous boundary conditions. This work is well known and is not cited herein (see Chapter 3). The advent of solid adaptable walls for 2-Dimensional testing led to the use of a viscous correction. As model size and loading has increased, the impact of the model imposed pressure gradient on the wall boundary layer has forced adjustments to solid wall boundary conditions to take in to account the effect of change in displacement thickness caused by strong pressure gradients. Further, measurement of mass flux normal to the wall of a ventilated tunnel has led to the recognition that the viscous interaction amplifies the effect of the normal mass flux resulting in a higher order adjustment to the boundary condition. Additionally, pressure drop of flow through porous walls becomes dominated by the second power of normal velocity as expansion and viscous losses through the porous channel increase. Walls with open slots also exhibit fairly strong localised flow curvature effects which has led to higher order representations. Practically speaking, one should always use as simple a form as possible, consistent with the flow physics and the uncertainty requirement for computing wall corrections. It is important to understand the contribution the wall model makes to the uncertainty of a wall correction. It would be highly beneficial to investigate wall models systematically for non-linear effects caused by strong gradients and substantial boundary layer thickness (typical of large models in major wind tunnels) and report the results in a standard format. This would aid the user in a choice of wall boundary condition form to use.

12.2.2.2 VISCOUS EFFECTS

Modification of solid wall boundary condition by a correction to account for changes in boundary-layer behaviour owing to model-imposed pressure gradients currently is done in an approximate sense. Ashill, Taylor, and Simmons [2], for example treat the normal velocity at the wall as being related to the rate of growth of the displacement thickness, including the effects of pressure gradient. Some approximations were done. With their approach, computed wall pressure distribution from testing of a research body (representative of a civil transport volume) show significantly improved agreement with experimental results at high subsonic speeds in the DRA 8ft. x 8ft. Wind Tunnel. Some improvements are possible and are probably required for bodies producing stronger pressure gradients.

An elemental analysis employing continuity shows that for zero velocity gradient, the flow angle at a height, delta, from the wall due to boundary layer growth equals the rate of growth in displacement thickness. Velocity gradient (independent of changes to the rate of displacement thickness growth) changes the flow angle. Favourable gradient reduces the flow angle in an amount approximately proportional to boundary layer thickness. Further, it is argued that the boundary condition at the wall could then be represented by an analytic extension of the flow angle. For small tunnels, where the boundary layer is thin, this disparity may not be of enough significance to even warrant consideration. However, for tunnels in which the boundary layer height is of the order of 5% of the test section height or width, (either because of size or low Re) this difference may be an important consideration.

For porous walls, mass and momentum flux through the walls complicate the picture. Some progress has been made with incorporating adjustments to wall characteristics for distributed porous walls to account for changes in boundary layer properties. Vidal & Erickson [36], Jacocks [16], Crites & Rueger [9] have reported results from tests of mass flow through porous walls and the amplification of flow angle by the boundary layer interaction. Vidal measured his results directly. Both Jacocks and Crites & Rueger determined their results indirectly. Jacocks determined his by matching computed pressures with an assumed boundary condition. Crites & Rueger determined theirs by measuring the change in displacement thickness with wall normal velocity and using an expression for effective normal velocity at the wall which was derived from continuity considerations, the definition of displacement thickness, and an assumption of a constant edge velocity extension of the boundary layer. Both Jacocks' and Crites & Rueger's results match for low values of wall mass flux, Since Jacocks' results were, in essence, empirically derived on the basis of matching a CFD solution, they are only as good as the CFD model allows for the test installation. The match with the results for Crites and Rueger indicates that the non-analytic extension (constant velocity) of the flow to the wall boundary they used is not a bad assumption for their case. The results of all of the foregoing were from small-scale tests with a thin boundary layer. Flow curvature effects associated with large models and high loading may make it advisable to have a further analytic refinement. Likewise, the effects of a thick boundary layer are expected to further contribute to the need for an analytic extension. Matyk and Kobayashi [25] investigated cross-flow resistance for two porous slotted wall samples where the displacement thickness of the boundary layer was much less than the width of the porous slot (one was a full-scale representation of the NASA Ames 11-Foot Tunnel wall). This experiment showed that cross-flow resistance was basically insensitive to Mach number as did the later work of Crites & Rueger for a porous wall. Unpublished work by Steinle [32] established empirically the effective cross-flow property of the 11-Foot Tunnel wall (displacement thickness of the order 80% of the porous-slot width) by utilising wing pressure distribution and tests with closed walls and a closed floor and ceiling for a large seem-span model mounted off the floor of the tunnel. The theory by Kraft and Lo [17] was used to determine the stream correction angle along the span of the wing and the wing pressure coefficient sensitivity to angle of attack was used to determine the flow correction along the span for both wall configurations. A variation of slot and porosity parameters led to the extrapolated porosity result. The Kraft and Lo result (semi-empirical with boundary-layer displacement thickness of the order of the slot width) differed significantly from the cross flow measurements of Matyk and Kobayashi (direct measurement, boundary-layer small with respect to slot width) which indicates that boundary layer effects are significant for this type of wall as well. In general then, considerable opportunity remains to improve our understanding of the wall boundary conditions for both solid and ventilated walls to capture the effects of boundary layer, pressure gradient, and mass flux for application to large-scale tunnels. A systematic approach to determining the wall boundary conditions which utilises empiricism and CFD, as appropriate, is needed. An agreed upon format for reporting the results of such work, along with a means of making the results available to the technical community would benefit all. Any results that can be reported in the near term will be quite beneficial to those contemplating test section improvements.

12.2.2.3 UPSTREAM BOUNDARY CONDITIONS

Upstream boundary conditions are usually treated by extending the computational boundary sufficiently far upstream in a constant cross section and assuming a constant velocity and Mach number profile. Some work has been done to consider representation of the model effects at the upstream boundary in an asymptotic sense. Other work, concerning finite test section length has been done. However, work to include boundary layer growth and wall divergence effects on the upstream flow field is lacking. A further complication is non-uniformity of flow at the upstream boundary (e.g., swirl or some other horrible condition). These three effects are clearly not separable. Although upstream nonuniformity is not a wall interference concern, it should be included in any improved modelling of the tunnel flow to compute wall corrections since the effects can not be separated.

12.2.2.4 DOWNSTREAM BOUNDARY CONDITIONS

Downstream boundary conditions are generally not faithfully modelled. However, as models become larger, the need to increase the fidelity of the representation of the downstream conditions increases. More work is required to characterise the effects of downstream condition should be done to aid in the understanding of what modelling is required.

Notable areas include the interaction at the plenum flow re-entry region, if used, as well as the presence of the model support system. The model support system is also of importance for transonic tunnels. These systems are generally not removable. Consequently, tests of large semi-span tests model with the model in the plane of the support strut do occur (e.g., the NASA Ames 11-Foot Transonic Wind Tunnel). Although probably less important than the model support system the proper characterisation of the re-entry region also should be done. Here, empiricism is expected to be the only viable approach. Bui [7] modelled the discrete porous-slotted walls and both the model support system and the re-entry flow field for a large semispan model installed in the Ames 11-Foot Transonic Wind Tunnel using a panel code. Treating the mixing at the end of the test section as a ramp gave a reasonable match with measured ceiling pressure data near the exit of the test section. Trial and error was required to obtain the best match. Thus, it appears that an empirical approach, aided by inviscid calculations is practical. More work is required to characterise these effects and should be done to aid in the understanding of what modelling is required.

12.2.3 COMPUTATIONAL METHODOLOGY, ASSESSMENT AND VALIDATION

The current collection of methods for determining wall corrections has not reached maturity. Methods for correcting results from dynamic tests have not received as much attention as for steady flow tests. All correction methods (classical, one-variable, two-variable, etc.) can produce an interference perturbation field at any point about the model. Assessment poses the problem of rating methods for utility (ease of application, cost, accuracy of results, limits of applicability). Validation is the process whereby uncertainty of results and limits of applicability are determined. A cursory assessment of some general application areas of computational methodology and challenges associated with developing validated methodology for those areas follows:

12.2.3.1 TEST CONDITION CORRECTION TO REFERENCE CONDITIONS

It is assumed that there is no universally best method for determining test condition corrections to reference conditions. The challenge is to evaluate and report the results of investigating any and all methods for accuracy and limitations.

With modern high lift designs, or advanced configurations such as the HSCT, it is by no means obvious how to use the wall interference perturbation field to obtain a test condition correction -- or sectional weighted correction for that matter. Taylor (Chapter 1.3) has used linear theory ideas in conjunction with the Reverse Flow Theorem to provide simple rules for applying global corrections. Since these rules are based on linear theory, they might not be expected to be valid for transonic flows and for high-lift conditions. Goodier and his colleagues at Southampton University have found that the ¾ chord point for the correction of angle of incidence applies for certain transonic airfoil applications. Lewis and Goodyer's work [21] utilised an adaptive-wall tunnel to impose various variations of wall-induced velocities along the chord of the airfoil. Additional work is reported by Ashill, Goodyer, and Lewis [21]. Experiments of this nature are quite useful and further work is welcome.

Sickles and Steinle in their studies in support of the NWTC project investigated the choice of correction approach as well as reference positions for arriving at a correction to Mach number and angle of attack by considering separate locations for each including matching wing lift coefficient. In this study, "truth" is the result of an Euler calculation that imposes free air conditions on the computational domain four body lengths upstream and downstream and six wing spans horizontally and vertically from the model. For the two cases investigated (25% semispan and mid-semispan), the mid-semispan wing position gave the best overall results for the wing (pressure distribution). Applying a correction to Mach number and angle of attack reduced the residual wall interference to low values. Since this was a numerical experiment, blockage and angle of attack corrections were determined from a stream-tube calculation which used the difference between prior solutions in the tunnel with a prescribed wall model and free air to determine the boundary flow at the stream tube. The flow field caused by this interference stream-tube was then interrogated to determine angle of attack and Mach number increments at chosen positions. With these corrections to Mach number and angle-of attack, computed tunnel results were scaled for dynamic pressure changes and the free air solution was recomputed for the new angle of attack. This method employed is equivalent to either a two-variable measured approach in the tunnel or a direct method where flow conditions on the boundary would be computed and compared with measurement. It is just one approach to be considered in evaluating the collection of 3-D methods either available, or coming in to existence. It serves to illustrate that work needs to be done to verify the range and quality of all correction methods.

12.2.3.2 HIGH LIFT

The wind tunnel testing needs of the commercial aircraft community seem to be focused toward high lift development and cruise performance. High lift equates to large wall interference (lift and blockage.) Maximum lift capability is a primary factor determining wing area which in turn affects cruise drag, and thus fuel consumption, gross take-off weight, passenger capacity, etc. High lift is dominated by 3-D viscous flows with separation and is very sensitive to Reynolds number (e.g., Lynch, et. al.[22]) Although CFD is useful for providing guidance for attached flow conditions, it is not (and is not expected to be for some time) capable of providing the needed accuracy for high lift conditions. This mandates an experimental high Reynolds number approach to design and development which leads the industry toward testing very large semi-span models in large, pressurised (or cryogenic) facilities. The trend for high speed cruise performance wing development is also toward achieving higher Reynolds by employing large models, including semi-span (e.g. Goldhammer and Steinle [13])

High lift testing is commonly done in solid wall or open jet low speed wind tunnels. The model flow field, at conditions of maximum interest, is dominated by viscous flows with off-body separations. As a result, because current CFD can not be used to predict high-lift performance as well as desired and because wing separation can be significantly affected by wall induced gradients, wall corrections to test conditions will not be sufficient for achieving satisfactory free air results. Regardless of how the wall-induced flow field corrections are to be used, the numerical representation of the model only needs to be aerodynamically correct in a far-field sense. Therefore, although it may not be possible to satisfactorily predict high lift performance, it should be possible to simulate the model well enough for the purpose of calculating the wall induced flow field. Some trial and error adjustment of the simulation would probably be necessary to obtain agreement between measured and computed wall pressures -- a necessary condition for valid correction.

At high model loads (high Reynolds number) the user of the test results is faced with the prospect of accounting for aero-elastic distortions. Consequently, if the flow conditions are in the range of linear aerodynamics, the induced distribution of flow angle can be treated as a global correction plus a localised twist and camber modification of the wing shape. Thus, if the blockage induced velocity gradient over the wing is negligible, then wall corrections of this nature can be adequately performed. To apply a correction for other than test conditions to say, wing flow development, would require a CFD code wherein the boundary condition at the model surface can be altered to accommodate a modification of the surface flow velocity by amount of the local induced velocity. This approach is not known to have been tried, but does seem possible as a means of extending the applicability of even a classical or panel method. Such an approach to extending test condition corrections to include streamwise induced velocity gradient should be investigated.

Care must be taken in sizing models for high lift testing (with and with-out engine simulation). Currently, flow field correction techniques do not capture the detailed effects of pressure gradients. When these gradients are the determining factor in sizing, a numerical simulation of the model is required that at least predicts correct increments to small changes. Unless suitable predictive methods, based on CFD simulation of the model can be developed and validated, sizing will remain a subjective procedure that must rely on experience and judgement. Consequently, work is needed in the process of evaluating methods to develop and report criteria which can be used to establish model size and correct the data once obtained.

12.2.3.3 PERFORMANCE TESTING

Performance testing for commercial transports is usually limited to Mach numbers less than 1.0. Tactical aircraft require force and moment data through the transonic range. Between Mach numbers 0.6 and .95, correction methods based on transonic small disturbance, full potential, or Euler methods have been shown to provide corrections with varying degrees of uncertainty depending upon the relative appropriateness of the assumptions and the flow field characteristics. Above a Mach number at which viscous forces influence shock position (Sickles and Erickson [29] suggest Mach 0.90) inviscid representation of the model flow field becomes questionable and Navier-Stokes or boundary layer interaction methods are indicated. The point at which one must transition from one method to another is model and interference field dependent. As the test Mach number approaches about 1.2 to 1.25, the strength of the wall interference effects in ventilated wall tunnels sharply decrease to a generally acceptable value (Rueger, et. al. [28] and Martin, et. al. [24])

As gradients in the interference field become larger, the wall effects become less and equivalent to a change in Mach number and angle-of-attack. As the severity of the gradients increase, flow field correction methods begin to yield corrections representative of an equivalent distorted geometry that do not correspond to any real flight condition. The wall effects for such a situation become "uncorrectable." However, this is not necessarily the case for the surface pressure correction methods. Such methods inherently account for gradients in the interference field. Ideally, within the limits of the flow solver and the treatment of the boundary conditions, there are no uncorrectable cases, providing the model shape is properly represented. Practically speaking though, there are always situations where the flow field distortions are so large that any methodology is incapable of computing valid corrections. The challenge is to establish the uncertainty envelope and limiting conditions for any correction method.

12.2.3.4 STABILITY AND CONTROL TESTING

The determination of longitudinal and lateral directional forces is carried out at all speeds and over a large range of model attitude settings. High-lift devices may be employed to a varying extent -- clean configuration at high speeds to full deployment at low speeds. The wing plane may not be aligned with any of the tunnel walls, and the model may be located a considerable distance from the tunnel centreline. Furthermore, some model positioning systems allow considerable vertical travel of the model during pitch sweeps. Angle-of-attack can be very large so that massive separation on the wings and fuselage is common. From a wall correction point of view, this kind of testing combines many of the most difficult aspects of performance and high-lift testing. Fortunately, the uncertainty requirements are not as stringent as for performance testing. Nevertheless, wall corrections may be necessary, particularly if the model to tunnel size ratio is large. Here, the method of choice is clearly open to question. It seems as if the two-variable boundary value approach which avoids the necessity of simulating the model is to be preferred, followed by the generalised wall pressure signature method which generates an aerodynamically equivalent model (in a far-field sense). However, if the wall interference field is strong enough to influence the separation characteristics of the model, a more exact representation of the model and flow field will be required. Methods for the various installations against agreed criteria should be evaluated and reported.

12.2.3.5 BUFFET AND UNSTEADY AERODYNAMICS

Buffet boundaries obtained in the wind tunnel have not been noted for precisely matching flight experience. Furthermore, it is seriously doubtful that wall interference effects are the main cause of the discrepancy. Buffet is caused by unsteady separation phenomena. It is sensitive to Reynolds number and model fidelity, among other things. If proper viscous scaling can be achieved, the model is built to the deflected aircraft shape, and the wind tunnel background noise is low enough, then perhaps wall effects might be the limiting factor.

To avoid a numerical representation of the model, a two-variable boundary value approach would likely be selected. However, the problem of deciding maximum model size, or allowable gradients, is more difficult. Gradients in the interference field have the effect of modifying model geometry (camber, twist, and thickness, separation bubble size and shape.) If small, the effects may be acceptable if the regions of separation or attached flow are stable. However, for buffet, the three-dimensional unsteady partial separation effects may be very sensitive to wall induced flow gradients. The determination of a valid assessment of this sensitivity is a challenge to be met.

To avoid the gradient problem, adaptive walls are an attractive option. Use of an adaptive wall tunnel (Taylor and Goodyear, [34], [35]) offers the potential to improve buffet assessment by additively inducing the equivalent of wing twist in opposition to aero-elastic distortion. Further, since wall effects can be made variable, added value in assessing both wall effects and corrective methods is realised. Alternatively, a surface correction method might be used. This type of correction can preserve the effective shape integrity of the model in the presence of strong interference gradients. Only valid increments between in-tunnel and free-flight conditions are needed. Absolute accuracy is not required. There is, however, a problem of interpretation. The surface pressure correction methods produce corrections to the forces and moments. It is not clear how the increments in forces are related to increments in buffet intensity. Perhaps it would be possible to compute the extent of unsteady separation. Even so, this does not guarantee success since buffet is controlled not only by the extent of unsteady separation, but by the phase relation and spatial distribution. A CFD code that could accurately provide that kind of information (in useful time) for the model in free air and in the wind tunnel might give better results than the wind tunnel.

The problems associated with wall corrections for buffet boundary testing are severe. Additional research into the fundamental physics of buffet is needed. In the meantime, some form of empirical correction seems to be the only option for meaningful wall correction in buffet studies. Such a validated method has not been developed and remains a challenge. An experimental investigation aimed at the establishment of scaling laws and the generation of semi-empirical predictive capability is essential to solve this problem.

Dynamic testing poses severe challenges. Acoustic disturbances in the flow can affect dynamic phenomena (e.g., Mabey [23]). Coupling between the model flow field, support system, and test section walls can pose problems. For rotary-balance and oscillatory testing, the model support structure must be massive to provide the necessary stiffness while forcing the desired model motions. These model support structures lead to strong unsteady coupling with wall effects. The model generated dynamic loads interact with model support unsteady loads and the reaction at the walls. Together, the interactions are characterised by different convective lag times. Therefore, at various discrete reduced frequencies of model motion, the coupled interference reactions can amplify or damp unsteady flows on the model.

The interference effect can be strong, even for small models in big tunnels. For example, it has been observed (Ericsson and Beyers [12]) in rotary-balance testing that unsteady interference effect on vortex breakdown becomes a strong function of reduced roll rate. When phase relations are right the unsteady interference can alter even the qualitative nature of the aircraft manoeuvre characteristics. Rotary balance testing of an advanced tactical aircraft model was conducted in two different tunnels at the same Reynolds number. The smaller tunnel was the 2.4 x 1.8 m (b/w = 0.6) Trisonic Wind Tunnel at DRA Farnborough. The larger tunnel was the 4 x 2.7 m Low Speed Wind Tunnel (b/w = 0.4) at DRA Bedford. Beyers reported that unsteady interference effects completely masked a known unstable yawing-moment characteristic of the model in the smaller facility, but not the larger one. This kind of problem is not unique (e.g., den Boer, et. al.). Oscillating wing studies were conducted with the NORA wing & oscillator (Lambourne, et. al.) at several facilities. It was found that unsteady interference in smaller tunnels (DRA 3 ft. - Bedford, and DLR 1m - Göttingen) suppressed oscillatory pressure spikes (shock motion) that were clearly present in larger tunnels (ONERA S2 - Modane, and NLR HST - Amsterdam). The approximate span to width ratios were 0.45 for small tunnels and 0.25 for large tunnels.

Currently, there are no validated wall correction methods available for these dynamic tests that are available for general use. It seems that empirical or semi-empirical methods hold the greater promise for early application. However, there is a growing interest in unsteady testing.

Improved wall correction methods are needed for all dynamic type testing. Chapter 9 (R. Voss) of this report provides an excellent overview of the current wall correction methodology for dynamic tests that is available. Voss indicates that validation experiments for CFD methods are needed. Further, the need exists to continue development of promising concepts in wall adaptation to minimise unsteady wall interference effects. Feasibility of unsteady wall adaptation has not yet been demonstrated. A form of wall adaptation that may be possible is the modification of the boundary-jet self-streamlining wall concept. In this concept, wall jets would be actively driven (phase locked) to model motion to create a dynamic oscillation in wall boundary "stiffness" and thereby reduce the unsteady wave structures at the wall.

12.3 COUPLING OF WALL INTERFERENCE WITH OTHER PHENOMENA

As long as the sought after corrections can be determined by a linear method, wall corrections can be uncoupled from other considerations (non-linear compressibility effects, viscous interactions, support interference, and tunnel flow non-uniformity's) with reasonable success. However, as the flow interactions become large (as Mach number and/or attitude increase), the coupling increasingly warrants a single integrated computation. If accomplishable with sufficient accuracy, such a computation is the recommended approach. Characterisation of the limits wherein it is best to perform an integrated computation remains to be accomplished and should be done.

12.3.1 COMPRESSIBILITY EFFECTS

It is suggested that the first degree of coupling is associated with compressibility effects in the determination of test condition corrections. Rizk [27], for example, proposed a scheme whereby corrections to Mach number and angle of attack are determined iteratively for 2-D flow by matching the pressure distribution in some least squares sense as opposed to a classical based approach of say, selecting the 1/4 chord location for the Mach number blockage correction and the 3/4 chord location for angle-of-attack. Sickles and Steinle [30] investigated two different wing span locations at Mach number .85 using this classical-based approach as well as using the 1/4 chord location at 50% semi-span for Mach number correction and then adjusting angle of attack to obtain the best match of wing lift between tunnel and free-air conditions, corrected for blockage. This latter approach gave an excellent match with wing pressure distribution, including shock location. Since the inviscid solution provided a close match with the wing pressure distribution, incremental differences due to viscous effects are expected to be minimal. Guidelines are needed as to how to determine the best location to use as a reference for computing test condition corrections. Beyond that, the issues are what method should be used and how should they be determined.

12.3.2 VISCOUS EFFECTS FOR HIGH LIFT AND TRANSONIC INTERACTIONS

The importance of viscous effects for high lift has been touched upon in section 12.2. Situations of incipient separation are expected to be quite critical in determining maximum lift as well as shock-induced separation. In these instances, nothing short of a Navier Stokes method is apt to approach a useful answer. In this case, the turbulence model is the limiting factor, just as it is for the free air case. The other obvious situations for strong viscous coupling occurs for vortex and jet interaction with wall boundary layers and the shape of trailing wakes. Here, empiricism may be sufficient. Work is needed to understand the limitations and to develop useful empirical data.

12.3.3 SUPPORT INTERFERENCE EFFECTS

It is quite convenient to determine wall corrections by computing the difference between a solution for a model in tunnel and in flight. Since the support sting, or strut, looks like model to the walls, the interference free case is a model in free air without a support mechanism. Viscous wakes for vertical struts or blades complicate the computational problem. On the other hand, if flow physics are reasonably modelled, one can go from the model with support directly to a model in free air with proper closure. It is much more appealing to not have to expend the computer budget attempting to compute the effects separately. This approach of not separating support interference from wall corrections is seldom (if at all) done. Work to develop a technique to do this direct approach could be highly beneficial. There are formidable problems of empirically modelling viscous wake effects.

12.3.4 Tunnel Non-uniform Flow

Some discussion of upstream boundary effects is in section 12.2. Presumably, if the flow field at the upstream boundary (velocity and temperature), the model, and the wall boundary characteristics were sufficiently well known, it would be possible for the computation to replicate the convection of the stream non-uniformity's and thus capture the effect of tunnel non-uniform flow directly. Otherwise, a tunnel survey of the flow field in the test volume is required. To apply this information linearly, the survey results are then added as a vector to the calculated wall interference flow field disturbances. This latter approach (tunnel empty survey) neglects the change in location of flow non-uniformity caused by the upstream influence of the model pressure field. If the flow quality of the tunnel is relatively good, the impact of not simulating the change in location is expected to be negligible. A systematic study to investigate the effects of flow non-uniformity, typical of today's facilities, at both low speeds and transonic conditions is yet to be done.

12.4 Reduction of Wall Interference

It is well known that it is possible to improve the design of current wind tunnels to reduce wall interference; however, to do so is costly and thus, the community has seen almost no improvements in existing tunnels. Historically, in the course of developing a facility or a major modification to a facility, costs generally escalate beyond reserves, forcing compromise of a portion of original objectives or planned sophistication. It is expected that future improvements to significantly reduce wall interference by a redesign of a test section to incorporate advanced technology will experience funding difficulties unless the economic benefits of the full technology can be clearly demonstrated. To achieve success in marketing any such improvement, a means of assessing payback to the ultimate source of funding is needed. Such an assessment will undoubtedly include a high degree of subjectivity. A working group to discuss and establish a method for determining benefits of any improvement seems worthwhile. A compelling reason for pursuit of reduced wall interference arises from discovery that increasing complexity of methodology is required to assess wall corrections to a desired accuracy. Barring interference-free conditions, the least objectionable state is to achieve either negligible interference or low enough interference such that rapid and simple correction methods can produce acceptable results. Any improvement effort is expected to involve a design cycle of redefining a model of the tunnel wall boundary conditions. Comments concerning wall types for reduction of wall interference follow:

12.4.1 Passive Wall Design

A passive wall is one that has fixed geometry. This includes a closed wall. Work has been done with the intent of capitalising on viscous effects for solid walls as a means of reducing choking for slightly supersonic operation and for reducing wall interference. Taylor [33], Petersohn [26], Berndt [4], [5] and more recently Crites [10] addressed some of the benefits and limitations of using viscous effects to advantage. The use of such a technique has not been explored to the point of being routinely employed and is an opportunity for further study. Other forms of passive walls (holes, slots, porous slots) were established on the basis of model to tunnel size ratios smaller than the current trend. It should be relatively inexpensive to introduce redesigned porous plates or slotted sections that are shaped to passively minimise wall interference for larger models in current test sections. Current technology should be capable of defining such improved sections.

12.4.2 Variable Characteristics Wall Design

The next best wall toward a fully adaptive wall is one that has variable characteristics which can be used to segmentally throttle the mass flux through the walls either in real time, or pre-settable. Such a wall requires appropriate instrumentation and methodology to determine the proper wall settings. A globally adjustable wall such as the AEDC 4T tunnel (e.g. Kraft and Parker [18]) is the simplest form of variable characteristic wall. Mechanically speaking, either a globally or segmentally variable characteristic wall is practical (e.g., T-128 facility at Zhukovsky, Russia.)

The addition of the ventilated wall for low speed, high lift testing listed in section 12.2.1 is a departure from the accepted norm of today. However, in anticipation of gains in wall correction methodology, it is quite likely that a significant portion of future high-lift testing will be done in tunnels with ventilated walls (lower wall interference than solid walls.) The argument against this concept is that one does not know the boundary conditions well enough to obtain a satisfactory answer. The counter argument is, if the wall interference is reduced by a properly configured ventilated wall, then any error in assessing the boundary condition influence is less than the error generated by having the substantially larger closed-wall induced flow field effects on the model. Calculations performed by Sickles and Steinle [30] in support of the NWTC project confirmed that significant reductions in wall interference for high-lift testing are possible by utilising a properly ventilated wall if the boundary condition is known. This, among other considerations led to the selection of a porous-slotted wall with controllable segments (including closed wall conditions) for the NWTC. Consideration should be given as to the benefits of incorporating this capability as a future upgrade to current closed wall tunnels.

12.4.3 Adaptive Walls

It can be seen that the need for high Reynolds number capability is a mutual concern for the development of tactical and commercial transport aircraft, and both are tending toward the same solution -- big models in big tunnels. Current large pressurised (and cryogenic) facilities do not use wall streamlining, nor are any known to be planned. The NWTC project planned to use a form of passive-adaptive walls (Crites & Steinle [10]), controllable in real time, to minimise the wall interference. However, that project has been postponed for an indefinite time. Even with that type of test section which would provide reduced wall interference, the emphasis is still on correction as opposed to elimination. This is not to say that adaptive wall technology is unimportant. On the contrary, it is crucial that it be developed to a mature, highly productive state and it may ultimately be shown that for the large models necessary in future testing, some streamlining must be done to reduce the magnitude of the wall effects to a correctable value. However, in the near future it appears that adaptive wall technology will not play a major role in aircraft development simply because the major wind tunnels that must be used do not provide this capability. It seems more likely that the near term contribution of adaptive wall tunnels will lie in research directed toward application of wall corrections (e.g., Lewis & Goodyer, [21]. Work of this nature is needed.

12.5 Summary of Recommendations

By following the prevailing thread in the above discussion, it should be obvious to the reader that the characterisation of wall interference for all types of testing and test conditions is a formidable problem. Its solution requires physical knowledge and numeric capability that are either non-existent or too costly to implement in today's market. The current trend is to maximise test Reynolds number by pushing the model to tunnel size ratio to its limit. That situation, coupled with high subsonic Mach numbers or high lift, undoubtedly causes wall interference to be a major contributor to data uncertainty. While there are wall interference correction methods available, their uncertainty and range of applicability are not well known. Nevertheless, if the data quality requirements demanded by competitive aircraft manufacturers are to be achieved, wall corrections must be applied at least to the critical performance parameters. The challenge to the testing community is to provide the required corrections with a validated, time and cost-effective methodology.

A systematic, co-ordinated program to improve wall interference assessment and correction methodology and to both understand the limitations of proposed methods and develop useful empirical data is needed to meet the challenge. An AGARD FDP sponsored working group would be appropriate to plan such a systematic, co-ordinated program. The program should include the following elements :

1. Standard approaches of assessing the range of applicability (model and tunnel configuration, test type, Mach Number, attitude, tunnel and model Reynolds number, etc.) and determining the uncertainty of wall correction methods and data bases. The first requirement in devising such a standard is to define the method to determine "truth" against which the various methods will be assessed.

2. A systematic approach to determining the upstream, wall, and downstream boundary conditions using modelling, empiricism and CFD, as appropriate. There are three primary concerns :

   First, the correction scheme should include the effects of non-uniform upstream flow, wall boundary layer, and wall divergence in the wall interference assessment. Although these three elements are not, strictly speaking, a wall interference concern their effects can not be empirically separated from wall interference.

Second, it is important to understand the contribution the wall model makes to the uncertainty of a wall correction. It would be highly beneficial to investigate wall models systematically for non-linear effects caused by strong gradients typical of large models and report the results in a standard format. This would aid in the choice of which wall boundary condition model to use for a given wall configuration.

Third, the downstream boundary conditions must include the wakes, model support system, and the diffuser entry region (including plenum flow re-entry, if re-entry occurs at the end of the test section). More work is required to characterise the support and diffuser entry region effects to aid in the understanding of what modelling is required. The approach of including support interference with wall corrections is seldom (if at all) done. However, since each of these elements affects the flow gradients in the region of the model, their effects cannot be empirically separated from wall interference.

3. An approach that yields guidelines for determining the best reference location and captures the detailed effects of interference gradients in order to assess their effects on pitching moment when using a method that corrects test conditions.

4. An experimental investigation aimed at the establishment of scaling laws and the generation of a semi-empirical predictive capability for correcting dynamic and buffet boundary test results. The problems associated with wall corrections for dynamic and buffet boundary tests are difficult. Additional research into the fundamental physics is needed and is essential to solving this problem. In the meantime, some form of empirical correction seems to be the only mechanism for meaningful wall correction in dynamic or buffet studies. Such a validated method has not been developed and remains a challenge.

5. A mathematical formulation that properly poses the wall interference problem, especially for Reynolds Averaged Navier Stokes formulation.

In the final analysis, any correction method to improve data quality must be verified, its uncertainty quantified, and its application economically justified in order to be useful to the community of vehicle developers. Economic justification to the community of developers implies establishment of a close working relationship with the developers so as to trace correction benefits directly to the cost-benefit uncertainty trades of their product. This need for understanding both the uncertainty of a method and the benefits to the user should be foremost in the mind of researchers as they tackle this very difficult problem. The product of that research which is vital to the future of both the testing community and the users of the information must be in a form useful and understandable to both parties. Thus, it is imperative that representatives from both groups be *involved in both the near and far term efforts. To that end, it is strongly recommended that the* AGARD FDP charter a working group to plan, co-ordinate, and guide the needed improvements to wall interference correction methodology.

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