Transonic Wind Tunnel Wall Interference Minimization

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Obtaining accurate predictions of aircraft aerodynamic coefficients from wind tunnel tests is a difficult task Wind tunnel users have struggled with the effects of wall interference, model support interference, subscale Reynolds number, etc for almost the entire history of powered flight Since wall interference is one of the principal problems this paper emphasizes the need to minimize it, especially in the near sonic test regime Practical ways of minimizing wall interference are identified This is best accomplished for near sonic testing by locally variable porosity with inclined hole perforations A number of porosity setting schemes are identified some of which are quite simple

Nomenclature

b	= wing span
c	= coefficient
C_p	= pressure coefficient $p_n - p/q$
C_D	= drag coefficient
D	= cone cylinder diameter
M	= freestream Mach number
M_{critical}	= freestream M at which sonic velocity is reached locally on shape moving through air
$M_{\text{wall local}}$	= flowfield Mach number adjacent to particular position on test section wall
$M_{\text{wall critical}}$	= freestream M at which sonic velocity exists locally at test section wall
P	= stream static pressure
P_n	= static pressure at arbitrary location (for wall characteristic, plenum pressure)
P_T	= stream total pressure
q	= freestream dynamic pressure
Re	= chord Reynolds number
X	= axial distance
α	= angle of attack
β	= Mach function, $1/\sqrt{1-M^2}$
δ	= relative downwash velocity error on tunnel centerline
Δ	= difference between two values
θ	= flow angle through porous wall

Introduction

WIND tunnel testing problems are exemplified by dif ferent test results on a test model run in different wind tunnels[1] and by existing aircraft with performance or structural problems arising from shortcomings in wind tunnel data [2] Such discrepancies result from many problems associated with wind tunnel testing, perhaps the chief problem being the effect of the tunnel walls on the flowfield around the configuration being tested Thus, the emphasis in this paper will be three dimensional wall interference and its minimiza tion, especially at near sonic test Mach numbers A wind tunnel wall configuration and porosity setting schemes which will permit minimum interference testing through $M=1$ are defined on the basis of conclusions drawn from existing transonic wind tunnel experience

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Early Transonic Wind Tunnels

Transonic test section wind tunnels have been in use for about 40 years Typically, they incorporate ventilated test section walls surrounded by a plenum Their function was described initially as eliminating the premature choking around a model as experienced in closed test sections The function of ventilated walls can also be described as minimizing wall interference at subsonic speeds This possibility was recognized in the 1930's [3] Since closed walls prevent streamline bulging and downwash at the wall, the measured lift is usually too high primarily because of blocking effects while the effect on drag depends on whether a blockage model or a lifting model is being tested Open walls permit excessive streamline bulging and downwash (The measured lift is usually too low) The obvious compromise is to incorporate partly open partly closed (ventilated) test section walls, with due consideration for the need to simulate infinite flowfield conditions over the length of the model with respect to the effects of blockage downwash, etc , sometimes over a trisonic speed range Such considerations resulted in the fixed open-area ratio slotted and 22% porosity normal hole perforated wall transonic test sections of the 1950's (Fig 1) [4] These walls were "passive" in the sense that there was no overt control of the flow direction through the ventilation Some of the 1950 vintage test sections are still in use

It soon became apparent that an optimum slotted wall does a better job of simulating unrestricted flow, especially with respect to pitching moment, for subsonic wing body-tail model tests up to M_{critical} This is illustrated in Fig 2 (derived from Ref 5) which compares the test section centerline down wash error due to wall interference for uniform fixed open area ratio slotted walls and perforated walls giving zero blockage interference Pitching moment errors result when the downwash errors at the wing and tail locations are dif ferent The slotted wall advantage accrues because the slot flow preserves some of the expelled stream tube momentum The uniform porosity perforated wall square test section does not result in correct streamline patterns subsonically but can give reasonable subsonic lift and drag data for moderate α's in tests up to just above M_{critical} on a lifting model of span no greater than 50 60% of the test section width This has been established by comparative tests using the same model, balance, and sting in a 4×4 ft tunnel and in a larger tunnel. It is also consistent with the theoretical results for uniform porosity walls presented in Ref 5 The 22% open perforated wall configuration was chosen mainly because it cancelled shock waves during supersonic tests It was found, however, that the normal hole walls of 22% porosity used in the 1950's allowed expansion waves to reflect and hit the model in tests above $M=1$ 2 and did little to alleviate the severe interference experienced near $M=1$

Finding a Good Wave Cancellation Wall Configuration

During the late 1950's and early 1960's, therefore, effort went into finding a wall configuration which would cancel both shock and expansion waves in the test range from $M=1.2$ to 2 0 (above $M=2$ wall interference is rarely a problem) The efforts included the examination of the wall pressure signature and pressure vs deflection angle relationship created by cone cylinder models (Fig 3) [6] An essentially linear $\Delta P/q$ (C_p) vs θ relationship was discovered The linear model signature was then compared with the ex perimentally determined wall crossflow characteristics (in the presence of freestream flow) for various wall configurations in search of a wall with matching characteristics It was discovered as shown in Fig 4 that normal hole walls have a linear characteristic, but the slope changes near $\theta=0$ deg; slots have a slope that varies with θ; and only the 30 deg inclined hole perforated wall shows the desired constant slope linear characteristic, and this only for rather thin wall boundary layers (The inclined hole wall was misnamed the "differential resistance wall ")

In studies of the inclined hole wall, it was discovered that supersonically, the model signature and the wall crossflow characteristics both vary in the same manner with test section Mach number Thus a uniform 6% open inclined hole wall gives nearly interference free supersonic test conditions from $M=1$ 2 to 1 6 (see Fig 5) Like the 22% open normal wall, it also gives correct lift and drag data on lifting models at $M<M_{\text{wall critical}}$ while creating a downwash error at the tail as illustrated in Fig. 2 Figure 5 quantifies the inability of the 22% porosity normal hole wall to cancel both shock and expansion waves This results from the change in charac teristic slope between inflow and outflow With normal holes, the hole discharge coefficient for outflow is reduced by the effect of the mainstream flow The 30 deg inclined hole wall is successful because aiming the holes into the wind results in the same flow resistance for inflow and outflow

Figure 5 also illustrates the severe interference effects which occur near $M=1$ for fixed porosity walls optimized for the subsonic and supersonic regimes These effects are also shown in Fig 6, which compares free flight transonic drag rise data on a body of revolution shape with data taken in a fixed porosity wind tunnel [7,8] Note that these effects are significant even at very small model blockages They are associated with the growth of a supersonic bubble around the test model and its extension to the test section wall as the test Mach number approaches 1 0 (see Fig. 7) $M_{\text{wall critical}}$ will be defined as the

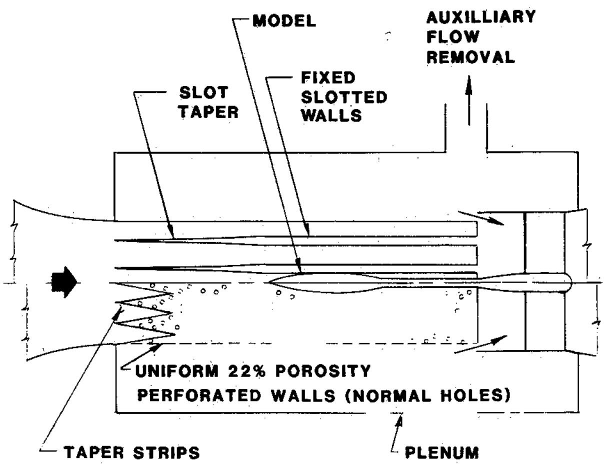

Fig 1 Early ventilated wall concepts

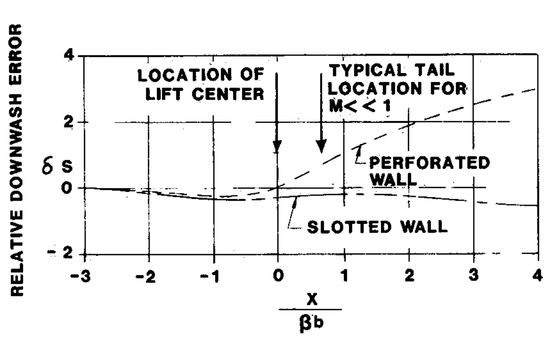

Fig 2 Relative downwash interference distribution for walls with uniformly distributed open area ratio giving zero overall blockage interference.[5]

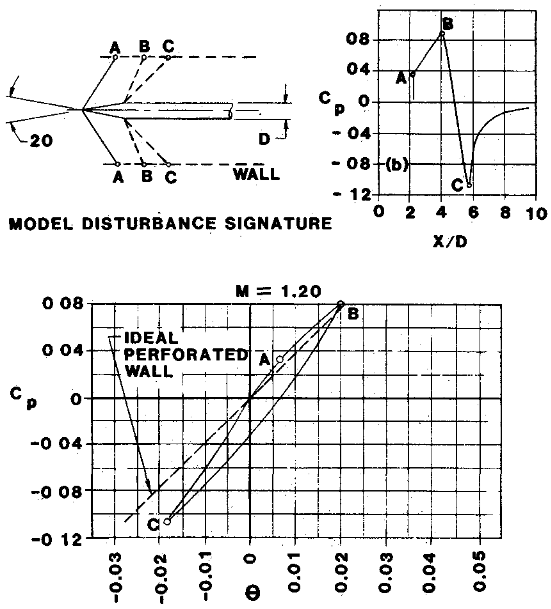

Fig 3 Model disturbance signature and the desired wall charac teristic for $M>1$ testing [4,6]

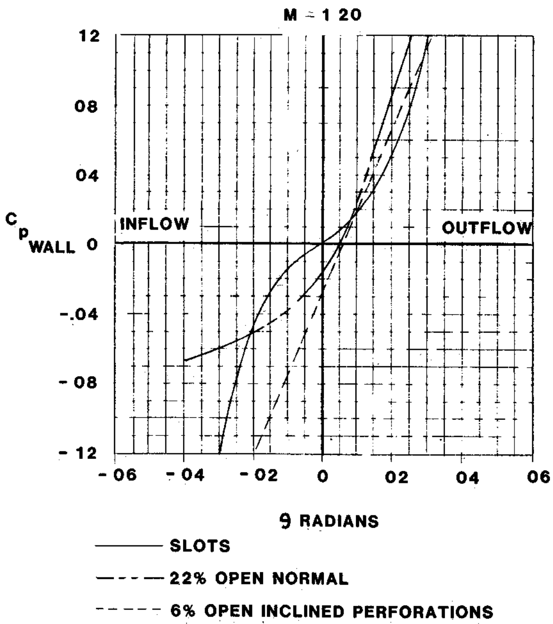

Fig 4 Comparison of wall characteristics for various wall con figurations [4]

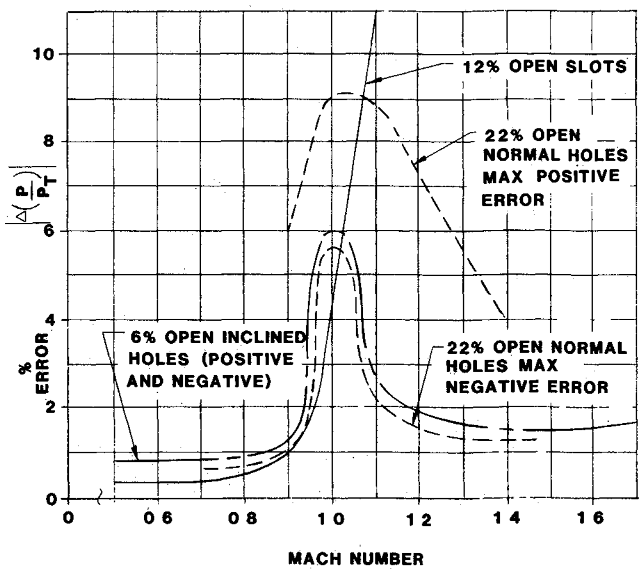

Fig 5 Model surface pressure error for different walls [6]

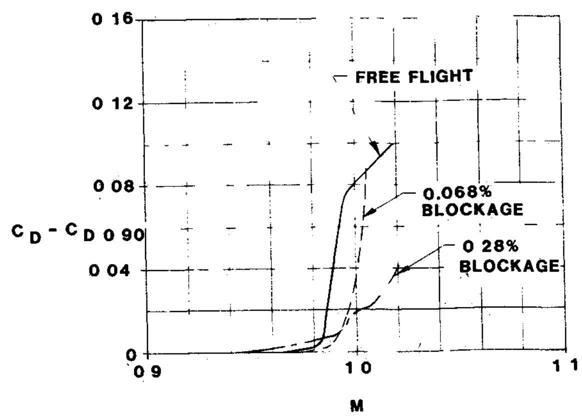

Fig 6 Body of revolution drag increment vs Mach number in free flight and for different wind tunnel blockages [7]

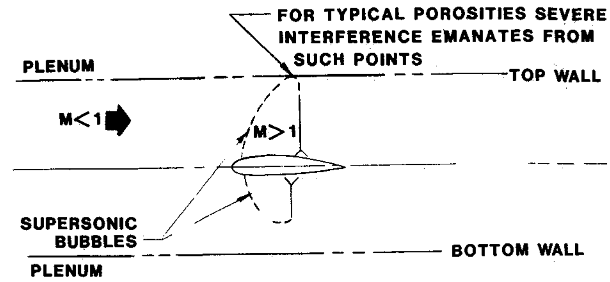

Fig 7 Wall interference problems associated with growth of supersonic bubble

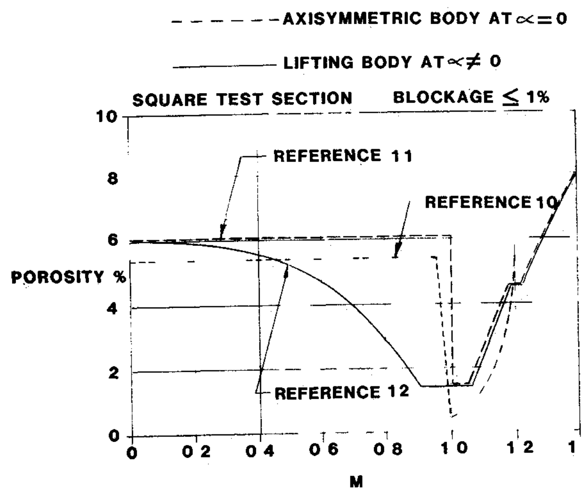

Fig. 8 Optimum porosity schedule for inclined hole perforated walls with global porosity variation.

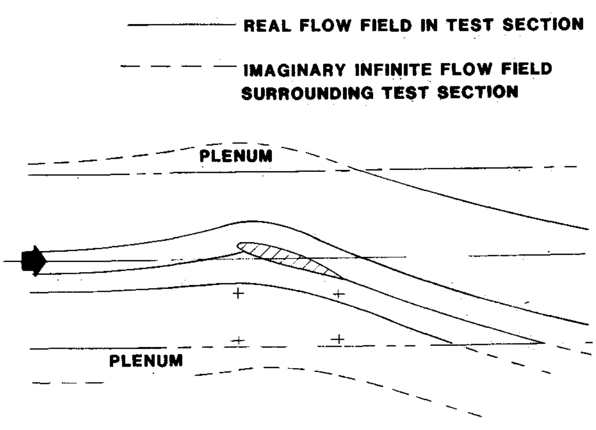

Fig. 9 Required consistency between test section flowfield and imaginary flowfield.[13]

freestream Mach number at which the Mach number at the test section wall becomes sonic locally When the Mach number at the wall approaches 1 0 ($M \rightarrow M_{\text{wall critical}}$), an almost singular change in the match between the model disturbance signature and the wall characteristic occurs which requires a lower porosity than either the subsonic or supersonic regimes

Near-Sonic Model Flowfield

It is appropriate to examine the flowfield portrayed by Fig 7 The Mach number regime associated with Fig 7 is of special concern with respect to transonic testing It is characterized locally by mixed (subsonic supersonic) flow over the model with embedded shocks intersecting the model surfaces The aerodynamic forces experienced by the model will be sensitive to shock location, which, in turn is sensitive to both boundary layer thickness (*Re*) and tunnel wall in terference [2] With shock induced boundary layer effects, it is impossible to make corrections for Reynolds number and wall interference (though some extrapolation of *Re* effects may be possible) Thus correct Reynolds number and near zero wall interference at flow locations such as the upper wing surface become important, even for testing just above the critical Mach number Also the near sonic mixed flow regime is of more than academic interest because it is the cruise regime for the current generation of subsonic transports; and also because future fighters may enter dogfights here to minimize the deceleration and energy loss currently suffered The National Transonic Facility (NTF) raison d'etre is its ability to provide full scale Reynolds number in this regime[9] but this is only part of the problem; and in this mixed flow regime neither uniform fixed wall porosity nor fixed slotted walls will minimize wall interference adequately

Shortly after the effectiveness of the inclined hole wall was recognized, it was also recognized that variable open area ratio could be provided by incorporating a translating perforated backup plate making possible excellent wave cancellation at all Mach numbers above 1 0, and permitting nearly complete closure of the walls for tests at $M=1$ where the freestream flow conditions are extremely sensitive to flow through the walls The action of such a wall can still be referred to as "passive " that is, flow through the wall is defined by the porosity and the difference between the flow side wall pressure and the plenum pressure, which is basically uncontrolled and nearly equal to freestream static pressure

Optimum Porosity Determination for Perforated Walls with Global Porosity Variation

In the mid-to late 1960's and early 1970's, tests were run on simple geometry blockage models at $\alpha=0$ deg to determine the wall porosity giving near zero blockage interference with inclined hole perforated walls [10 11] These tests were run in tunnels with global porosity adjustment (variable but uniform porosity) Figure 8 presents a typical schedule of porosity vs Mach number giving zero blockage interference for simple bodies, and shows the significant porosity reduction required near $M=1$ 0 Since the wall porosity is not important upstream and downstream of the model disturbance region the optimum global porosity vs test section Mach number for small blockage models can be construed to be an indication of the optimum local porosity vs local wall Mach number Similar tests were also run on lifting models[12] with less conclusive results subsonically because local wall Mach numbers varied with model angle of attack, and at high α differed greatly from the test Mach number At this point, it is appropriate to recall that the development of uniform fixed and uniform variable porosity perforated walls arose because of the need to cancel shock and expansion waves in the regime from $M=1$ 2 to 2 0 In this strictly supersonic regime, 6% uniform porosity does a reasonable job of eliminating lift, drag and pitching moment errors due to wave reflections from the walls during tests at $M=1.2$ to 1 6 up to moderate α on complete wing body tail models Also during subsonic tests below the wall critical Mach number, fixed uniform porosity walls (22% open normal hole or 6% open inclined hole) eliminate lift and blockage interference very well, and the remaining downwash errors fore and aft of the lift center can usually be corrected for With typical fixed porosities, however, the interference effects resulting from $M_{\text{wall local}} \approx$ 1 0 produce unacceptable coefficient errors, even with very small blockage Thus global porosity variation in perforated wall test sections has been employed from roughly $M=0$ 7 (for lifting models) to $M=1$ 2 to counter the effect of local sonic conditions at the wall Using global porosity reduction to handle the local effect of a supersonic bubble at the test section wall, however can have a detrimental effect on local flow conditions over a reasonably sized lifting model

Adaptive Wall Developments

It is worth describing some wind tunnel developments begun in the 1970's in the area of adaptive walls Three factors provided the launching pad for adaptive wall work: 1) renewed recognition that uniform width slots and uniform porosity could not minimize lift drag and pitching moment errors simultaneously in subsonic tests, especially above $M_{\text{wall critical}}$, 2) development of computational fluid dynamics permitting inviscid flowfield characterization and 3) the development of affordable digital computers which could be applied to adaptive wall research The operating philosophy behind the adaptive wall is that for interference free conditions around the test article, there must be a unique imaginary flowfield extending from a reference flow surface to infinity which is consistent with the flow conditions at the surface (Fig 9) [13] Typically, local flow direction and velocity distributions are measured on a reference surface inside the test section walls The adaptive feature exists if it is possible to modify the test section boundary conditions to bring the real and imaginary flowfields into conformity With present computer power, it is possible to do this automatically in an interactive manner although it may consume 10s of test time (a problem for blowdown tunnels)

Early in the development of adaptive walls, two concepts received most of the attention: 1) self streamlining solid walls (Fig 10),[14] and 2) perforated or slotted walls with segmented, pumped plena (Fig 11) [15] These might be referred to as "active" wall concepts. The use of solid self-streamlining walls is well justified for two dimensional airfoil tests because it permits a large wing chord in a relatively small low power test section Also the development of self streamlining walls[14] is aimed at a unified wind tunnel concept involving cryogenics to permit high Reynolds numbers with low model loads magnetic suspension to eliminate model support interference, and flexible, self-streamlining walls which might allow the magnets to surround the model closely Nevertheless, these two adaptive wall concepts do not cope successfully with mixed flow and concentrated shock waves at the walls These "active" adaptive wall concepts, even for two dimensional tests, involve complicated hardware and considerable computer power to perform a function which at subsonic speeds is not much better than that already done by "passive" fixed geometry uniform slotted walls

Wall Interference Minimization with Perforated Walls Having Distributed Porosity

The best wall geometry compromise appears to be the inclined hole perforated wall with locally adjustable porosity

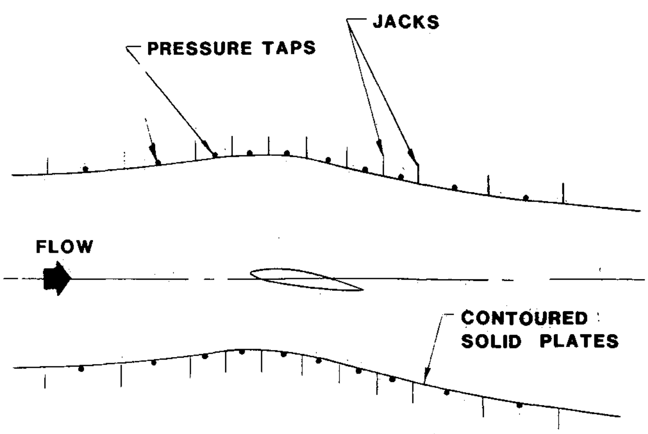

Fig 10 Self streamlining adaptive walls [14]

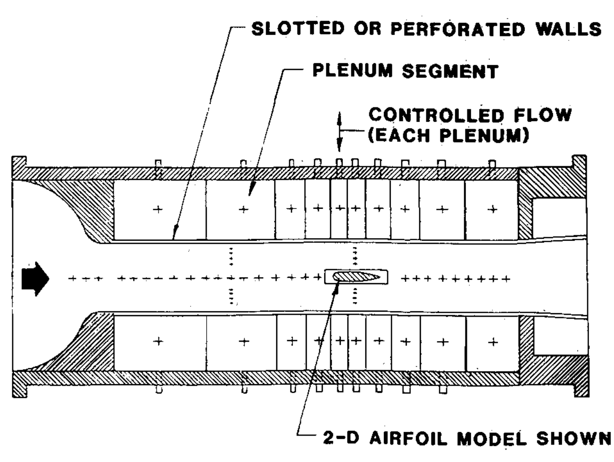

Fig 11 Segmented plenum adaptive wall concept [15]

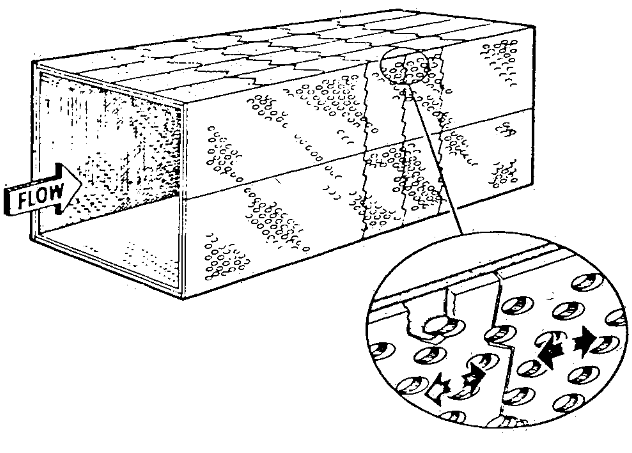

Fig 12 Segmented variable porosity perforated test section [16]

surrounded by an undivided plenum. This essentially passive wall concept was first proposed in the early 1970's, and is now being demonstrated to be successful in AEDC 1T (Fig 12) [16 17] It is understood that $M_{wall\ local}$ reaches 1 0 at a test Mach number which is a function of model attitude and blockage, and that the relationship between the model dis turbance signature and the wall characteristic changes sud denly near $M_{wall} = 1\ 0$, necessitating a local porosity reduc tion Thus local wall porosity reductions should be employed, perhaps based on $M_{wall\ local}$ At the least, each wall should function independently as is currently possible in AEDC 4T The need for porosity to be locally variable rather than uniform, in order to minimize wall interference over the entire transonic test regime has now been identified Ideally this will involve the ability to vary porosity locally either by segmentation and local control of the movable backup plates, or by manual porosity reduction using tape[18] or backside blocker plates. Four control methodologies can be utilized for setting local porosities: 1) true adaptation, wherein flow con dition measurements on a control surface are made and checked for consistency with infinite flowfield conditions and adjustments made automatically to the walls until consistency is obtained (as in AEDC 1T) 2) direct algorithm automatic wall adjustment based upon the test Mach number, the local wall Mach number, and the axial location relative to the model center of lift in order to counter downwash errors (The local Mach number adjustment might reduce the local poro sity to 0 5% where $M_{wall\ local}$ is between 0 97 and 1.05), 3) manual prerun local porosity reduction to counter im pending sonic conditions at the wall for the particular test conditions, and 4) fixed porosity distribution with porosity preset at near zero above the model wing planform (The small region of near zero porosity will have only a small effect on wall interference at $M < M_{wall\ critical}$ but will counter the severe interference at Mach numbers where the supersonic bubble reaches the wall above a lifting wing at angle of at tack)

Periodic surveys to verify consistency with infinite flow-field conditions are called for in those schemes which are not truly adaptive Note that the most important porosity ad justment requirement for extending the useable subsonic Mach number range beyond $M_{wall\ critical}$ is the ability to reduce the porosity to near zero where $M_{wall\ local}$ is sonic (which may work with slots, too) This will normally occur above the wing planform of a lifting model which suggests that the variable porosity feature may be conveniently restricted to a small region above the model if testing above $M \doteq 0\ 95$ is not required The advantages of the proposed locally variable porosity scheme are: the capability of providing acceptable levels of wall interference through the entire transonic regime; applicability of a variety of porosity setting schemes which will constitute an improvement over the current uniform porosity situation, some of which are quite simple; and the ability to reproduce fixed porosity and uniform variable porosity conditions from previous tests

Conclusions

For transonic tests of reasonably sized models (blockage <2%, span <60% test section width) at moderate (unstalled) α's:

1) In the strictly subsonic regime, fixed slots minimize lift drag, and pitching moment interference effects better than do fixed, uniform porosity perforated walls

2) In the strictly supersonic regime, inclined hole per forated walls of uniform but variable porosity, or even with 6% fixed uniform porosity, minimize wall interference reasonably well where other wall concepts fail

3) In the strictly subsonic regime, inclined hole perforated walls of 6% uniform porosity minimize lift and drag in terference effects, and the remaining downwash errors fore and aft of the lift center can be corrected for

4) In the near sonic Mach numbers regime between $M_{wall\ critical}$ and $M = 1\ 2$ neither globally fixed nor variable porosity effectively minimizes wall interference The main need is for local porosity reduction to handle local sonic conditions at the walls

5) The need to reduce porosity locally where $M_{wall\ local} = 1\ 0$ and the desire to minimize wall interference related down wash errors subsonically, as well as to provide wave can cellation supersonically, leads one to an inclined hole per forated wall with locally variable porosity

6) A number of porosity schemes are available, some quite simple, which will minimize wall interference at subsonic Mach numbers above $M_{wall\ critical}$ These include true adap tation, direct algorithms, manual prerun local porosity reductions where $M_{wall\ local} \approx 1\ 0$ is expected, or fixed areas of reduced porosity above the wing planform

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