Development of Minimum-Correction Wind Tunnels

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Flow distortions due to wind-tunnel wall interference may be accounted for if the model-to-tunnel ratio is small, but the theory becomes less reliable as the model becomes larger. This paper presents theoretical analysis and experimental evidence that supports a new concept of wind tunnel. The method employs active control of flow through the walls so that the model is in approximately free air conditions during the test. Practical considerations in the design of such a tunnel are presented. Results indicate that a minimum-correction wind tunnel may be achieved with active walls of relatively low porosity.

Nomenclature

C = model chord
C_L = lift coefficient (three dimensions)
C_ℓ = lift coefficient (two dimensions)
H = wind-tunnel height
i = index of series
K = function of model chord to tunnel height ratio defined by Eq. (3)
n = index of summation
p = index of summation
V = velocity
α = angle of attack

Subscripts

∞ = freestream condition
O = arbitrary initial measurement

Introduction

INTEREST in wind-tunnel interference in recent years has increased with interest in STOL vehicles. The requirements to simulate flight vehicles at extreme lift coefficients with possible partial flow separation at hovering flight or at transition flight have imposed a new challenge for the wind-tunnel designers. The need to test large models results from several requirements. In order to match dynamic similarity rules, a high Reynolds number is required. Large models often are required also because of the difficulty in construction of small models with intricate components of high lift devices. Flow distortions due to wind-tunnel wall interference may be accounted for if the model-to-tunnel ratio is small, but the theory becomes less reliable as the model becomes larger.[1,2]

The foregoing reasoning and future projections of testing requirements provided the incentive drive to construct very large wind tunnels.[3,4] This effort is led by NASA, which currently is considering seriously the construction of a wind tunnel that will have a test cross section with an area of 9600 ft.[2]

This paper presents a new approach to wind-tunnel simulation which may provide a complementary technique for improved tests of V/STOL models even in a large wind tunnel. The flow in the proposed tunnel is controlled so that the model is in an approximate free-flight condition during the test. The method employs active monitoring and controlling of flow through the tunnel walls. This type of wind tunnel is capable of a wider test range than that of the conventional wind tunnel, since the flow condition resembles the free airflow even for relatively large models at high lift coefficients. Inot limited to a particular model or geometrical configuration. The investigation presents theoretical analysis and experimental evidence in support of this concept of wind tunnels. Practical design considerations on the flow control and manner of injection also are presented.

The desire to obtain a minimum-correction wind tunnel was documented in earlier experimental works by Kroeger. His method employed semi-active walls by adjustable wall louvers. Partial success of the technique was summarized in the final report of that investigation.[5] However, analytical foundations for further design of such a tunnel have not been published.

During the preparation of this study, some work on minimum-correction wind tunnels was published by the staff of the Calspan Corporation.[6] Their proposal calls for the use of a comparison between two flow components in order to evaluate the flow improvement in the tunnel. Experimental data to evaluate that proposal are not yet available.

Minimum-Correction Wind Tunnel

The present development of minimum-correction wind tunnels employs active flow control through the tunnel walls. The amount of flow to be regulated through the wind-tunnel surface is computed by potential theory and is based on the actual lift measured on the model'The pertinent questions in the design of such a wind tunnel were evaluated analytically and experimentally. The discussion in the paper is addressed to the following objectives: 1) Show that, in principle, it is possible to obtain a minimum-correction wnd tunnel by controlling theflow at the walls. 2) Analyze an appropriate way to regulate the flow through the walls. 3) Develop a principle of operation for an arbitrary lifting body. 4) Assess practical considerations to be used in the construction of an active wall wind tunnel.

Theoretical Analysis

Analytical Considerations

The basic assumption of the active wall wind tunnel is that potential flow analysis provides an accurate description of the flow far away from the model. Although the detailed structure of the flow may vary widely with the aerodynamic body very close to that body, it assumes the model of a simple horse-shoe vortex in a short distance.

This description is supported by experimental evidence. The familiar wake of a contrarotating vortex pair has been documented for a wide variety of lifting bodies. A reference is made to works by Heyson et al.,[7] which illustrate experimentally that the wake behind a helicopter rotor blade is

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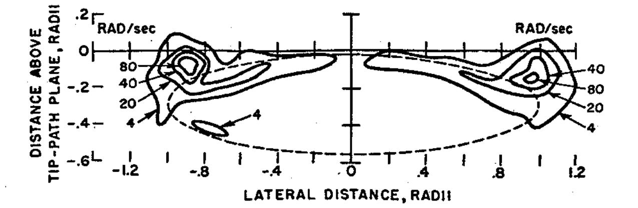

Fig. 1 Vorticity distribution at 7% of radius behind a helicopter rotor.

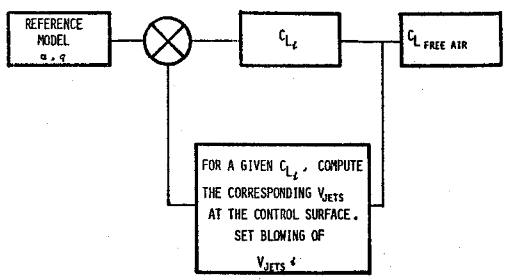

Fig. 2 Feedback model of the minimum-correction wind tunnel.

rolled up into a vortex pair at 7% of the blade radius behind the rotor. The distance to the location at which the potential model representation is valid will be longer for high disk loading. This pattern is reproduced in Fig. 1.

In accordance with the preceding discussion, at some distance from the model (i.e., near the wind-tunnel walls) a fictitious control surface may be constructed. On this control surface, potential theory is applicable in an arbitrary wind tunnel and for an arbitrary aerodynamic body. In particular, it is recalled that the solution to the potential flow problem is unique. Therefore, if we assure that at every point on the control surface the flow is identical to that of free air, the model inside the control volume will experience free-flight flow. It is summarized then that the applicability of potential theory to this physical problem provides a theoretical basisfor coneructing a minimum-correction wind tunnel.

A practical consequence of the potential theory is that it is sufficient to control only the normal component of the flow on the boundary. This result occurs because a potential function (in this case, the free air potential of the model) is aniquely defined by its normal derivative on the control surface (assuming the potential to vanish at infinity). (See, for example, Ref. 8.)

The principle operation of the proposed new tunnel is as follows. Starting with an arbitrary model and configuration, the lift is measured. Potential theory is utilized with a simple flow model to compute the required flow conditions along the wall. This computed flow then is provided by injection or extrction. Because such flow modifications change the lift, a continuous feedback process occurs, as illustrated in Fig. 2.

It is now necessary to prove that this process converges and the measured lift will assume the free air value. For the sake of simplicity, the proof is presented for a two-dimensional case where the model is represented by a discrete vortex. Since in the far field the more complicated flow models are reduced to the simple flow representation, it is suggested that the proof of convergence using a simple flow analogy is applicable to the general case.

The analysis is described as a stepwise process, although in practice it may be continuous. The steps are designated by the index i, and each one contains two paths, as illustrated in the feedback model in Fig. 2. In the forward path, the lift is measured in a given configuration of the model, angle of attack, and the wind-tunnel dynamic pressure. The lift coefficient, C_{ℓ_i}, is used to compute the appropriate jets of the active wall system. In the feedback path, the controlled flow is

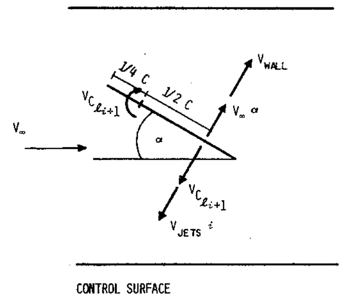

Fig. 3 Mathematical analogy of the minimum-correction wind tunnel.

introduced at the wall. The lift on the model is changed, and a new value of lift coefficient, $C_{\ell_{i+1}}$, will be measured.

The analytical relation between the new lift coefficient $C_{\ell_{i+1}}$ and the lift coefficient of the previous step, C_{ℓ_i}, is describebeeeed as follows. The flight vehicle is represented by a simple vortex at its quarter-chord, and its boundary condition is satisfied at its ¾-chord. The normal velocity at that point is the sum of velocities due to each influence in the field, as illustrated in Fig. 3. These are first the velocity due to the wing itself and the normal component of the freestream, as usually is done in free air. In the presence of the wind-tunnel walls, a third component represents the effect of the walls. This flow component can be calculated by the method of images in the usual way. A fourth velocity component that is introduced at the model ¾-chord is due to the flow through the tunnel walls. This latter flow is regulated at will through the walls. The sum of these velocities is given by the following

$$V_{C_{\ell_{i+1}}} + V_{\text{jets}_i} - V_{\text{wall}} = V_\infty \alpha \qquad (1)$$

It should be noted that the index of the velocity induced by the model is $i+1$, whereas the jets at the wall were computed on the basis of the previous value of lift coefficient in ith step.

It may be shown (using the method of images; see, for example, 1) that the velocity induced by the walls on the ¾-chord point is given by the following

$$V_{\text{wall}} = C_{\ell_{i+1}} (V_\infty / 2\pi) K \qquad (2)$$

where the function, K, represents the sum of the infinte images that satisfy the boundary condition at the wall. K may be computed by

$$K = \frac{1}{2}\left(\frac{C}{H}\right)\sum_{p=1}^{\infty}(-1)^{p+1}\frac{C/H}{(C/2H)^2+p^2} \qquad (3)$$

The controlled flow through the surface is made to match the flow due to the model that would exist at the wall proximity in free air. It may be calculated mathematically by images outside the tunnel. The flow induced by the wall jets on the model ¾-chord is given by

$$V_{\text{jets}_i} = C_{\ell_i} (V_\infty / 2\pi) K \qquad (4)$$

Substituting Eq. (2) and (4) into Eq. (1) and expressing the velocity induced by the model in terms of the lift coefficient will result, after simplification, in

$$C_{\ell_{i+1}} = [2\pi\alpha / (1-K)] - C_{\ell_i}[K/(1-K)] \qquad (5)$$

This recursion relation does not necessarily imply a discrete process rather than a continuous one, but it is introduced as a convenient device to prove the convergence of the technique. For n iterations, Eq. (5) may be written as

$$C_{\ell_n} = \frac{2\pi\alpha}{1-K}\left[1-\left(\frac{K}{1-K}\right)+\left(\frac{L}{1-K}\right)^2-\ldots\right] + (-1)^n C_{\ell_0}\left(\frac{K}{1-K}\right)^n \qquad (6)$$

This alternating geometrical series converges to the free air value of $2\pi\alpha$ provided that the function K is less than one-half. Simple calculation will show that this is indeed the case when the ratio of model chord to tunnel height is less than 1.

It is of interest to note that in this theoretical model, given an initial value of lift coefficient and an error bound on the desired accuracy, one may compute the number of iterations necessary to obtain the approximate free air lift coefficient. This proof applies to the ideal case where the injection is distributed continuously. Then both mass flow and momentum across the control surface will be matched with free air condition to obtain a perfect simulation.

Practical Considerations

In practice, the flow is injected through a porous wall so that, if the mass flow is matched over an area, its momentum is greater than that of the ideal case. Alternatively, the integral of the momentum through the surface may be equated to the momentum through the porous area, resulting in a mass mismatch. The ratio given by the area of the holes in the porous walls to the total area of the wall henceforth will be referred to as porosity. It follows that the design of a minimum-correction wind tunnel may be constructed on the principle of either mass flow matching or momentum flow matching. In the one approach, the surface of the tunnel is divided into segments, each of which is made to match the mass flow that would exist there without the presence of the walls. The momentum injected or extracted through each segment would be larger than that of free air. The excess momentum will cause an overcorrection to the measured force on the model. This effect would be in a manner that is observed in open wind tunnels in which the momentum wake deflects through a larger angle than that of free air.

A minimum-correction wind tunnel may be designed to match the momentum flow. In this case, the momentum through each segment of the wind-tunnel surface is equated to the momentum flow through the porous area of that segment. Consequently, a mass flow mismatch would result, and the force on the model would be undercorrected. As the wall porosity increases, the mismatch between mass flow and momentum would decrease.

As a closing note to the analytical study, the mechanism of injection and extraction of flow through the control surface is discussed. Although flow extraction may be represented sufficiently by a mathematical analogy of a sink,[9] injection of flow may not be represented by a potential model. A difference in the physical phenomena is apparent by the following example: the human body would have suffocated in its sleep if inhaling would have been the true inverse of exhaling.

Injection of flow in the minimum-correction wind tunnel may be described as the introduction of normal jets into a uniform flow. This subject was the topic of numerous papers[10] but remains an open question to date. The implication of these differences for the problem of minimum-correction wind tunnels are under continued study at present. The discussion suggests, however, that flow injection should be introduced through a large number of small jets. For a given porosity, a large number of small jets will provide better matching of momentum and mass flow. The theoretical analysis suggests that the relative merits of momentum or mass matching and the effect of wall porosity should be the subjects of interest in the experimental investigation.

Experimental Study

Design Considerations

Experimental evaluation of the concept was carried out utilizing a two-dimensional model for its simplicity. Injection and extraction through the walls were carried out with a pattern of holes so that the active wall jets were three-dimensional. Consequently, the method of flow control through porous walls is identical to that which would be implemented in a three-dimensional tunnel, whereas the necessary corrections are simple. In this case, two-dimensional tests provide a more direct approach than three-dimensional tests to investigate design parameters represented by the concepts of mass matching and momentum matching and the effect of porosity on such a wind tunnel.

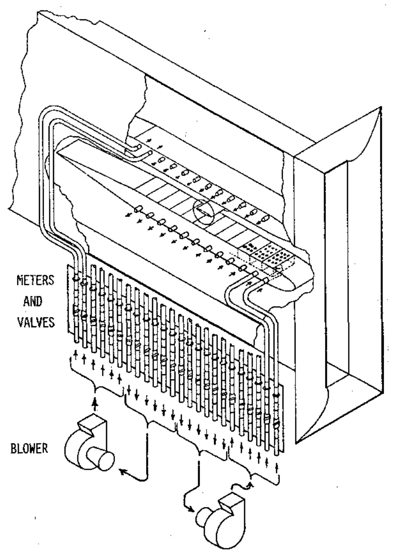

Fig. 4 Schematic of the minimum-correction wind tunnel.

A construction of a wind tunnel with adjustable floor and ceiling permitted the variation of the tunnel height from 12 times the chord to twice the chord. The variation of the tunnel height represents two limiting cases. The one case with tunnel height of 12 times the chord may be taken as a close approximation to free-flight conditions, whereas the latter case of tunnel height equal to twice the model chord represents an extremely small tunnel. Such a tunnel is probably smaller than that which would be used for practical research work. The advantage of the variable-height wind tunnel to study the concept of minimum-correction wind tunnel is that all of the necessary apparatus is self-contained. The model is placed in effectively the same experimental facility to provide approximate free air data, distorted data due to wall constraints in a small tunnel, and finally the data of the proposed new wind tunnel. The same model, instrumentation, and Reynolds' number were used in all of the stages.

Test Setup and Procedure

A prototype minimum-correction wind tunnel was constructed by installation of movable floor and ceiling in an 8×1 subsonic wind tunnel. A sketch of this tunnel is given in Fig. 4. Initial tests were run in the original tunnel having a height of 12 times the chord. With the installation of the movable floor and ceiling, the model was in a small tunnel with height of two model chords.

The flow quality in terms of pressure gradient and velocity profile was evaluated in the tunnel at each stage of the investigation. An appropriate boundary-layer allowance was designed and confirmed experimentally to assure no velocity gradients along the streamwise axis of the tunnel. The control surface as illustrated by the controlled segments of the floor and ceiling in Fig. 4 extended 4½ model chords upstream and 4½ model chords downstream from the model. A maximum number of 24 plenum chambers was used to regulate the flow through the surface.

The flow into or from each plenum chamber was generated by two blowers. The flow was controlled by manual valves and monitored through orifice-type flow meters. The meters were calibrated individually to assure the accuracy of the flow

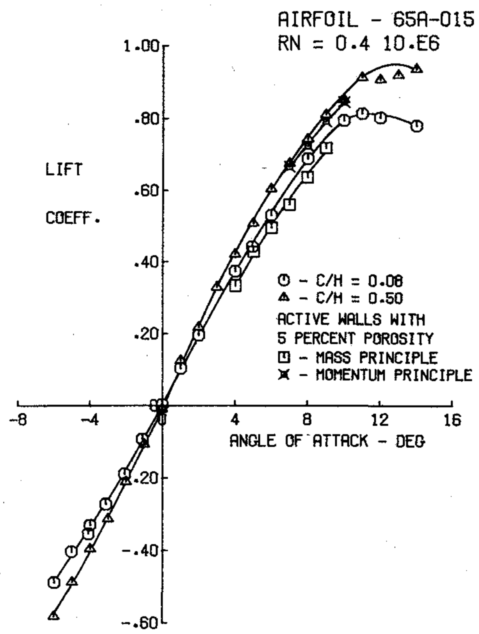

Fig. 5 Effect of active walls on lift interference in a two-dimensional wind tunnel.

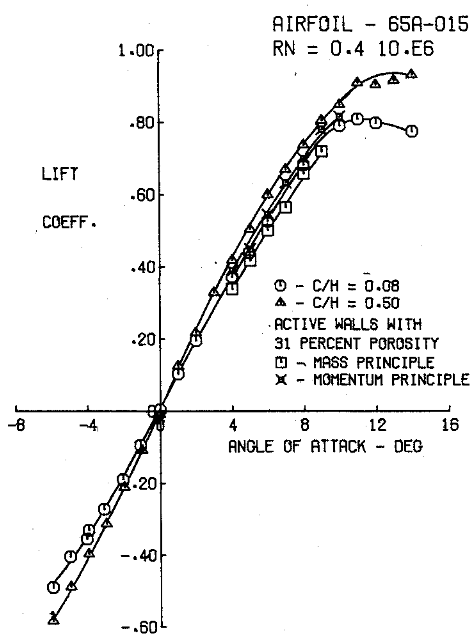

Fig. 6 Effect of active walls on lift interference in a two-dimensional wind tunnel.

measurement. Lift data were taken utilizing chordwise pressure taps at the midspan of the model. Data reduction and analysis were performed by a digital computer. Tests were run with dynamic pressure of 12 psf at a Reynolds number of 0.4×10^6. The model used was a symmetrical airfoil section NACA 65A015. Initial tests were made with tunnel wall porosity of 5%, and later tests were made with wall porosity of approximately 31%.

Results and Discussion

Results are presented in the form of lift curves for various model-to-tunnel-height ratios and injection rates. Injection rates range from complete mass flow matching to momentum match. Typical results for the experiments are shown in Fig. 5. Model chord to tunnel height ratio, C/H, of 0.08 represents free air data, and model chord to tunnel height ratio of 0.5

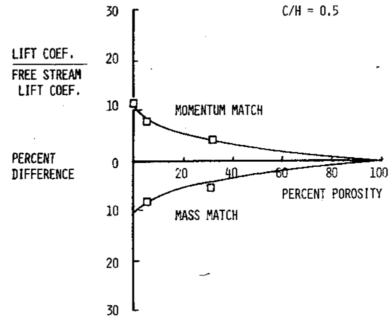

Fig. 7 Active walls effectiveness as a function of porosity.

represents the confined flow in a small tunnel. The classical effect of the wind-tunnel interference is to reduce the curvature of flow at the wing position. This effect is the same as a progressive increase in camber with increase in the angle of attack, and it results in a steeper lift curve slope.

This figure also presents the effects of active control of flow with wind-tunnel wall porosity of 5%. It is seen that the mass principle causes overcorrection because of large momentum mismatch, whereas momentum match undercorrects the flow. Similar observation is made for the data obtained with wind-tunnel wall porosity of approximately 31%, as illustrated in Fig. 6. It is noted further that, as the porosity increases, a decrease is observed in the difference between lift curve based on the mass principle and that which is based on momentum principle.

Even with 5% porosity, the improvement in lift curve slope is significant. The rate of flow improvement in the tunnel is shown in Fig. 7 as a function of porosity. The lift at zero porosity represents the interference of a closed-wall wind tunnel. The results converge at moderate values of wall porosity, as evidenced by the data obtained for the wall porosity of 31%.

Conclusions

The results of the investigation demonstrate both theoretically and experimentally the utility of this new concept in wind tunnels. Theoretical analysis supports the philosophy of constructing a minimum-correction wind tunnel using active walls. The analytical study substantiates the convergence of flow conditions in the tunnel to those of free air using the lift as a measure of the flow improvement. Of practical interest is the theoretical conclusion that it is necessary to control only the flow normal to the wall surface of the tunnel.

When the design is based on matching mass flow, the excess momentum caused an overcorrection; when momentum is matched, the mass flow is deficient, so that the lift curve is undercorrected. The difference between the two cases decreases rapidly as the porosity increases. This result indicates that a minimum-correction wind tunnel may be achieved with relatively low porosity of active walls. Although an exact value of porosity would depend on the accuracy requirements, the results presented indicate that the interference was substantially reduced with approximately 30% wall porosity. It is recommended on the basis of this investigation that further effort should be directed to study a minimum-correction wind tunnel in three dimensions.

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