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V/STOL Aircraft Model in Wind-Tunnel Testing from Model Design to Data Reduction

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Low-speed wind-tunnel testing of V/STOL aircraft concepts to determine the aerodynamic-propulsion interaction effects during the transition between hover and wingborne flight is a necessary step in the development cycle of this type of aircraft. Several factors must be dealt with to assure that the information obtained in experiments is accurate and representative of the full-scale aircraft modeled. Proper engine simulator selection is important based on resultant model size and assembly problems associated with small sizes, engine-inlet mass-flow simulation requirements, and required simulator drive air related to available supply. It is shown that at a given exit area and thrust level that the fan-type engine simulators provide a higher amount of inlet flow per unit of inlet area. In addition, a fan usually provides much more thrust per unit of primary mass flow. However, fans are more limited in maximum pressure ratio which they can develop as well as more expensive and more difficult to operate when compared with ejectors. A judgement of the best "power-off reference configuration" for each power-on configuration must be made such that interference parameters can be determined. Generally configurations which allow flow through the thrust simulator do not provide a useful power-off reference. The operating conditions must be at least estimated throughout transition such that the investigation can be planned efficiently to represent realistic flight conditions with a minimum of useless data collected. The influence of tunnel walls should be considered so that no data are obtained which cannot be corrected by available techniques. Particular attention is needed avoid testing at very low effective velocity ratios where a floor induced vortex is formed ahead of the model.

Nomenclature

A_e = engine exit cross-sectional area, m^2 (ft^2)
A_i = engine inlet cross-sectional area, m^2 (ft^2)
b = wing span, m (ft)
C_D = drag coefficient, drag/$q_\infty S$
C_L = lift coefficient, lift/$q_\infty S$
$C_{N,T}$ = tail normal force coefficient, $N/q_\infty S_T$
D_e = equivalent diameter, the diameter of a circle whose area equals the sum of the areas of all the engine exits, m (ft)
h = height of jet above ground, m (ft)
N = tail normal force, N (lb)
q_∞ = freestream dynamic pressure, Pa (lb/ft^2)
S = wing area, m^2 (ft^2)
S_T = tail area, m^2 (ft^2)
T = static thrust, N (lb)
V = freestream velocity, m/s (ft/s)
V_e = effective velocity ratio, $\sqrt{q_\infty/(T/2A_e)}$
V_e' = stagnation point velocity ratio, $1.31\, D_e/h$
$V_{e_{min}}$ = minimum effective velocity ratio for which data can be corrected to free air conditions, $0.65\, V_e'$
V_j = jet velocity, m/s (ft/s)
$\dot{w}$ = inlet weight flow, N/s (lb/s)
$\dot{w}_p$ = drive weight flow, N/s (lb/s)
α = angle of attack, deg
δ_j = jet deflection angle, deg
$\Delta\alpha$ = change in angle of attack due to wall effects, deg

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Introduction

V/STOL aircraft concept development begins as a preliminary design to define the configuration and operating conditions required to perform a desired mission. Conceptual design studies are refined many times before an aircraft configuration is acceptable. While a V/STOL aircraft design must achieve efficient performance throughout the entire mission, particular emphasis is given to performance in low-speed transition between wingborne flight and hover.

The propulsion systems of V/STOL aircraft must be designed to generate the forward thrust for conventional flight, the lift force for hovering flight, and in many cases, additional force components for control purposes during hover and transition flight. This dual- or triple-function character of V/STOL propulsion systems leads to design features which make them significantly different from conventional airbreathing propulsion systems. In most aircraft configurations, the lifting force for hovering flight is provided at two or more locations to permit moment trim and control about all three axes.

The lift jets issuing from the aircraft mix with the eternal flow to generate an extremely complicated three-dimensional flow. In general, the jet-induced effects caused additional forces and moments on the aircraft both statically and dynamically. The character and magnitude of these jet-induced effects is influenced by the flight regime being encountered as well as the specific aircraft configuration.

Several authors have surveyed and described these V/STOL propulsion-induced effects.[1-4]

In the low-speed flight regime, these effects are present in several areas: 1) the performance losses sustained while hovering out-of-ground effect; 2) the performance changes and hot-gas ingestion problems occurring while hovering in-ground effect; and 3) the induced aerodynamic effects in transition flight from hover to wing-borne flight out-of-ground effect and in-ground effect during a horizontal flight mode. Resolution of the conflicts which arise from the design requirements imposed by these different modes of flight present a significant challenge to the aircraft designer. Satisfactory solution is needed to provide necessary lift forces and adequate control power in low-speed flight.

The designer must be able to estimate the performance of the aircraft in this low-speed flight regime. Since very few proven predictive methods are available,[5] extensive wind-tunnel investigations must be conducted to verify the performance estimates. The results of these investigation are used to refine the configuration if necessary, and the design process continues to prototype flight and production.

Techniques for low-speed wind-tunnel tests of conventional aircraft configurations are fairly well established;[6] however, additional factors must be considered with V/STOL configurations. The purpose of the present paper is to examine a few of the more critical factors which must be dealt with to assure that the information obtained in experiments is accurate and representative of the full-scale aircraft. In particular, the following topics are discussed:

1) Proper engine simulation selection determines the resultant model size and can reduce assembly problems associated with small sizes, engine-inlet mass-flow simulation requirements, and required simulator drive air related to available supply.

2) A judgement of the best "power-off reference configuration" for each power-on configuration must be made so that interference parameters can be determined.

3) Modeling of realistic low-speed flight conditions to obtain a comprehensive evaluation of the entire transition flight envelope with a minimum of unrepresentative data.

4) Attention must be focused on the influence of the tunnel wall so that no data are obtained which cannot be corrected techniques are highly configuration dependent.

Discussion

V/STOL aircraft includes a very large variety of configurations. The most common category is the low disk loading rotorcraft. Examples of powered rotorcraft models are the AH-1G,[7] the ABC (advancing blade concept),[8] the RSRA (rotor systems research aircraft),[9] and the tilt-proprotor configuration.[10] These models typically use electric motors, gear boxes, rotating shafts and variable pitch rotors to represent their powered lift. As a class, rotorcraft models are very complex mechanically, especially the dynamic aspects. For example, the general rotor model system (GRMS)[11] used for the AH-1G[7] and RSRA[9] models is an extremely complex piece of equipment. Detailed discussion of the complexities of such rotorcraft models will not be attempted in the scope of the present paper. The GRMS is discussed in detail in Ref. 11, and a broader look at rotorcraft models is presented in Ref. 12.

The second major category of V/STOL aircraft configurations is the high disk loading vehicles. Examples of STOL aircraft models include externally blown flap,[13] upper surface blown flap,[14] and internally blown jet flaps.[15,16] Examples of V/STOL aircraft models include lift jet plus lift/cruise,[17] deflected thrust,[18] augmentor, and lift fan. Since the latter group of configurations have more demanding test requirements than the STOL configuration, the present paper will emphasize factors which influence wind-tunnel tests of high disk loading V/STOL aircraft.

The first, and most obvious, requirement in representing flight vehicles using wind-tunnel data is that the flight model must be duplicated faithfully in the wind-tunnel model. Unfortunately, this duplication is seldom achieved in practice. The reasons are manifold. Often power-train components cannot be obtained in physical sizes that permit direct scaling. The wind-tunnel tests are accomplished before flight, and changes may be incorporated in the actual aircraft subsequent to the wind-tunnel tests. Often the cost of a completely scaled model is prohibitive in relation to the purposes of a particular test. In any event, complete model-scale duplication of the flight aircraft is seldom accomplished. It then becomes important to reduce the significance of the differences by careful representation of the actual aircraft and by careful testing techniques.

When designing a wind-tunnel model to represent a powered V/STOL configuration, an engineer must concern himself with many facets of the results he expects to obtain in the wind tunnel. Some of the major factors which should be considered are: engine simulator selection for best simulation, model scale size for maximum model-construction efficiency, model scale size to tunnel size ratio for minimum wall-induced interference, engine-inlet mass-flow simulation (critical to V/STOL concepts), and drive-air mass-flow requirements as related to available air supply (if high-pressure air is used).

Engine Simulator Selection

Model Size

Since the engine exhaust is the most critical factor in the transition regime of V/STOL concepts, the most important model design decision will be the engine simulator selection. Figure 1 presents a comparison of a full-scale fan configuration and three available simulators. Descriptions and calibration data have been published for the 14-cm (5.5-in.) diam fan[19] and for the small ejector.[20] The model scale will

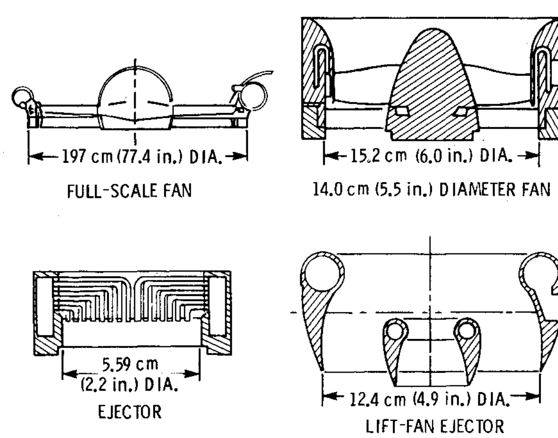

Fig. 1 Example of a full-scale fan configuration and three simulators which can be used in powered wind-tunnel models.

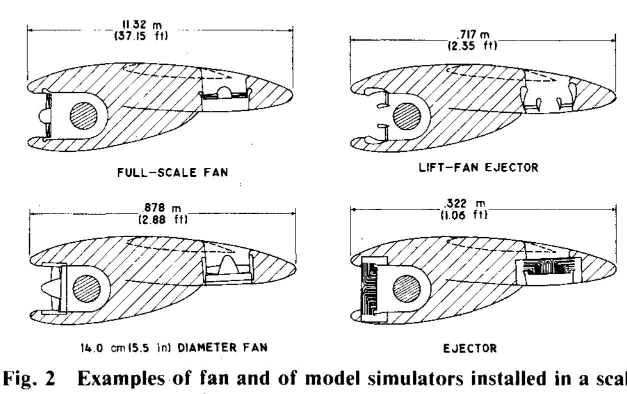

Fig. 2 Examples of fan and of model simulators installed in a scale model of a lift-fan pod.

be determined by the ratio of simulator diameter to full-scale diameter; therefore, once an existing simulator has been chosen, the model size is fixed. For an example model, three model scales were possible: 14-cm (5.5-in.) diam fan would provide an 8.6% scaled model, the lift-fan ejector would be a 7.4% scaled model, and the ejector would be a 3.4% scaled model. A definite decision between the 14-cm (5.5-in.) diam fan and the lift-fan ejector cannot be based on model size alone since the use of each results in nearly the same size model. However, the ejector simulator requires such a small model that it would be difficult to install the necessary instrumentation. Figure 2 presents a comparison of the installation of these simulators in a proposed scale model lift-fan pod. The following discussion compares the operating characteristics of fans and ejectors. It should also be noted that fans are usually more expensive to procure and more difficult to operate when compared with ejectors.

Inlet-Flow Simulation

The positions of the engine inlets in V/STOL aircraft configurations can also be critical to the external flow over the surfaces involved. The inlets of lifting engines are quite often located on the upper surface of the fuselage, wing, or pod. The engines must operate efficiently with the inlet-flow distortion caused by the external flow over the upper surfaces, and the engine inlet flow will influence these external flow patterns extensively. These factors, peculiar to many V/STOL concepts, require that the engine inlet flow be simulated properly. Figure 3 presents a comparison of inlet mass flow of each engine simulation with that of the full-scale engine. The inlet mass flow is ratioed to the inlet cross-sectional area and is presented as a function of the static thrust ratioed to the exit cross-sectional area. This figure indicates that the 14-cm (5.5-in.) diam fan simulates the full-scale article very well, while the ejector simulator provides only about half of the scaled inlet flow. In the case of the 14-cm (5.5-in.) diam fan, if the exit-flow characteristics are simulated properly, the inlet-flow characteristics will also be simulated properly.

Fan-Drive Air Requirements

After indicating the possible ramifications as to the adequacy of each engine simulator in producing an effective investigation, it must be decided if the tunnel facility will provide the necessary power to drive the simulators in question. Figure 4 presents a comparison of the drive air required to operate these simulators. The scale on the right indicates that the thrust required is a direct function of the model scale factor squared. The total scaled thrust required to simulate aircraft operating conditions throughout transition is presented as a function of required drive air mass flow and effective velocity ratio as defined as

$$V_e = \sqrt{q_\infty / (T/2A_e)}$$

The determination of required thrust at particular effective velocity ratios will be described later.

The termination of the thrust vs drive-air mass flow curves indicates the maximum thrust required to properly simulate the transition as shown on the right of Fig. 4. The curves do not indicate the maximum available thrust from the simulators but do indicate that there is sufficient thrust to operate these simulators. The air supply available in the Langley V/STOL tunnel is limited to 62 N/s (14 lb/s). Figure 4 indicates that the lift-fan ejector simulators will require a maximum of 44 N/s (10 lb/s); however, plumbing bends, unions, and valves could possibly increase line loss to a value which might make it difficult to deliver full flow to the model simulators. Based on the reasons previously discussed (Figs. 1-4), it was decided that the 14-cm (5.5-in) diam fans would be appropriate engine simulators for the example.

Exit-Flow Simulation

Since the simulated aircraft operating condition is dependent on the effective velocity ratio, it is imperative that the thrust level be scaled properly according to the equation above. Thrust should be large enough to permit testing at as high a freestream dynamic pressure as possible to maximize Reynolds number for aerodynamic characteristics. Generally ejectors provide larger exit pressure ratios than fan simulators. For high performance supersonic fighter configurations with convergent-divergent nozzles, high nozzle pressure ratio simulation can be important.[14,17] For subsonic configurations with convergent nozzles, the importance of the nozzle pressure ratio[1,14,18] and the engine exit velocity profile[21,22] in simulating the V/STOL hover and transition aerodynamic performance have been shown to be secondary factors. References 21 and 22 have shown that the exhaust dynamic pressure decay with increasing distance from the nozzle exit can affect the experimental aero-propulsion interaction on performance at all tunnel velocities from hover through transition.

Thermal gradients and turbulence levels in the engine exhaust are also possible areas of interest for proper simulation of engine exhaust flows. However, little information exists to provide an evaluation of their significance on the interaction effects with the vehicle aerodynamic characteristics. Reference 4 does show that the thermal effects on induced vehicle aerodynamics are secondary; however, hot-gas ingestion on engine performance due to exhaust recirculation can be serious. Those two areas of simulation requirements should receive major consideration for future V/STOL research.

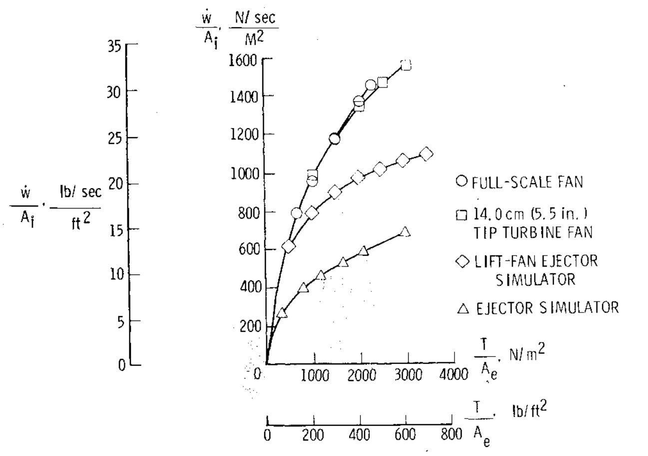

Fig. 3 Comparison of inlet-weight flow for the fan and model simulators.

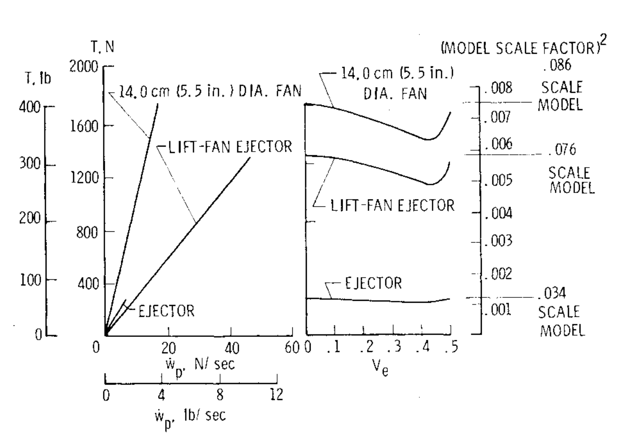

Fig. 4 Comparison of high pressure drive air required to power the model simulators.

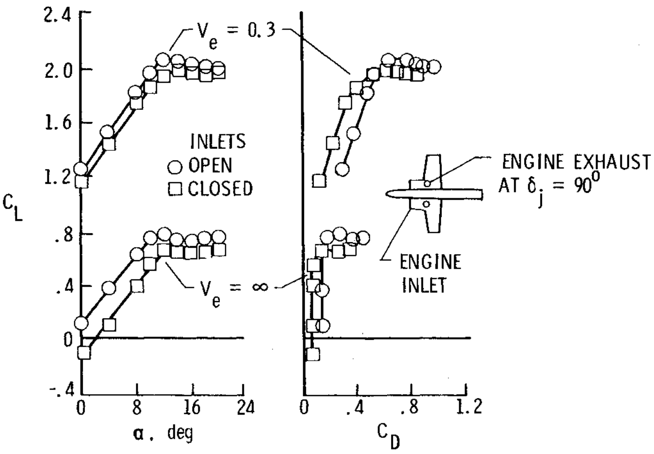

Fig. 5 Effect of inlet-weight flow on the longitudinal aerodynamic characteristics of a subsonic, vectored-thrust V/STOL configuration.

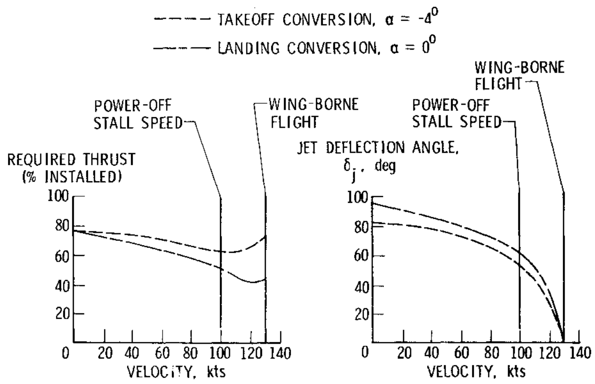

Fig. 6 Estimated requirements for installed thrust and jet deflection through the transition-flight regime.

Power-Off Model Reference Configuration

One particularly important aspect of V/STOL model testing is the need to describe a "power-off reference configuration" for each power-on configuration tested. These data are then used to provide a basis for determining the interference of the lifting jets on the transition flight aerodynamic characteristics. When a model has a flow-through nacelle for the cruise configuration, it provides the least restriction to air flow and, as a result, the lowest interference drag force. When an engine simulator is installed, it provides a restriction to flow and, as a result, an increased interference drag force and a reduced inlet-mass flow. When either the nacelle exit or the entire nacelle is deflected, the flow interference becomes more complex and produces larger effects on the model aerodynamic performance.

Previous work[23-26] has shown that the effect of engine inlet flow can be significant. An example of these effects are presented in Fig. 5 for a subsonic, vectored-thrust V/STOL configuration with the nozzles deflected 90 deg. Longitudinal aerodynamic performance characteristics are presented for the model with inlets either open or closed for identical operating conditions. Ejectors similar to those described in Ref. 20 were used in the wind-tunnel model. With the inlets open, the inlet weight flow was measured. Without thrust, the inlet weight was dependent on the freestream dynamic pressure. With thrust, the inlet weight flow was nearly independent of freestream dynamic pressure and thrust level.

Data were also taken with the inlets closed. By use of the product of inlet weight flow rate and the freestream velocity, the increment in lift due to the inlet flow was calculated to be significantly less than the measured lift increment. A comparison of a very limited amount of wing pressure profile

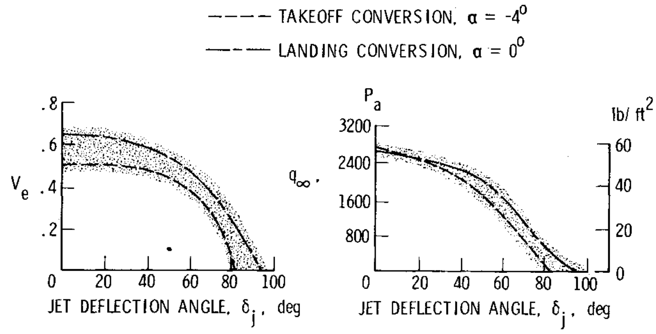

Fig. 7 Powered wind-tunnel model operating conditions required to represent transition flight.

data[26] without power for the inlets open and inlets closed for the front vectored-thrust configuration helped explain part of this difference. These data show that closing the inlets induced a downwash on the wing which decreases local angle of attack between 1 deg and 2 deg. Fuselage and nacelle pressure data indicate that opening the inlets produces flow changes similar to those associated with jet-exit interference effect at high velocity ratios. These results indicate the inlet effect is largely caused by the exit of the flow through the nozzles. These results are discussed in detail in Ref. 24.

Even though there were no external geometric changes in the configuration in the preceding example that would influence the overall aerodynamic characteristics, it was difficult to precisely identify the effects of power. The problem becomes more complex when V/STOL aircraft configurations have tilted nacelles where flow separation effects exist or have augmentors built into the wing which totally change the external aerodynamic shape.

Aircraft Transition Flight Representation

To determine the maximum thrust required for the engine simulator selection it is necessary to know the estimated operating conditions of the full-scale aircraft configuration throughout transition. Figure 6 presents these estimated conditions for the configuration in the takeoff and in the landing conversions. The required percentage of installed thrust and resulting forward speed for equilibrium flight throughout transition is shown in Fig. 6. To indicate the relationship between thrust deflection and forward speed, curves are presented in Fig. 7 as a function of the jet-deflection angle for the landing and takeoff conversions. To keep the tunnel entry down to a reasonable length of time, the number of test conditions can be reduced by obtaining aerodynamic data only near the estimated operational effective velocity ratios and the full-scale dynamic pressure (see Fig. 7) shown by the shaded regions. For example, detailed aerodynamic performance testing of the configuration with a jet deflection of 0 deg at very low velocity ratios, or with a jet deflection of 90 deg at very high velocity ratios, would be unrealistic. The flight vehicle could not operate at these conditions, and the data generated would not be representative of a realistic flight envelope.

Wind-Tunnel Wall Effects

The primary work in wind-tunnel wall effects and their corrections for V/STOL configurations was done by Heyson.[27-29] This work differs from classical corrections[30] because it eliminates the small angle assumption for the wing and engine efflux wake deflection angles. It was shown that theoretical treatment is possible if the magnitude of wall interference is kept within reasonable bounds. The wall interference tends to be proportional to lift coefficient. As a result, it is quite large for V/STOL configurations where the lift coefficient approaches infinity as the forward speed approaches zero.

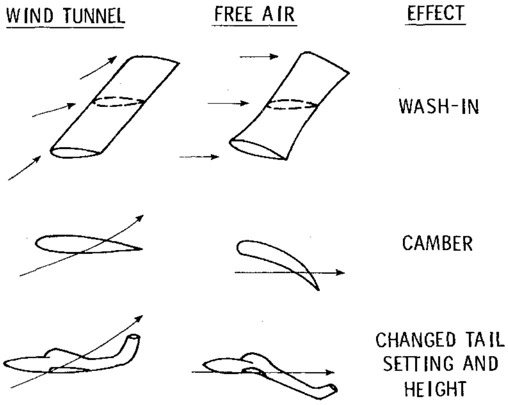

Fig. 8 Nonuniform flow interference on wind-tunnel models which represents an effective distortion of the corresponding vehicle in free air.

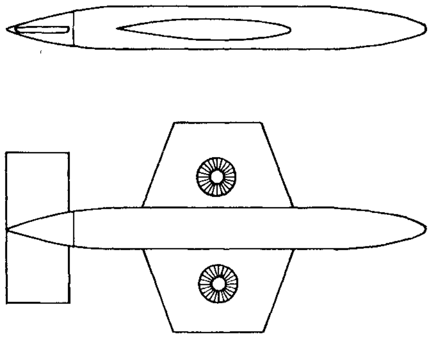

Fig. 9 Fan-in-wind wind-tunnel model used to investigate wind-tunnel wall effects.

The character of wall effects as nonuniform interference is shown in Fig. 8. Variations of flow angularity occur across the span of the test section and affect the wind-tunnel model as a wash-in twist distribution. Proper correction requires that the wing spanload distribution be corrected to the uniform free-air flow angle. Variations of flow angularity along the length of the test section can present a more serious problem. The airfoil appears to have a camber shape. A lift fan can have a distorted inflow pattern. Over the length of the vehicle, the distortion can be large enough to provide an aerodynamic change in both tail incidence and height. Effectively, the model is distorted from the configuration which it originally was intended to represent. Corrections to the longitudinal angularity variations are more difficult as shown by the following investigation.

A systematic investigation[31] of wind-tunnel wall effects was conducted in several different wind-tunnel tests sections using the model shown in Fig. 9. The fan-in-wing model used a 20 cm (8-in.) fan mounted in each side of a low-aspect-ratio wing. The wing/fuselage was mounted on a strain-gage balance. The horizontal tail was mounted on a separate strain-gage balance.

A sample of the data obtained on the wing/fuselage at an angle of attack of 16 deg is presented in Fig. 10. Without corrections, the lift/thrust ratio appears to be inversely proportional to the cross-sectional area of the test section. With corrections,[27,28] excellent correlation for the wing lift parameter is achieved throughout the use of effective velocity ratio. This indicates that the chordwise and spanwise variations of flow angularity at the wing are corrected properly.

A sample of the data obtained on the tail at an angle of attack of only 0 deg is presented in Fig. 11. Without corrections, the tail normal-force coefficient shows considerable scatter at the low velocity ratios. There are no

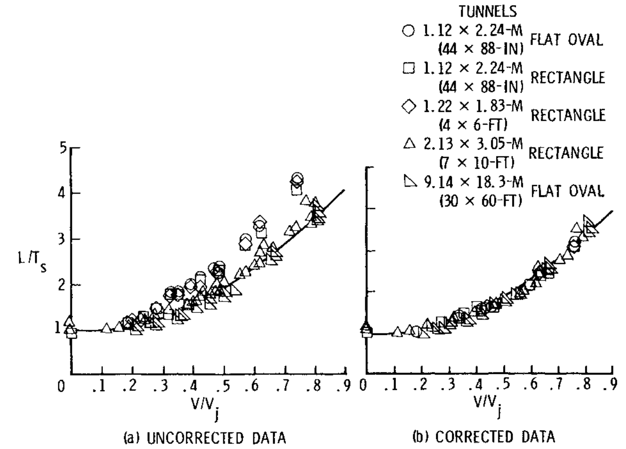

Fig. 10 Sample of wind-tunnel wall effects showing the effect of test section size and the effect of wall correction theory on wing lift at an angle of attack of 160 deg.

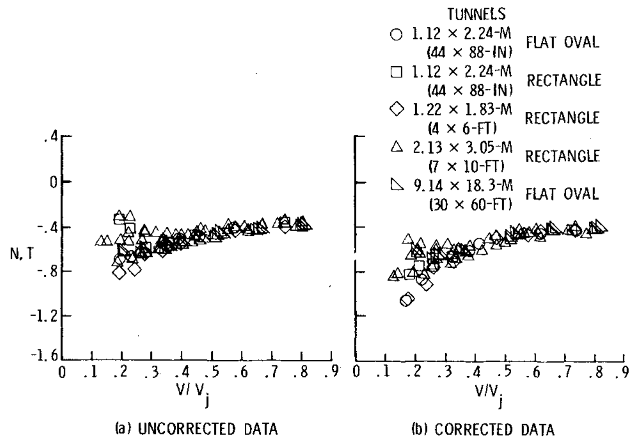

Fig. 11 Sample of wind-tunnel wall effects showing the effect of test section size and the effect of wall correction theory on tall normal force at an angle of attack of 0 deg.

discernible trends with change in test section cross-sectional area. With corrections,[27,28] there is a change in local angle of attack especially at the low velocity ratios as shown by the more negative tail normal force coefficients. However, the corrections are not effective in reducing the data scatter and providing consistent experimental results. These data show that there is a limit to which these corrections can be applied.

This limit was experimentally investigated in detail by Tyler and Williamson[32] and was found to be a function of the jet height above the tunnel floor and the effective diameter of the jets (see Fig. 12). The effective velocity ratio (for a configuration with two laterally spread jets) at which the jet exhaust impinged on the floor forming a stagnation point was experimentally determined to be:

$$V_e' = 1.31 D_e / h$$

Assuming a D_e/h of 0.143 for a typical model which is mounted 7 effective diam above the floor, V_e' becomes 0.187. It was found, based on data taken with a model in various tunnel sizes, that the effect of the walls could be corrected to free air with an effective velocity ratio as low as 65% of the stagnation point velocity ratio V_e'. For a model position with S_e/h at 0.143, $V_{e_{\min}}$ becomes 0.121. For comparison, the correction technique described in Refs. 27 and 28 was used with a maximum angle-of-attack correction at the tail of 5 deg. This more complex method gave a $V_{e_{\min}}$ of 0.125. Testing below this minimum velocity ratio would cause a vortex to be formed ahead of the model (as shown on the

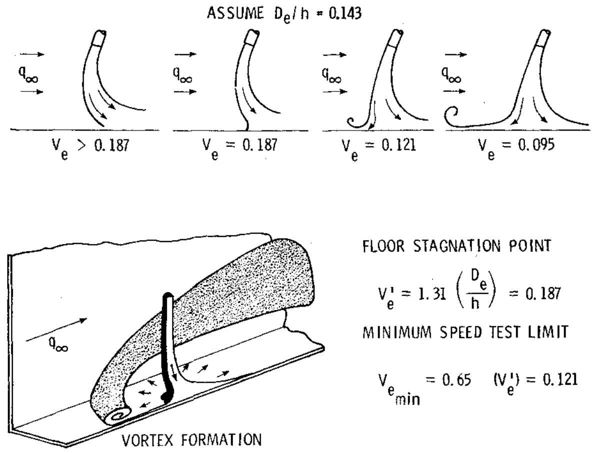

Fig. 12 Minimum speed testing limit for a configuration with two side-by-side lifting jets at $h/D_e = 7$.

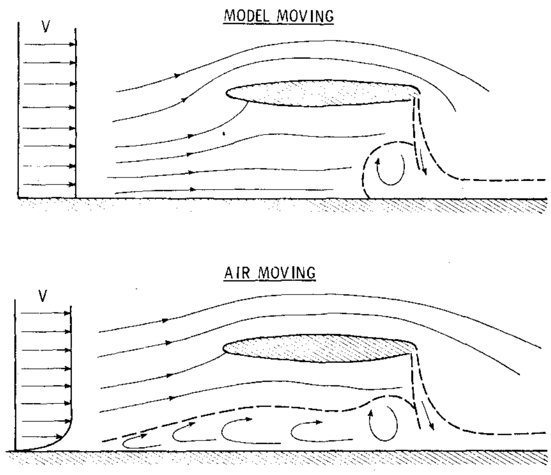

Fig. 13 Sketches of flow over a groundplane for both the case with the model moving and the case with only the air moving.

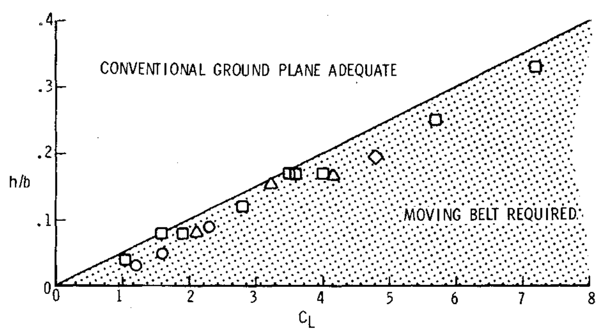

Fig. 14 Correlation of combinations of lift coefficient and model height to span ratio to show which combinations require use of moving belt of which combinations allow use of conventional ground plane.[33]

lower left in Fig. 12) which would encircle the model inducing flow patterns inconsistent with the free-air conditions.

Ground Effects

Another factor which influences the minimum velocity for useful test results is flow impingement on the test section floor. As shown in Fig. 13, when the model or aircraft is moving with respect to both the air and the ground, it is in a uniform velocity field. In a wind tunnel with the air moving with respect to the model and to the groundplane, there is a boundary layer on the floor. Wakes from the model can impinge at appropriate test conditions and flow forward under the model changing the flowfield under the model significantly. Turner[33] showed that this problem can be eliminated using a moving-belt groundplane. The test parameters which indicate the need for a moving belt are lift coefficient and model height. Turner[33] developed the correlation presented in Fig. 14 which shows that the moving belt should be operated whenever the combination of C_L and h/b cause a test condition to fall below the correlation curve. While other methods of boundary-layer control on the floor, such as suction of blowing should also be effective, they may require significant development to be effective.

Conclusions

This paper has looked at some of the critical considerations for wind-tunnel investigations of V/STOL aircraft configurations from model design through data reduction. Possible problems can be anticipated and corrected before they are irreparable. The following is a summary of some of the techniques and possible problems pertinent to testing V/STOL aircraft models:

1) Proper engine selection is important based on resultant model size and assembly problems associated with small sizes, engine-inlet mass-flow simulation requirements, and required simulator drive air related to available supply.

2) A judgement of the best "power-off reference configuration" for each power-on configuration must be made such that interference parameters can be determined.

3) The operating conditions must be at least estimated throughout transition such that the investigation can be planned efficiently with a minimum of useless data collected.

4) Attention must be focused on the influence of the tunnel walls such that no data are obtained which could not be corrected to free-air condition by available techniques.

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