Development of a Nonrecirculating Wind-Tunnel Configuration Insensitive to External Winds

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The extreme size of facilities required for aerodynamics testing of V/STOL vehicles has prompted an investigation of a wind-tunnel configuration other than the conventional closed-return type. Because the open-return type selected is vulnerable to atmospheric wind effects, an extensive experimental program to minimize wind disturbances has been run on scale models. One $\frac{1}{24}$-scale model and two $\frac{1}{81}$-scale models were used to study test section flow distribution and speed changes due to winds from various directions. A complete $\frac{1}{81}$-scale configuration was immersed in the flow of a large wind tunnel simulating winds up to 30 mph. Results are presented for variations of tunnel components, test section airspeed, wind speed and direction, and presence of nearby buildings. Wind effects cannot be sufficiently attenuated by inlet shape modifications or addition of screens and honeycomb. Complete enclosure of the inlet in a protective housing, combined with a vertical cylindrical exhaust stack, will reduce wind disturbances to a satisfactory level. For configurations developed in this investigation, test-section disturbances have been held within $\pm 1\%$ of dynamic pressures as low as 2 psf with a 20-mph wind blowing from any direction.

Nomenclature

q_{AVG} = average test-section dynamic pressure, psf
q_{REF} = reference dynamic pressure, 2 psf
$\Delta q_w/q_{AVG}$ = $q_{AVG\ (wind\ on)} - q_{AVG\ (wind\ off)}/q_{AVG\ (wind\ off)}$
y/b = horizontal distance from ℄ tunnel/test-section half-width
Δp = change in total pressure inside enclosure due to wind, psf
θ_w = direction of wind, measured clockwise about center of enclosure, zero directly upstream, deg
V_w = velocity of wind, mph
h_0 = height of basic exhaust stack
h_f = height of front wall of stack
h_r = height of rear wall of stack

Introduction

TESTING of V/STOL models in wind tunnels brings out several problems not normally encountered with conventional models. Low speeds required for much of the critical V/STOL testing are well below the design speeds for which conventional tunnels can provide good speed control. Airspeed regulation is further complicated by the extremely high model power, which tends to drive the primary flow of the tunnel. Requirements for simulating hovering and transition flight create conditions which produce reingestion of exhaust gases, and large wall interactions with jet, propeller, or ducted fan slipstreams.

The only reliable way at present to insure freedom from wall effects in V/STOL data is to test in oversized test sections, five to ten times as large as conventional sections. One way to achieve a large test section is to convert the settling chamber or other large component of an existing low-speed tunnel into a test section. The advantage in cost due to such a choice, however, is compromised by such factors as limited space, poor flow quality, and maximum test speed. No wonder then that numerous organizations are considering or have already taken steps to acquire new facilities for V/STOL testing.

In designing a new wind-tunnel facility to meet the needs of V/STOL model testing, the two basic types of wind-tunnel arrangements to be considered are the open-return and the closed-return circuits. Where climates are mild, economic factors make it attractive to consider a configuration whose inlet and exhaust are open to the atmosphere. Construction of expensive items like corners, turning vanes, scavenging equipment, and air coolers are thereby avoided. On the other hand, the influence of the ambient winds on this type of configuration is a serious problem to both velocity distribution and maintenance of steady flow conditions in the test section at very low speeds. Two British firms have considered these factors and chose to construct full-scale open-return V/STOL test facilities.[1,2]

The open-return configuration was selected for a proposed new V/STOL wind-tunnel for North American Rockwell Corporation. In this paper, the process of developing a wind-insensitive configuration, shown in Fig. 1, is described.

Program Objectives

The primary objective of this program was to develop an open-return tunnel configuration with flow quality equivalent to a closed-return tunnel. Since the flow characteristics of the two tunnel types should be practically identical in the

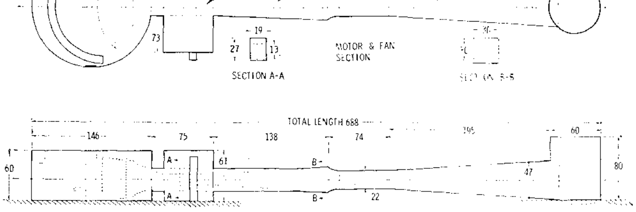

Fig. 1 Configuration of nonrecirculating wind tunnel.

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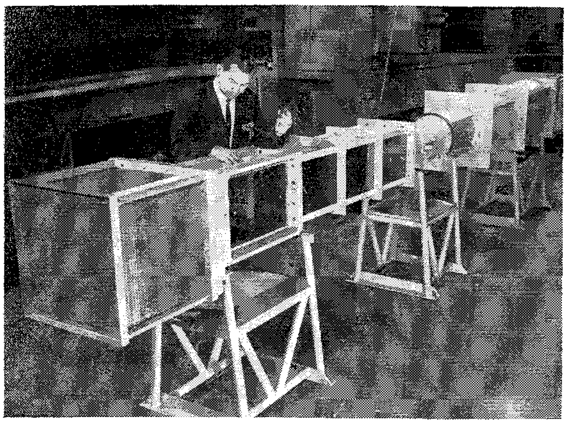

Fig. 2 $\frac{1}{24}$-scale model tunnel.

test section except for disturbances caused by winds, the emphasis herein is placed entirely upon investigation of the magnitude of wind effects and the means for attenuating them. Satisfactory flow quality is considered to be uniformity of test-section dynamic pressure distributions within ±1% and maintenance of average dynamic pressure within ±1% when operating at a q of 2 psf and subjected to a wind gust of 20 mph from any compass direction.

Scope of Program

A necessary starting point was assessment of the local wind problem at the probable location of the proposed full-scale tunnel. A detailed review was made of Weather Bureau reports documenting the history of local winds over a 3-yr period.

More than one model was necessary. A $\frac{1}{24}$-scale model was sized adequately to study pressure distributions across the test section. On this model, many inlet modifications were tested: screened plenum, contraction ratio changes, bellmouth lips, screens, honeycombs, and fences. A movable wind machine was used to generate winds over the inlet from different directions.

Development of a wind-insensitive inlet enclosure configuration was undertaken with $\frac{1}{81}$-scale models so that the enclosure could be totally immersed in the air stream from the wind machine. Of primary concern in these tests were enclosure shape, porosity of walls, and ventilation of the roof. Wind direction was varied through 360°.

To study the effect of winds on the complete tunnel, a $\frac{1}{81}$-scale tunnel model was constructed and tested in the North American Aerodynamics Laboratory (NAAL) 7.75- by 11-ft low-speed wind tunnel. In addition to confirming and refining performance of the previously developed inlet enclosure, effort was concentrated on minimizing wind disturbances due to the exit. Among exit variations tested were shape, height, diameter, and porosity. The effect of nearby buildings was obtained. Although the majority of tests were run at a single q (2 psf) to limit the number of variables affecting the problem, the wind effects were checked at several test section airspeeds. Similarly, wind velocity was varied from the standard 20 mph. For most configurations, wind direction was varied through 360°.

Description of Equipment

$\frac{1}{24}$-Scale Model Tunnel

This model had a test section 12 in. high by 8.5 in. wide and an over-all length of 22.5 ft. It was powered by a 10-hp variable-speed electric motor driving a 10-in.-diam fan, which could vary the test-section speed from 0 to 120 mph. Inlet and exit sections were replaceable for testing of alternate configurations. The scale of the model was later changed to $\frac{1}{27}$ to correspond with an increase in size of the proposed full-scale tunnel, but model dimensions were not changed.

Inlet modifications consisted of variations on three basic configurations; 1) a 4:1 contraction with square inlet, 2) a 8.62:1 two-dimensional contraction, and 3) a 9:1 quasi-two-dimensional contraction. The latter two were formed by adding extensions to the 4:1 inlet–constant height in the case of the 8.62:1, and slightly converged for the 9:1 contraction. The $\frac{1}{24}$-scale model is illustrated in Fig. 2.

The wind machine was a 30-in.-diam, 4-bladed ducted fan powered by a 10-hp, 1800-rpm motor. It was placed on a support stand with wheels so that it could be easily moved from one position to another at approximately tunnel centerline height. A honeycomb and a 50% porosity screen covered the wind-machine exit to provide a nonrotational, well-diffused wind stream.

$\frac{1}{81}$-Scale Enclosure Models

The enclosure models tested varied primarily in wall and roof porosity and height. Wall configurations ranged from 0% porous (solid) to 50% porous screens, with most of the testing being done on 25% porous screen walls. Roof porosity varied from 100% to 0% porous (open to closed). Flapper valves used on the walls were constructed of thin vinyl plastic film.

The model tunnel was roughly simulated by an inlet and test section constructed of wooden blocks to form their general shapes. No attempt was made to simulate entrance screens or honeycomb since the primary purpose of this study was to develop an enclosure configuration that would attenuate wind-gust dynamic pressure levels only. The tunnel inlet was about 9 in. high, and inlet and test section combined were about 2 ft long. Enclosure and simulated tunnel were mounted on a circular base so that they could be rotated as a unit on a ground plane in front of the wind machine. The only instrumentation required for this study was a single total pressure probe mounted in a fixed direction inside the enclosure.

$\frac{1}{81}$-Scale Complete Model Tunnel

This model was $\frac{1}{3}$ the size of the larger model tunnel, and was designed to be tested in the NAAL 7.75- by 11-ft low-speed wind tunnel. It was powered by a small high-speed motor-blower which could vary test-section airspeed from 0 to 40 mph. The model tunnel was mounted on a 9-ft-diam turntable built into a 11-ft-wide by 17-ft-long ground plane, which spanned the low-speed wind tunnel, and which was installed 2 ft above the tunnel floor. Five total pressures from a rake and test-section static pressure were sensed by transducers.

Test Procedure

For each configuration of the $\frac{1}{24}$-scale model, the dynamic pressure distribution across the test section was measured for a series of airspeeds with and without an external wind of 20 mph. The wind machine was set in positions for most configurations where it could generate wind from the directions 0° (straight ahead), and −45°, −90°, and −135°. Test-section speeds were set by regulating the speed of the tunnel fan.

Tests were conducted on the $\frac{1}{81}$-scale circular enclosures with the total pressure probe mounted at first in the center of the enclosure. In the presence of a steady-state wind, pressure variations were measured at various heights of the probe inside the enclosure. When a simulated tunnel was added, the probe was moved into the simulated inlet. Directional effects of the wind were obtained by rotating the enclosure model by $22\frac{1}{2}°$ increments through 360° in front of the wind machine.

Most of the $\frac{1}{81}$-scale complete model testing was done with test-section dynamic pressure set at 2 psf. Flow was controlled by speed of the model fan. Wind direction was governed by the yaw angle of the turntable which was set at 15° increments through 360°. Simulated wind velocities (NAAL tunnel speed) were set at 10, 20, and 30 mph during the course of this test.

Discussion of Results

Detailed records on local weather conditions[3] showed occasional wind gusts up to 30 mph, but the frequently occurring gusts up to 20 mph were judged to be the probable maximum speed of importance for design. Although wind was predominantly from the west, there was a sufficient number of gust occurrences from other directions to warrant developing a tunnel configuration capable of attenuating winds up to 20 mph from all compass directions.

$\frac{1}{24}$-Scale Model Tests

Screened plenum boxes at the tunnel inlet and exit (Fig. 2) were the initial configuration intended to attenuate wind effects. Extreme distortion of the dynamic pressure profile across the test section is evident for this configuration in Fig. 3 when the wind blows across the inlet at right angles to the tunnel axis. Similar distortion occurs when the wind blows from any other direction except from straight ahead.[4] These results are also typical of other methods of covering the box configuration; i.e., with various arrangements of slats, louvers, or multiple screens. When the plenum box is removed and the bare inlet exposed, distortion is even worse.

Flow separation revealed by tuft studies in the 4:1 contraction inlet was shown to be reduced by extending the side walls, thereby increasing the contraction ratio in a two-dimensional manner. Redesign of the inlet resulted in a 8.62:1 contraction which unfortunately did not significantly improve dynamic pressure distributions with wind on and, if anything, worsened the wind-off distributions.[5] Installation of a fence as a windbreak in front of the inlet further deteriorated the wind-off distributions and was still inadequate for attenuating wind effects. The effectiveness of the fence furthermore changed with wind direction.

One series of tests with this configuration was run with a simple guillotine arrangement on the wind machine so that a transient in the nature of a wind "gust" could be generated.[5] The results indicated that transient disturbances approach but do not exceed the steady-state wind effects. Since the results of the two methods appeared to be roughly equivalent, the simpler and more conservative steady-state technique was used for the balance of the tests.

Another inlet, with 9:1 contraction, was built to lessen the power loss through entrance screens, and hopefully to improve the wind-off distributions by providing 5° of convergence to top and bottom walls. Transducers were used instead of manometers to increase sensitivity of measurements.

With the 9:1 contraction inlet, the q distributions vary less than ±2% with wind off. Figure 4a shows that there are wide variations in distribution and average dynamic pressure when the wind is blowing from angles of 0° and 270°. The addition of honeycomb and 25% porous screen deteriorates the basic wind-off distribution, but considerably lessens the variations due to the wind (Figs. 4b and 4c). The 25% porous screen has been judged too dense. Even small variations in screen geometry due to manufacturing are liable to be noticed as variations in pressure drop across the screen, corresponding to distortion of the test-section dynamic pressure profile.

Dynamic instabilities such as flow-angle fluctuations and vortices discovered by a tuft probe survey in the test section were found to be almost completely controlled by addition of the honeycomb, whereas changes in inlet shape were ineffective.[6]

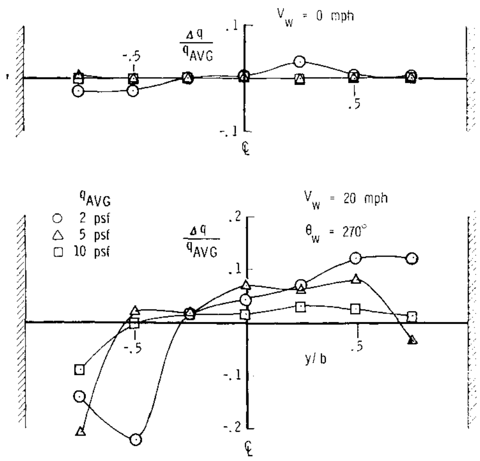

Fig. 3 Effect of wind on test-section dynamic pressure distribution; 4:1 contraction; screened box inlet; $\frac{1}{24}$-scale model.

$\frac{1}{81}$-Scale Enclosure Tests

Based on $\frac{1}{24}$-scale test results, it was obvious that a more effective configuration was necessary to protect the inlet from wind effects. Attention was directed toward development of a cylindrical entrance enclosure on the premise that wind effects would be the same for all directions. Models were built to the smaller $\frac{1}{81}$ scale so that they would be completely inundated by flow from the wind machine. A typical model is illustrated in Fig. 5.

Early testing on circular fence enclosures[7] showed that, for solid walls and open top, wind gusts generate subatmospheric pressures inside the enclosure. As wall porosity is increased, these pressures become more positive. In no case is there a strong vertical pressure gradient. However, when the wall becomes too porous, a crossflow develops within the enclosure and causes the pitot-measured pressure to vary substantially with wind direction (Fig. 6). It should be pointed out that pressure changes within the enclosure have a direct relationship to speed changes in the test section. Since the tunnel inlet is analogous to the pitot tube with respect to the pressures experienced, it was deemed necessary to eliminate crossflow by using wall porosity of 25% or less.

With the 25% porous walls, pressure in the enclosure is independent of wind direction but is always negative, or subatmospheric, when the wind blows. Some pressurization scheme making use of the wind itself would be the ideal way to compensate for this loss of pressure. Addition of a roof is a step in the right direction, but is not powerful enough by itself to compensate for the negative pressure, as shown in Fig. 7. Some wall blockage on the downwind side of the enclosure is needed to trap the dynamic component of the wind and convert it to static pressure. To provide wall blockage that is effective for all wind directions and yet allow sufficient porosity for normal tunnel operation, the entire inner wall of the enclosure was lined with flapper valves. Air is thereby permitted to flow freely into the enclosure but is restricted from being drawn out. Figure 7 shows that the combined effect of a solid roof and flapper valves is more than adequate to correct the pressure deficiency.

The final configuration and pressure characteristics developed from the enclosure tests are illustrated in Fig. 8. The roof has been ventilated with a slot of proper size and location to balance the enclosure pressure disturbance as close to zero as possible. Solid wall panels have been added to compensate for asymmetry of the configuration relative to the wind. Pressure disturbances have been attenuated to

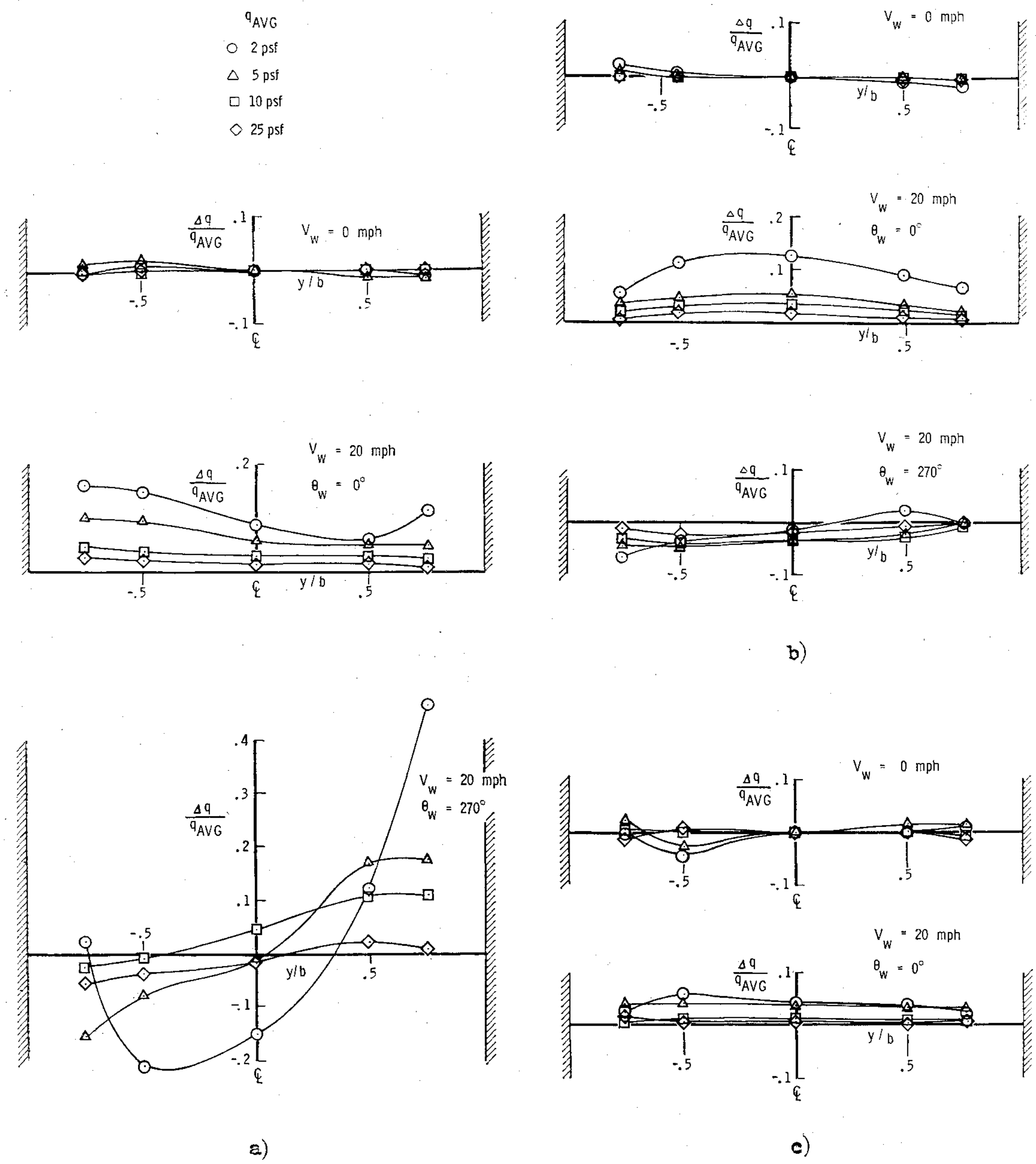

Fig. 4 Effect on wind on test-section dynamic pressure distribution; two-dimensional inlet; $\frac{1}{24}$-scale model: a) screen out, honeycomb out, b) screen out, honeycomb in, c) screen in, honeycomb in.

less than $1\frac{1}{2}\%$ of test section q (based on $q = 2$ psf) for any wind direction, and less than $\frac{1}{2}\%$ for most wind directions.

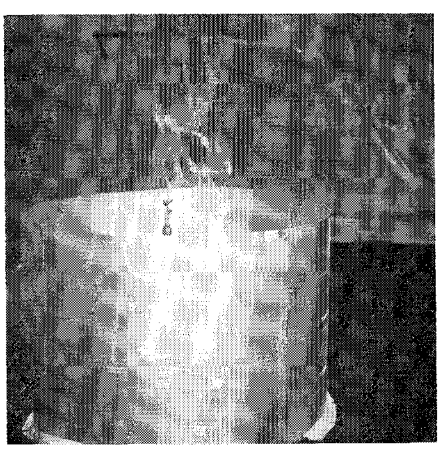

Fig. 5 $\frac{1}{81}$-scale circular fence enclosure with 25% porous wall and open top.

$\frac{1}{81}$-Scale Complete Model Tests

Because of a desire to test a complete model tunnel configuration totally immersed in a uniform wind, a $\frac{1}{81}$-scale tunnel was built to be installed as shown in Fig. 9, in the NAAL low-speed wind tunnel. The main objective of this study was to determine and minimize changes in test-section speed caused by external winds. In some areas, investigations were not as complete as desired due to curtailment of

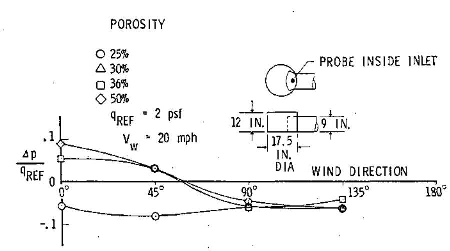

Fig. 6 Effect of enclosure wall porosity on inlet total pressure for different wind directions; no roof; $\frac{1}{81}$-scale enclosure model.

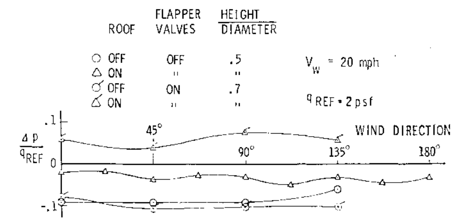

Fig. 7 Effect of enclosure roof on inlet total pressure for different wind directions, with and without flapper valves; $\frac{1}{81}$-scale enclosure model.

tests. Variables of the test were entrance enclosure, exit stack, test-section airspeed, wind velocity, and nearby buildings.

The first tests of the $\frac{1}{81}$-scale complete model utilized the previously developed enclosure configuration and were intended to verify the results of the enclosure models tests. Tunnel inlet components tested are sketched in Fig. 10. The effect on wind disturbances in the test section due to a buildup of both entrance and exit components is shown in Figure 11a on a very compressed scale. Based on a q of 2 psf, variations in test-section dynamic pressure exceed 30% due to the wind when enclosure, screens, and honeycomb are omitted. Addition of two screens and honeycomb reduce the variation to about 15%, and addition of an entrance enclosure drops the variations to about $\pm 2\%$ even with a square exit stack of unknown merit. When the stack is removed, the q disturbance jumps to 9%.

Effect of enclosure wall porosity was run again on the complete model with a roofed enclosure. The previously chosen 25% porosity now shows up slightly inferior to 33% porosity (Fig. 11b). Figure 11c shows the degree of control that can be imposed by the use of solid wall panels on the inlet enclosure to smooth out disturbances due to localized wind angles.

The effectiveness of a dense grove of trees arranged around the inlet was investigated as an alternate method of providing wind protection to the inlet. Figure 12 illustrates one of two arrangements tested. The data comparing trees vs enclosure are shown in Fig. 13a where the $\pm 2\%$ variation with trees is cut to a third for most wind directions by use of the enclosure. Location of a V/STOL open-ended tunnel in a forest would be ideal for maximum wind attenuation, but it can be appreciated that planting a grove of 60-ft trees for the same purpose is not likely to be practicable.

Until the $\frac{1}{81}$-scale complete model tests began, little attention had been given to investigating the influence of the ex-

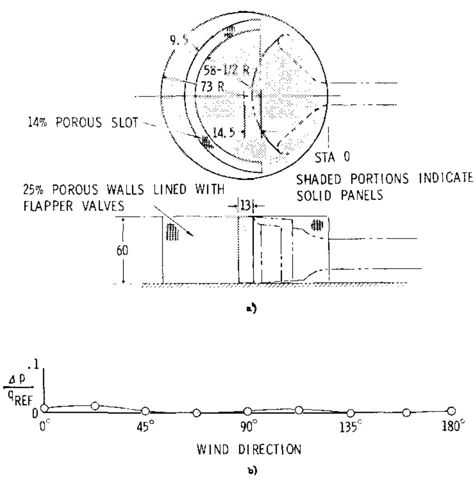

Fig. 8 Final results developed from $\frac{1}{81}$-scale enclosure model tests: a) entrance enclosure configuration, b) disturbance to inlet total pressure due to winds from different directions.

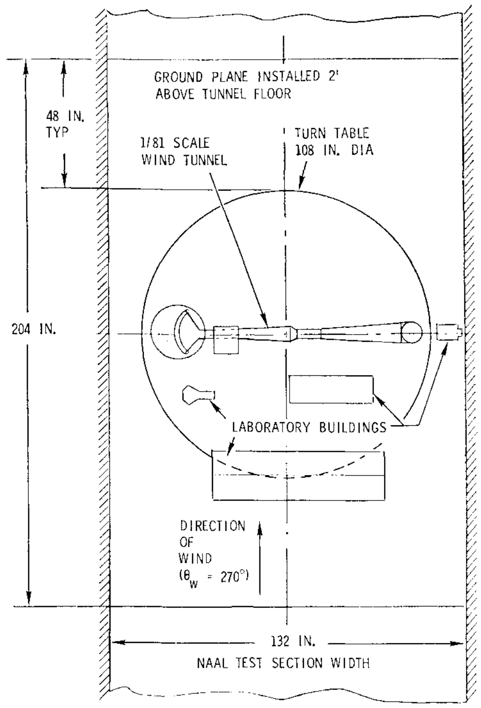

Fig. 9 Model installation in NAAL wind tunnel.

haust stack. Consequently, it was necessary to center an extensive part of this test around the study of exit configurations.

Exit flow is discharged as a concentrated stream into the surrounding atmosphere where it acts much like a solid body to the approaching wind. A pressure field generated by the wind interacting with this discharge airflow affects the average pressure at the exit. In an attempt to obtain symmetry of this interaction for any wind direction, it was decided to raise the exit orifice significantly above adjacent structures and discharge the flow vertically.

Figure 13b contrasts the data of some of the basic shapes tested, including exit stack off, which has q variations up to 9%. Square exit stack results are more sensitive to wind direction than the vertical cylinder exit stack, although the total variation of q in both cases is about 3%. Because the cylindrical stack is less erratic, most of the exit configuration study has been devoted to variations of this shape.

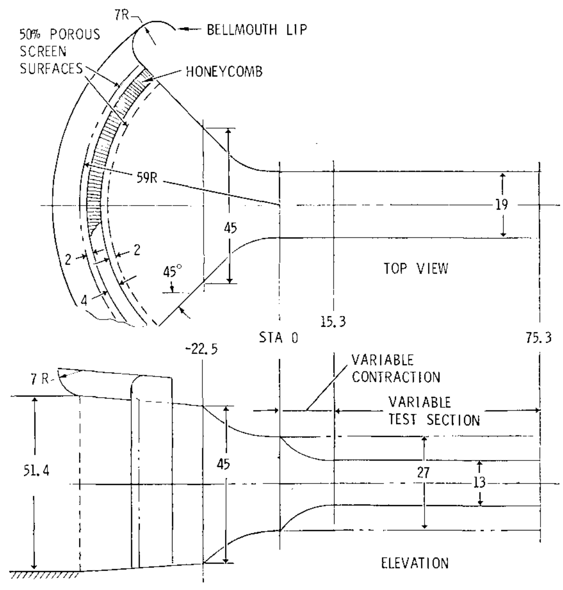

Fig. 10 Tunnel inlet configuration.

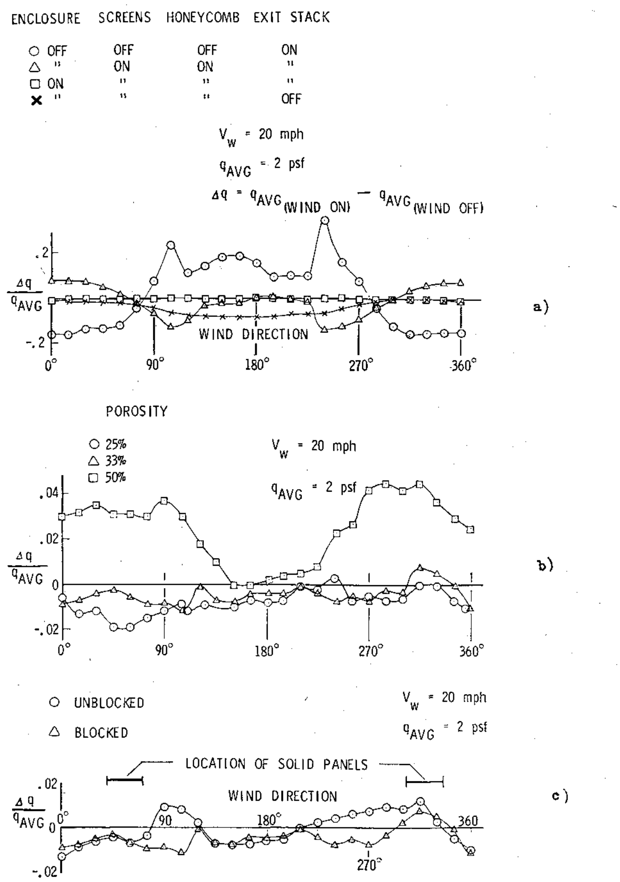

Fig. 11 Test-section dynamic pressure disturbance due to external winds; $\frac{1}{81}$-scale complete model: a) effect of entrance and exit components; b) effect of entrance enclosure wall porosity, roof on; c) effect of selective blockage of enclosure side walls.

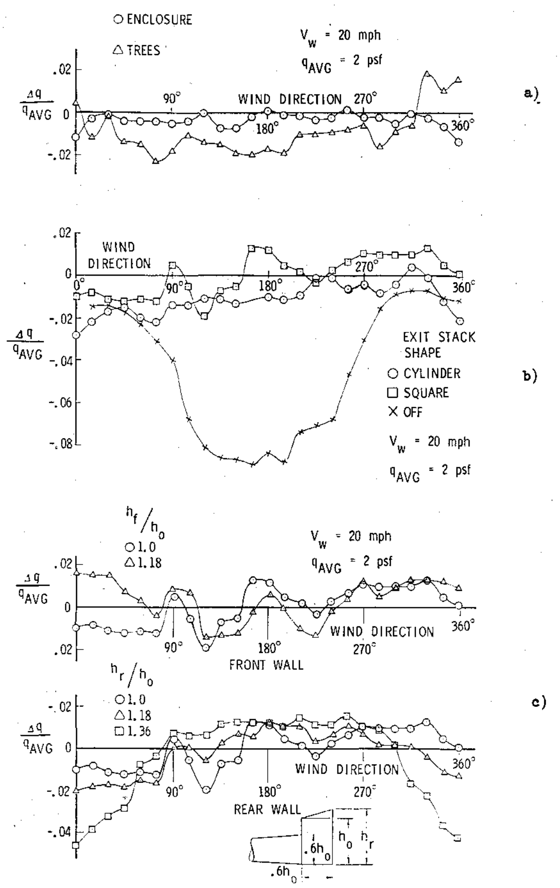

Fig. 13 Test-section dynamic pressure disturbance due to external winds: a) effectiveness of entrance enclosure vs a grove of trees; b) effect of exit stack shape; c) effect of height of square exit stack front and rear walls.

An increase in exit stack diameter tends to speed up the flow in the test section when the wind blows, but does not change the q variation with wind direction.[8] Thirty percent changes in height of the stack have no noteworthy influence on wind disturbances. However, extending the height of the front wall of the exit stack increases test section q when wind blows from the vicinity of 0°, and extending the rear wall of the stack reduces q for winds from the same direction (Fig. 13c). This action is characteristic of both square and round exit stacks.

After the configuration with least wind interference (Fig. 14) had been selected on the basis of $q = 2$ psf data, wind interference effects with varying test-section airspeeds were investigated. For the best configuration, disturbances are held within $\frac{1}{2}\%$ q at a q of 2 psf, except for a very narrow range of compass directions. One would expect the interferences to decrease and become negligible as q increases, but Fig. 15a shows the reverse to happen between q's of 2 and 4 psf. Thus, the ability of the configuration to cope with wind disturbances when operating at moderately higher test speeds is somewhat impaired for unknown reasons. At a test speed corresponding to $q = 1$ psf (data not shown), wind disturbances are very pronounced. Effective wind control for these very low-speed cases was achieved by installation of a flow restrictor resembling motor nacelle flaps which increased the flow circuit resistance by a large factor.[8] Wind velocities less than 20 mph create negligible changes in test

Fig. 12 Simulated grove of trees around inlet; $\frac{1}{81}$-scale model.

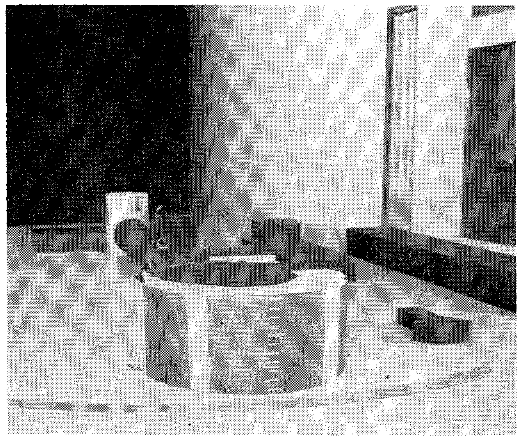

Fig. 14 Final configuration of tunnel; nearby buildings simulated; $\frac{1}{81}$-scale complete model.

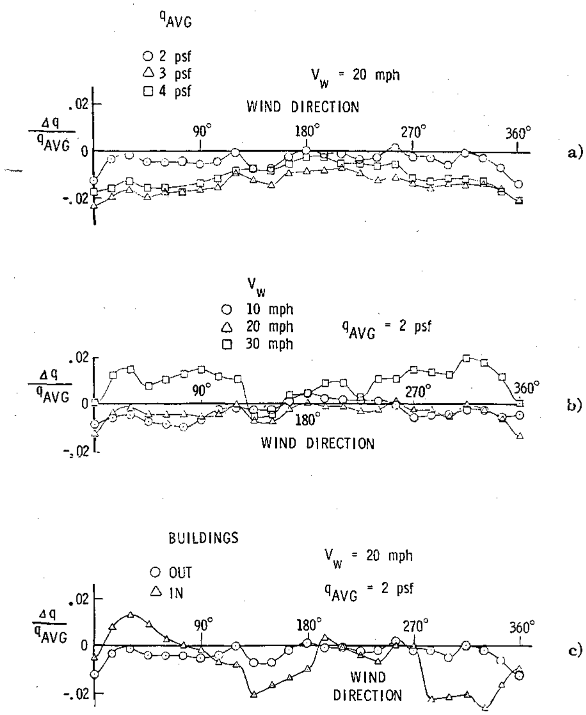

Fig. 15 Test-section dynamic pressure disturbance due to external winds; $\frac{1}{81}$-scale complete model: a) effect of varying the dynamic pressure; b) effect of wind velocity; c) effect of nearby buildings.

section q; wind velocities of 30 mph essentially double the q disturbance at 20 mph (Fig. 15b).

Nearby buildings as depicted in Figs. 9 and 14 appreciably affect the q variation due to wind. Their influence, shown in the limited data of Fig. 15c, requires careful additional investigation before tunnel characteristics can be considered satisfactory. It is obvious that not only the present but also possible future obstructions in the neighborhood of the tunnel must be dealt with when the tunnel is being designed.

Conclusions

An unshielded inlet of a nonreturn tunnel exposed to wind gusts will produce irregularities in test-section airspeed which are intolerable for normal testing. Wind effects are inadequately attenuated by modifying the inlet shape or adding screens, honeycomb, and fences.

Complete enclosure of the inlet in a protective housing provides satisfactory attenuation of disturbances due to winds from any direction. Features producing maximum abatement of wind disturbances were found to be 1) cylindrical shape, 2) approximately 33% porous walls internally lined with flapper valves, and 3) solid roof with approximately 14% porous annular vent. Test section q disturbances with this configuration do not exceed $\frac{1}{2}\%$ at $q = 2$ psf for most wind directions.

Tests of a complete model tunnel immersed in a uniform wind show that wind disturbances generated by the exit are of equal importance to those of the inlet. Of the shapes investigated, a cylindrical vertical stack was the most effective method to discharge tunnel flow.

Most of the program and configuration development was run at $q = 2$ psf. At this airspeed, the most effective configuration limits test-section disturbances due to winds from any direction to less than $\pm\frac{3}{4}\%$ of q. Several configurations were roughly equivalent in their capability to attenuate wind gusts. At q's other than 2 (viz., between 1 and 4) the test-section disturbances are proportionately greater, but are still contained within $\pm 2\%$ of q. A 30-mph gust doubles the q disturbances caused by a 20-mph gust. Interference of nearby projecting features of the terrain, such as large buildings, significantly affects test-section conditions when the wind is blowing.

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