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A New Design Concept for Indraft Wind-Tunnel Inlets with Application to the National Full-Scale Aerodynamics Complex

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Abstract

A unique inlet design concept for indraft wind tunnels is presented. The concept is particularly useful for applications for which a specific test section flow quality is required with minimum inlet size. Indraft wind tunnels require flow straighteners and antiturbulence screens at the front of the inlet in order to isolate the test section from turbulent atmospheric winds. For inlets with small length-to-diameter ratios, the inlet treatment may be located in a markedly nonuniform velocity field. Since the pressure loss caused by the treatment is proportional to the local dynamic pressure, nonuniform flow through the inlet screen results in nonuniform total pressure downstream of the screen. This nonuniformity in the total pressure distribution at the inlet persists into the test section. A cascade or vaneset can be used to control the flow at the inlet plane so that the variation in test-section total pressure is minimized. Potential-flow panel methods coupled with empirical pressure loss predictions are used to predict the performance of the inlet cascade. The cascade concept was used to develop an alternative inlet design for the 80- by 120-Foot Wind Tunnel at NASA Ames Research Center. The results of the numerical predictions are in good agreement with the experimentally measured performance of a 1/15 scale model of the wind tunnel. The experimental results demonstrate that it is possible to design a short length-to-diameter ratio wind tunnel inlet which provides atmospheric wind isolation and uniform test section flow.

I. Nomenclature

A = empirical coefficient in drag equation
c = vane chord
C_d = drag coefficient
C_l = section lift coefficient
C_p = static pressure coefficient, = $\frac{p-p_{ts}}{q_{ts}}$
d = screen wire diameter
P = cascade pitch (distance between vane trailing edges)
p = static pressure
p_t = total pressure
q = dynamic pressure
Re_β = screen Reynolds number
U = average axial velocity component
u' = fluctuating axial velocity
V = resolved velocity
w = test section width
x = axial coordinate
y = horizontal coordinate
z = vertical coordinate
β = screen porosity
η = pressure loss coefficient
θ = angle of onset or splay angle

subscripts:

cl = at test section centerline
i = inlet
s = screen
ts = test section
v = vane
o = zero lift or zero onset angle

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II. Introduction

The purpose of an indraft wind-tunnel inlet is to condition the entrained air so that the test section flow is steady and uniform. The success of the inlet depends on many factors, but two of the major ones are the geometry of the contraction and the condition of the flow entering the inlet. For indraft wind tunnels located outdoors, the inlet must be capable of isolating the test section from very turbulent atmospheric winds. This requirement can to lead long inlets with extensive treatment at the plane of the inlet. Unfortunately, space and budget constraints often require the inlet to be smaller than that desired from an aerodynamic standpoint. The usual result is less than optimum test section flow quality. Therefore, a minimum size inlet which provides good flow quality is therefore desirable. This paper presents a design concept which can be used to accomplish such a goal.

One of the problems with a short inlet is that the wind isolation devices must often be placed in a location where the flow is very nonuniform. Typical wind isolation devices include screens and honeycomb, both of which cause a drop in pressure proportional to the dynamic pressure of the local onset flow. The nonuniform flow through the inlet treatment, therefore, causes the total pressure and velocity in the test section to be nonuniform. If the contraction ratio is large, more screens can be added to the inlet treatment without drastically affecting the maximum velocity of the tunnel. This approach is not always practical for inlets with lower contraction ratios because the higher drag of the screen has a large effect on the maximum tunnel velocity.

The 80- by 120-Foot Wind Tunnel located at NASA Ames Research Center is good example of the results of the conflict between aerodynamic requirements and constraints of space and budget. The large size of the facility made the use of a long, large contraction ratio inlet impractical from both a space and cost standpoint. The tunnel therefore required a relatively short inlet with a contraction ratio of approximately 5. Conventional inlet designs cannot provide the desired test section flow quality (less than 0.5% turbulence intensity, angle variations less than $\pm0.5^\circ$, and dynamic pressure variation across the test section less than $\pm0.5\%$ of the mean).

The present study was undertaken in order to investigate alternative inlet designs for this wind tunnel which would provide the desired flow quality without increasing the size of the inlet. The use of a cascade at the inlet plane was found to be effective in producing the desired flow quality. The function of the cascade is to redistribute the entrained flow so that the loss incurred by the combination of screens and vanes is constant across the width of the inlet. An additional benefit of the cascade is that horizontal splitters or vanes can be placed on several horizontal planes between the vanes. This forms a large honeycomb which provides improved isolation from atmospheric winds. This paper presents the development of the cascade concept. Particular attention is paid to the analytical methods which were developed to predict inlet performance. The results of scale model testing of the proposed inlet and comparisons with the predictions are also presented.

III. Previous Work

The use of a cascade as a flow manipulation device in wind tunnels has been reported in at least two instances.[1,2] Kelly et al.,[1] describe the design and construction of the General Motors Engineering Staff Aerodynamics Laboratory Wind Tunnel. As part of the design, the turning vanes at each corner of the closed circuit were made adjustable in order to minimize flow nonuniformity in the test section. The adjustable feature was not used in that facility since the flow quality was acceptable with no adjustments. Corsiglia et al.,[2] present results of 1/10 scale model testing of a turning vane set in the 40- by 80-Foot Wind Tunnel which has an adjustable trailing edge flap on each vane. The experimental data indicates that the angle of the flaps can have a strong influence on the flow uniformity downstream of the vanes.

Very little work has been reported in the literature which deals directly with the design of indraft wind-tunnel inlets. Most reports on the subject describe the procedure followed to improve the performance of an existing facility or model.[3-5] The reports by Kirk,[3] and Leef and Hendry[5] present designs for wind isolation devices located upstream of the actual inlet. Open return inlet designs are generally developed either from existing designs, or by applying one of the design methods developed for contractions in closed-circuit wind tunnels. These methods, however, are not intended for open-circuit inlet design. The upstream conditions are sufficiently different for indraft inlets to make the methods inaccurate or even misleading.

Prediction of indraft wind-tunnel inlet performance is hindered by the lack of computational methods applicable to the problem. There are, however, a large number of methods pertaining to the design and analysis of contractions for closed-circuit wind tunnels. Keeping in mind the difference in upstream conditions, much of this work provides information and insight into the fluid dynamics of contractions which can be useful for inlet design.

The earliest analytical efforts made use of hodograph methods.[6-8] These methods are generally applicable only to contractions of infinite length and are, therefore, of limited use in the design process. The work by Morel,[9,10] on the other hand, is very useful in preliminary design of closed-circuit contractions. In these reports, design charts are presented for a family of contraction shapes which relate the geometry of the contraction to such features of the flow field as wall pressure gradients and flow uniformity at the inlet and at the exit of the nozzle.

More recent work using computational methods in the analysis of 3-dimensional contractions is presented in references 11-14. Most of the computational work is done using finite difference solutions of the Laplace equation which limits the methods to irrotational flow. A 3-dimensional Euler analysis of the flow into the 80- by 120-Foot Wind Tunnel inlet is presented by Kaul et al.[15] The results were in good agreement with the experimental data. The Euler calculations, however, proved to be too time consuming for routine design work.

IV. Inlet Cascade Analysis Method

Potential Flow Calculations

Computational methods capable of a complete analysis of indraft wind-tunnel inlets, including wind isolation treatments, have not been reported in the literature. In order to properly design the cascade for the present investigation, some sort of prediction method was required. An analysis procedure was developed which is based on both 2- and 3-dimensional panel methods coupled with an empirical representation of the pressure drop caused by the screens at the inlet plane. Previous investigators have noted that the source panel method suffers from "leakage" (i.e., an inability to satisfy conservation of mass) when applied to internal flow problems.[14] Fortunately, more advanced panel methods which use doublet panels do not suffer from this drawback.

The program VSAERO[16] was used in the present investigation in order to perform a 3-dimensional (3-d) analysis of the flow into the inlet. The limit of 3000 panels for VSAERO prevented its use in the analysis of both the inlet and the inlet cascade. The analysis of the inlet and cascade was, therefore, performed using the 2-dimensional (2-d) panel program HILIFT.[17] This program was originally developed to predict the 2-d aerodynamics of multi-element airfoils and was modified to allow a maximum of 140 elements in order to perform the cascade analysis.

The 3-d analysis was used to define an inlet wall shape which minimized both adverse wall pressure gradients and flow nonuniformity at the entrance plane. In addition, it proved to be a useful tool for gaining an understanding of the flow field associated with indraft inlets. Figure 1 shows the paneling of the 80- by 120-Foot Wind Tunnel inlet. The calculations were performed for both quiescent ambient conditions and for steady onset flows of varying magnitude and direction. The paneled representation extends downstream of the test section. Flow through the tunnel is controlled by specifying a normal velocity on the panels which close off the downstream end of the tunnel. The ground plane was also paneled to obtain the correct inflow conditions because its absence allows flow to be entrained from below as well as above the inlet. This cannot occur for the 80- by 120-Foot Wind Tunnel inlet since it rests on the ground. The program can perform streamline traces and velocity calculations at discreet points in the flow-field. These capabilities greatly aid in developing an understanding of the flow.

The streamline traces in Fig. 2 show some important features of the flow into the inlet. In particular, the angle of inflow varies both horizontally and vertically across the inlet plane. The angle variation requires that each vane in the cascade has a different orientation in order to operate at the proper conditions. A contour plot of the flow velocity at the inlet plane is shown in Fig. 3. The velocity is highest at the top center of the inlet. As mentioned previously, the velocity variation at the screen is responsible for the nonuniform test section total pressure because higher speed flow experiences a larger drop in total pressure as it passes through the screen than does the slower moving parts of the flow. This results in a local total-pressure deficit (or reduced local dynamic pressure, assuming that static pressure is constant in the test section) in the center of the test section.

The results of the 3-d calculations are in good agreement with the experimental data as shown in Figs. 4 and 5. The predicted and experimentally measured wall pressure distributions are shown in Fig. 4. The pressures are measured along the mid-height of the wall. The predicted values are very close to the measured ones. A comparison of the predicted and measured axial velocity distributions along a horizontal line just upstream of the inlet is shown in Fig. 5. The velocity data was obtained using the Long Range Laser Velocimeter which were designed for use in the NFAC. The agreement again is quite good.

A plan view of the tunnel is shown in Fig. 6. The 2-d calculations were performed on this geometry. Predicted streamlines are also shown in the figure. This representation of the wind tunnel has the obvious disadvantage of not matching the actual contraction ratio of the inlet (2.7:1 versus 5:1 for the complete inlet). Comparisons between the predicted 2-d flow-field upstream of the inlet and the 3-d predictions at the vertical centerline show very good agreement when corrections are applied to the 2-d results. (The correction will be described in the next section.)

In the 2-d calculations, the vanes can be positioned and rotated to redistribute the flow at the inlet plane as desired. The angle of rotation of an individual vane relative to the tunnel centerline is referred to as its splay angle. The distribution of the splay angles across the cascade determines the velocity downstream of the vanes which is calculated by HILIFT and is used for the subsequent calculation of the total pressure distribution in the test section. The analysis method provides predictions of only the steady-state flow uniformity in the test section. The effect of upstream disturbances on flow quality is ignored in these calculations.

Total Pressure Calculation

The antiturbulence treatment for the inlet consists of the inlet cascade and a screen with a loss coefficient of 1.6. The screen is attached to the trailing edges of the vanes as shown in Fig. 7. The screen serves three important functions:

(1) Reduce the turbulence caused by separation on the rear of the vanes.

(2) Reduce the scale of turbulence entering the contraction thereby allowing it to decay faster.

(3) Decrease sensitivity of the tunnel to unsteady external winds.

Since it is located in a region of nonuniform flow, the inlet treatment can induce variations in total pressure downstream of the screen. The prediction of these variations was accomplished using an empirical analysis method based on experimental measurements of vane drag obtained in the 7- by 10-Foot Wind Tunnel at NASA Ames,[18] as well as in the 1/10 Scale Component Tester,[2] and on methods for calculating screen loss coefficients.[19–22] The experiment by Dudley et al.[18] indicated that the loss of a vane-screen combination is approximately equal to the sum of the individual losses of the vanes and screen. Such an approximation greatly simplifies the analysis.

The local cascade loss depends on the drag coefficient of the individual vanes. The 2-d analysis does not accurately predict the drag of the vanes, but does predict an accurate lift coefficient. The drag coefficient is related to the vane lift coefficient by the empirical equation:

$$C_d = C_{d_o} + AC_l^2, \tag{1}$$

where $C_{d_o} = .102$ and $A = 0.2$. This formula agrees with the data of Ref. 18. The individual vane drag coefficient is used to calculate a local loss coefficient for the cascade using the equation of Horlock:[23]

$$\eta_v = C_d \frac{c}{P} \tag{2}$$

where c is the vane chord and P is the pitch of the cascade (distance between trailing edges).

The screen loss coefficient is calculated using the empirical formula of Wieghardt:[19]

$$\eta_{so} = 5.5\frac{(1-\beta)}{\beta^2} Re_\beta^{-\frac{1}{3}} \tag{3}$$

for $60 < Re_\beta < 600$ where β is the screen porosity and Re_β is given by:

$$Re_\beta = \frac{dV}{\beta\nu} \tag{4}$$

d is the wire diameter and ν is kinematic viscosity. The screen loss coefficient varies with the angle of onset flow according to:

$$\eta_s = \eta_{so} cos^{1.1}(\Theta) \tag{5}$$

The local loss for the inlet treatment is then simply given by:

$$\eta = \eta_v + \eta_s \tag{6}$$

Once the local flow conditions at the screen location and the lift coefficient of each of the vanes are obtained from the 2-d calculation, the drop in total pressure can be calculated at each point across the inlet. This total pressure distribution is simply convected into the test section.

Corrections to 2-d Calculations

Since the 2-d calculations are performed for a geometry generated by a horizontal cut through the tunnel, the velocities calculated downstream of the vanes are not the same as those for the actual facility. A correction is made to the calculated velocities based on the ratio of contraction ratios for the 2-d and full 3-d geometries. The 3-d contraction ratio is 5:1, while the 2-d contraction is only 2.7:1 owing to the lack of vertical contraction in the 2-d representation. A uniform factor of $\frac{2.7}{5.0} = 0.54$ is then applied to the calculated velocities.

An additional correction was necessary in order to gain the required accuracy for the design process. This correction is to subtract the difference between the predicted and measured total pressure distributions for a particular vane splay distribution. This allows the method to accurately predict the total pressure distribution for configurations which do not differ greatly from those of the test case. The magnitude of the correction varies from zero at the test section centerline to approximately 2% of test section q near the side walls. The larger correction near the walls is due to the large onset angle of the flow relative to the screen. A screen inclined at an angle to the flow turns the flow toward the direction normal to the screen. This effect is not accounted for in the predictions. Near the walls this turning can be as high as 10°.[20,22] The corrections are intended to make the predictions accurate over the central 75% of the test section.

Sample Calculations

The ability of the inlet cascade to alter the total pressure distribution is demonstrated by the results of two sample calculations. The first case is that of a cascade which does not do much toward redistributing the inlet flow. In this calculation, the vanes were placed in the inlet with nearly the same splay angle as a streamline would have at that point if the vane were not there. This splay distribution is shown in Fig. 8, along with a second distribution which was designed to decrease the velocity through the center of the inlet. The second splay distribution should result in higher total pressure in the center of the test section.

The results of these calculations are shown in Fig. 9. The plot shows the variation of the normalized total pressure versus lateral position in the test section. The ΔP_t parameter is defined by:

$$\Delta P_t = P_t - P_{t\,cl} \tag{7}$$

where $P_{t\,cl}$ is the total pressure at the test section centerline. Static pressure is assumed to be constant in the test section. Therefore, higher values of $\frac{\Delta P_t}{q}$ correspond to higher local dynamic pressure. The second splay distribution resulted in higher total pressure in the center of the test section than that near the walls. This is the reverse of the behavior of the first splay distribution and demonstrates the ability of the cascade to alter the test section velocity distribution over a wide range of conditions.

The effect of the screen loss coefficient on test section flow uniformity for a given splay distribution is shown in Fig. 10. Two calculations were made with the first splay distribution from above for screen loss coefficients of 1.0 and 2.0. To a first approximation, the magnitude of the nonuniformity varies directly with the loss coefficient. Making these types of parametric studies was easily done on the computer and drastically reduced the amount of testing required.

V. Experimental Program

A 1/15 scale model of the inlet proposed for the 80- by 120-Foot Wind Tunnel inlet was built and tested. The data obtained were used to validate and to "fine tune" the analysis, as well as to demonstrate the ability of the inlet cascade to tailor the test section flow uniformity. The model is shown in Fig. 11. In this view, the vanes are clearly visible as are the horizontal splitter plates between the vanes. The vanes have a chord of 12.8 inches with a spacing of approximately 1.8 inches. The model tunnel was powered by a single fan which is driven by an electric motor. The maximum test section velocity attained was 88 knots.

The data obtained include extensive surveys of the test section flow, wall and ceiling pressure distributions, and surveys of the flow upstream of the inlet. The test section surveys included measurements of total and static pressures, flow angularity in both the pitch and yaw directions, and all three components of turbulence. In addition, the upstream flow conditions were measured during all of the testing. A wide variety of onset conditions were encountered during the tests, ranging from calm air, to steady winds which blew from many different directions, to extremely gusty, high velocity winds (greater than 20% of test section velocity).

VI. Results and Discussion

In general, the predictions of total pressure distribution in the test section agreed well with the experimental results. Predicted and measured total pressure distributions for two different splay distributions are shown in Fig. 12a and 12b. These two comparisons show good agreement between theory and experiment across the central portion of the test section. The prediction is not as good near the side walls owing to stronger 3-dimensional and screen-turning effects in that part of the inlet. The experimental results of these two splay distributions demonstrate that it is possible to adjust the test section total pressure (and hence, velocity) distribution by proper tailoring of the vane splay angles.

The variation of total pressure along a horizontal survey line through the center of the test section is shown in Fig. 13. The total pressure variation is less than $\pm 0.5\%$ of the average dynamic pressure across more than 80% of the test section. The rectangle in the figure indicates the design goal for test section flow uniformity along horizontal survey lines. The table summarizes the overall flow quality measured in the 1/15 scale model tunnel as compared to the design goals for atmospheric winds less than $1.5 m/s$ ($3 kts$). Flow uniformity, angle of attack fluctuations (α), and turbulence intensity all meet or exceed these design goals.

Flow quality measurements were made under various atmospheric wind conditions; from no wind up to winds blowing at approximately 30% of the test section velocity. The inlet cascade and horizontal splitter plates form a large honeycomb which is effective in blocking much of the atmospheric turbulence. For winds greater than 15% of test section velocity flow quality was not always within specifications. This was most apparent in the axial turbulence intensity and yaw angle fluctuations. The other flow quality parameters were not strongly affected by high winds.

VII. Concluding Remarks

The use of an inlet cascade with a tailored splay distribution was shown to be practical and effective for control of test section flow uniformity. An analytical procedure was developed by which the aerodynamic performance of the cascade could be predicted. The analysis was shown to be in good agreement with experimental data. The design of the cascade was greatly accelerated by using the analysis to determine the necessary vane angles without performing numerous experiments.

Addition of horizontal splitters between the vanes increases the effectiveness of the cascade in providing isolation from atmospheric winds and turbulence. The results of this study were used to design an improved inlet for the 80- by 120-Foot Wind Tunnel at NASA Ames Research Center. Use of this technology allowed the inlet to be smaller and simpler than would have been possible using conventional design methods. Scale model tests of the new design showed good inlet performance for both calm and windy conditions.

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Table 1. Comparison of Flow Quality Objective
With 1/15-Scale Model Test Results

PARAMETER	OBJECTIVE*	TEST RESULTS
MEAN FLOW		
q	$\leq \pm 0.5\%$ OF $\bar{q}$	WITHIN SPEC. OVER 80% OF TEST-SECTION WIDTH
α	$\leq \pm 0.5°$	WITHIN SPEC. OVER MORE THAN 85% OF TEST-SECTION WIDTH
β	$\leq \pm 0.5°$	WITHIN SPEC. OVER MORE THAN 85% OF TEST-SECTION WIDTH
TURBULENCE		
I_u	< 0.5%	$I_u < 0.4\%$
I_v	< 0.5%	$I_v < 0.5\%$
I_w	< 0.5%	$I_w < 0.5\%$

*FLOW QUALITY OBJECTIVES TO BE MET OVER 75% OF TEST-SECTION WIDTH (ATMOSPHERIC WINDS LESS THAN 3 knots, V = 100 knots)

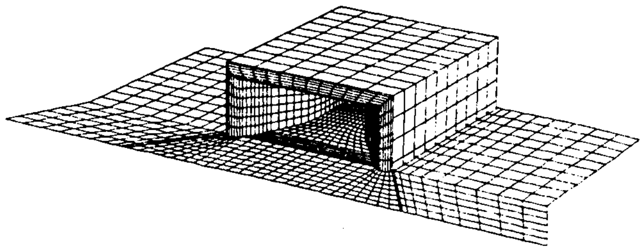
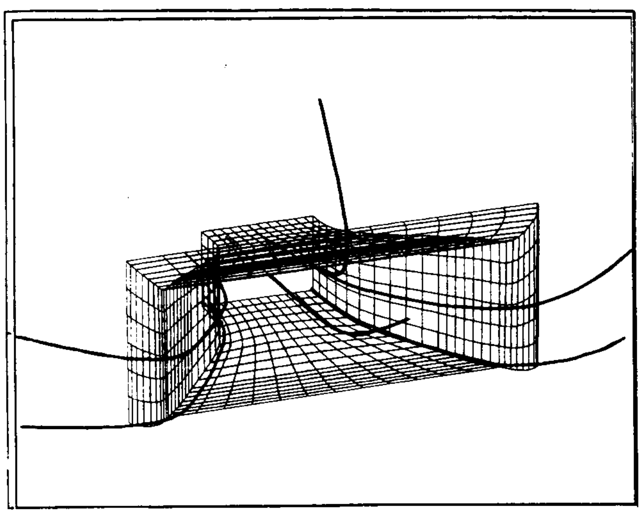
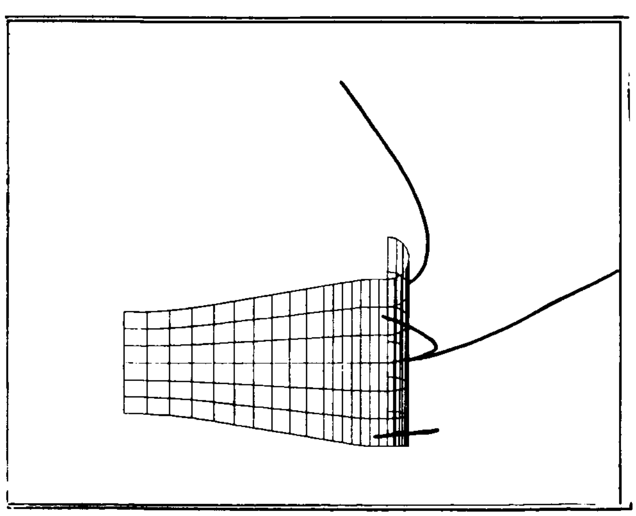


Fig. 1 Three-dimensional paneling used for numerical simulation of flow into inlet.



(a)



(b)

Fig. 2 Predicted three-dimensional streamlines about the inlet.
(a) Front view.
(b) Side view.

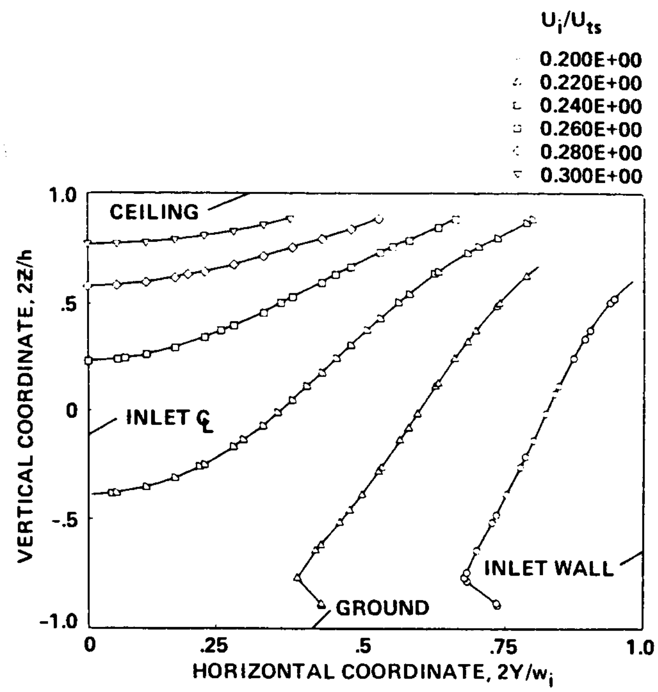


Fig. 3 Contours of constant velocity at the plane of the inlet (survey plane is inside the cowling at $x = 0.0$).

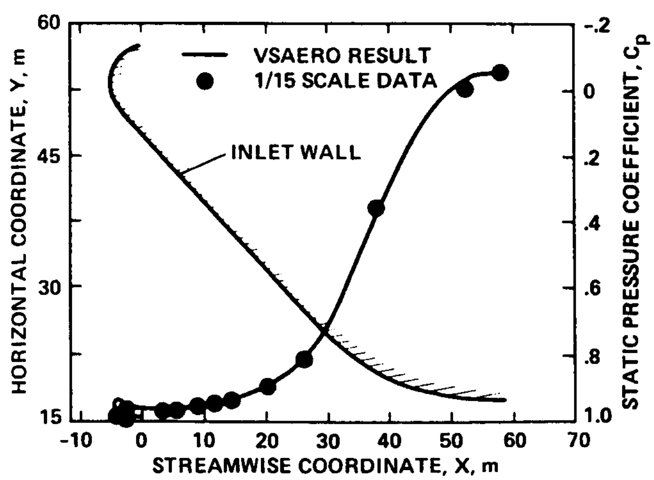


Fig. 4 Comparison of predicted and measured pressures on the wall of the inlet.

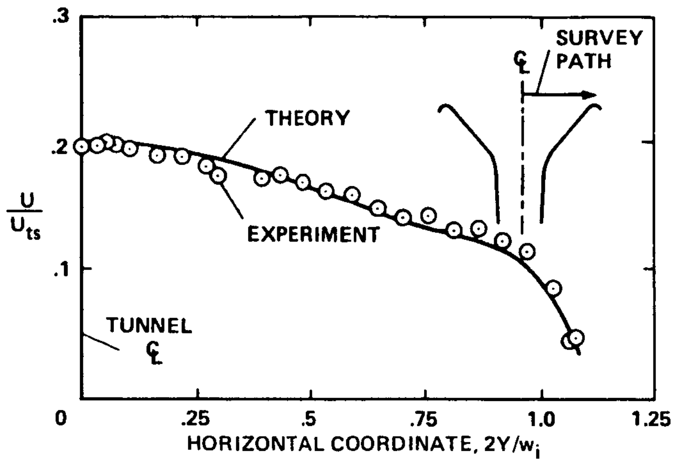


Fig. 5 Comparison of predicted and measured axial velocity upstream of inlet inlet cowl (survey is at the horizontal centerline, $z = 0.0$, of the inlet).

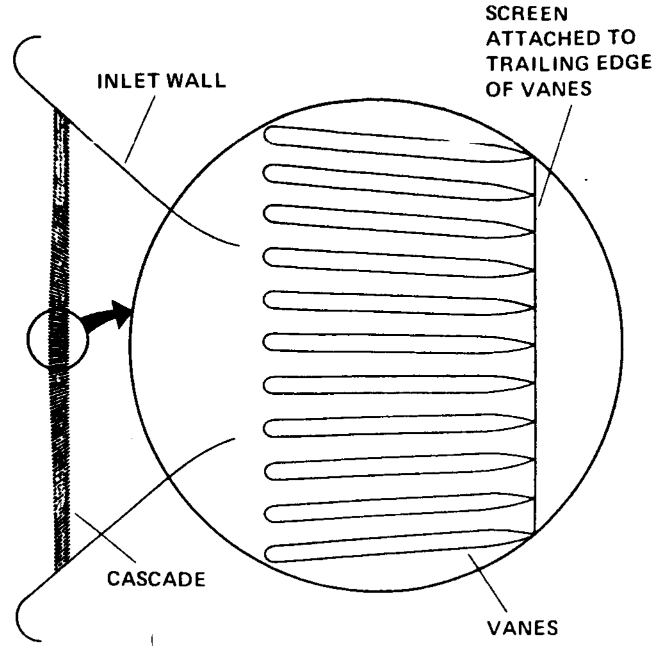


Fig. 7 Detail of inlet cascade and screen.

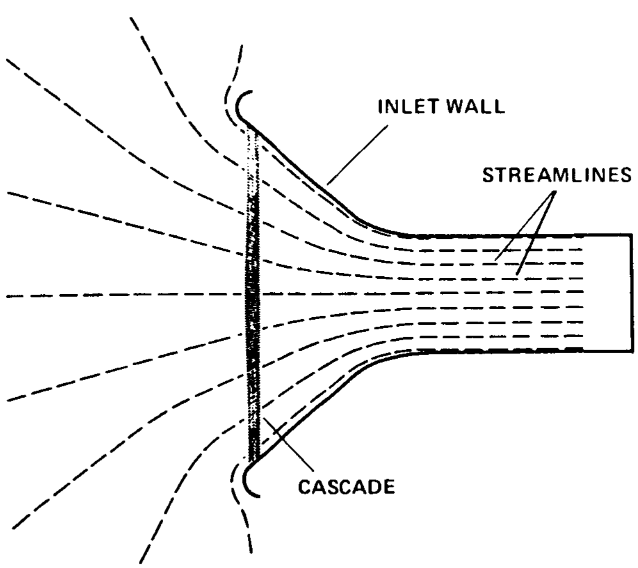


Fig. 6 Plan view of inlet and cascade used for two-dimensional flow analysis and predicted streamline paths.

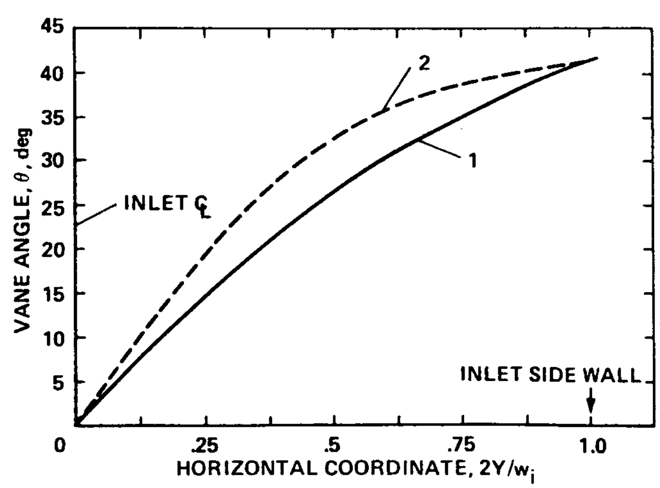


Fig. 8 Comparison of two splay distributions designed to demonstrate the ability of the cascade to systematically control the total pressure distribution in the test section.

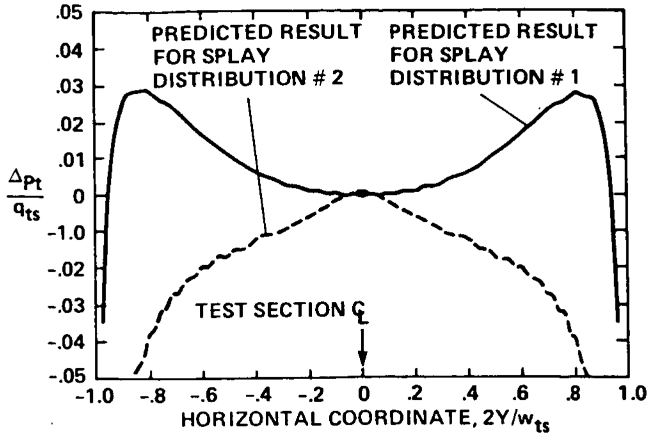


Fig. 9 Effect of the splay distributions shown in Fig. 8 on predicted test section total pressure distribution.

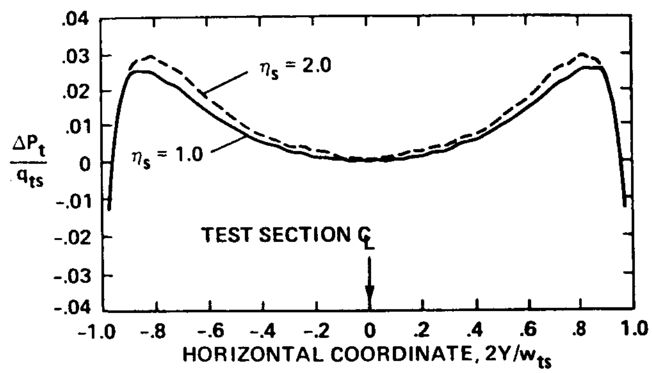


Fig. 10 Effect of the inlet screen loss coefficient on total pressure distribution in the test section.

Fig. 11 1/15 scale model of the 80- by 120-Foot Wind Tunnel Inlet. Width = 21.3′ (320′ full-scale), height = 8.8′ (132′ full-scale).

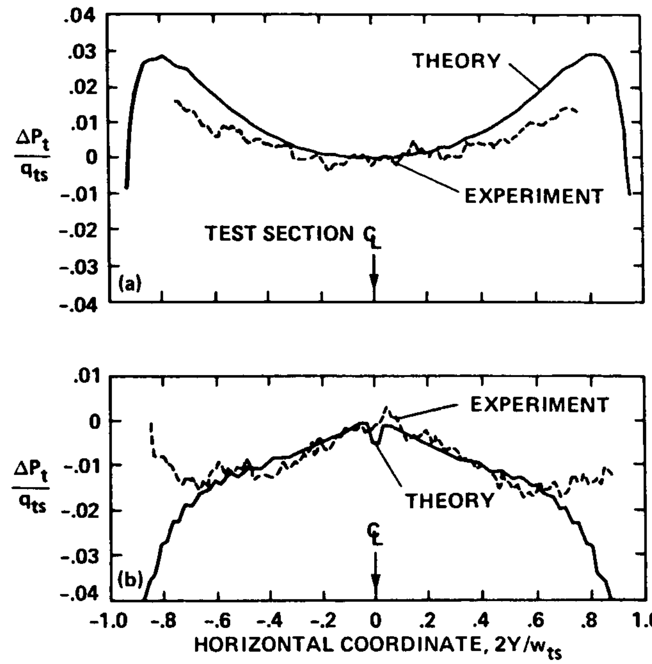


Fig. 12 Comparison of predicted measured test section total pressure at mid-height of test section (z = 0.0).
(a) Splay distribution #1.
(b) Splay distribution #2.

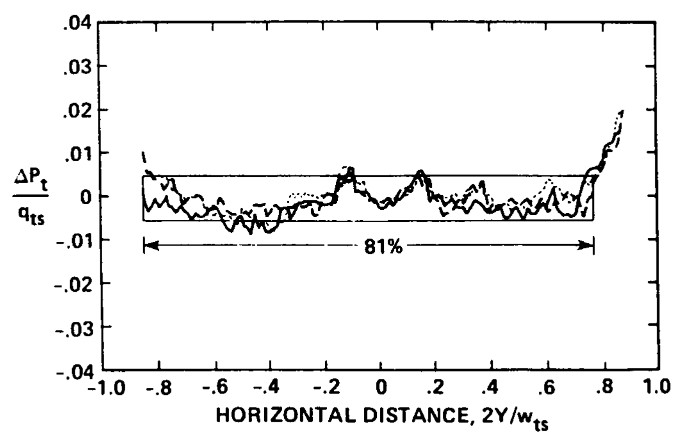


Fig. 13 Test section total pressure distribution for proposed 80- by 120-Foot Wind Tunnel Inlet (1/15 scale data at mid-height).

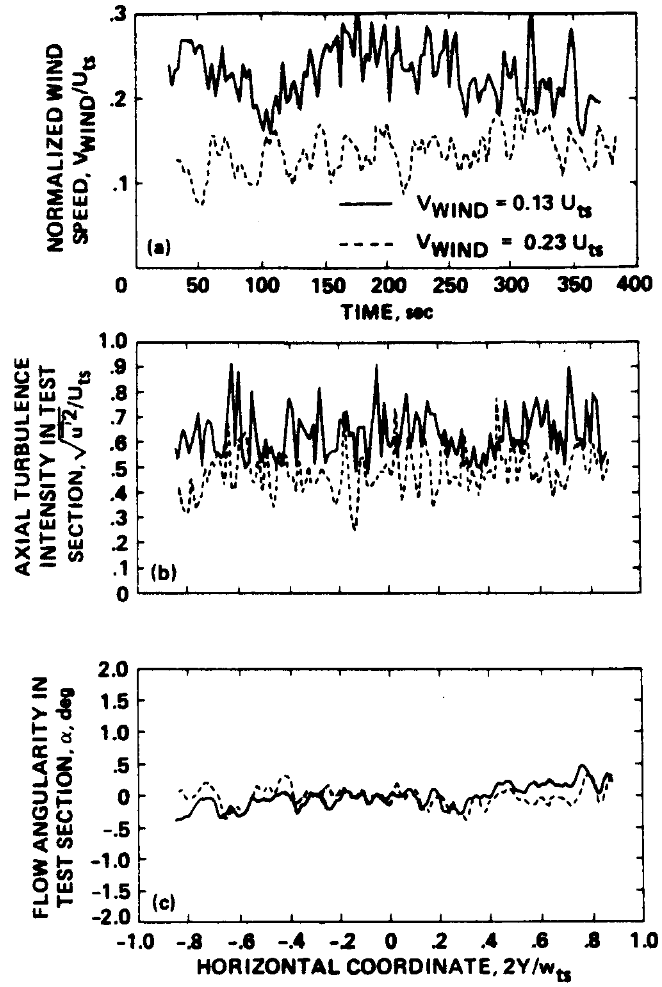


Fig. 14 Effect of wind on test section flow quality (horizontal survey at mid-height in test section).
(a) Normalized wind speed.
(b) Axial component of turbulence in test section.

(c) Flow angularity in test section.

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15. Supplementary Notes

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16. Abstract A unique inlet design concept for indraft wind tunnels is presented. The concept is particularly useful for applications for which a specific test section quality is required with minimum inlet size. Indraft wind tunnels require flow straighteners and antiturbulence screens at the front of the inlet in order to isolate the test section from turbulent atmospheric winds. For inlets with small length-to-diameter ratios, the inlet treatment may be located in a markedly nonuniform velocity field. Since the pressure loss caused by the treatment is proportional to the local dynamic pressure, nonuniform flow through the inlet screen results in nonuniform total pressure downstream of the screen. This nonuniformity in the total pressure distribution at the inlet persists into the test section. A cascade or vaneset can be used to control the flow at the inlet plane so that the variation in test-section total pressure is minimized. Potential-flow panel methods coupled with empirical pressure loss predictions are used to predict the performance of the inlet cascade. The cascade concept was used to develop an alternative inlet design for the 80- by 120-Foot Wind Tunnel at NASA Ames Research Center. The results of the numerical predictions are in good agreement with the experimentally measured performance of a 1/15 scale model of the wind tunnel. The experimental results demonstrate that it is possible to design a short length-to-diameter ratio wind tunnel inlet which provides atmospheric wind isolation and uniform test section flow.

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