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UNIFORM INLET CONDITIONS FOR THE
NPS SUBSONIC CASCADE WIND TUNNEL

Donald M. McEligot

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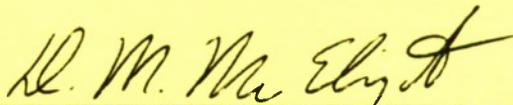
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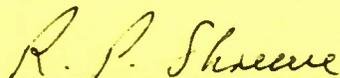
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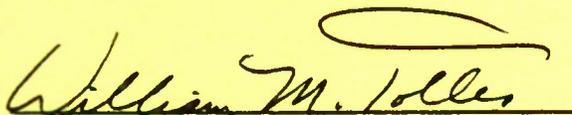


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approaches are suggested. From a study of simple analyses for turbulent wakes and of the effects of wire gauze screens, it is predicted that the desired uniformity may be obtained by installing a single screen of high resistance coefficient; the necessary pressure drop and turning of the flow would be substantial. Placing the turning vanes at a closer pitch might be adequate, but further measurements and numerical analysis would probably be necessary for design purposes.

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UNIFORM INLET CONDITIONS FOR THE
NPS SUBSONIC CASCADE WIND TUNNEL

by

CAPT Donald M. McEligot, USNR-R

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1. INTRODUCTION

The Cascade Wind Tunnel (Figure 1) of the Turbopropulsion Laboratory at the U.S. Naval Postgraduate School is a unique facility (Rose and Guttormson, 1964). The test cascade is fixed in position and the inlet flow angle is adjustable in contrast to other rectilinear cascades which use fixed inlet sections and vary the test cascade in order to change the angle of incidence and to investigate the effects of off-design conditions. Common cascade facilities rotate blades individually (and thereby change the stagger angle), or rotate a set of blades (and vary the inlet boundary layer) in order to change the incidence angle. In the latter case it can be difficult to achieve periodicity, especially when heavily loaded. Further, the NPS facility has a cascade length of 5 feet so that with a blade pitch of 4 inches the cascade includes 15 blades. This characteristic makes it easier to attain periodicity and two-dimensionality than in other cascades, which typically are limited to about five blades. Further characteristics are listed in Table I.

In the NPS facility the contraction from the supply and plenum occurs ahead of a set of inlet guide vanes which are adjustable in angle (Figure 2). The cross section is then held constant, at 10 in. x 60 in. in the horizontal plane, between the trailing edges of the guide vanes and the leading edges of the test blades. A manifold is provided in the sides of this

section to provide suction to reduce the wall boundary layers; however, in this design suction is generally not necessary. The streamwise length of this section varies with the angle of the flow, being least with vertical guide vanes.

As currently constructed (January 1981), the inlet flow to the test blades includes the remnants of the wakes from the turning vanes. The decay of these wakes therefore determines the turbulence level and the degree of non-uniformity in the mean flow and turbulence at the inlet plane. The design and concept of this cascade tunnel preclude the use of an expansion, plenum and contraction section to modify the flow after the turning vanes as in normal wind tunnels.

The purpose of the study reported here was to investigate means of modifying the turbulence level and uniformity of the inlet flow within the constraints of the existing construction.

2. REVIEW OF THE PROBLEM

2.1. Desired Inlet Conditions

Specifications for cascade tests typically call for uniformity of flow, two-dimensionality and periodicity across the cascade. Examples of recommendations are: 1) uniform upstream conditions should be attained by one-half a blade pitch ahead of the test cascade (Starken et al., 1975), 2) upstream measurements should be within one blade chord of the leading edge plane (NASA RFP3-837388Q). Other typical requirements are:

$$Re_{\text{chord}} > 5 \times 10^5$$

Turbulence intensity variable up to 6%

Incidence angle: $\pm 10^\circ$

Number of blades ≥ 7

For the NPS Subsonic Cascade Wind Tunnel the desired uniformity in the mean velocity is to within one percent. Here uniformity is defined in terms of the maximum difference in velocity. Alternatively, one could specify the goal as a maximum amplitude of 1/2% about $\bar{U}_{\infty, \text{avg}}$.

Typical NASA specifications (RFP3-837388Q) request that turbulence intensity be variable up to 6 percent, and ask that it and the transverse macro-(integral)scale be measured. The definition is presumably based on that of Dryden and Kuethe

$$\text{turbulence intensity} = u' = \sqrt{u'^2} = u_{\text{rms}}$$

where u is the streamwise component of the turbulence defined, in turn, by the Reynolds decomposition $U = \bar{U} + u$. The relative intensity is then defined as u'/\bar{U} , which is also called "degree of turbulence". "turbulence level" and simply "intensity" by many investigators (Hinze, 1975, p. 4).

2.2. Possible Approaches

A variety of techniques can be conceived to modify pre-existing distributions of mean velocity or turbulence, as introduced by the wakes of two-dimensional bodies such as turning vanes. A few are listed below.

1. The standard technique for wind tunnels is to introduce screens, or honeycombs and screens, followed by a large area contraction (Pankhurst and Holder, 1952; Loehrke and Nagib, 1976). In a low velocity flow the pressure drop introduced by a high blockage screen can be negligible. With velocities of the order of 100 - 200 ft/sec after the turning vanes it is questionable whether the normal screens would be feasible. Most of the present report is aimed at answering the question whether a single screen would be practical in the NPS facility.
2. Since the vane wakes cause a deficit in the momentum of the fluid, a variety of jet geometries could be envisioned to counteract the momentum loss in the

wake: trailing edge slots, cylindrical manifolds, etc.

3. The distance for readjustment of wakes behind a row of bars is reduced by reducing the spacing between the bars (Schlichting, 1960). By placing rods or other two-dimensional bodies between the vanes - with wakes equivalent to those of the vanes - the downstream distances for uniform flow would be reduced. It would probably require detailed velocity and turbulence surveys of the vane wakes plus advanced wake modeling to deduce the necessary size and spacing of the additional bodies. It is possible that a different design would be necessary for each operating condition.
4. New vanes of thin sheet metal and closer spacing (Salter, 1946), in place of the existing vanes, would automatically provide equivalent wakes and would have shorter readjustment lengths. This idea is addressed briefly in a later section.
5. Non-uniform grids of bars have been applied to modify a uniform velocity profile to a desired distribution (Peacock, El-Attar and Robinson, 1979; McCarthy, 1964; Owen and Zienkiewicz, 1957). Presumably the procedure can be inverted to yield a uniform velocity from a pre-existing gradient. However, the 2-inch spacing of the existing vanes is likely too small for such an approach to be practical.

6. A flow inclined to a fine gauze mesh is turned by the mesh (Taylor, 1944), therefore non-uniform curvature of a mesh can be applied to modify a velocity profile (Castro, 1976). Again the scale of the present situation is probably too small for this idea to be feasible.
7. The length available between turning vanes and test blades can be increased by installing an additional vertical section in the cascade apparatus. This step would require a major reconstruction effort.

3. FUNDAMENTAL CONSIDERATIONS

Design of screens or additional vanes, to modify the wakes from existing vanes, requires an understanding of the behavior of two-dimensional wakes and the effects of wire gauzes. This section is included to provide an introduction to the necessary background.

3.1. Laminar Cylinder Wakes

Schlichting (1960, p. 160 et seq.) presents an analysis for the laminar wake behind an infinitely thin flat plate. The extension to a cylindrical cross section is comparable; it is presented in the following development. The range of validity is expected to be limited to $Re_d \lesssim 50$.

The solution is assumed to be of the form*

$$u_1 = U_\infty C \left(\frac{x}{d} \right)^{-\frac{1}{2}} g(\eta) \quad (\sim S9.45)$$

The drag is

$$D = W\rho U_\infty \int_{y=-\infty}^{+\infty} u_1 dy \quad (\sim S9.46)$$

by a momentum integral with W being the width or length of the cylinder. By substitution of u_1 and definition of η as $y\sqrt{U_\infty/\nu x}$, one obtains

$$D = W\rho U_\infty^2 C \sqrt{\frac{\nu d}{U_\infty}} \int_{-\infty}^{\infty} g(\eta) d\eta \quad (\sim S9.46)$$

* In the remainder of this report equations and figures presented by Schlichting (1960) are identified as (Sx.xx) and Figure Sx.x, respectively.

The solution for $g(\eta)$ proceeds as for the flat plate since the equation and boundary conditions are the same. The result is

$$g = \exp\{-\eta^2/4\} \quad (S9.48)$$

and

$$\int g(\eta) d\eta = 2\sqrt{\pi}$$

The coefficient C can be evaluated from empirical data on the drag on an infinite cylinder. From Figure S1.4 two regions with different slopes can be identified. The regions can be approximated as

$$\begin{aligned} \text{I. } C_D &\approx 10 \operatorname{Re}_d^{-0.778} & \operatorname{Re}_d &\lesssim 4 \\ \text{II. } C_D &\approx 5.57 \operatorname{Re}_d^{-1/4} & 10 &\lesssim \operatorname{Re}_d \lesssim 1.5 \times 10^3 \end{aligned}$$

In terms of drag coefficients the drag can be represented as

$$D = \frac{1}{2} \rho U_\infty^2 A_p C_D = \frac{1}{2} \rho U_\infty^2 d W C_D$$

We equate this relation to equation (\sim S9.46) with inclusion of the integral and obtain

$$C = \frac{C_D \sqrt{\operatorname{Re}_d}}{4\sqrt{\pi}}$$

The wake defect from Equation (\sim S9.45) becomes

$$\frac{u_1}{U_\infty} = \frac{C_D \sqrt{\operatorname{Re}_d}}{4\sqrt{\pi}} \left(\frac{x}{d}\right)^{-1/2} \exp\{-\eta^2/4\}$$

where $\eta = y\sqrt{U_\infty/ux}$.

The spreading of the wake may be estimated by considering its velocity profile (Figure S9.12). The half-width b could be taken as the location where $\eta \approx 4$ or 5. By substitution in the definition of η we obtain .

$$4 = b \cdot \sqrt{U_\infty / \nu x}$$

or

$$\frac{b}{x} = \frac{4}{\sqrt{Re_d \cdot (x/d)}}$$

or

$$\frac{b}{d} = 4 \cdot \sqrt{\frac{x/d}{Re_d}}$$

The local maximum defect is given by evaluating u_1 at $y = 0$, i.e., $\eta = 0$. Then

$$\frac{u_1}{U_\infty} = \frac{C_D \sqrt{Re_d}}{4\sqrt{\pi}} \left(\frac{x}{d}\right)^{-\frac{1}{2}}$$

The distance to decay to an amplitude of one percent would be

$$\left(\frac{x}{d}\right)_{0.01} = \frac{C_D^2 Re_d}{16 \times 10^{-4} \pi} \approx 200 C_D^2 Re_d$$

In the range $10 \lesssim Re_d \lesssim 1.5 \times 10^3$

$$\left(\frac{x}{d}\right)_{0.01} = \frac{5.57^2 Re_d^{-\frac{1}{2}} Re_d}{16 \times 10^{-4} \cdot \pi} = \frac{6.17 \times 10^3}{\sqrt{Re_d}}$$

At $Re_d = 50$, to correspond to the appropriate limit for laminar flow without eddy shedding, the distance would be about 900 cylinder diameters!

The approximate distance for wakes from parallel cylinders to interact, x_m , can be estimated from Figure 3. The wakes interact at $b = \lambda/2$ so we can set

$$\frac{\lambda}{2d} = \frac{b}{d} = 4 \cdot \sqrt{\frac{x_m/d}{Re_d}}$$

giving

$$\frac{x_m}{d} = \frac{(\lambda/d)^2}{64} Re_d$$

or

$$\frac{x_m}{\lambda} = \frac{\lambda/d}{64} Re_d.$$

3.2. Turbulent Cylinder Wakes

Schlichting (1960, p. 565) suggests that the half-width b of a two-dimensional turbulent wake varies according to

$$b \sim (\beta x \cdot C_D d)^{1/2} \sim \sqrt{x} \quad (S23.15)$$

and the center-line velocity defect, $u_1 = U_\infty - u$, varies as

$$u_1/U_\infty \sim (C_D d/\beta x)^{1/2} \sim 1/\sqrt{x} \quad (S23.16)$$

Experiments by Reichardt and by Schlichting in conjunction with the approximate analysis of Schlichting* give

$$b_{1/2} = \frac{1}{4}(xC_D d)^{1/2} \text{ or } \frac{b_{1/2}}{d} = \frac{1}{4}(C_D \frac{x}{d})^{1/2} \quad (S23.36)$$

* Hinze (1975, p. 496 et seq.) presents a comparable development but includes an allowance for the apparent origin of the wake so that x is replaced by $x + a$ as shown in his Figure 6-1.

and

$$\frac{u_1}{U_\infty} = \frac{\sqrt{10}}{18\beta} \left(\frac{x}{C_D d} \right)^{-1/2} \left\{ 1 - \left(\frac{y}{b} \right)^{3/2} \right\}^2 \quad (\text{S23.37})$$

where $\beta \approx 0.18$ and C_D is defined in terms of the cylinder diameter by $D = (1/2) C_D W d \rho U_\infty^2$. Measurements show validity for large distances, $x/C_D d > 50$. An alternate approach gives

$$\frac{u_1}{U_\infty} = \frac{1}{4\sqrt{\pi}} \sqrt{\frac{U_\infty C_D d}{\epsilon_0}} \left(\frac{x}{C_D d} \right)^{-1/2} \exp\left\{-\frac{\eta^4}{4}\right\} \quad (\text{S23.39})$$

where, empirically, $\epsilon_0/(U_\infty C_D d) = 0.0222$ and $\eta = y \sqrt{U_\infty/\epsilon_0 x}$.

For cylinders (Figure S1.4)

$$C_D \approx 1.0 \quad \text{for } 600 \lesssim Re_d \lesssim 3 \times 10^5$$

$$C_D \approx 0.4 \quad \text{for } Re_d > 5 \times 10^5$$

Thus, the center plane defect would be approximately (from Equation S23.37)

$$\frac{u_1}{U_\infty} \approx 0.976 \left(\frac{x}{d} \right)^{-1/2} \approx \left(\frac{x}{d} \right)^{-1/2}$$

and the width (Equation S23.36) would be

$$\frac{b_{1/2}}{d} \approx \frac{1}{4} \left(\frac{x}{d} \right)^{1/2}$$

3.3. Turbulent Wakes behind a Row of Cylinders

Schlichting (1960, p. 604) also treats the non-uniformity behind a row of circular cylinders of pitch λ after the wakes have begun to interact (Figure S23.6). For $x/\lambda > 4$, he gives

$$\frac{u_1}{U_\infty} = \frac{1}{8\pi^3} \left(\frac{\lambda}{\ell}\right)^2 \frac{\lambda}{x} \cos\left\{\frac{2\pi y}{\lambda}\right\} \quad (\text{S23.41})$$

and for the particular case with $\lambda/d = 8$ the mixing length ℓ is approximately $\ell/\lambda = 0.103$. For the near wake region Schlichting refers one to G. Cordes (1937).

The implication of Equation (S23.41) is that the wakes begin to interact before $x/\lambda = 4$ so that by that location the flow pattern can be approximated as sinusoidal. It seems to the present author that the distance necessary would be a function of λ/d with longer distances required for larger λ/d and less for small λ/d .

An estimate of the distance for turbulent wakes to meet (Figure 3) can be made from the single wake result above, i.e., $b_{1/2}/d \approx \frac{1}{4}(x/d)^{1/2}$ provided Re_d is sufficiently large. Since $b_{1/2} \approx 0.44b$ in the simple theory, we can approximate the half width as $\frac{b}{d} \approx \frac{2b_{1/2}}{d} = \frac{1}{2}\left(\frac{x}{d}\right)^{1/2}$. The distance for the wakes to meet, x_m , must again correspond to $b = \lambda/2$. Substitution gives $x_m/\lambda \approx \lambda/d$. Thus, the requirement presented by Schlichting (that $x/\lambda > 4$) would correspond to $\lambda/d \gtrsim 4$.

Ideally, for application to the wakes of vanes an equivalent diameter must be identified through the analysis from measurement or prediction of the half width of the wake or boundary layer near the trailing edge of the vane. Equivalency of wakes would require equal widths, momentum defects (velocity disturbance) and turbulence distributions. However, in the following Section 4, experimental evidence is presented which shows

that the present analysis can provide predictions which are of the proper order-of-magnitude for a set of turning vanes.

For application of analyses for the effect of wire gauze, the local disturbance due to the wires should have decayed sufficiently so that the usual assumption of boundaries far downstream (and far upstream) is met. A further constraint usually suggested is that the Reynolds number based on wire diameter be less than 40 so it does not shed eddies itself (Pankhurst and Holder, 1952, p. 78). At $U_\infty = 100$ ft/sec and sea level conditions $Re = 40$ corresponds to $d = 7.2 \times 10^{-4}$ inch \approx 1 mil! Thus a wire gauze should be considered a turbulence-producing grid for the conditions in the Cascade Wind Tunnel.

From Equation (S23.41) one can estimate the distance for the mean disturbance in grid turbulence to decrease to one percent as

$$0.01 \approx \frac{1}{8\pi^3} \left(\frac{\lambda}{\ell} \right)^2 \frac{\lambda}{x}$$

or $\frac{x}{\lambda} \approx 40.$

This value should only be considered an order-of-magnitude estimate since a gauze mesh is not a two-dimensional row of bars and, further, we do not know whether the mixing length estimate is valid at low Reynolds numbers. Intuition suggests that the mixing due to the wires in the second direction will accelerate the decay of disturbances.

Hinze (1975, p. 268 et seq.) discusses the decay of turbulence behind square-mesh grids but does not mention the

readjustment of the disturbance to the mean flow. His suggestion that "grid-generated turbulence usually becomes practically homogeneous only when $x/M > 10$ to 15 " might imply that the mean disturbance would be negligible within this distance.* However, his references should be consulted to see whether the mean profile was measured in the experiments cited.

If we require $x/\lambda \gtrsim 50$ as an estimate of the necessary distance, with $\lambda \approx 1/8$ inch the distance would be about 6 inches.

3.4. Effects of Gauze Screens - Mean Disturbance

Taylor and Batchelor (1949) consider a $u = u_1 \cos(py)$ disturbance to the mean flow \bar{U} of the form $u = u_1 \cos(py)$ and attack the same problem as Prandtl and Collar (Parkhurst and Holder, 1952). Their result is

$$\frac{u_2}{u_1} = \frac{1 + \alpha - \alpha K}{1 + \alpha + K} = f(K)$$

where $K = (P_1 - P_2) / \frac{1}{2} \rho U^2$ is the resistance coefficient and $\alpha = \phi_2 / \phi_1$ is the change in angle of flow due to the screen (Figure 4). They indicate $\alpha \approx 1.1(1 + K)^{-\frac{1}{2}}$.

The result reduces to Prandtl's when $\alpha = 0$ and to Collar's when $\alpha = 1$. Agreement to data of Collar and of MacPhail is fair for $1 \lesssim K \lesssim 8$ (they plot no data below $K \approx 1$).

If the approximation for α is adopted, the function $u_2/u_1 = f(K)$ can be tabulated as in Table II and plotted as in Figure 5. Since α gives the change in angle relative to the gauze, ϕ_2/ϕ_1 ,

*M = λ = mesh pitch

it can be seen that large resistance coefficients K cause substantial modification of the flow angle.

The effect of screens in series can be examined by example. Consider two screens with $K = 1$ versus one with $K = 2$, i.e., same total drop. In the first case $u_2 \approx 0.36u_1$ and $u_3 = 0.36u_2 = 0.36^2u_1 \approx 0.13u_1$. In general we can say $u_{n+1} = K^n u_1$. For $K = 2$, $u_2 \approx 0.1$, so in this case the single screen would be better for removing the nonuniformity in the mean flow (also for $K_{\text{total}} = 1.5$ and 2.2).

Typical British wire gauze giving a resistance coefficient of $K \approx 1$ would have a blockage coefficient $\beta = (1 - d/\lambda)^2$ of about 0.6, wire diameter of 0.028 inches $\approx 1/32$ inch and a mesh of about 8 openings/inch (Pankhurst and Holder, 1952, App 2) or $4\lambda/d \approx 4$. At $U_\infty = 30$ ft/sec, Re_d would be about 450 for this wire size. At $Re_d = 50$, $\frac{x_m}{\lambda} \approx \frac{4.4}{64} \times 50 \approx 5$ or $x_m/d \approx 20$.

With close spacing the flow is intermediate between being the wake of a cylinder and a jet flowing through the opening. Schlichting (1960, p. 168) suggests that a two-dimensional jet will only be laminar to $Re_j \approx 30$ with Re_j based on the spacing of the opening and the efflux velocity. Thus, it is unlikely that the wakes/jets combination would remain laminar at the conditions of the cascade experiments ($U_\infty \gtrsim 100$ ft/sec); for this application the gauze flow would correspond to turbulent flow behind a grid.

3.5. Effects of Gauze Screens - Turbulence

The effects of gauze on isotropic turbulence in an incident flow are predicted by Taylor and Batchelor (1949) to be reductions in the fluctuating components approximately as follows:

$$\mu = \frac{\overline{(u_2')^2}}{\overline{(u_1')^2}} \approx \left[\frac{1 + \alpha - \alpha K}{1 + \alpha + K} \right]^2 = [f(K)]^2$$

and

$$\nu = \frac{\overline{(v_2')^2} + \overline{(w_2')^2}}{\overline{(v_1')^2} + \overline{(w_1')^2}} \approx \alpha^2$$

Since the intensity is defined as u'/\bar{U} , the reduction in intensity $(u_2'/\bar{U})/(u_1'/\bar{U})$ is predicted to be simply $f(K)$. This value is the same as the reduction in the disturbance to the mean flow (turbulence kinetic energy is reduced further since it is defined in terms of $(u')^2$ and $f(K) < 1$).

Hinze (1975, p. 268 et seq.) treats turbulence measurements behind grids, usually square meshes of circular rods, in considering isotropic turbulence. He suggests that the grid-generated turbulence becomes practically isotropic when $x/M > 10$ to 15 and recommends requiring $x/M \gtrsim 20$ before expecting homogeneous turbulence. He also notes the work of Grand and Nisbet (1957) who reported departures from homogeneity up to $x/M = 80$.

Hinze cites Batchelor and Townsend (1948) as proposing the downstream decay of grid turbulence to follow the relation

$$\frac{\bar{U}^2}{(u')^2} = \frac{C}{C_D} \left[\frac{x}{M} - \frac{x}{M_0} \right]$$

with

$$C_D = \frac{(d/M)(2 - d/M)}{(1 - d/M)^4}$$

and $C \approx 106$

so $C/C_D \approx 135$ for typical grids. Their data for $5,500 \leq Re_M \leq 44,000$ and $M/d = 5.3$ (Hinze Fig 3-25a) give $(x/M)_0 \approx 10 - 15$.

Rephrased in terms of intensity their relation would be

$$\frac{u'}{\bar{U}} = \left\{ \frac{C}{C_D} \left[\frac{x}{M} - \frac{x}{M_0} \right] \right\}^{-\frac{1}{2}} \approx \left[\frac{1}{135 \left(\frac{d}{M} - 15 \right)} \right]^{\frac{1}{2}}$$

This relation is plotted as Figure 6 as guidance for distances from the grid to expect a given level for the intensity. However, since the intercept $(x/M)_0$ has been estimated from a small graph, the values are highly uncertain in the region where $x/M \approx (x/m)_0$. In particular, the location could not be considered reliable for intensities of the order of 5 percent.

Considering the data of Batchelor and Townsend (1949) for grid turbulence and the analysis of Schlichting (1960) for mean disturbances behind a row of cylinders, this author doubts that a grid of cylinders can be used to provide a turbulence intensity of 6 percent and spatial uniformity within 1% at the same location. A grid may be used to adjust the turbulence intensity at a measuring plane at the expense of uniform conditions. Further,

if the intensity is 6% at the measuring plane Figure 6 shows one can expect it to be much less by the time it reaches the plane of the leading edge in a test cascade.

4. RELATED WORK

DuVal (1980) has measured profiles ahead and behind two sets of test blades. For the second configuration, measurements with the test cascade removed showed that the guide vane wakes persisted to the upstream (lower) measuring plane. His Figure 20 (with test blades apparently inserted) shows a typical pattern. Inlet angle was about 40° ; pressure drop from plenum to atmospheric through the test section was 16 to 20 inches H_2O ; $P_{static} - P_{atm} \approx 2$ inches H_2O downstream; P_{static} at the upstream location does not appear to be given. One can say $P_{plen} - P_s \approx \rho V_\infty^2$ since $P_{plen} - P_T \rightarrow \sim 0$ between guide vanes. Across the cross-section P_s is approximately constant. Therefore the pressure can be related to the velocity disturbance as

$$\frac{P_{plen} - P_s - (P_T - P_s)}{P_{plen} - P_s} \approx \frac{V_\infty^2 - u^2}{V_\infty^2} = 1 - \frac{u^2}{V_\infty^2}$$

Thus $U_{w,c}$ can be estimated as $1 - \frac{u_w^2}{V_\infty^2} \approx 0.1$ or $u_w^2 \approx 0.9V_\infty^2$,

giving $u_w \approx 0.95V_\infty$. From a treatment involving functions with small arguments, one can probably show

$$\frac{V_\infty - u_w}{V_\infty} \approx \frac{1}{2} \cdot \frac{P_{plen} - P_T}{Q_{ref}}$$

Therefore in this case the wake disturbance was roughly 4 - 5% of the bulk velocity at the lower measuring plane. The shape

of the profile measurements shows the wakes almost meeting at the measurement plane.

Preliminary data by McGuire (1980), with the same guide vanes but without a test cascade installed, show the same pattern and perhaps slightly less magnitude. However, the traverse was slightly less detailed so it may have missed the absolute peaks.

Since the profile is almost sinusoidal, the differences from the average velocity would only be half the wake defect or about 2%.

With a hot wire anemometer Miller (1979) measured the mean streamwise velocity and rms u profiles in the transverse direction at mid-span with and without vertical guide vanes. No test blades were installed. His Figure 7 shows a mean velocity variation of about 8%. The spacing of the measurement points was too coarse to detect the wake. With the turbulence intensity defined in terms of the streamwise component, $T_i = u'/U$, he found no significant difference in T_i between the configurations with and without guide vanes. Near the center of the span T_i was of the order of 2 to 3% with a gradual variation across the tunnel in the blade-to-blade direction.

Traganza (1980) experimented with various available meshes: expanded sheet metal, 1/4 in. chicken wire and 1/2 in. square wire mesh. All had low ratios of wire diameter/mesh spacing or low solidity. His total pressure profile measurements showed substantial variations in mean velocity, in some cases possibly caused by the method of attachment. The wakes from the 1/2 inch

spacing persist to the measurement plane where they can be seen to interact with the wakes from the turning vanes; the peak-to-peak variation in $(P_{\text{plen}} - P_{\text{probe}})/(P_{\text{plen}} - P_{\text{atm}})$ is about 0.1 around an average of 0.27 (approximate). Without screens the variation was also about 0.1 with an average near 0.05 or so. Thus, at his conditions the guide vanes reduce the available stagnation pressure by about 5 percent and the mesh reduced it about 20 percent more; there was no substantial modification of the non-uniformity at the scale of the vane spacing. Turbulence was not measured.

Detailed measurements of the near wakes of blades in a compressor cascade are presented by Hobbs et al. (1980). Some results are compared to predictions from potential flow solutions and wake models. They concluded that far wake velocity profiles satisfy a universal wake function and that they develop in a way similar to those of isolated airfoils. Exponents determined for wake centerline velocity and wake width decay rate agree with exact solutions presented by Schlichting (1960) for an isolated two-dimensional wake.

5. CHOICE OF GAUZE SCREENS

5.1. Estimate of Correction Required for Wakes

As an approximation we consider the wakes of the turning vanes to be comparable to the wake behind a row of cylinders with the origin $x = 0$ corresponding to the trailing edges.* At the centerplane of a disturbance Equation (S23.41) reduces to

$$\frac{u_1}{U_\infty} \approx \frac{1}{8\pi^3} \left(\frac{1}{0.1} \right)^2 \frac{M}{x} \approx 0.4 \frac{M}{x}$$

In general for the geometry of the Cascade Tunnel we can write (see Figure 7)

$$\frac{u_1}{U_\infty} \approx 0.4 \frac{P \cos\phi}{x_v / \cos\phi} = 0.4 \cdot \frac{P}{x_v} \cos^2\phi$$

once the wakes have merged sufficiently.

The pitch p is 2 in. and the vertical distance to the measuring plane x_v is about 13 in. In the most restrictive case (vertical) the disturbance amplitude is predicted to be $u_1/U_\infty \approx 0.036$ or about 4%.

The observations by Miller (1979) for vertical flow gave $u_1/U_\infty \approx 4\%$ while DuVal (1980) found $u_1/U_\infty \approx 2 \rightarrow 3\%$ for flow at an angle of about 40° . These disturbances are of the same order of magnitude as the predictions but 30 to 50% less. The trend is in the same direction as the predictions.

* These calculations must be recognized as order-of-magnitude estimates since the initial condition implied by the evaluation of A , then ℓ , in Equation (S23.41) (Schlichting, 1960) is not exactly the same with the vanes.

If the 1/2 inch grid used by Traganza (1980) had been constructed of parallel circular bars on the same spacing, its wake disturbances would have been about 1/4th of those observed by Miller, i.e., an amplitude of about $1/2 + 3/4\%$, if the source were at the same level. (Dimensions of grids used included 1/2 and 1/4 inch meshes with approximately 1/32 inch wire.) The estimate of Shreeve (unpublished sketch, 1981) shows a pressure variation of about 0.04 which would correspond to an amplitude of about 1%.

Proposed test blade spacings are 4, 6, 8 and 10 inches. However, a 10-inch spacing would give a cascade of only 5 blades and 8 inches would give 7 blades; the former is probably not feasible while the latter would be barely. Thus, a logical location for the required "uniform" inlet conditions would be no more than 4 inches ahead of the leading edges. The minimum distance from the trailing edge of the guide vanes would be 18 inches (Figure 2). The predicted disturbance for the worst case (vertical) then becomes 0.04, or a non-uniformity ($2u_1$) of 8 percent. (At 40° it would be ~5%.)

As noted later, a likely and convenient location for a gauze screen would be at the top of the suction manifolds about 8 inches above the trailing edges of the turning vanes. The worst case there is predicted to be $u_1/U_\infty \approx 0.1$ or a non-uniformity of 20%. (At 40° it would be ~12%.) The desired correction for this case becomes $u_2/u_1 = 1/20$.

For 60° at $x_v = 8$ in., one would have $u_1/U_\infty \approx 0.025$ or 5% requiring a reduction $u_2/u_1 = 0.2$, or $K = 1.5$ approximately.

Since the decay in the disturbance from the blades is estimated to vary as $1/x$, an effect of passing through the gauze may be considered to be comparable to shifting to a larger distance from the blades (see Figure 6). Since the decay then depends on the shear stress which depends in turn on the velocity gradient, the rate of decay is expected to be reduced to that corresponding to the larger distance. Thus, the rate of decay would probably be much slower than ahead of the gauze. Therefore it would be better to place the gauze as close to the working section as possible - allowing sufficient distance for the disturbances which it induces to decay - rather than placing it near the turning vanes.

From the Figure 6 we see that reduction of 20% and 12% non-uniformities to 1% would require resistance coefficients K of about 2.4 and 2.2, respectively. The necessary blockage coefficient $\beta = (1 - d/M)^2$ can be estimated from Figure 371 of Pankhurst and Holder (1952) or from existing correlations as by Cornell (1958),

$$K(1 - s)^2/s \approx 6 \text{Re}_s^{-1/3} \quad 60 \lesssim \text{Re}_s \lesssim 1000$$

where $\text{Re}_s = U_\infty d/\nu(1 - s)$ and s is the solidity (blocked area/total area). Inserting screens with K of this order would reduce the performance of the Cascade Wind Tunnel substantially. The screen would become the dominant flow resistance, and thereby determine the maximum possible velocity in the test section.

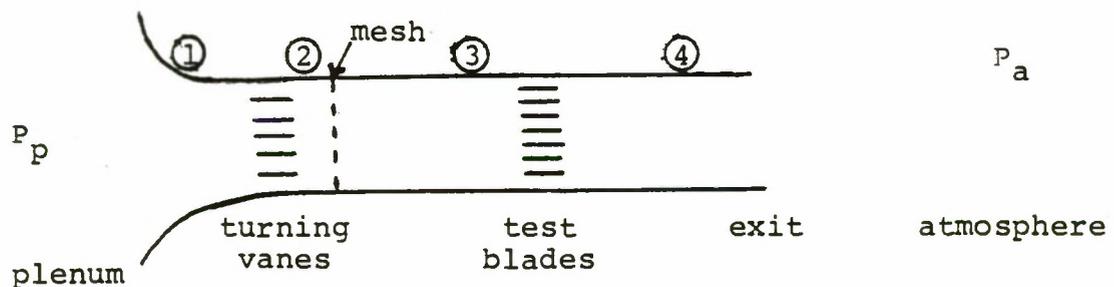
5.2. Maximum Velocity

If the screen dominates the flow resistance, the maximum possible velocity through the tunnel can be calculated. If one assumes the maximum pressure drop available is about 40 in. H₂O, the velocity would be

$$V_{\max} = \left[\frac{P_1 - P_2}{\frac{1}{2}\rho K} \right]^{\frac{1}{2}} = \frac{\sqrt{2(P_1 - P_2)/\rho}}{\sqrt{K}} = 418.4/\sqrt{K} \text{ ft/sec.}$$

Thus, for a range $1.5 < K < 2.4$, the range of maximum velocity would be $341 > V_{\max} > 270$ ft/sec, respectively.

The velocity estimate above essentially considers only the pressure drop across the mesh as if it were from a plenum to the free atmosphere through the mesh only. In the cascade tunnel the flow starts from a plenum and passes over two sets of blades in the rectangular duct. While the pressure drop due to the blades is probably small, one must consider the change necessary to accelerate the flow.



If one neglects the change in density in the duct, the maximum possible velocity can be shown to be

$$V_{\max} = \sqrt{\frac{2g_C(P_p - P_{\text{atm}})}{\rho(1+C_{DV}+K+C_{Db})}}$$

where C_{DV} and C_{Db} are the drag coefficients for the turning vanes and cascade blades, respectively. This value differs from that above by the ratio

$$\frac{\sqrt{K}}{\sqrt{1 + C_{DV} + K + C_b}}$$

or, under the present estimates,

$$\sim \sqrt{K}/\sqrt{1.2 + K}.$$

The values become

K		2.4	2.2	1.5
V with mesh alone	ft/sec	270	282	342
V for cascade	ft/sec	220	227	255

5.3. Forces

The force on a screen 10 inches wide with $\Delta P = 40$ inches H_2O would be about 180 lbf/ft. Consequently, the strength of screen frame and its anchors must be considered in the design of the installation.

5.4. Recommended Gauze

Based on the considerations above, gauze screens are recommended as follows to achieve spatial uniformity of about 1% maximum to minimum velocity.

Inlet Flow Angle, ϕ_1	0°	40°	60°
Resistance coefficient, K	2.4	2.2	1.5
Approximate blockage, β	0.46	0.47	0.55
Disturbance reduction, u_2/u_1	0.04	0.07	0.20
Turbulence reduction, u_2'/u_1'	0.04	0.07	0.20
Fractional turning, $\alpha = \phi_2/\phi_1$	0.60	0.62	0.70
Outlet flow angle, ϕ_2	0°	25°	42°
Maximum velocity, ft/sec	220	227	255
Turbulence intensity at test vanes minus half-pitch*, u'/U	$\sim 1\%$	$\sim 1\%$	$\sim 1\%$

Since the required blockage differs only slightly from 0° to 40° , it is not necessary to use separate screens for each different flow angle. A choice from two (or from three with one of considerably lower K for other tests) should be sufficient.

5.5. Installation

The frame to support a gauze screen should have an opening as large or larger than the rectangular duct so that it does not block or disturb the flow itself.

Between the vanes and blades the one relatively convenient location for installing such a frame and its anchor bolts appears to be in the suction manifolds as shown in Figure 8. This location is approximately 8 inches vertically above the trailing edges of the turning vanes and 22 inches ahead of the leading edge of the test blades.

* $M < 1/8$ inch

From the earlier discussion, it is noted that a position closer to the test blades would be preferable. One other possible location would be in place of traversing slot 1 (Figure 2) if new static tops were installed and a glass or plastic wall were used on one side so that the laser Doppler velocimeter could be used for measurement of the velocity field.

With $K = 1.5$ to 2.5 gauze will change the flow angle significantly. Unless the screen is upstream from the tunnel end walls, it will be necessary to modify the end walls to include another pivot point at the location of the screen. However, with the present construction it would not be feasible to place a screen between the turning vanes and the end wall pivots.

5.6. Possible Sources of Gauze Screens

Suitable gauze screen material may be available as stock in the Aeronautics Department. Alternate new sources (Blackwelder, 1981) may be (a) Kressilk Products, Los Angeles* or (b) Tyler Industrial Products, 1756 Holmes Street, Livermore, California, 94550 (phone: 415-443-5900) with the manufacturing plant in Mentor, Ohio (216-255-9131).

* No telephone is listed in the Los Angeles directory so this source may no longer be available.

6. ADDITIONAL TURNING VANES

For turbulent wakes the non-uniformity behind the guide vanes can be reduced by increasing the number of vanes. The effect is to reduce p in the relation

$$\frac{u_1}{U_\infty} \approx 0.4 \frac{p}{x_v} \cos^2 \phi$$

The worst case would be for vertical flow which would require a pitch of 0.225 inches for spatial uniformity within 1% at the measuring plane. With finite thicknesses the manufacturing tolerances necessary to maintain equal flow rates between all pairs of adjacent blades would probably be impractical.

The smallest feasible pitch, for a set of adjustable turning vanes made of thin sheet metal, is likely to be of the order of 1/2 inch. Then the expected non-uniformity would be about 2% for vertical flow, 1.6% for 30° and 0.6% for 60° . Either the specifications would have to be relaxed or a screen or such would still be required except at large angles. (If these estimates overpredict the wake disturbance by a factor of two, a screen would not be necessary.) Use of additional turning vanes plus a gauze screen would be comparable to the configuration of honeycomb plus screens for normal wind tunnels as studied by Loehrke and Nagib (1976).

Additional turning vanes would provide the further advantage of reducing the effects of corner separation and secondary circulation along the tunnel sidewalls (Peacock, 1971).

The order of magnitude of the pressure drop for 1/2 inch guide vanes would be four times the current pressure drop of about 5%. Then they would be equivalent to $K \approx 0.2$ for a mesh unless the Reynolds number based on hydraulic diameter of the passages were less than the transition Reynolds number (with $Re \approx 5.5 \times 10^4$ /in. at 100 ft/sec laminar flow is not likely).

Parkhurst and Holder (1952) refer to a series of ARC reports on turning vane design and experiments (Salter, 1946; Winter, 1947; Patterson, 1936; Collar, 1937). Their figures for wide aspect ratios and short chords show resistance coefficients, $C = \Delta H / (1/2\rho U^2)$, of the order of 0.1 to 0.2 to be attainable.

7. CONCLUSIONS

1. Some modification of the flow between the turning vanes and test blades will be necessary to obtain uniformity of the inlet mean velocity to within one percent maximum-to-minimum.
2. It should be possible to obtain the desired uniformity by installation of a single gauze screen of high blockage ($\beta = [1 - d/M]^2 \approx 1/2$) at the cost of substantial pressure drop ($K = (p_1 - p_2) / \frac{1}{2}\rho U_\infty^2 \approx 2.4$).
3. Preliminary calculations predict that additional turning vanes would not provide the desired uniformity alone (further work is necessary for a more definitive prediction).
4. Initial considerations of flow in the wakes of parallel cylinders imply that it is not likely that the desired conditions of uniform flow (1%) with a turbulence intensity of 6% can be achieved in grid turbulence.

8. RECOMMENDATIONS

1. Further testing of gauze screens is warranted. Initial attempts could be made with screens giving $K = 1/2$, 1 and 2 in temporary installations to check the predictions in this application. Velocity fields should be measured ahead of the screen and at the test blade inlet plane by means of the laser Doppler velocimeter (LDV).
2. To improve the predictions of wake development behind turning vanes alone, the wake flow field should be measured from the turning vanes to the inlet plane with the LDV and the results should be compared to numerical predictions developed by extending the programs of Professor D. Netzer.
3. Literature surveys should be conducted in several areas as background for further understanding, prediction and design. Some topics would be:
 - a. Techniques for generating high turbulence levels;
 - b. Near and far field data and analyses for the wakes of parallel airfoils.

ACKNOWLEDGMENTS

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Table I. Characteristics of Cascade Wind Tunnel

Pressure*	P_t (in. H ₂ O)	5.6	10.3	11.5	26.6	16.6	46.7
	P_s (in. H ₂ O)	1.1	2.0	2.0	4.0	2.7	8.7
Velocity	V (ft./sec)	140	191	204	314	247	407
Re (for chord = 8.5 in) x 10 ⁻⁶		0.63	0.86	0.92	1.41	1.11	1.83

Test section cross-section: 60 in. x 10 in.

Guide vanes: 29, chord 5 1/4 in, ± 60° (0°, 30°, 60°)

Static ports: 3 in. intervals

Blower: 750 HP

* Pressures vary with motor speed and blower vane setting.

Table II. Reduction of Mean Disturbance by Gauze
Taylor and Batchelor, 1949)

Resistance Coefficient	Turning Angle	u_2/u_1
K	$\alpha = 1.1 (1 + K)^{-1/2}$	f(K)
0.5	0.898	0.604
1.0	0.778	0.360
1.5	0.696	0.204
2.0	0.635	0.100
2.3	0.606	0.0546
2.5	0.588	0.0289
2.8	0.564	-0.00360
3.0	0.55	-0.0220

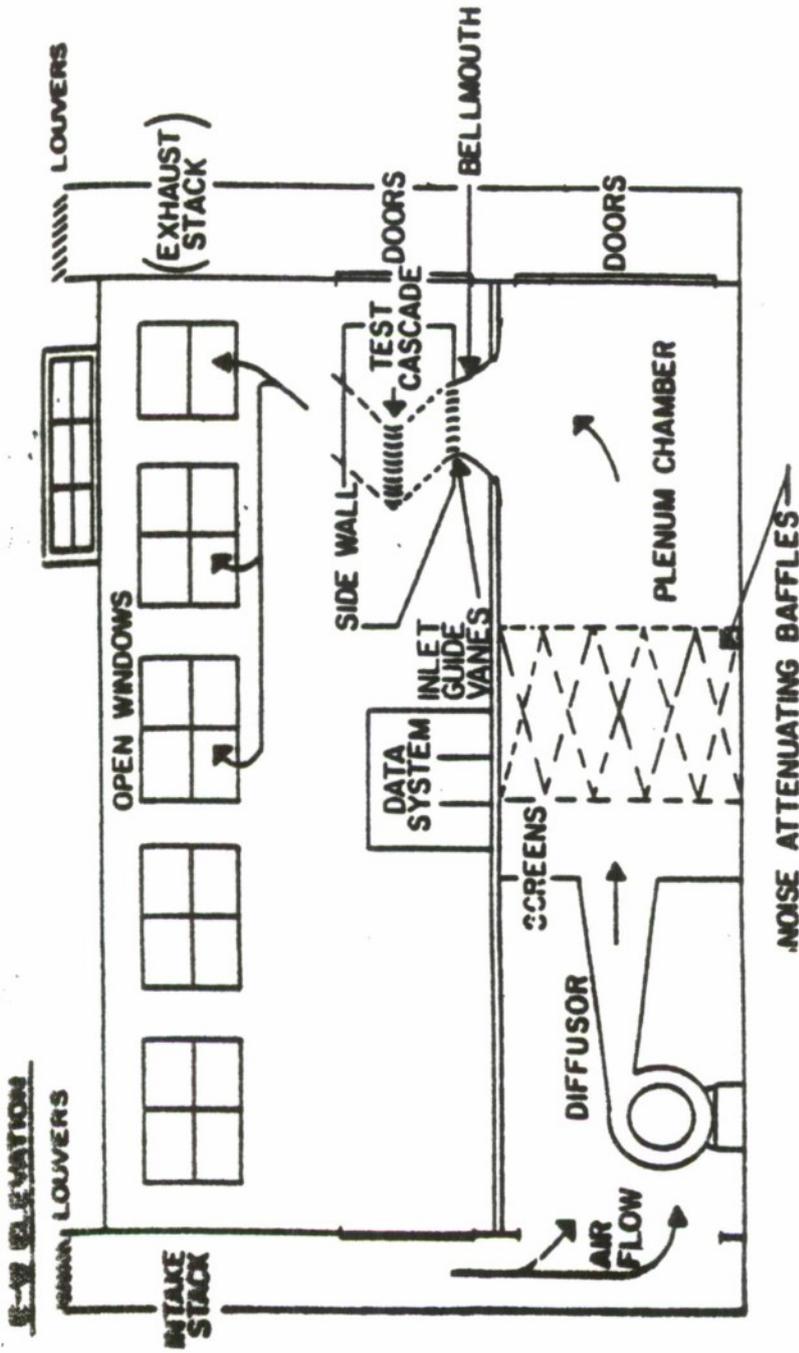


Figure 1. Cascade Facility

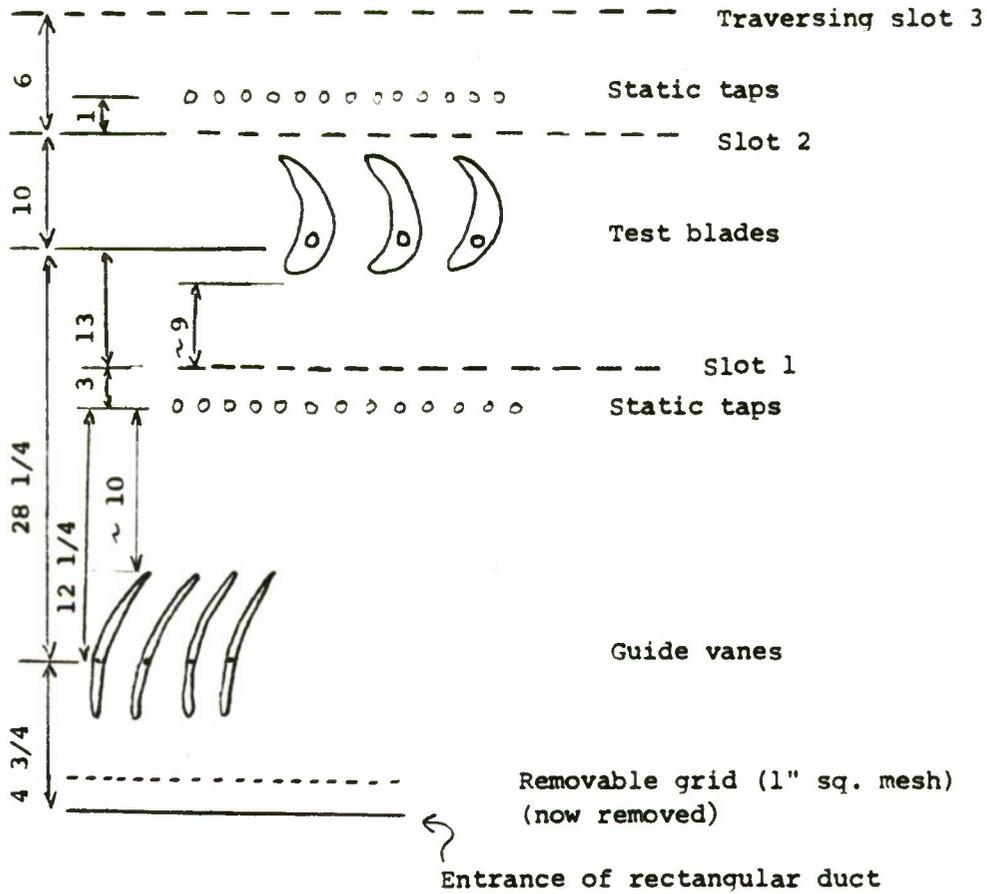


Figure 2. Relation of Test Blades, Guide Vanes and Instrumentation (distances in inches)

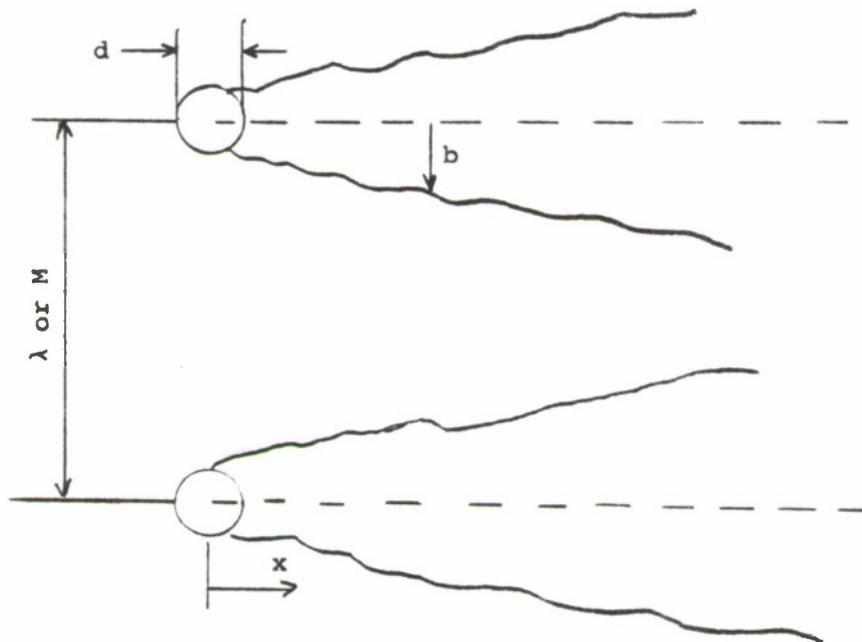


Figure 3. Parallel Cylinders or Typical Screen Geometry

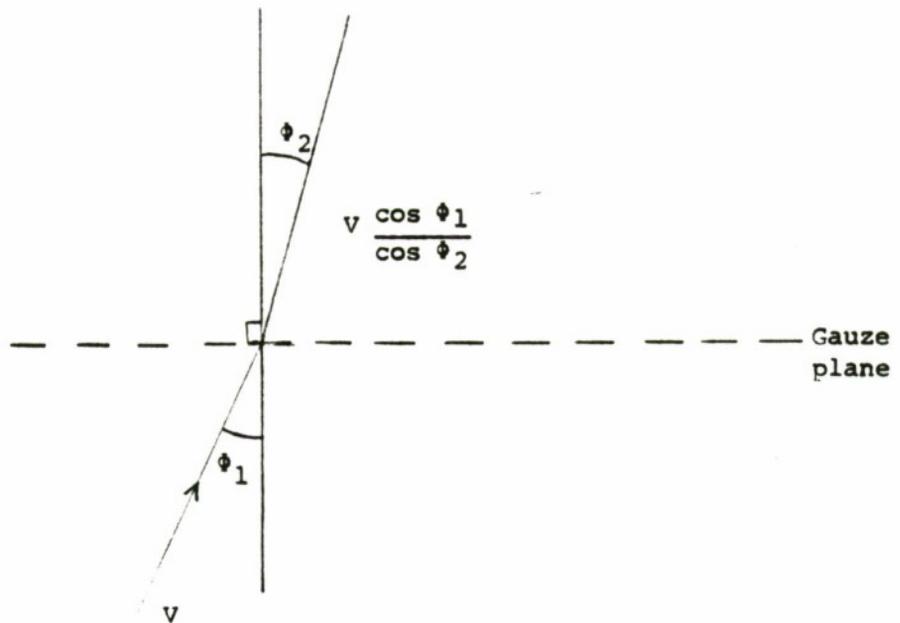


Figure 4. Definition of Angles for Flow Through Gauze Screen

$$\frac{u_2}{u_1} = \frac{1 + \alpha - \alpha K}{1 + \alpha + K}$$

with $\alpha = 1.1 \sqrt{1 + K}$

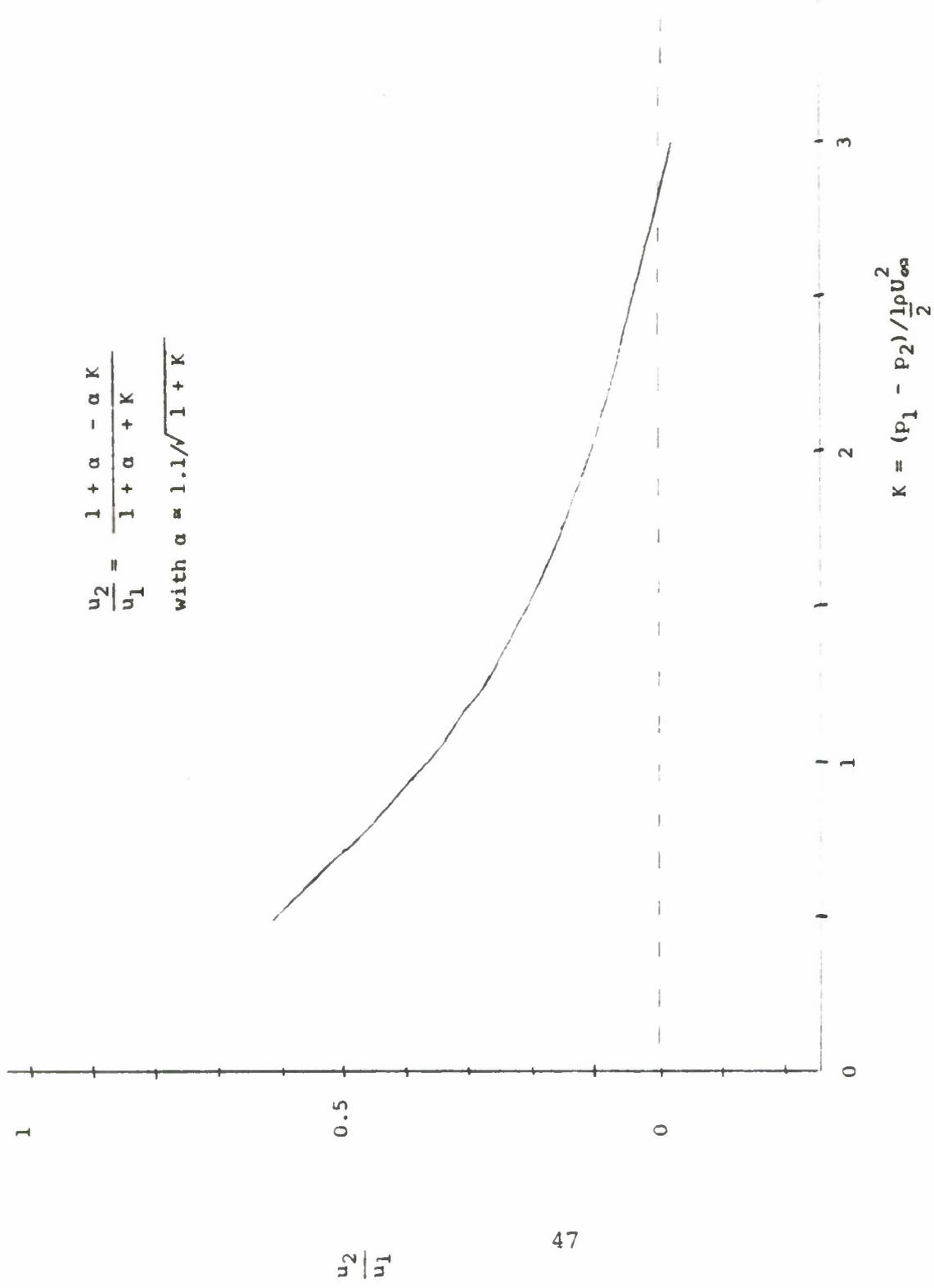


Figure 5. Analysis of Taylor and Batchelor [1949] for Reduction of Spatial Disturbances by Wire Mesh Gauze

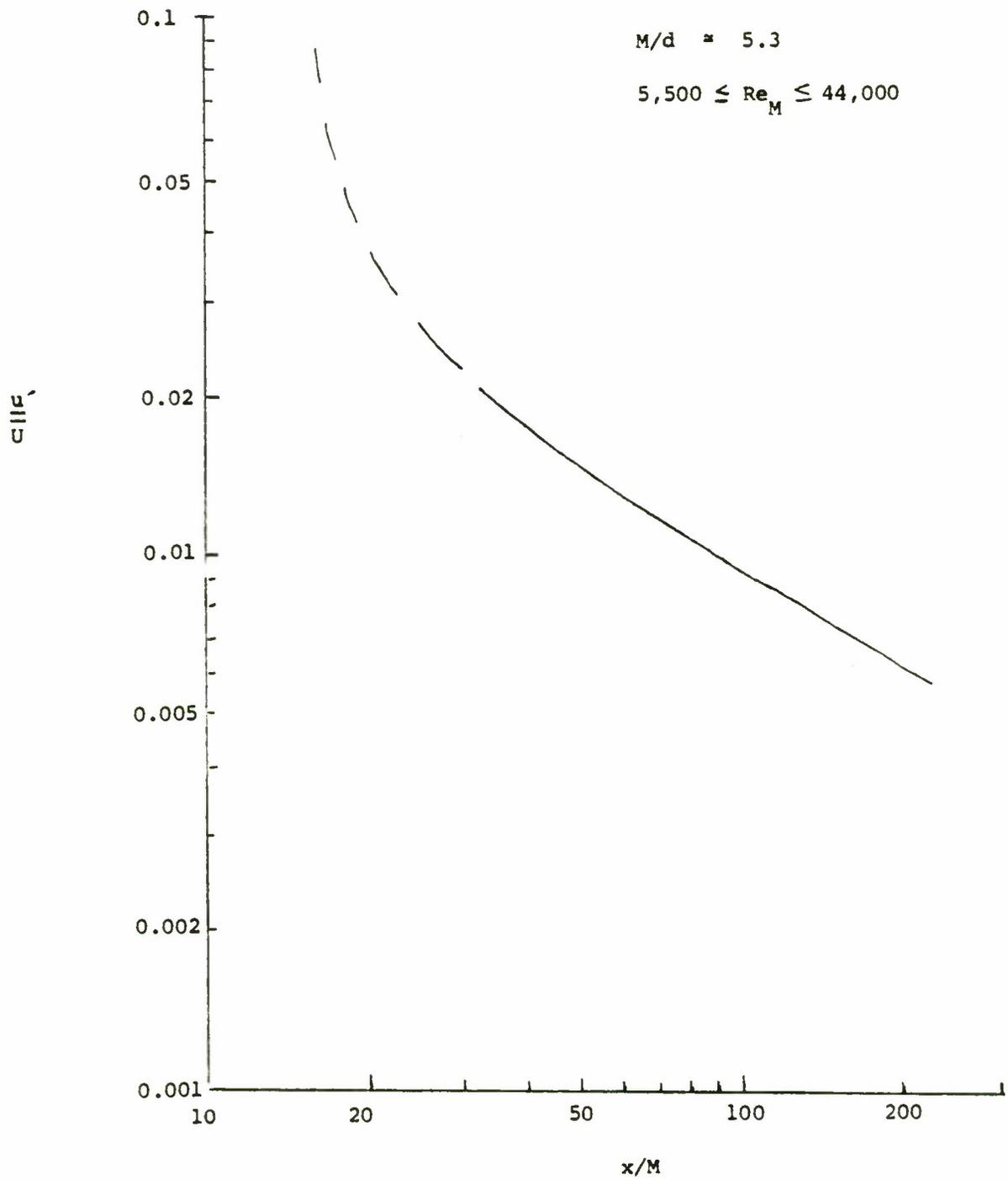


Figure 6. Approximate Decay of Turbulence Intensity Behind a Square Mesh of Circular Bars from the Data of Batchelor and Townsend [1948].

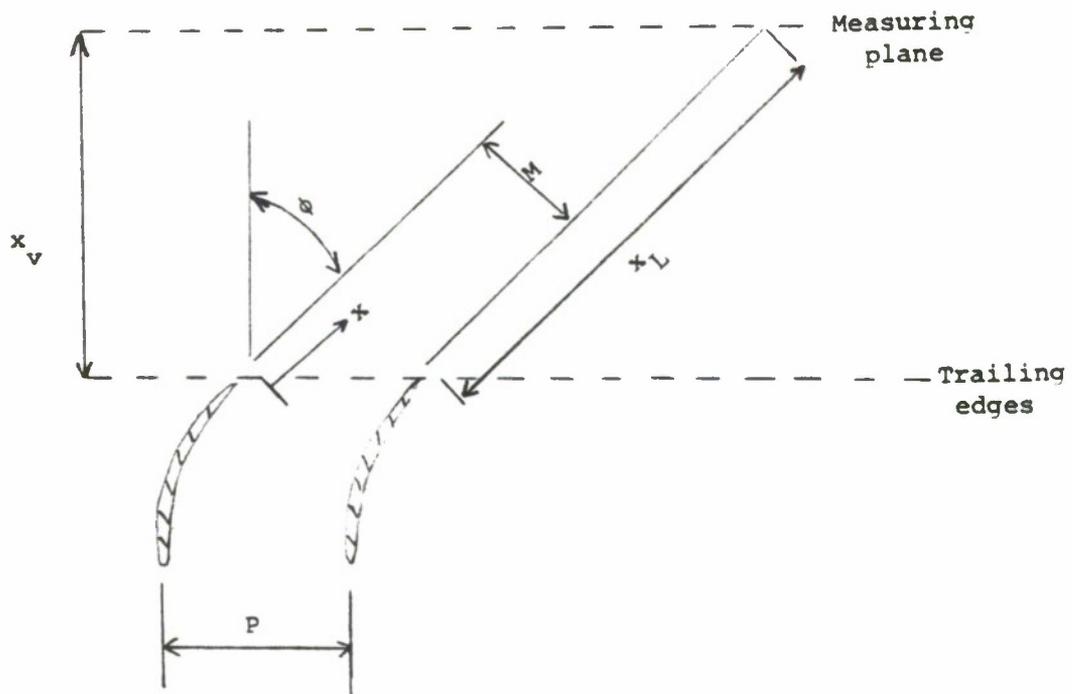


Figure 7. Geometry for Wakes of Turning Vanes

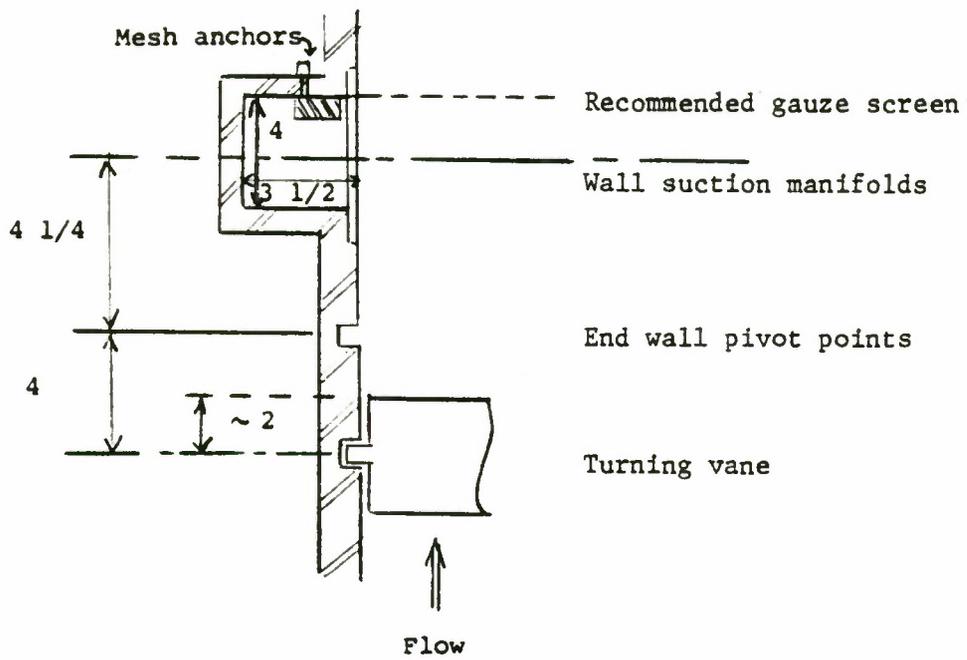


Figure 8. Recommended Installation of Gauze Screen (dimensions in inches)

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