Aerodynamic Design of Three-Dimensional Subsonic Wind Tunnel Inlets

Stephen M. Batill* and Joseph J. Hoffman†
University of Notre Dame, Notre Dame, Indiana

Abstract

A NUMERICAL study was conducted in order to establish a set of preliminary design guidelines and performance criteria for three-dimensional subsonic wind tunnel contraction sections. Inlet geometries for both square and rectangular cross-sectional inlets were considered for a range of contraction ratios of 10-40. Wall geometries were defined using a single-parameter, matched cubic profile. Finite difference field solutions were developed for a potential flow model and the inlet performance quantified in terms of mean flowfield distortion and adverse wall pressure gradients. A turbulent boundary-layer separation prediction is included based on Stratford's criteria. The results are presented in terms of design charts that should prove useful for preliminary, three-dimensional inlet design.

Contents

The aerodynamic design of the wind tunnel presents many challenging and complex problems. The wind tunnel designer is often faced with having to develop a tunnel without the aid of the sophisticated predictive "tools" that are useful in many other aerodynamic system designs. This is not to say that current wind tunnel facilities are not well designed or operate in a less than satisfactory manner, but on occasion the development of these facilities has been a painful trial-and-error process. The design of the wind tunnel inlet has been particularly susceptible to this trial-and-error approach, with the result that many inlets do not perform as originally expected. There currently exist a number of detailed analysis techniques that can be effectively used to predict accurately certain aspects of inlet performance. In order to apply these complex and expensive techniques, a "preliminary" inlet design is required. It was the purpose of this work to provide the preliminary inlet geometries necessary for detailed studies.

Inlet design must be approached from the point of view that a well-designed inlet may not compensate for problems associated with other components of the tunnel, but an inadequately designed inlet can create significant problems and degrade performance. Nonuniformity of the velocity near the entrance plane can influence the design and function of turbulence managing devices. (It is important to note that this numerical work did not directly include the influence of turbulence management devices, but in tunnel design their interaction with the inlet is critical.) Nonuniformity at the exit plane influences the length of the test section and allowable model locations. Adverse pressure gradients, which can exist near the entrance and exit planes and particularly in a corner region, may cause significant flow separation and unsteadiness.

The designer must be able to establish a set of quantifiable criteria to guide design decisions and a set of parameters to define the design. Geometric criteria (height, length, width) are easily quantified and bounds on these are often set by the buildings that will house a facility or by the models to be tested. The criteria associated with the flow quality are more complex. They can be quantified in the form of velocity distributions, turbulence intensities, and pressure distributions. There are only a few parameters that can be controlled in order to achieve allowable limits on these criteria; i.e., contraction ratio, cross-sectional shape, length, and wall contour. Unfortunately, there exists no simple relationship between the design parameters and the design criteria.

Numerical solutions for the inlet flowfield were developed using a three-dimensional, finite difference solution for the potential flow in a converging channel with square or rectangular cross section. The method used was similar to Ref. 1. Calculations were performed for a complete family of wall geometries defined by matched cubic polynomials. The matched cubic allows for the complete definition of the wall geometry with a single parameter referred to as the match point X.[2] By moving the match point, the locations of maximum curvature can be positioned within the inlet. The complete inlet geometry can be defined using the contraction ratio (CR), the aspect ratio (ratio of height to width, H/W), the length-to-height ratio L/H, and the match point. Reference 3 includes the results for calculations with contraction ratios of 10-40 for square and rectangular cross sections. The result of each simulation was the complete, inviscid velocity field. The results are presented in terms of wall pressure distributions and entrance and exit plane velocity profiles.

Figure 1 presents the computed wall centerline pressure coefficient distribution for a CR = 30 inlet and a comparison with experimental results. The pressure coefficient C_{p_e} is based on the exit plane mean axial velocity U_e and is defined as

$$C_{p_e} = 1 - (q/U_e)^2$$

where q is the local wall velocity. Although not obvious in this figure, there exist adverse pressure gradients at both the entrance and exit planes in the streamwise direction.

The severity of the adverse gradient near the entrance can be shown by defining a modified pressure coefficient C_{p_i},

$$C_{p_i} = 1 - (v_{\min}/U_i)^2$$

Here $v_{\min}$ is the minimum velocity occurring along the corner near the entrance plane and U_i is the mean axial velocity at the entrance plane. Figure 2 is a plot of C_{p_i} for a CR = 25 inlet for the complete range of match points and length to height ratios. If the flow were one-dimensional, $C_{p_i} = 0$ for each inlet.

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*Associate Professor, Department of Aerospace and Mechanical Engineering.

†Graduate Research Assistant, Department of Aerospace and Mechanical Engineering.

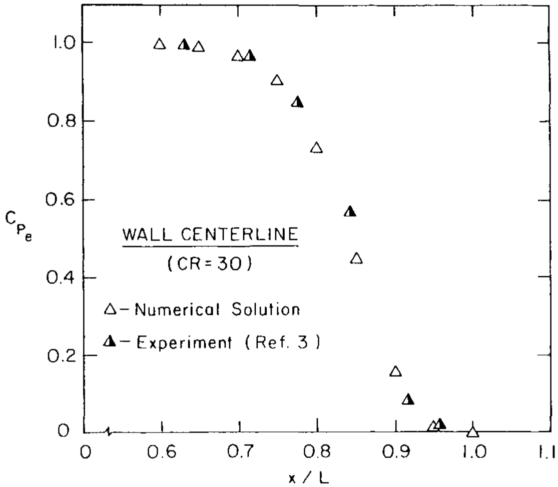

Fig. 1 Wall pressure coefficient vs non-dimensional distance along the inlet centerline (CR = 30, X = 0.71).

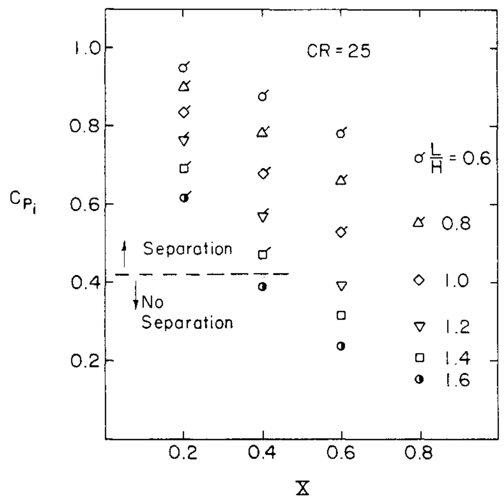

Fig. 2 Entrance region modified pressure coefficient vs match point X (CR = 25).

The stronger the adverse pressure gradient, the lower the value of $v_{\min}$ and the greater the C_{p_i}. Stratford's turbulent boundary-layer separation criteria[4] were also applied and the flagged symbols indicate those inlets for which separation is predicted. It appears as though there is a limiting value for C_{p_i} that could be used as an upper bound if separation is to be avoided.

The exit plane nonuniformity $\tilde{u}_e$ is shown in Fig. 3 for the same CR = 25 inlet as a function of each of the design parameters. This parameter represents the percent maximum variation in velocity across the exit plane. For either short inlets or those in which the match point X is well downstream,

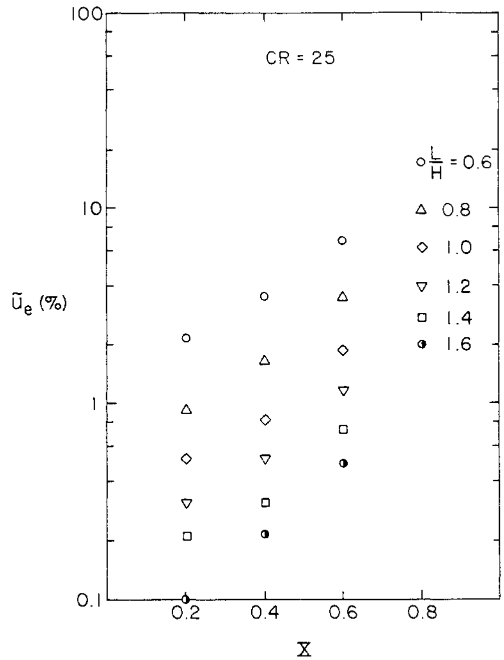

Fig. 3 Exit plane nonuniformity (CR = 25).

this nonuniformity can approach 10%. Similar parameters for the exit plane pressure and entrance plane velocity were also developed.

The complete set of design charts appear in Ref. 3. These charts provide a rational method for the preliminary aerodynamic design of three-dimensional wind tunnel inlets. Although they represent only an initial step, they should provide useful design information. It will be only through experience and additional analysis that more confidence in these and other design parameters can be achieved. The current study provides direction for future work.

Acknowledgment

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