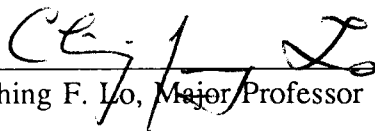
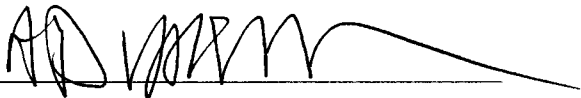
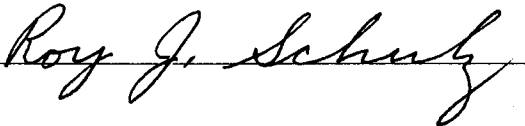


To the Graduate Council:

I am submitting herewith a thesis written by Charles Daniel Vision entitled "A Study of Tunnel Boundary Interference in a Perforated Wall Wind Tunnel Using a Panel Method." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.


Ching F. Lo, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:


Associate Vice Chancellor
and Dean of the Graduate School

**A Study of Tunnel Boundary Interference in a Perforated Wall
Wind Tunnel Using a Panel Method**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Charles Daniel Vision

May 1996

DEDICATION

This thesis is dedicated to my parents

Mr Alan G. Vision

and

Mrs. Lois M. Vision

without whose support, both emotionally and monetarily,

none of this would have been possible.

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ABSTRACT

The objective of this study is to find a fast and effective method of estimating tunnel boundary interference for a subsonic perforated wall wind tunnel. The study consists of three parts. In the first part, a theoretical approach is investigated for finding the boundary interference solutions which utilize both the wall interference and free-air model potential functions, and could be placed into a modified PMARC code for use with perforated walls. This theoretical method involved three steps which could be compared with each other in order to check the process. The first and second steps of the theoretical method dealt with solid wall wind tunnels while the last step used a perforated wall wind tunnel. The final results for the last step were compared and plotted against various values for the porosity coefficient to examine the sensitivity of the solution with respect to the value of porosity. The second part of the study used the equations and method which were proved in the first part to modify the panel code PMARC for perforated wall wind tunnels. The modified PMARC code was then used to predict the boundary interference in various wind tunnels with uniform porosities. The values found in the second part were compared with known values and the results were found to be of good agreement. The third part of the theoretical study used the panel code obtained in the second part and continued the modifications to include distributed porosities along the length of the wind tunnel. A study was performed which used very low values, between 0.05 and 0.2, for the porosity of the upstream portion of the wind tunnel test section, and values near the exit of the test

section were set between 0.25 and 0.35. The tunnel boundary interference was calculated by the modified PMARC code and these values were compared with the values found in the second part. As expected, the predicted values for tunnel boundary interference decreases as the porosity of the upstream portion of the test section is reduced and the porosity near the exit is increased.

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NOMENCLATURE

A,B,C,D	constants used in Appendix A
C_1, C_2	constants used in Appendix A
CONVW, ω	convergence coefficient
C_p	wall pressure coefficient
C_{p_i}	wind tunnel wall interference pressure coefficient
d	strength of doublet
h	height of the wind tunnel
ITCOEF	iteration counter
l	distance of a half cycle of the wavy wall
M, M_∞	free-stream Mach number
modpmf1	porous wall wind tunnel case involving a uniform porosity of 0.25
Q	new porosity parameter
R, RCOEF	wind tunnel wall porosity coefficient
RA	starting porosity coefficient for Taylor series expansion
R_1 , RCOEF1	wind tunnel wall porosity coefficient for the inlet
R_2 , RCOEF2	wind tunnel wall porosity coefficient for the test section
R_3 , RCOEF3	wind tunnel wall porosity coefficient for the outlet
try1h	porous wall wind tunnel case involving distributed porosities of $R_1=0.18, R_2=0.25, R_3=0.3$
try1k	porous wall wind tunnel case involving distributed porosities of $R_1=0.08, R_2=0.25, R_3=0.34$

try1n	porous wall wind tunnel case involving distributed porosities of $R_1=0.13$, $R_2=0.25$, $R_3=0.32$
try1o	porous wall wind tunnel case involving distributed porosities of $R_1=0.11$, $R_2=0.25$, $R_3=0.33$
u	perturbation velocity
U_∞	free-stream velocity
U_m	model induced velocity in the x-direction along the wall
U_i	interference velocity in the x-direction along the wall
$V_{i,n}$	interference velocity normal to the wind tunnel wall
$V_{m,n}$	model induced velocity normal to the wind tunnel wall
Vol	volume of the doublet
w	width of the wind tunnel
x,y,z	cartesian coordinates
β	compressibility factor, $\beta^2=1-M^2$
ϵ	amplitude of the wavy wall
ϕ	small perturbation potential function
ϕ_i	wall interference potential function
ϕ_m	small perturbation potential function for model in free-air
ϕ_t	total small perturbation potential function
AEDC	Arnold Engineering Development Center
CFD	Computational Fluid Dynamics
CSTAR	Center for Space Transportation and Applied Research

NASA/ARC NASA Ames Research Center

PMARC Panel Method Ames Research Center

CHAPTER 1

INTRODUCTION

For many years, wind tunnels have been used in the design of airframes and aircraft engines. However, the values of the flow variables and aerodynamic coefficients obtained from the wind tunnel tests do not exactly match the values for the same aircraft in free-air flight at the same flight speed. One reason for this is tunnel wall or boundary interference, which involves perturbations induced in the model flow field by the walls of the wind tunnel. Many techniques have been used to decrease or eliminate the amount of wall interference. Such variables as the geometry of the wind tunnel or the use of ventilated walls for the wind tunnel can successfully decrease the amount of wall interference placed on the testing model. More information about wind tunnel tests and boundary interference can be found in Goethert[1]. Various methods including CFD and panel methods have been used to analytically determine the amount of boundary interference generated from the walls in various types of wind tunnels. These techniques are summarized in Hornung[2]. The panel method code PMARC[3] has been used to predict tunnel boundary interference inside of solid wall wind tunnels, however, the code has never been modified to include porous walls. One of the main components of this thesis is the modification of the panel code PMARC in order to include perforated wall wind tunnels as part of its simulation capability.

This study involves the prediction of tunnel boundary interference inside of a rectangular subsonic wind tunnel with perforated walls. The study was separated into

three parts. In the first part, the theoretical approaches were investigated starting with the solid wall cases and ending with an interference potential equation which could be useful for perforated wall wind tunnels. The case when a wind tunnel contains a single porosity value for the entire length of the wind tunnel was investigated in the second part. This part includes the iteration method and modifications needed to allow PMARC to work with porous walls. The values found in this group was compared with values found using analytical methods. The third part consisted of the case where variable porosity values were used along the length of the wind tunnel. This group also included various modifications needed so that this case would be included in the PMARC code.

The next three sections will introduce two different methods for calculating tunnel boundary interference, classical methods and panel methods, as well as an introduction to the panel method code PMARC.

1.1 Tunnel Boundary Interference Using Classical Methods

The classical method for determining the wall interference of a subsonic wind tunnel with perforated walls involves much the same processes that are needed for wind tunnels with fully closed solid walls. The classical method and boundary conditions needed for perforated wall wind tunnels is described in detail by Pindzola and Lo[4]. An analytical investigation into the boundary interference of a three-dimensional blockage in a rectangular wind tunnel with perforated walls was performed by Lo and Oliver[5]. The analytical method is based on irrotational and inviscid flow theory. The governing equation for the theory is the linearized perturbation velocity potential

equation

$$(1-M^2)\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \quad (1.1)$$

where ϕ is the perturbation velocity potential of the flow inside the wind tunnel was given by Anderson[6]. The above equation is valid for subsonic or supersonic wind tunnels. Also, the model inside of the tunnel must be much smaller than the tunnel cross-sectional dimensions so that the interference of the wall on the body is very small. In order to simplify the equation, the value for x is transformed using the Prandtl-Glauert transformation

$$x = \frac{\bar{x}}{\sqrt{1-M^2}} \quad (1.2)$$

This allows equation (1.1) to be represented by the Laplace equation. Therefore, the perturbation equation can be written, $\nabla^2\phi = 0$, which is equivalent to the disturbance potential equation for incompressible flow.

In our case, the tunnel perturbation velocity potential is broken up into two parts

$$\phi_t = \phi_m + \phi_i \quad (1.3)$$

where ϕ_m is the free-air model perturbation potential and ϕ_i is the wall interference perturbation potential now in the transformed coordinate system. Therefore, the Laplace equation will be expanded into

$$\nabla^2\phi_t = \nabla^2\phi_m + \nabla^2\phi_i = 0 \quad (1.4)$$

The model inside of the wind tunnel can be represented by many types of singularities.

In this case, a doublet is used to represent a solid blockage or sphere inside of the tunnel. The mathematical equation for the velocity potential of the doublet in the transformed plane is

$$\phi_m(x,y,z) = \frac{d}{4\pi} \frac{x}{[x^2+y^2+z^2]^{\frac{3}{2}}} \quad (1.5)$$

or in the physical plane,

$$\phi_m(\bar{x},y,z) = \frac{d}{4\pi} \frac{\bar{x}}{[\bar{x}^2 + \beta^2(y^2+z^2)]^{\frac{3}{2}}} \quad (1.6)$$

where d is the free-stream velocity multiplied with the volume of the doublet and $\beta^2 = (1-M^2)$.

The model perturbation potential, ϕ_m , in the transformed plane fulfills the Laplace equation so $\nabla^2 \phi_m = 0$ which gives

$$\nabla^2 \phi_i = 0 \quad (1.7)$$

The boundary conditions needed for this study involves two types of wind tunnels. For the solid wall wind tunnels, the boundary condition can be found using the fact that there is no flow through a solid boundary. Therefore,

$$\frac{\partial \phi}{\partial n} = 0 = \frac{\partial \phi_i}{\partial n} + \frac{\partial \phi_m}{\partial n} \quad (1.8)$$

The above equation can then be used to formulate the final boundary equation for solid walls which can be written as

$$\frac{\partial \phi_i}{\partial n} = -\frac{\partial \phi_m}{\partial n} \quad (1.9)$$

where n is normal to the tunnel wall.

For perforated wall wind tunnels, the boundary condition is modified to include a porosity coefficient, R . The porosity coefficient is derived from the fact that the average velocity of the flow normal to the wall is proportional to the pressure drop across the wall[4]. The equation for defining the porosity coefficient is as follows

$$R = \frac{2V/U}{\Delta p/q_\infty} \quad (1.10)$$

where V = velocity of the flow normal to the wall

U = velocity of the undisturbed stream

Δp = pressure difference across the wall

q_∞ = dynamic pressure of the undisturbed stream

This above equation leads directly to the boundary condition for perforated walls

which is

$$\frac{\partial \phi}{\partial x} + \frac{1}{R} \frac{\partial \phi}{\partial n} = 0 \quad (1.11)$$

or

$$\frac{\partial \phi_i}{\partial n} + R \frac{\partial \phi_i}{\partial x} = \left[-\frac{\partial \phi_m}{\partial n} - R \frac{\partial \phi_m}{\partial x} \right] \quad (1.12)$$

Since the porosity coefficient, R , can range from zero to infinity, another porosity parameter was introduced to limit the range to values between 0 and 1. The equation

for the new porosity parameter or Q is as follows

$$Q = \frac{1}{1 + \frac{\beta}{R}} \quad (1.13)$$

There are many methods which could be used to solve for tunnel boundary interference including both CFD and panel methods. The main method used in this study to solve boundary value problems is the panel method.

1.2 Tunnel Boundary Interference Using Panel Methods

The panel method is a technique which can be used to solve potential flow problems for realistic and complex geometries. The method is only designed for inviscid and irrotational flows. A full explanation of the panel method can be found in Katz and Plotkin[7]. The method simulates either a two- or three-dimensional body which is represented by a contiguous group of surface panels. Potential flow functions or singularities such as sources, sinks, or doublets are placed onto each panel to create a part of a disturbance flow field. There are two types of panel methods, a low order and a high order panel method. A low order panel method is one where the strengths of the singularities does not vary over the panels. A high order panel method is one where the strengths of the singularities are varied linearly or quadratically over the panels. The high order variety is much more accurate than the low order variety but also requires more computational power. When compared to CFD methods, both types of panel methods are more economical but less accurate when viscous effects dominate the flow. Many potential flow panel codes have been made to aid in finding flow fields for complex geometries. This study uses one such code, PMARC, which

will be introduced in the next section.

1.3 General Remarks on PMARC Code

PMARC was created as a low-order potential flow panel code for modelling complex three-dimensional geometries. The original code was developed by Ashby, Dudley, Iguchi, Brown and Katz[3] at NASA Ames Research Center. PMARC can be run on many different types of computers including Sun workstations and the Cray Y-MP.

One feature of PMARC that sets it apart from other panel codes is its ability to model internal flows, those inside of ducts or wind tunnels. Ulbrich and Lo[8] modified PMARC to include the wall signature method which uses various velocity and pressure measurements along the wind tunnel wall to predict wall interference effects on model pressure distributions. The PMARC code was also modified by Qian[9] to predict the wall interference effects on various test body configurations in a subsonic wind tunnel. The modification to PMARC developed in this study was based on the use of a doublet to represent a test body.

This study will deal with and make modification to the main program and three different subroutines. The main part of the program, PMARSHOE, is used to call various subroutines in order to perform the task. The subroutine SURPAN calculates the normal velocities on the surface panels and checks these velocities with the boundary condition. The subroutine AERODAT evaluates the surface velocity vectors, forces, moments, and pressure coefficients at each panel. The subroutine VELFIELD is called by both of the above subroutines and calculates the velocity vector induced by a single three-dimensional doublet on a selected point in the flow field.

In PMARC, the geometry is separated into panels which in turn are grouped into patches. In most cases, the patches are limited to four-sided geometries. Each patch is also made up of two or more sections which are sets of points that involve a cross-sectional cut through the geometry being modelled. PMARC is a very important tool for modelling internal flows and was a valuable asset for this study.

1.4 Objectives and Approaches

The total objective for this study was to find a fast and effective method for predicting the tunnel wall interference in wind tunnels with perforated walls. Currently, only CFD and analytical methods have been used for perforated walls. Solid walls have been treated with panel codes such as PMARC but not perforated walls. There were three distinct parts to this thesis.

The first part of this study was used to find a theoretical basis for the iterative process needed to model perforated wall wind tunnels. Three different methods were used to investigate the theoretical proof needed for the process. A program and various plots were also constructed in order to find the characteristics and sensitivity of the final iteration method.

The second part of the study involved the modification of the panel code PMARC in order to handle the iterative process needed for perforated walls. Various new input and output files were needed to complete the task. Once the modification were completed, the modified PMARC was run for various porosities and the output results from the program were compared with known values found from both Qian[9] and Lo and Oliver[5].

The third part of the study used the modified PMARC code which was evaluated in the second part of the study. It was further modified to allow variable porosity to be distributed along the length of the tunnel. Then, this modified code was run for various porosity distributions and its results were compared with values found in the second part. The objective of this part was to try and minimize the amount of wall interference by optimizing the distribution of the porosities along the length of the tunnel.

CHAPTER 2

THEORETICAL APPROACHES

One of the main components needed for this study involved the verification of the theoretical approaches used for the modifications of the PMARC code. The purpose of the theoretical part can be separated into two main ideas. The first purpose is to check if the total potential equation can be broken up into two parts, the free-air model and interference potential functions. The other purpose is to find the final interference potential equation for perforated walls and to check the sensitivity of the final equation with respect to the porosity coefficient. There are three main parts to the theoretical portion of the study. The first two parts of the theoretical proof involve the use of a solid wall wind tunnel. Different boundary conditions will be used for each part and the final equations will be utilized together for use in the third part. The third part uses a perforated wall wind tunnel for the upper boundary equation and a porosity coefficient will be introduced into the equation. The third part also deals with how the values of the wind tunnel interference potential function are changed with differing porosity coefficients. Much of the procedure and equations for subsonic linearized flow can be found in Chapter 9 of Anderson[6]. Each part of the theoretical approach is started with a wind tunnel of height, h . A schematic of the wind tunnel can be found in Figure 2.1. A finite length wavy wall condition is placed at the centerline of the wind tunnel test section to portray a wind tunnel model and is represented by the equation

$$f = \epsilon \sin\left(\frac{\pi x}{l}\right) \quad (2.1)$$

where ϵ is the amplitude and l is the distance of a half cycle. The free stream velocity is assumed to be $U_\infty = 1$.

Each of the three parts of the total theoretical approach contain different boundary conditions which will be introduced later. The two different wind tunnel configurations will be discussed in the next three sections. The full theoretical process including algebra is located in Appendix A.

2.1 Solution One of Method for Solid Wall Wind Tunnels

The first part of the proof to show the validity of the boundary interference solution used for the PMARC code involves a solid wall wind tunnel. This part utilizes flow over a solid wavy wall with a given contour and a solid boundary at an upper wall at $y=h$. A schematic of the tunnel test section can be found in Figure 2.1. A step by step mathematical process involving the theoretical proof is located in Appendix A. The theoretical process begins with a general two-dimensional subsonic flow field equation of incompressible form

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \quad (2.2)$$

Two different boundary conditions are used to solve the differential equation. The first boundary condition is given by

$$\frac{\partial \phi}{\partial y} \Big|_{y=0} = f' = \frac{\pi \epsilon}{l} \cos\left(\frac{\pi x}{l}\right) \quad (2.3)$$

and signifies that the flow over the wavy wall must remain tangent to the wall. The equation for the second boundary condition is

$$\frac{\partial \phi}{\partial y} \Big|_{y=h} = 0 \quad (2.4)$$

and represents the fact that flow at the upper wall in the vertical direction must be zero since no flow is out of the solid boundary.

The solution to the first part of the theoretical proof is determined using the method of separation of variables. The final equations for the total potential equation, the interference, and the free-air model potential equations are as follows

$$\phi(x,y) = \cos\left(\frac{\pi x}{l}\right) \left[\frac{\epsilon e^{\frac{\pi}{l}h} e^{-\frac{\pi}{l}y} + \epsilon e^{-\frac{\pi}{l}h} e^{\frac{\pi}{l}y}}{e^{\frac{\pi}{l}h} - e^{-\frac{\pi}{l}h}} \right] \quad (2.5)$$

or

$$\phi(x,y) = \epsilon \cos\left(\frac{\pi x}{l}\right) \left[\frac{\cosh\left(\frac{\pi}{l}(h-y)\right)}{-\sinh\left(\frac{\pi}{l}h\right)} \right] \quad (2.6)$$

$$\phi_m = \phi(x,y) \Big|_{y \rightarrow \infty} = -\epsilon \cos\left(\frac{\pi x}{l}\right) e^{-\frac{\pi}{l}y} \quad (2.7)$$

$$\phi_i = \varepsilon \cos\left(\frac{\pi x}{l}\right) \left[e^{-\frac{\pi}{l}h} \left(\frac{e^{\frac{\pi}{l}y} + e^{-\frac{\pi}{l}y}}{e^{-\frac{\pi}{l}h} - e^{\frac{\pi}{l}h}} \right) \right] \quad (2.8)$$

or

$$\phi_i = -\varepsilon \cos\left(\frac{\pi x}{l}\right) e^{-\frac{\pi}{l}h} \left[\frac{\cosh\left(\frac{\pi}{l}y\right)}{\sinh\left(\frac{\pi}{l}h\right)} \right] \quad (2.9)$$

The above equations are then checked with the boundary conditions at $y=0$ and $y=h$.

The resulting equations gives

$$\frac{\partial \phi_i}{\partial y} = -\frac{\partial \phi}{\partial y} \Big|_{y=h} \quad (2.10)$$

and

$$\frac{\partial \phi}{\partial y} = \frac{\partial \phi_m}{\partial y} \Big|_{y=0} \quad (2.11)$$

which can be shown to be the same as equations (1.7) and (2.3). These equations will be used as boundary conditions for the next method in order to compare the final interference potential equation to prove that the first part of our theoretical approach is valid.

2.2 Solution Two of Method for Solid Wall Wind Tunnels

The second part of the solid wall theoretical proof uses the same wind tunnel model as in the first part but the general differential equation and boundary conditions are

different. The new flow field equation used for this part is

$$\frac{\partial^2 \phi_i}{\partial x^2} + \frac{\partial^2 \phi_i}{\partial y^2} + \frac{\partial^2 \phi_m}{\partial x^2} + \frac{\partial^2 \phi_m}{\partial y^2} = 0 \quad (2.12)$$

or

$$\frac{\partial^2 \phi_i}{\partial x^2} + \frac{\partial^2 \phi_i}{\partial y^2} = -\left(\frac{\partial^2 \phi_m}{\partial x^2} + \frac{\partial^2 \phi_m}{\partial y^2}\right) \quad (2.13)$$

Since $\nabla^2 \phi_m = 0$,

$$\frac{\partial^2 \phi_i}{\partial x^2} + \frac{\partial^2 \phi_i}{\partial y^2} = 0 \quad (2.14)$$

The two boundary conditions which are used for this method are as follows

$$\frac{\partial \phi_i}{\partial y} = -\frac{\partial \phi_m}{\partial y} \Big|_{y=h} \quad (2.15)$$

$$\frac{\partial \phi_i}{\partial y} \Big|_{y=0} = 0 \quad (2.16)$$

The flow field equation is once again solved using the method of separation of variables and the final interference potential equation is

$$\phi_i(x, y) = -\epsilon \cos\left(\frac{\pi x}{l}\right) e^{\frac{-\pi y}{l} h} \left[\frac{\cosh\left(\frac{\pi y}{l}\right)}{\sinh\left(\frac{\pi h}{l}\right)} \right] \quad (2.17)$$

It is obvious that the equation above for the interference velocity potential is the same

as equation (2.9). This fact validates that dividing the boundary condition into components of interference and free-air model potentials does not change the solution. The next section will use the findings from the second method and expand them to include perforated wall wind tunnels.

2.3 Solution Method for Perforated Wall Wind Tunnels

The solution of method for perforated wall wind tunnels can be separated into two portions. The first portion uses various equations found in earlier sections as well as perforated wall boundary conditions in order to find a final interference equation. The second portion employs the found equation and solves it for various porosity coefficients to find the characteristics of the equation. The process needed to prove the validity of the boundary interference equation used for perforated wall wind tunnels is started using the same model, flow field equation, and second boundary condition as the second method. The first boundary condition needed for the solution deals with flow at the- upper porous wall. It can be written as follows

$$\frac{\partial \phi_i}{\partial y} + R \frac{\partial \phi_i}{\partial x} = - \left(\frac{\partial \phi_m}{\partial y} + R \frac{\partial \phi_m}{\partial x} \right) \Big|_{y=h} \quad (2.18)$$

The proof is started with an equation from the second method after the second boundary condition has been applied. The interference velocity potential is

$$\phi_i = (B \sin(mx) + C \cos(mx)) \cosh(my) \quad (2.19)$$

The next step involves the solution of the constants B and C in the above equation. This is obtained using equation (2.19), the boundary condition equation (2.18), the free-air model interference potential equation (2.76), and considerable algebra. The

resulting constants are

$$B = \frac{-R\epsilon}{\sinh^2(mh) + R^2 \cosh^2(mh)} \quad (2.20)$$

$$C = \frac{[R^2 \cosh(mh) - \sinh(mh)] \epsilon e^{-mh}}{\sinh^2(mh) + R^2 \cosh^2(mh)} \quad (2.21)$$

These constants are then joined with equation (2.19) to create the final interference potential equation.

$$\begin{aligned} \phi_i = & \left(\frac{-R\epsilon}{\sinh^2(mh) + R^2 \cosh^2(mh)} \sin(mx) \right. \\ & \left. + \frac{[R^2 \cosh(mh) - \sinh(mh)] \epsilon e^{-mh}}{\sinh^2(mh) + R^2 \cosh^2(mh)} \cos(mx) \right) \cosh(my) \end{aligned} \quad (2.22)$$

The algebraic process used for the solution of the constants and final equation can be found in Appendix A.

2.3.1 Characteristics of the Final Interference Equation

The second portion begins with the equation for the two constants, equation (2.20) and (2.21). These equations are used to find the characteristics of the final interference potential with varying values of the porosity coefficient. The partial derivatives of the constants with respect to R were calculated to find how the constants varied with different porosity coefficients. This would lead to a study of the sensitivity of the constants with various values of the porosity coefficient. The partial derivatives of the constants are

$$\frac{\partial B}{\partial R} = \frac{-\epsilon \sinh^2(mh) + R^2 \epsilon \cosh^2(mh)}{(\sinh^2(mh) + R^2 \cosh^2(mh))^2} \quad (2.40)$$

$$\frac{\partial C}{\partial R} = \frac{2R \cosh(mh) \epsilon e^{-mh} (\sinh^2(mh) + \sinh(mh) \cosh(mh))}{(\sinh^2(mh) + R^2 \cosh^2(mh))^2} \quad (2.41)$$

To illustrate the behavior of $B(R)$ and $C(R)$ and their partial derivatives, as functions of R , several plots of these functions were made. For the plots, two sets of porosity coefficients were used. The porosity coefficient for the first plots was varied from 0 to 9 in increments of 0.5 and 0 to 1 in increments of 0.5 were used for the second plots. The value for the amplitude, ϵ , was placed at 0.005 and a value of 12.56 was used for mh . The plots for the constants versus porosity coefficients can be found in Figures 2.2 to 2.5. The partial derivative plots used the same two sets of porosity coefficients and can be found in Figures 2.6 to 2.9. These plots were used to estimate the difficulty involved in getting a solution to converge. The values of the constants rapidly change in the area where the porosity coefficient varies from 0 to 1 which, the experience of this thesis showed, would sometimes make it difficult to obtain a converged solution. The sensitivity of the final equation can only be considered to be a guess since we are only performing a two-dimensional case and the results would not be directly correlated with the values found from PMARC.

Using the theoretical investigations shown in this chapter, the panel code PMARC was modified to include iteration methods for perforated wall wind tunnels with single or multiple values for porosities. The next two chapters will investigate the two different methods.

CHAPTER 3

VENTILATED WALL WIND TUNNEL BOUNDARY INTERFERENCE WITH UNIFORM POROSITY USING MODIFIED PMARC CODE

This chapter involves the modifications needed to allow PMARC to solve problems with ventilated wall wind tunnels. It can be separated into two sections, one which explains the modifications performed on the actual FORTRAN code and the other which uses the modifications to run cases and compare the solutions with known values. The main program of PMARC and two subroutines were changed in order to perform the required tasks. Three new output files were introduced and one existing input file was altered to include new values. The boundary condition used for solid walls was also converted to include a porosity coefficient. Modifications were also made to use the data from earlier iterations to find a more rapidly converging solution. As always, the flow is assumed to be inviscid, irrotational, and incompressible.

3.1 Modified PMARC code for Ventilated Wall Wind Tunnels with Uniform Porosity

The original PMARC code was produced by Ashby, Dudley, Iguchi, Browne, and Brown[3]. The code used to begin the modifications for ventilated walls was first changed by Ulbrich and Lo[8] as well as Qian[9]. Ulbrich and Lo[8] revised the code to allow PMARC to calculate the interference and wind tunnel flow field of a model in a three-dimensional wind tunnel. Qian[9] altered the panel code once again to use

mathematical models such as doublets, sources, and sinks for test articles instead of using surface panels for the test article. This was achieved by adding a subroutine named VELFIELD into PMARC which calculated the normal velocities of the singularities at the tunnel walls. The modifications needed for this study requires the use of a doublet to simulate a solid blockage. A new input file, BLOCK.INP, was also created to include data needed by VELFIELD in order to create the mathematical models. The boundary condition used in PMARC for the solid wall cases can be written as

$$V_{i,n} = -V_{m,n} \quad (3.1)$$

where $V_{i,n}$ is the interference velocity normal to the wind tunnel wall and $V_{m,n}$ is the model induced velocity normal to the wall. The subroutine, VELFIELD, was specifically created to find $V_{m,n}$. The boundary conditions for the inlet and exit to the test section consists of prescribed normal velocities which were set at 1 in our case. Three different subroutines required modifications in order to perform the required task. Explanations for each of the subroutines function were already addressed in Chapter 1. The reason an iteration process was necessary can be shown using equation (A.69) in Appendix A. The value for

$$\frac{\partial \phi_i}{\partial x}$$

is not calculated in PMARC until after the boundary condition is checked. Therefore, values from the previous iteration must be used in place of the unknown value. A flowchart of the iteration procedure which was written for the second iteration and

beyond, can be found in Figure 3.1 in Appendix B. The same flowchart for the iteration method can be used to show the other two iteration methods by excluding some of the output files. For the zeroth iteration, the output files ITER2.OUT and NITER2.OUT will not be used in the iteration procedure. For the first iteration, NITER2.OUT will not be used and the values from ITER1.OUT will be written directly to ITER2.OUT.

The main modifications to PMARC consisted of the generation of three new boundary conditions. These boundary conditions require different routines so the procedure is dependant on the iteration number. Each of the three procedures is contained inside of the subroutine SURPAN. For the zeroth iteration, the boundary condition is

$$V_{i,n} = -V_{m,n} - RU_m \quad (3.2)$$

where $V_{m,n}$ and U_m are found from the VELFIELD subroutine. The first iteration uses data from the zeroth iteration in the boundary condition. This condition can be written

$$V_{i,n} = -V_{m,n} - R[U_m - U_i]^{(1)} \quad (3.3)$$

where the (1) superscript constitutes data from the zeroth iteration. Data from the latest two iterations is required for the second iteration and beyond. The equation for the boundary condition iteration procedure is as follows

$$V_{i,n} = -V_{m,n} - R(\omega[U_m - U_i]^{(n-2)} + (1-\omega)[U_m - U_i]^{(n-1)}) \quad (3.4)$$

where the (n-2) and (n-1) superscript gives the iteration number needed for the data required.

More modifications to PMARC comprised the creation of four new output files and

the inclusion of new values into the input file, BLOCK.INP. The first output file included in the code is ITER1.OUT. Final values from the AERODAT subroutine is placed into the output file for use in the next iteration. The output consists of the addition of the model flow and interference velocities along the wall for every panel in the model. Since the velocities have been normalized, the free-stream velocity must be subtracted from the output values. This output file is brought into the SURPAN subroutine during the next iteration and is used in the calculation of the boundary condition. After these values are used, they are placed into the second new output file, ITER2.OUT. This output file is used to store the values of the (n-2) iteration for use in the next iteration. The second iteration and later requires another new output file, NITER2.OUT. Since the program continuously takes data from ITER2.OUT, a storage file was needed to hold the values taken from ITER1.OUT. This storage area was marked NITER2.OUT and this file must be renamed ITER2.OUT at the end of the iteration. The last output file required is CHECK.OUT which contains data such as panel number, location of panel, normal components, model induced velocity, and interference velocity. The file is used to check the calculations made during the SURPAN subroutine.

The modifications on the main part of the program, PMARSHOE, involved the introduction of three new variables into the data file, BLOCK.INP. RCOEF is the variable which contains the value for porosity coefficient for the wind tunnel wall. The porosity is assumed not to change, depending on the wall, so one boundary condition can be used for the entire length of the wind tunnel. An iteration counter,

ITCOEF, is the value which tells the program how to run the specific iteration.

CONVW is a convergence coefficient or relaxation factor which was introduced to aid in the speed of finding a specific solution. At higher values of porosity, PMARC was having difficulty converging on a solution so CONVW was introduced to help. The convergence coefficient regulates the percentage of the final values from earlier iterations which will be used in the present calculations. The symbol, ω , represents CONVW in the above boundary condition equations. The next section deals with the results found from a specific wind tunnel configuration using the modified panel code.

3.2 Tunnel Boundary Interference Prediction Using Modified PMARC Code

The calculation of the results using the modified panel code was done using one wind tunnel configuration but with many porosity values. A solid blockage inside of a 10 by 10 rectangular wind tunnel was the chosen case dealt with in this study. A total length of 100 was used for the predictions. The wind tunnel was separated into three sections; upstream of the test section, test section, and diffuser of the test section, and the porosity was assumed to stay constant over the entire wall. A schematic of the wind tunnel test section can be found in Figure 3.2. To make the calculations easier, both the volume of the solid blockage and the free-stream velocity was normalized to 1. Some cases used data from other cases in the first two iteration steps, in order to make the calculation procedure more efficient. The data for the interference pressure coefficient was recorded using increments of 1 along the centerline of the wind tunnel.

For the various plots included in this study, only the data from $X=-20$ to $X=20$ will be used. For the wall pressure coefficient at the upper wall, the data was taken at different locations in the center of the upper wall and graphed against the location along the wall.

The first case dealt with solid walls. This gave a starting point for the study. Since $R=0$ for solid walls, the boundary condition equation (3.2), was changed back the solid wall boundary condition used by Ulbrich and Lo[8] and Qian[9]. Only one iteration was needed for the calculation and the plots for the case can be found in Figures 3.3 and 3.4. The case was compared with Qian[9] and the results were identical.

The next case was used to check the accuracy of the modified program. A relatively large value for the porosity was needed for this next case. A value of $R=0.25$ (or $Q=0.2$) was adopted for the study since analytical data had already been produced.

This case needed 15 iterations and the output was compared with the analytical results found from Lo and Oliver[5]. A comparison plot between the two cases is provided by Figure 3.7. The plots of the pressure coefficient along the centerline and upper wall for the case can be found in Figures 3.5 and 3.6. The results were very close to the analytical values with percent error values of no more than 5 percent.

In order to check the time needed for a solution, the next case used a small value of $R=0.1111$ (or $Q=0.1$) for the porosity coefficient. This allowed the iteration method to be checked using a case which only changed the final results slightly. This case only required 8 iterations to complete and the results can be found in Figures 3.8 and 3.9.

The next case used the two different methods for solution in order to provide a

comparison between methods. A porosity coefficient of 0.3(or $Q=0.23$) was used for the comparison. The first part was run without initialization data for the first two iterations, and the final values were calculated in 51 iterations. However when the data from the $Q=0.2$ case was used for the first two iterations, the solution was obtained in 15 iterations. The final solutions were compared together and the results were very close. The values for the two sets of plots can be found in Figures 3.10 through 3.13.

The final case used a value of 0.43(or $Q=0.3$) for the porosity coefficient. Because of the size of the porosity coefficient used for the calculations, the solution began to diverge after a few iterations. The last iteration before divergence was inspected and the values were found to be very close to the solution which was expected. This case was run using initial values from the $Q=0.2$ case and a close answer was obtained in 3 iterations. The final plots can be found in Figures 3.14 and 3.15.

A last plot was prepared using the various values obtained for the interference pressure coefficient at porosities of $Q=0,0.1,0.2,0.3$. This plot was normalized with the highest value of the pressure coefficient using a solid wall wind tunnel or when $Q=0$. This plot is listed as Figure 3.16. This chart was compared with Figure 3.17 which was obtained from Lo and Oliver[5]. The results were very close which demonstrates that the method is viable.

One problem occurred with the use of large values for porosity. As the porosity coefficient was increased, the amount of difficulty in the calculations also increased. As the porosity coefficient increased, the time required for the calculations increased

greatly as did the number of iterations needed. One reason for this is a certain amount of error which is introduced in each iteration and is doubled and tripled as more iterations are performed. This caused the iteration process to diverge instead of converging on one solution. One solution to the problem may involve the study of the convergence coefficient to find out how the coefficient interacts with the boundary condition.

CHAPTER 4

VENTILATED WALL WIND TUNNEL BOUNDARY INTERFERENCE WITH DISTRIBUTED POROSITY USING MODIFIED PMARC CODE

This chapter deals with the modifications made to the program completed in the last chapter. In real world applications, the porosity of the wind tunnel wall does not stay constant as suggested in the last chapter. For this reason, the code was changed again to include three different porosities for different parts of the wind tunnel. Since the wind tunnel was already separated into three sections--the inlet, test section, and outlet, different porosities were designated for each section of the tunnel. The results of the modifications should give more accurate answers and should allow a study to be conducted involving how the variable porosities along the wall modify the amount of boundary interference experienced. As is usual, the flow is assumed to be irrotational, inviscid, and incompressible for the various calculations.

4.1 Modified PMARC Code for Porous Wall Wind Tunnels with Distributed Porosities

Additional modifications were performed on the modified PMARC code explained and used in the last chapter. The new modifications involved the use of three different porosity coefficients in the calculations instead of a single value used in the last chapter. This allowed the wind tunnel to be separated into three sections using the input file for the program. Each panel is placed into a patch and that patch is labeled

with a number defining within which part of the wind tunnel the patch is located. The inlet, test section, and outlet are made up of two, one, and two patches respectively. When each panel is generated from the input file, a patch number is placed on the panel and it is carried through the calculations. As the calculations are performed in the SURPAN subroutine, various IF-THEN statements check the patch number to find out what porosity coefficient is needed for the calculations. This allows the porosity to be varied along the length of the wall. Therefore, three different porosity coefficients were added to the code and were titled RCOEF1 through RCOEF3. One potential problem for this modified code involved changes needed as the geometry of the wind tunnel changed. As different geometries are calculated, the code will need to be refined to make sure that the correct porosity coefficient is being placed on the correct panel. This can be achieved by analyzing the wind tunnel to find the number of patches. The SURPAN subroutine then needs to be modified so that the IF-THEN statements which control the placement of porosity coefficients takes care of all of the sections of the tunnel. The modified panel code was used to calculate examples of wall interference inside of a rectangular porous wall wind tunnel which can be found in the next section.

4.2 Tunnel Wall Interference Prediction using a Modified PMARC Code

This section uses the modified code explained in the last section to perform calculations involving various wind tunnel wall porosity configurations. The case involving a single porosity value of 0.25 was chosen as the case to compare the values

found from this series of calculations. The same wind tunnel schematic shown in Figure 3.1 was used for the input to the modified PMARC code. Each of the parts of the wind tunnel was assigned a porosity value. Since this part of the study involved investigation of how varying the porosity at the inlet and exit of the test section would affect the final values, the porosity coefficient of the test section was placed at 0.25. The inlet and exit porosity values were varied in small increments so that a trend could be shown from the data. Since the downstream section of the test section is subjected to the largest amount of disturbances, the porosity coefficient at that location was increased while the porosity coefficient for the upstream section decreased. The number of iterations needed for various cases usually varied between 15 and 100. Final plots of interference pressure coefficient along the length of the wind tunnel were prepared for each case as well as a final comparison plot of all the cases. The first meaningful solution was obtained for the case where the values for inlet, test section, and outlet porosities was 0.18, 0.25, and 0.30 respectively. The calculations were started with the final iteration numbers for the single porosity case involving a value of 0.25. This solution was finished in 30 iterations and showed a small decrease in the values found for the interference pressure coefficient along the centerline of the wind tunnel. The final plot for this case can be found in Figure 4.1. The next case which was computed had values of 0.13, 0.25, and 0.32 for the porosity values. The process was started with the flow solution from the first case in this section, and the solution was found in 30 iterations. The values for the interference pressure coefficient continued with the decreasing trend found in the first case. The

plot for this case is Figure 4.2 located in Appendix B.

The third case analyzed was based on a decrease in the inlet porosity coefficient and a slight increase in the outlet porosity coefficient. The values were 0.11, 0.25, and 0.33.

The calculations were started once again with the final iteration of the first case and only required 30 iterations. The plots for the interference pressure coefficient along the centerline is listed as Figure 4.3.

The fourth and final case changed the porosity coefficients to 0.08 at the inlet and 0.34 at the outlet. The case was run for 30 iteration and the values for the first case was used for the starting point. As with all other cases, the values of the interference pressure coefficient continued to decrease. The final plot can be found in Figure 4.4.

A final plot was created which compared the final values for all of the cases. This plot is listed as Figure 4.5. The solution for the single porosity of 0.5 was placed in the graph in order to compare the results of using single and variable porosity coefficients. The names associated with each of the plots is modpmf1, try1h, try1n, try1o, and try1k for the single porosity case, first variable case where $R_1=0.18$, $R_2=0.25$, $R_3=0.3$, second case where $R_1=0.13$, $R_2=0.25$, $R_3=0.32$, third case where $R_1=0.11$, $R_2=0.25$, $R_3=0.33$, and the last case where $R_1=0.08$, $R_2=0.25$, $R_3=0.34$, respectively. As can be seen from the Figure 4.5, the interference pressure coefficient was definitely decreased as the inlet porosity was decreased and the outlet porosity coefficient was increased. This was as expected since a higher porosity at the outlet would allow more of the tunnel boundary interference to be dispersed through the wind tunnel wall.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The conclusions for this study can be separated into three parts. The main purpose of the first part or theoretical study was to see if the initial potential equation could be separated into two terms, the free-air model potential and the interference potential, and then to use this newly acquired information to solve for the final interference equation. The final interference potential equations were acquired for the two solid wall cases and were shown to be the same. The study was then continued with a perforated wall wind tunnel and the final interference equation was plotted versus various porosity coefficients.

The modifications of the panel method PMARC and the solutions for single uniform porosity cases constituted the second part. This involved applying the iteration method found in the last section to a panel method code in order to expand the capabilities of PMARC. Many cases were calculated with the modified PMARC code varying from $R=0$ (solid wall) to $R=0.43$. Values from Qian[9] and Lo and Oliver[5] were used to check the validity of the results found from the modified code and the comparison showed good agreement. Therefore, the modified PMARC code should work correctly for values of porosity under 0.5.

The third and last part of the study used the modified panel code from the previous section in order to complete more realistic cases. Many cases were run where the porosity at the upstream portion was decreased while the porosity at the diffuser section increased. As expected, the interference pressure coefficient decreased since

the diffuser section was allowing more of the disturbances to pass through the wall.

This signified that the modified PMARC code was working correctly.

A few problems became evident as more cases were run. For both the uniform and distributed porosity case, the magnitude of each of the porosity coefficients greatly influenced the time and ease of finding a solution. The use of initialization values from other cases was successful in decreasing the amount of iterations necessary for higher values of porosity. The convergence coefficient also was used to decrease the time necessary to run a full solution. With some future research, porosity cases above 0.5 should be solvable using the convergence coefficient and initialization values. The modified PMARC code should apply to many different wind tunnel geometries and test models although numerous cases should be calculated to validate the assumption. The values found in this study were very encouraging. With more research, the solution of a porous wall wind tunnel using a panel code should become standard for all values of porosity.

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APPENDIX A

Solution of Method for Perforated Wall Wind Tunnel

Method One - Solid Walls

Problem: Flow over a wavy wall with given contour and a boundary at the upper solid wall at $y=h$. A schematic of the wind tunnel can be found in Figure 2.1 in Appendix B.

Flow Field Equation:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \quad (\text{A.1})$$

BC #1: Lower wavy wall

- Flow at the wavy wall must be tangent to the wall therefore:

$$\left. \frac{\partial \phi}{\partial y} \right|_{y=0} = f' = \frac{\pi \epsilon}{l} \cos\left(\frac{\pi x}{l}\right) \quad (\text{A.2})$$

BC #2: Upper solid wall

- Flow at the upper wall in the y direction must be zero since no flow is out of a solid boundary therefore:

$$\left. \frac{\partial \phi}{\partial y} \right|_{y=h} = 0 \quad (\text{A.3})$$

Solution:

Method of Separation of Variables $\phi = G(x)H(y)$

$$\begin{aligned} \frac{\partial^2 \phi}{\partial x^2} &= G_{xx} H(y) \\ \frac{\partial^2 \phi}{\partial y^2} &= H_{yy} G(x) \end{aligned} \quad (\text{A.4})$$

$$H(y)G_{xx} + H_{yy}G(x) = 0$$

$$\frac{G_{xx}}{G} + \frac{H_{yy}}{H} = 0 \quad (A.5)$$

$$\frac{G_{xx}}{G} = -m^2 = -\frac{H_{yy}}{H} \quad (A.6)$$

$$\begin{aligned} G_{xx} + m^2 G &= 0 \\ H_{yy} - m^2 H &= 0 \end{aligned} \quad (A.7)$$

$$\begin{aligned} G(x) &= A \sin(mx) + B \cos(mx) \\ H(y) &= C e^{-my} + D e^{my} \end{aligned} \quad (A.8)$$

$$\phi(x,y) = (A \sin(mx) + B \cos(mx))(C e^{-my} + D e^{my}) \quad (A.9)$$

Now to apply the first boundary condition

$$\frac{\partial \phi}{\partial y} = (A \sin(mx) + B \cos(mx)) \frac{\partial (C e^{-my} + D e^{my})}{\partial y} \quad (A.10)$$

$$\frac{\partial \phi}{\partial y} = (A \sin(mx) + B \cos(mx))(-m C e^{-my} + m D e^{my}) \quad (A.11)$$

$$\left. \frac{\partial \phi}{\partial y} \right|_{y=0} = (A \sin(mx) + B \cos(mx))(-m C + m D) \quad (A.12)$$

$$(A \sin(mx) + B \cos(mx))(-m C + m D) = \frac{\epsilon \pi}{l} \cos\left(\frac{\pi x}{l}\right) \quad (A.13)$$

$A \sin(mx) = 0$ since no term exists on the other side $\therefore A = 0$

$$B\cos(mx)(-mC+mD)=\frac{\epsilon\pi}{l}\cos(\frac{\pi x}{l}) \quad (\text{A.14})$$

$$m=\frac{\pi}{l} \quad \text{since } \cos(mx)=\cos(\frac{\pi x}{l}) \quad (\text{A.15})$$

Join constants together and join the terms in the equations

$$\phi(x,y)=\cos(\frac{\pi x}{l})[C_1e^{-\frac{\pi y}{l}}+C_2e^{\frac{\pi y}{l}}] \quad (\text{A.16})$$

$$\frac{\partial\phi}{\partial y}=\cos(\frac{\pi x}{l})[-\frac{\pi}{l}C_1e^{-\frac{\pi y}{l}}+\frac{\pi}{l}C_2e^{\frac{\pi y}{l}}] \quad (\text{A.17})$$

$$\frac{\partial\phi}{\partial y}\bigg|_{y=0}=\cos(\frac{\pi x}{l})[-\frac{\pi}{l}C_1+\frac{\pi}{l}C_2] \quad (\text{A.18})$$

$$\therefore -C_1+C_2=\epsilon \quad (\text{A.19})$$

Now to the second boundary condition using equation (A.16)

$$\frac{\partial\phi}{\partial y}\bigg|_{y=h}=-C_1e^{-\frac{\pi h}{l}}+C_2e^{\frac{\pi h}{l}}=0 \quad (\text{A.20})$$

$$\therefore -C_1+C_2e^{\frac{2\pi h}{l}}=0 \quad (\text{A.21})$$

Now there are two equation and two unknowns using equations (A.19) and (A.21).

After considerable algebra:

$$C_1 = \frac{\varepsilon e^{\frac{\pi h}{l}}}{e^{-\frac{\pi h}{l}} - e^{\frac{\pi h}{l}}} \quad (\text{A.22})$$

$$C_2 = \frac{\varepsilon e^{-\frac{\pi h}{l}}}{e^{-\frac{\pi h}{l}} - e^{\frac{\pi h}{l}}} \quad (\text{A.23})$$

Now we have the final equations and the constants.

$$\phi(x,y) = \cos\left(\frac{\pi x}{l}\right) \left[\frac{\varepsilon e^{\frac{\pi h}{l}}}{e^{-\frac{\pi h}{l}} - e^{\frac{\pi h}{l}}} e^{-\frac{\pi}{l}y} + \frac{\varepsilon e^{-\frac{\pi h}{l}}}{e^{-\frac{\pi h}{l}} - e^{\frac{\pi h}{l}}} e^{\frac{\pi}{l}y} \right] \quad (\text{A.24})$$

$$\phi(x,y) = \cos\left(\frac{\pi x}{l}\right) \left[\frac{\varepsilon e^{\frac{\pi h}{l}} e^{-\frac{\pi}{l}y} + \varepsilon e^{-\frac{\pi h}{l}} e^{\frac{\pi}{l}y}}{e^{-\frac{\pi h}{l}} - e^{\frac{\pi h}{l}}} \right] \quad (\text{A.25})$$

$$\begin{aligned} e^{-\frac{\pi h}{l}} - e^{\frac{\pi h}{l}} &= -2\sinh\left(\frac{\pi h}{l}\right) \\ e^{\frac{\pi}{l}(h-y)} + e^{-\frac{\pi}{l}(h-y)} &= 2\cosh\frac{\pi}{l}(h-y) \end{aligned} \quad (\text{A.26})$$

$$\phi(x,y) = \varepsilon \cos\left(\frac{\pi x}{l}\right) \left[\frac{\cosh\frac{\pi}{l}(h-y)}{-\sinh\left(\frac{\pi}{l}h\right)} \right] \quad (\text{A.27})$$

Now to find the free-air model potential function

$$\phi_m = \phi_{h-\infty} = -\epsilon \cos\left(\frac{\pi x}{l}\right) e^{\frac{-\pi}{l}y} \quad (\text{A.28})$$

Now to find the wall interference potential function

$$\phi = \phi_i + \phi_m \rightarrow \phi_i = \phi - \phi_m \quad (\text{A.29})$$

$$\phi_i = \epsilon \cos\left(\frac{\pi x}{l}\right) \left[\frac{e^{\frac{\pi}{l}(h-y)} + e^{\frac{-\pi}{l}(h-y)}}{e^{\frac{-\pi h}{l}} - e^{\frac{\pi h}{l}}} + e^{\frac{-\pi}{l}y} \right] \quad (\text{A.30})$$

$$\phi_i = \epsilon \cos\left(\frac{\pi x}{l}\right) \left[\frac{e^{\frac{\pi}{l}(h-y)} + e^{\frac{-\pi}{l}(h-y)}}{e^{\frac{-\pi h}{l}} - e^{\frac{\pi h}{l}}} + \frac{e^{\frac{-\pi y}{l}} e^{\frac{-\pi h}{l}} - e^{\frac{-\pi y}{l}} e^{\frac{\pi h}{l}}}{e^{\frac{-\pi h}{l}} - e^{\frac{\pi h}{l}}} \right] \quad (\text{A.31})$$

$$\phi_i = \epsilon \cos\left(\frac{\pi x}{l}\right) \left[\frac{e^{\frac{-\pi}{l}(h-y)} + e^{\frac{-\pi}{l}(h+y)}}{e^{\frac{-\pi h}{l}} - e^{\frac{\pi h}{l}}} \right] \quad (\text{A.32})$$

$$\phi_i = \epsilon \cos\left(\frac{\pi x}{l}\right) \left[e^{\frac{-\pi h}{l}} \left(\frac{e^{\frac{\pi y}{l}} + e^{\frac{-\pi y}{l}}}{e^{\frac{-\pi h}{l}} - e^{\frac{\pi h}{l}}} \right) \right] \quad (\text{A.33})$$

$$\begin{aligned} e^{\frac{\pi y}{l}} + e^{\frac{-\pi y}{l}} &\rightarrow 2\cosh\left(\frac{\pi}{l}y\right) \\ e^{\frac{-\pi h}{l}} - e^{\frac{\pi h}{l}} &\rightarrow -2\sinh\left(\frac{\pi}{l}h\right) \end{aligned} \quad (\text{A.34})$$

Now check the boundary conditions at $y=h$

$$\phi_i = -\varepsilon \cos\left(\frac{\pi x}{l}\right) e^{\frac{-\pi h}{l}} \frac{\cosh\left(\frac{\pi y}{l}\right)}{\sinh\left(\frac{\pi h}{l}\right)} \quad (\text{A.35})$$

$$\frac{\partial \phi_i}{\partial y} = -\varepsilon \cos\left(\frac{\pi x}{l}\right) e^{\frac{-\pi h}{l}} \frac{\pi}{l} \frac{\sinh\left(\frac{\pi y}{l}\right)}{\sinh\left(\frac{\pi h}{l}\right)} \quad (\text{A.36})$$

$$\left. \frac{\partial \phi_i}{\partial y} \right|_{y=h} = -\varepsilon \frac{\pi}{l} \cos\left(\frac{\pi x}{l}\right) e^{\frac{-\pi h}{l}} \quad (\text{A.37})$$

$$\frac{\partial \phi_m}{\partial y} = \varepsilon \frac{\pi}{l} \cos\left(\frac{\pi x}{l}\right) e^{\frac{-\pi y}{l}} \quad (\text{A.38})$$

$$\left. \frac{\partial \phi_m}{\partial y} \right|_{y=h} = \varepsilon \frac{\pi}{l} \cos\left(\frac{\pi x}{l}\right) e^{\frac{-\pi h}{l}} \quad (\text{A.39})$$

Now to compare the interference and model potential functions

$$\left. \frac{\partial \phi_i}{\partial y} \right|_{y=h} = - \left. \frac{\partial \phi_m}{\partial y} \right|_{y=h} \quad (\text{A.40})$$

which is proven by the boundary condition at $y=h$

Now to check the boundary condition at $y=0$

$$\frac{\partial \phi}{\partial y} = \frac{\partial \phi_m}{\partial y} + \frac{\partial \phi_i}{\partial y} \quad \text{at } y=0 \quad (\text{A.41})$$

$$\left. \frac{\partial \phi_i}{\partial y} \right|_{y=0} = 0 \quad (\text{A.42})$$

$$\left. \frac{\partial \phi_m}{\partial y} \right|_{y=0} = \varepsilon \frac{\pi}{l} \cos\left(\frac{\pi x}{l}\right) \quad (\text{A.43})$$

Therefore at the centerline of the tunnel

$$\left. \frac{\partial \phi}{\partial y} \right|_{y=0} = \left. \frac{\partial \phi_m}{\partial y} \right|_{y=0} \quad (\text{A.44})$$

which is proven by the first boundary condition.

Solution of Method for Perforated Wall Wind Tunnels

Method Two - Solid Walls

Problem: Flow over a wavy wall with given contour and a boundary at the upper solid wall at $y=h$. A schematic of the wind tunnel test section can be found in Figure 2.1 in Appendix B.

$$\phi = \phi_i + \phi_m$$

$\phi_m \Rightarrow$ free-air model interference potential function

$\phi_i \Rightarrow$ wall interference potential function

Flow Field Equation: (Beginning with equation (A.1) from last proof)

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \quad (\text{A.1})$$

$$\frac{\partial^2 \phi_i}{\partial x^2} + \frac{\partial^2 \phi_i}{\partial y^2} + \frac{\partial^2 \phi_m}{\partial x^2} + \frac{\partial^2 \phi_m}{\partial y^2} = 0 \quad (\text{A.45})$$

$$\frac{\partial^2 \phi_i}{\partial x^2} + \frac{\partial^2 \phi_i}{\partial y^2} = -\left(\frac{\partial^2 \phi_m}{\partial x^2} + \frac{\partial^2 \phi_m}{\partial y^2}\right) \quad (\text{A.46})$$

$$\therefore \frac{\partial^2 \phi_i}{\partial x^2} + \frac{\partial^2 \phi_i}{\partial y^2} = 0 \quad \text{where} \quad -\left(\frac{\partial^2 \phi_m}{\partial x^2} + \frac{\partial^2 \phi_m}{\partial y^2}\right) = 0 \quad (\text{A.47})$$

In order to check the first method, the boundary conditions found in the first method will be used for this proof. This will allow a comparison between final equations.

BC #1:

$$\left. \frac{\partial \phi_i}{\partial y} \right|_{y=h} = - \left. \frac{\partial \phi_m}{\partial y} \right|_{y=h} \quad (\text{A.48})$$

BC # 2:

$$\left. \frac{\partial \phi_i}{\partial y} \right|_{y=0} = 0 \quad (\text{A.49})$$

The free-air model potential function was obtained in the first proof so there is no need to prove the equation again.

$$\phi_m = -\varepsilon \cos\left(\frac{\pi}{l}x\right)e^{\frac{-\pi y}{l}} \quad (\text{A.50})$$

$$\frac{\partial \phi_m}{\partial y} = \varepsilon \frac{\pi}{l} \cos\left(\frac{\pi}{l}x\right)e^{\frac{-\pi y}{l}} \quad (\text{A.51})$$

$$\left. \frac{\partial \phi_m}{\partial y} \right|_{y=h} = \varepsilon \frac{\pi}{l} \cos\left(\frac{\pi}{l}x\right)e^{\frac{-\pi h}{l}} \quad (\text{A.52})$$

$$\left. \frac{\partial \phi_m}{\partial y} \right|_{y=0} = \varepsilon \frac{\pi}{l} \cos\left(\frac{\pi}{l}x\right) \quad (\text{A.53})$$

Solution:

The same procedure found in the first proof is used at this point and the resulting equation is the same as equation (A.19).

$$\phi_i(x,y) = (A \sin(mx) + B \cos(mx))(C e^{-my} + D e^{my}) \quad (\text{A.54})$$

Now to apply the boundary conditions

At the centerline or $y = 0$,

$$\frac{\partial \phi_i}{\partial y} = (A \sin(mx) + B \cos(mx))(-mC e^{-my} + mD e^{my}) \quad (\text{A.55})$$

$$\text{if } \left. \frac{\partial \phi_i}{\partial y} \right|_{y=0} = 0 \text{ then } A \sin(mx) = 0 \quad (\text{A.56})$$

$$\frac{\partial \phi_i}{\partial y} = B \cos(mx)(-mC e^{-my} + mD e^{my}) \quad (\text{A.57})$$

$$\text{if } \left. \frac{\partial \phi_i}{\partial y} \right|_{y=0} = 0 \text{ then } -mC + mD = 0 \quad \therefore C = D \quad (\text{A.58})$$

$$\frac{\partial \phi_i}{\partial y} = B \cos(mx)[C(-m e^{-my} + m e^{my})] \quad (\text{A.59})$$

$$\frac{\partial \phi_i}{\partial y} = C m \cos(mx) \sinh(my) \quad (\text{A.60})$$

$$\phi_i(x, y) = C \cos(mx) \cosh(my) \quad (\text{A.61})$$

At the upper wall or at $y = h$,

$$\left. \frac{\partial \phi_i}{\partial y} \right|_{y=h} = C m \cos(mx) \sinh(my) = -\epsilon \frac{\pi}{l} \cos\left(\frac{\pi}{l}x\right) e^{\frac{-\pi h}{l}} \quad \therefore m = \frac{\pi}{l} \quad (\text{A.62})$$

$$\frac{\partial \phi_i}{\partial y} = C \frac{\pi}{l} \cos\left(\frac{\pi}{l}x\right) \sinh\left(\frac{\pi}{l}y\right) \quad (\text{A.63})$$

$$\therefore C \frac{\pi}{l} \cos\left(\frac{\pi}{l}x\right) \sinh\left(\frac{\pi}{l}h\right) = -\epsilon \frac{\pi}{l} \cos\left(\frac{\pi}{l}x\right) e^{\frac{-\pi h}{l}} \quad (\text{A.64})$$

This returns the equation for the constant C

$$C = \frac{-\epsilon e^{-\frac{\pi}{l}h}}{\sinh(\frac{\pi}{l}h)} \quad (\text{A.65})$$

$$\phi_i(x,y) = \frac{-\epsilon e^{-\frac{\pi}{l}h}}{\sinh(\frac{\pi}{l}h)} \cos(\frac{\pi}{l}x) \cosh(\frac{\pi}{l}y) \quad (\text{A.66})$$

$$\phi_i(x,y) = -\epsilon \cos(\frac{\pi}{l}x) e^{-\frac{\pi}{l}h} \frac{\cosh(\frac{\pi}{l}y)}{\sinh(\frac{\pi}{l}h)} \quad (\text{A.67})$$

The above equation is compared with the final equation for the interference potential function for the last proof. These equations are found to be identical which proves the theoretical approach used for the last two methods.

Solution of Method for Perforated Wall Wind Tunnel

Method Three - Perforated Walls

Problem: Flow over a wavy wall with given contour and a boundary at the upper perforated wall at $y=h$. A schematic of the wind tunnel test section can be found in Figure 2.1 in Appendix B. The proof is started with equation (A.54) and after the boundary condition at $y=0$ is taken in effect the starting equation is

$$\phi_i = (B\sin(mx) + C\cos(mx))\cosh(my) \quad \text{where } m = \frac{\pi}{l} \quad (\text{A.68})$$

A new boundary condition was necessary for the perforated upper wall which can be written as

$$\left(\frac{\partial \phi_i}{\partial y} + R \frac{\partial \phi_i}{\partial x} \right) \Big|_{y=h} = - \left(\frac{\partial \phi_m}{\partial y} + R \frac{\partial \phi_m}{\partial x} \right) \Big|_{y=h} \quad (\text{A.69})$$

Solution:

$$\phi_i = B\sin(mx)\cosh(my) + C\cos(mx)\cosh(my) \quad (\text{A.70})$$

$$\frac{\partial \phi_i}{\partial x} = (Bm\cos(mx) - Cmsin(mx))\cosh(my) \quad (\text{A.71})$$

$$\frac{\partial \phi_i}{\partial y} = (B\sin(mx) + C\cos(mx))m\sinh(my) \quad (\text{A.72})$$

The equations for the free-air model potential function and the partial derivatives of the function are as follows

$$\phi_m = -\epsilon \cos(mx) e^{-my} \text{ where } m = \frac{\pi}{l} \quad (\text{A.73})$$

$$\frac{\partial \phi_m}{\partial x} = \epsilon m \sin(mx) e^{-my} \quad (\text{A.74})$$

$$\frac{\partial \phi_m}{\partial y} = \epsilon m \cos(mx) e^{-my} \quad (\text{A.75})$$

Now to find the constants B and C in the interference potential function using the boundary condition at $y=h$.

$$(B \sin(mx) + C \cos(mx)) m \sinh(my) + R(B m \cos(mx) - C m \sin(mx)) \cosh(my) = -(\epsilon m \cos(mx) e^{-my} + R(\epsilon m \sin(mx) e^{-my})) \quad (\text{A.76})$$

Separate the equation into sine and cosine terms

$$\sin(mx)[B m \sinh(my) - R C m \cosh(my)] + \cos(mx)[C m \sinh(my) + R B m \cosh(my)] = -\epsilon m \cos(mx) e^{-mh} - R \epsilon m \sin(mx) e^{-mh} \quad (\text{A.77})$$

$$\begin{aligned} \sin(mx)[B m \sinh(my) - R C m \cosh(my)] &= -R \epsilon m \sin(mx) e^{-mh} \\ \cos(mx)[C m \sinh(my) + R B m \cosh(my)] &= -\epsilon m \cos(mx) e^{-mh} \end{aligned} \quad (\text{A.78})$$

Remove sine and cosine terms and constant m from the equations

$$\begin{aligned} B \sinh(my) - R C \cosh(my) &= -R \epsilon e^{-mh} \\ C \sinh(my) + R B \cosh(my) &= -\epsilon e^{-mh} \end{aligned} \quad (\text{A.79})$$

Solve for B and C using the above equations

$$B = RC \frac{\cosh(my)}{\sinh(my)} - \frac{R\epsilon e^{-mh}}{\sinh(my)} \quad (A.80)$$

$$C \sinh(my) + R \left(\frac{RC \cosh(my)}{\sinh(my)} - \frac{R\epsilon e^{-mh}}{\sinh(my)} \right) \cosh(my) = -\epsilon e^{-mh} \quad (A.81)$$

$$C \sinh(my) + R^2 C \frac{\cosh^2(my)}{\sinh(my)} - R^2 \frac{\epsilon e^{-mh} \cosh(my)}{\sinh(my)} = -\epsilon e^{-mh} \quad (A.82)$$

Multiply both sides by $\sinh(my)$

$$C \sinh^2(my) + R^2 C \cosh^2(my) - R^2 \cosh(my) \epsilon e^{-mh} = -\epsilon e^{-mh} \sinh(my) \quad (A.83)$$

Separate terms and divide the right side of the equation by the left side to get the constant C at $y=h$

$$C = \frac{[R^2 \cosh(mh) - \sinh(mh)] \epsilon e^{-mh}}{\sinh^2(mh) + R^2 \cosh^2(mh)} \quad (A.84)$$

Now to find the constant B

$$B \sinh(my) - R \left[\frac{(R^2 \cosh(mh) - \sinh(mh)) \epsilon e^{-mh}}{\sinh^2(mh) + R^2 \cosh^2(mh)} \right] \cosh(my) = -R \epsilon e^{-mh} \quad (A.85)$$

Multiply both sides by $\sinh^2(mh) + R^2 \cosh^2(mh)$

$$B \sinh(my) [\sinh^2(mh) + R^2 \cosh^2(mh)] - R [R^2 \cosh(mh) - \sinh(mh)] \epsilon e^{-mh} \cosh(my) = -R \epsilon e^{-mh} [\sinh^2(mh) + R^2 \cosh^2(mh)] \quad (A.86)$$

Separate terms and simplify the equation

$$B[\sinh^2(mh) + R^2 \cosh^2(mh)] = -R\epsilon e^{-mh} [\cosh(mh) + \sinh(mh)] \quad (\text{A.87})$$

$$\cosh(mh) + \sinh(mh) = e^{mh} \quad (\text{A.88})$$

$$B[\sinh^2(mh) + R^2 \cosh^2(mh)] = -R\epsilon e^{-mh} e^{mh} \quad (\text{A.89})$$

Therefore the equation for the constant B can be written

$$B = \frac{-R\epsilon}{\sinh^2(mh) + R^2 \cosh^2(mh)} \quad (\text{A.90})$$

Using the two equations for the constants and the initial equation for the interference potential function, equation (A.68), a final equation can be found for a perforated wall wind tunnel.

APPENDIX B

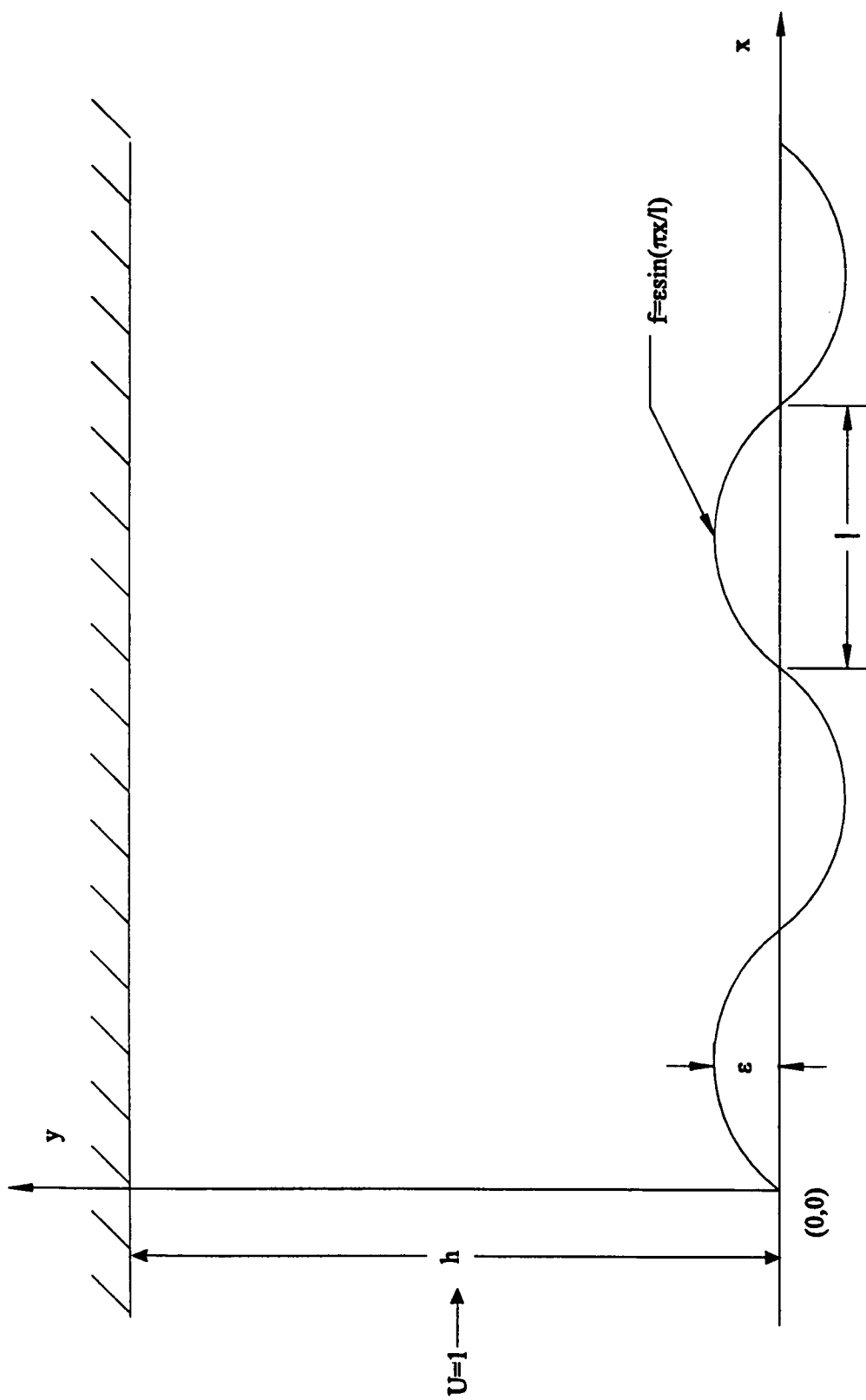


Figure 2.1 Schematic of the wind tunnel test section used for the theoretical study

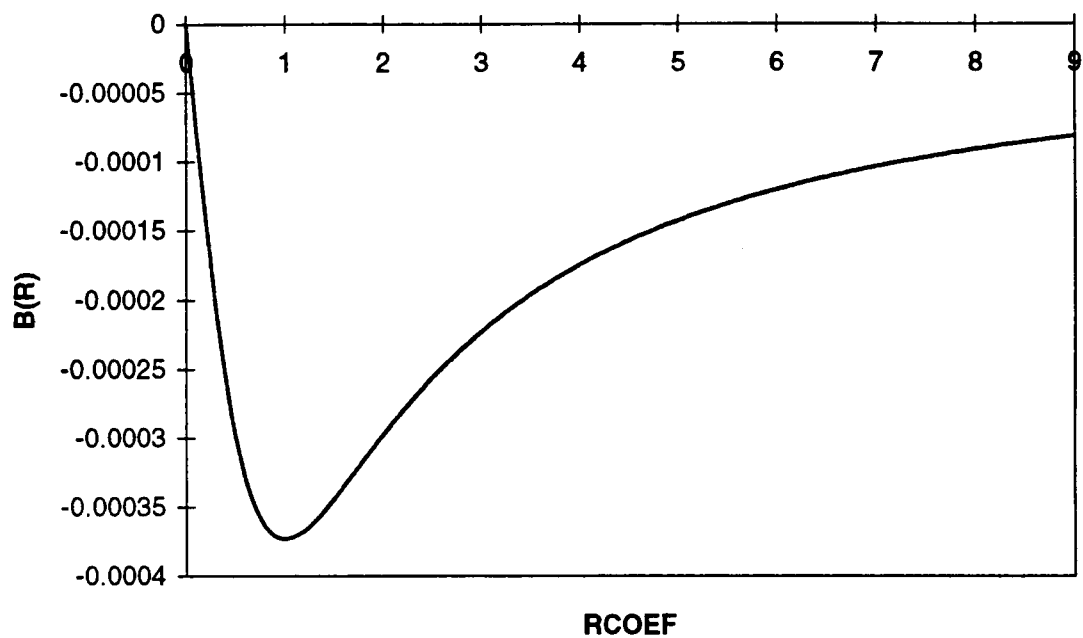


Figure 2.2 Variation of $B(R)$ versus R for a perforated wall wind tunnel

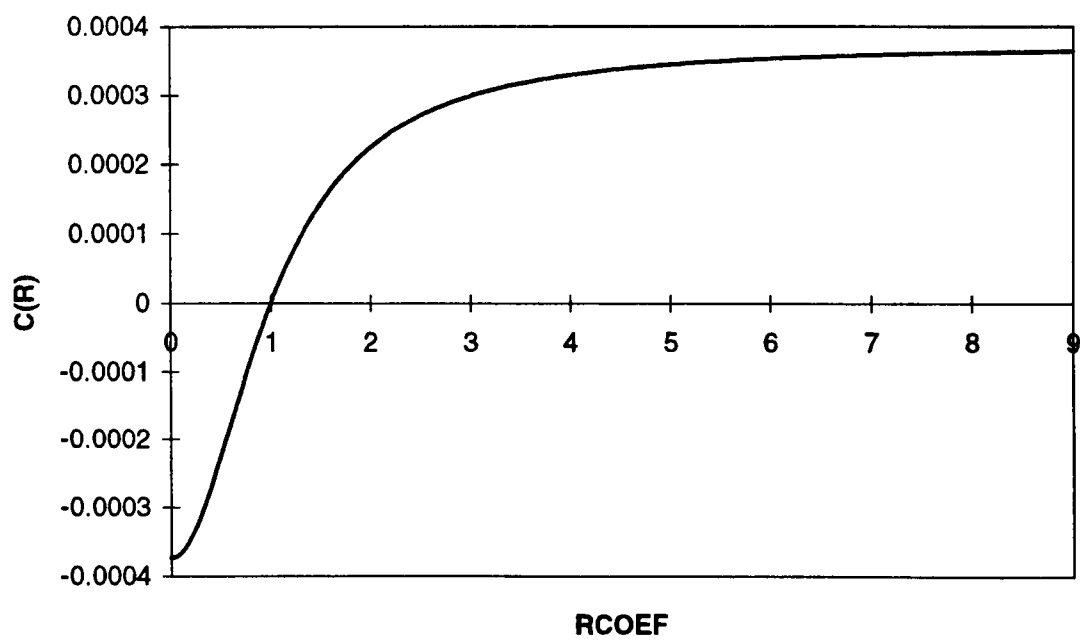


Figure 2.3 Variation of $C(R)$ versus R for a perforated wall wind tunnel

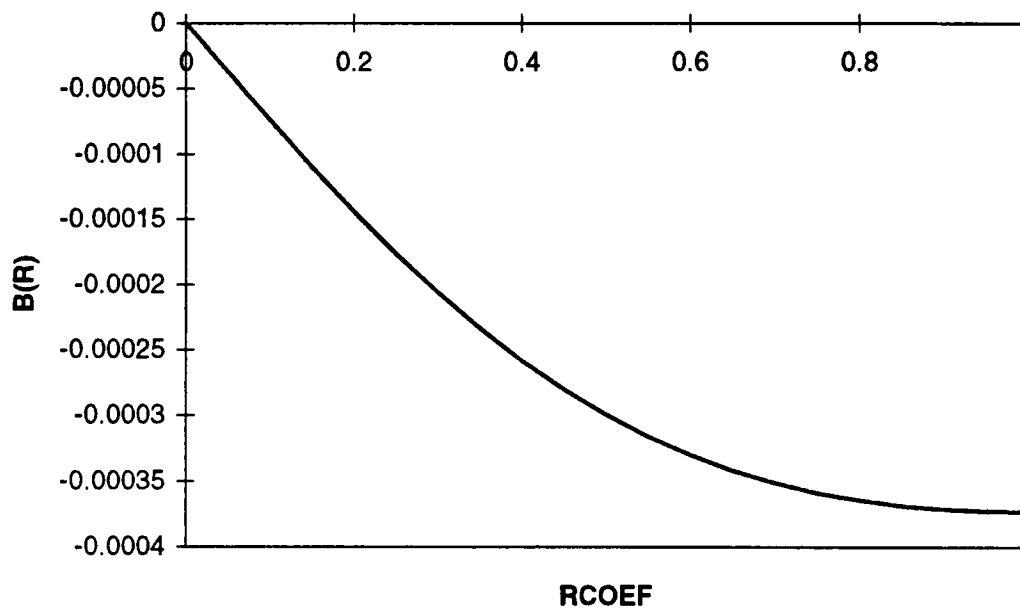


Figure 2.4 Variation of $B(R)$ versus R for porosities R between 0 and 1

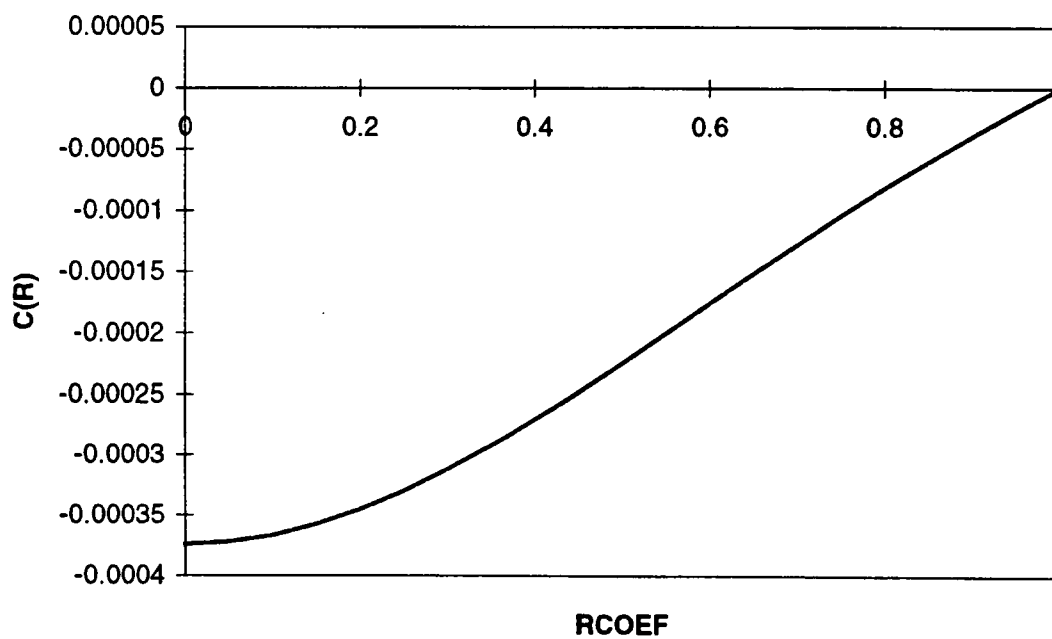


Figure 2.5 Variation of $C(R)$ versus R for porosities R between 0 and 1

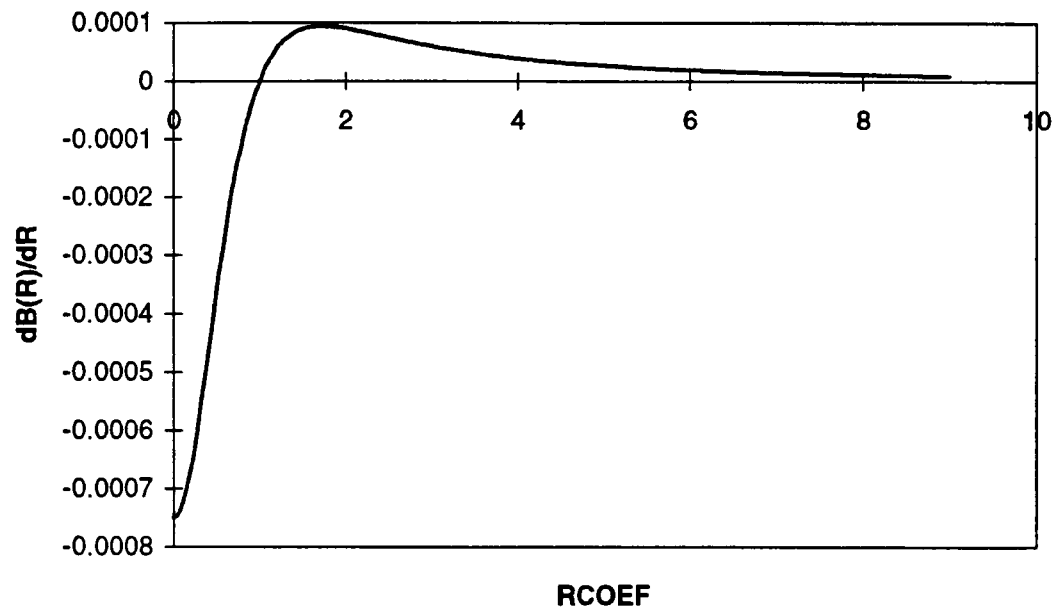


Figure 2.6 Plot of the partial derivative $\partial B/\partial R$ versus R for perforated wall wind tunnels

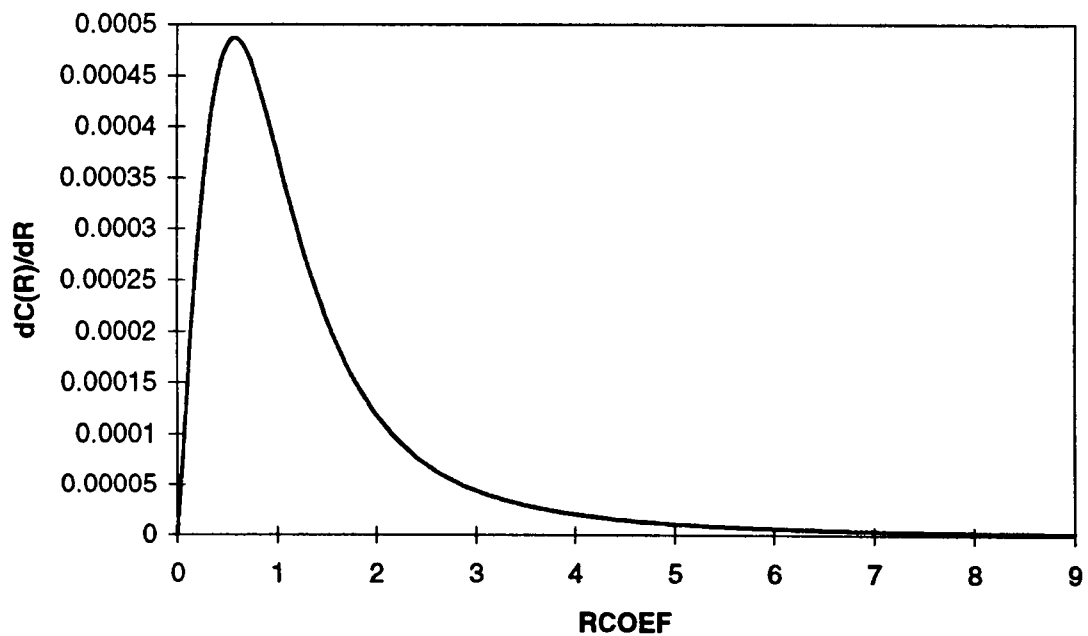


Figure 2.7 Plot of the partial derivative $\partial C/\partial R$ versus R for perforated wall wind tunnels

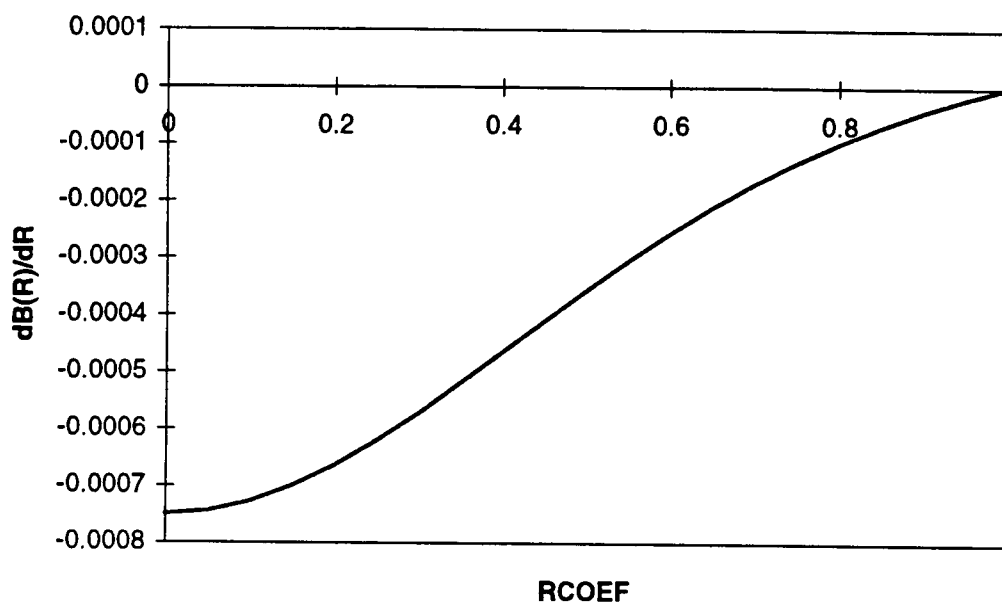


Figure 2.8 Plot of the partial derivative $\partial B/\partial R$ versus R for porosities R between 0 and 1

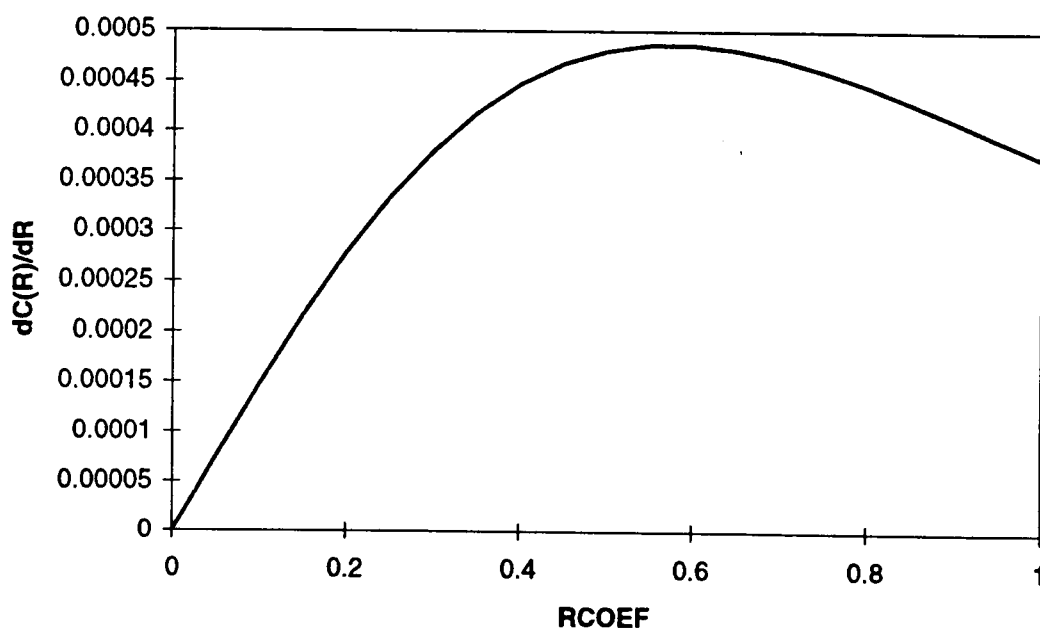


Figure 2.9 Plot of the partial derivative $\partial C/\partial R$ versus R for porosities R between 0 and 1

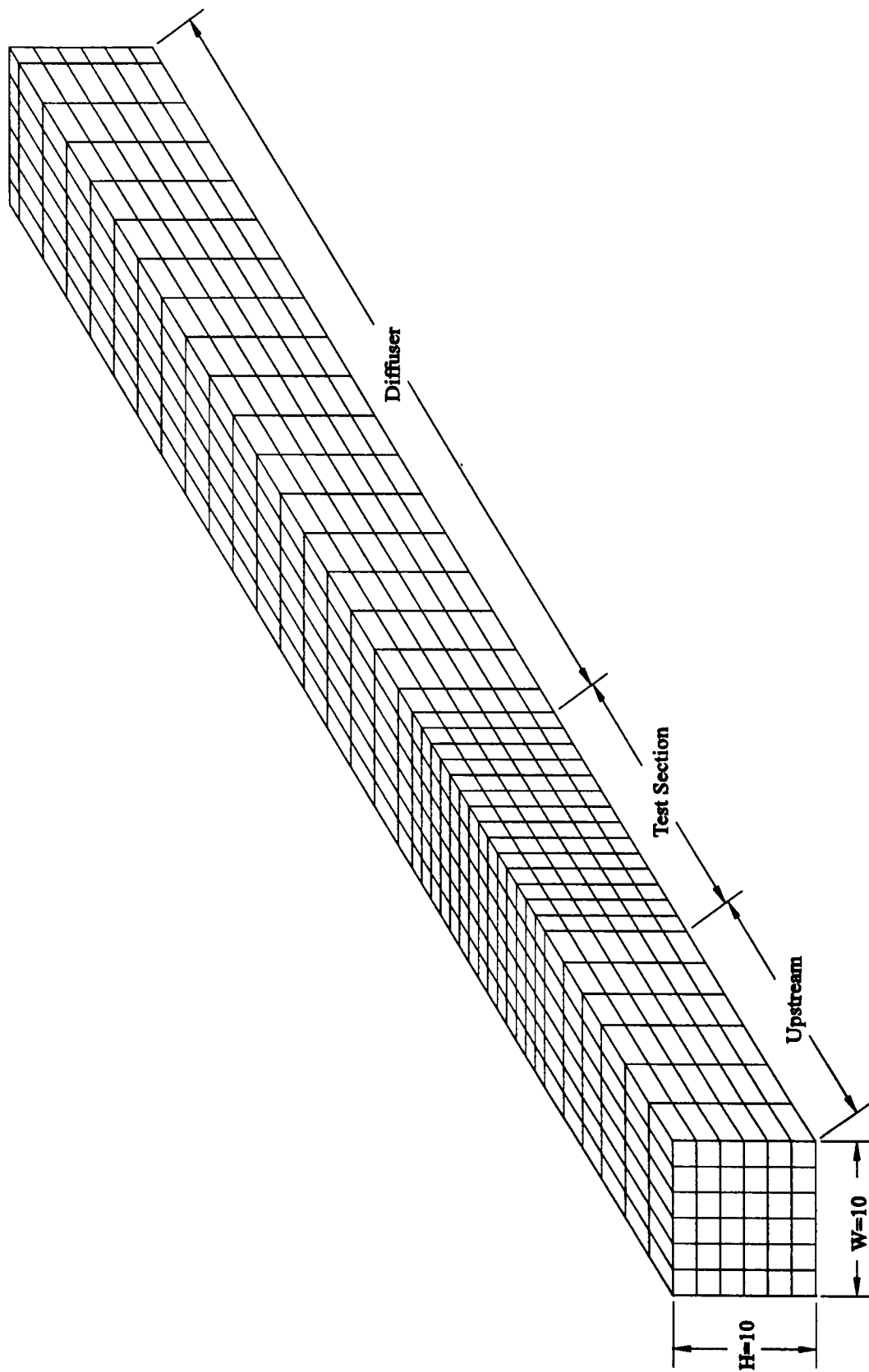


Figure 3.2 Schematic of the rectangular perforated wall wind tunnel for tunnel boundary interference calculations

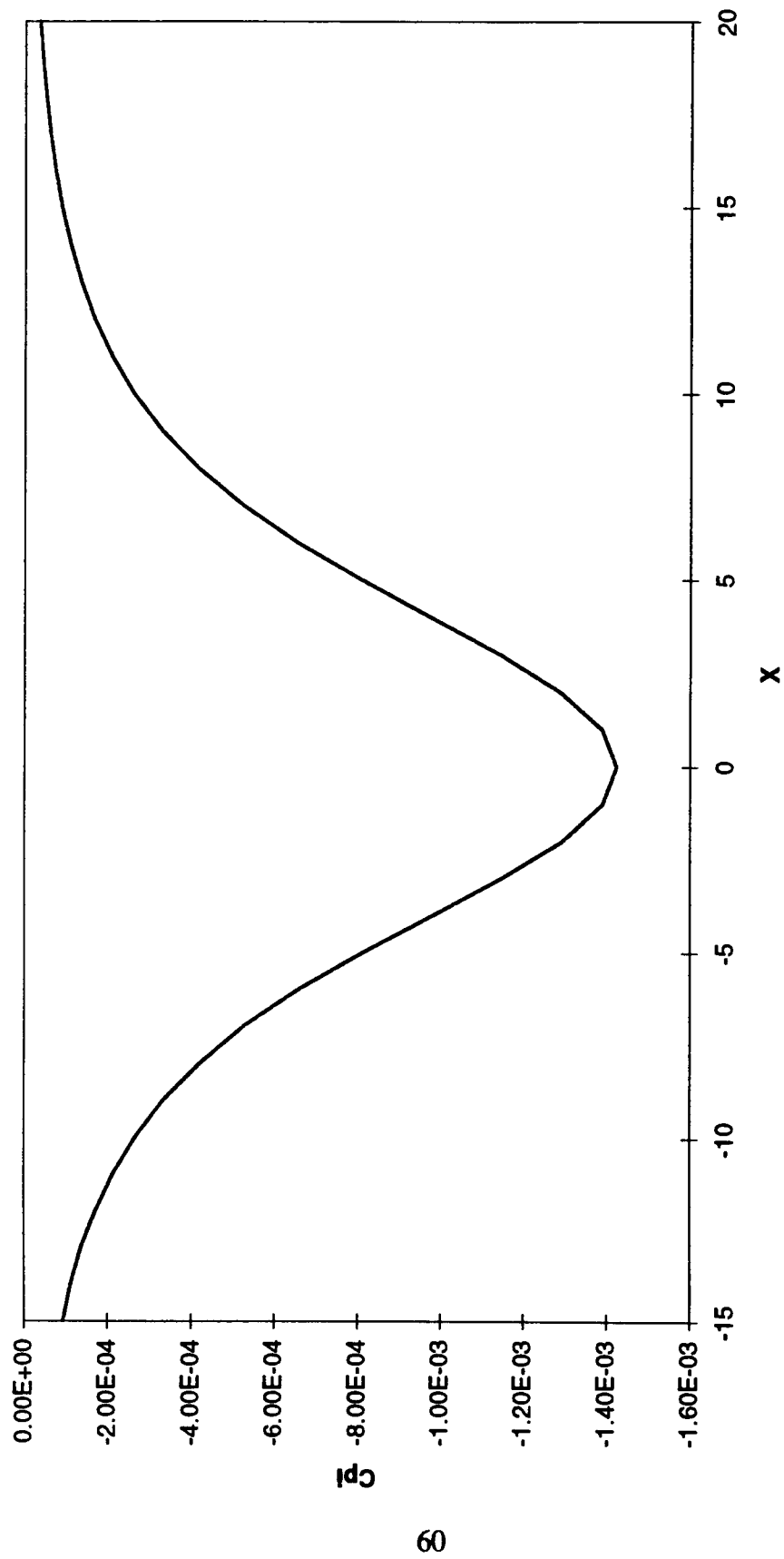


Figure 3.3 Plot of the interference pressure coefficient along the centerline for a solid wall wind tunnel

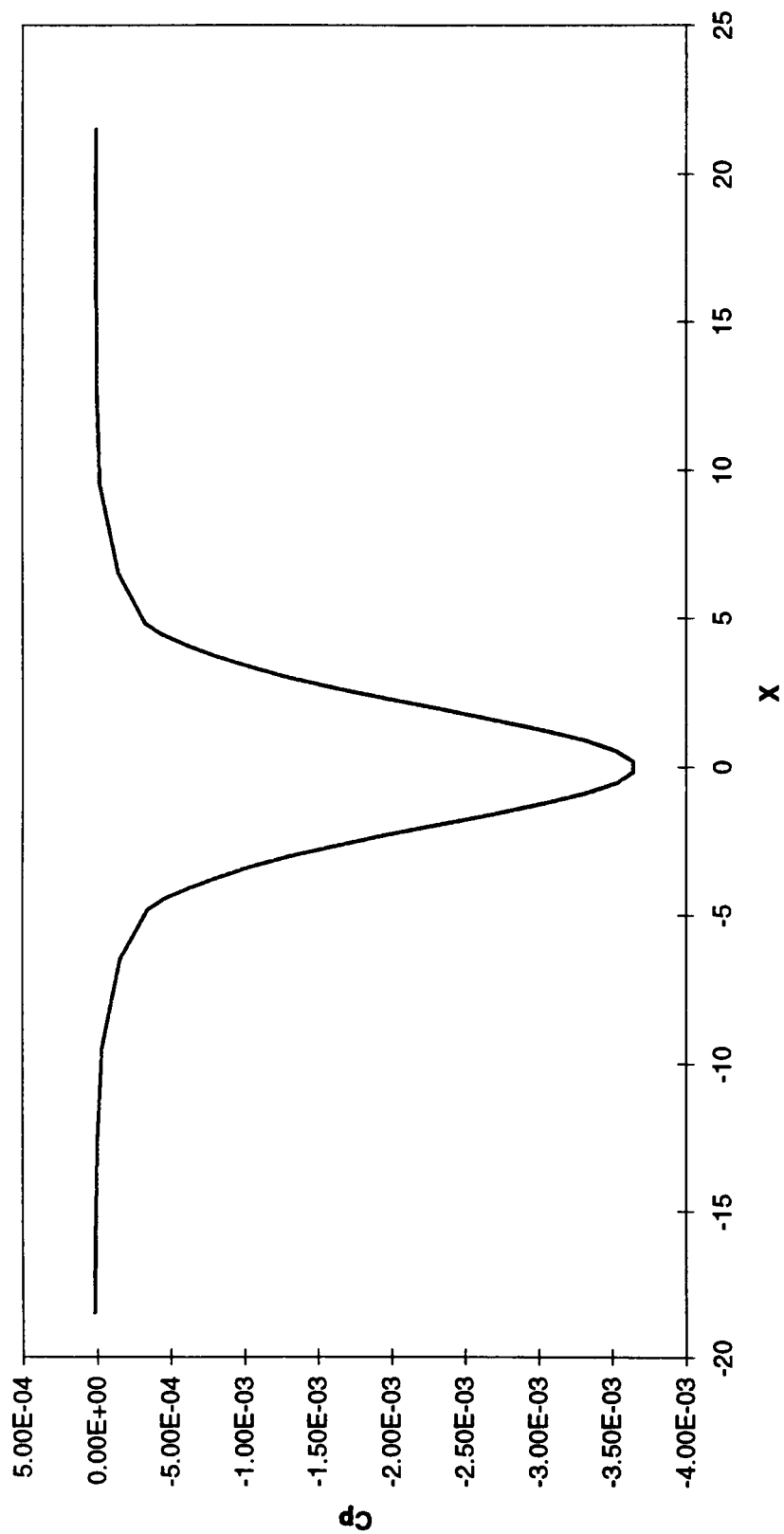


Figure 3.4 Plot of the pressure coefficient along the upper wall for a solid wall wind tunnel

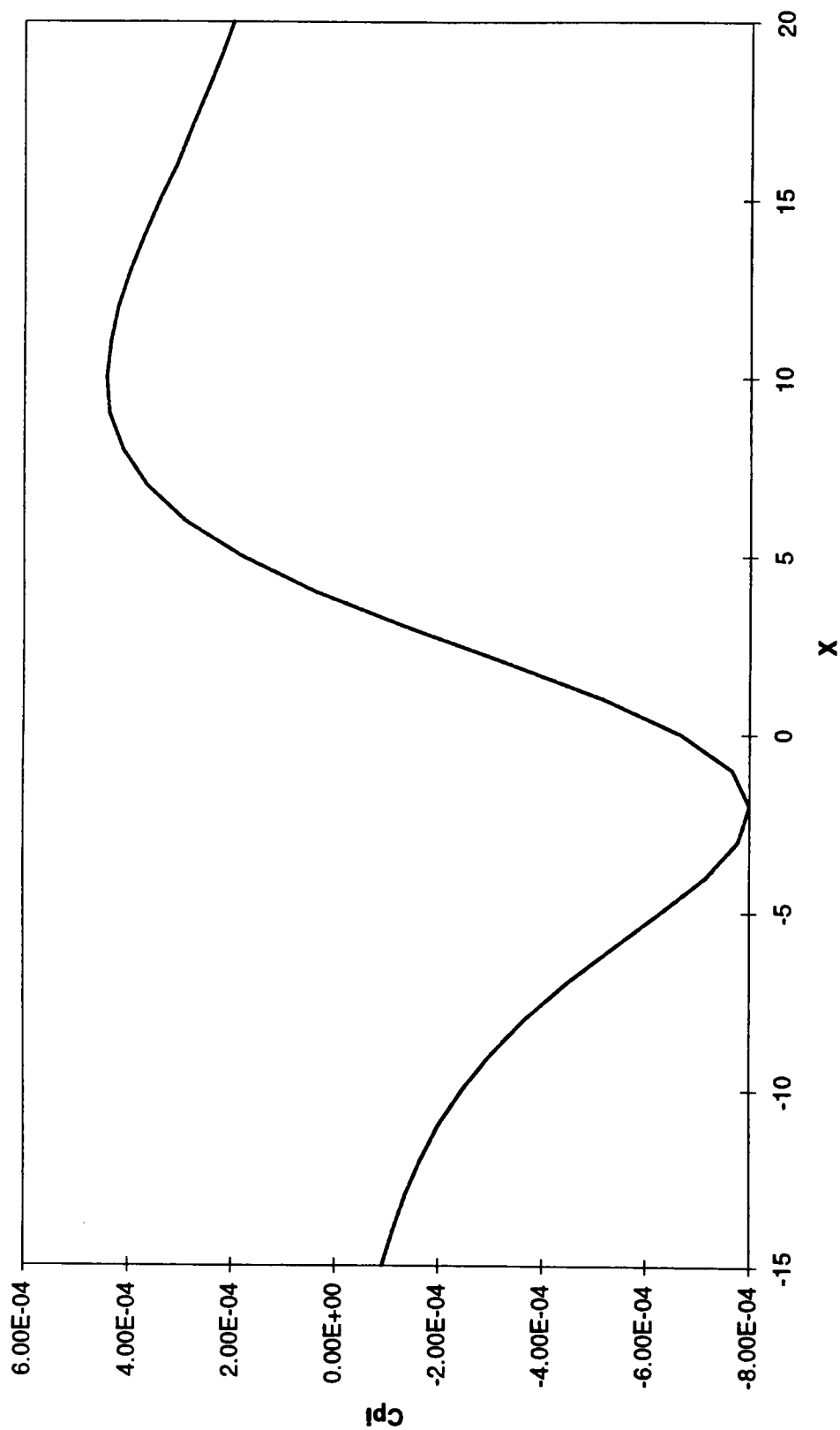


Figure 3.5 Plot of the interference pressure coefficient along the centerline for a wind tunnel with walls of porosity equal to 0.25 (or $Q=0.2$)

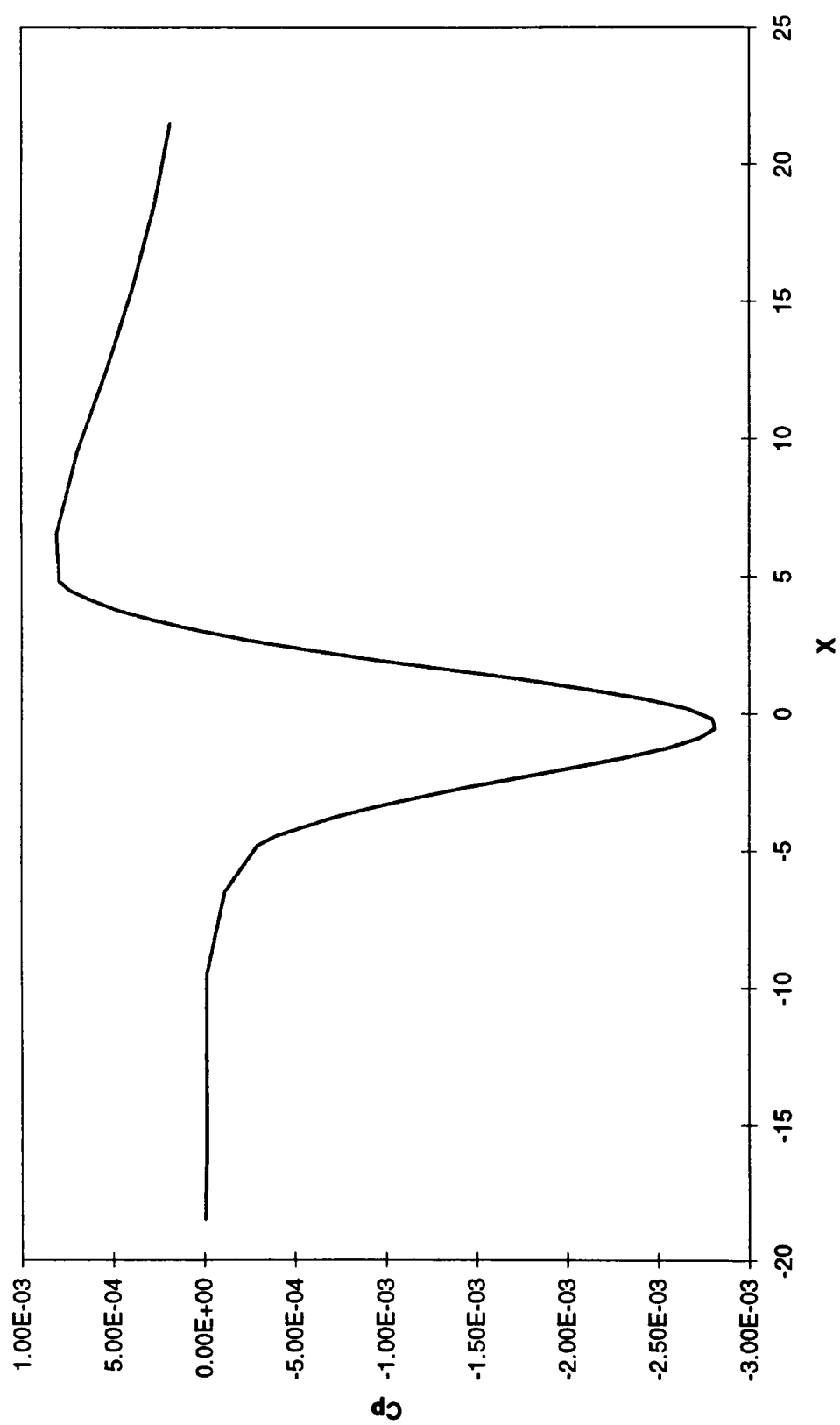


Figure 3.6 Plot of the pressure coefficient along the upper wall for a wind tunnel with walls of porosity equal to 0.25(or $Q=0.2$)

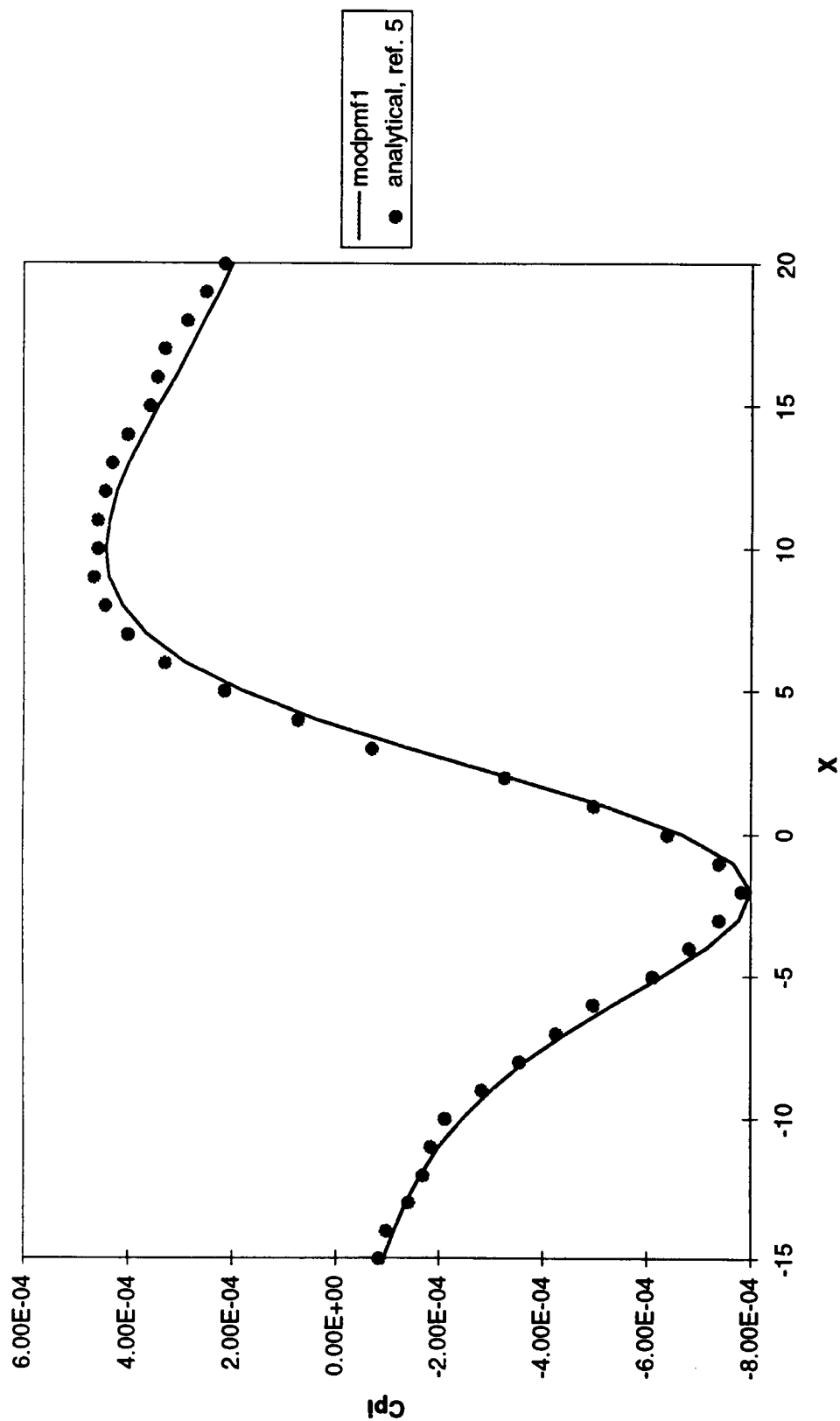


Figure 3.7 Comparison of the centerline values of the interference pressure coefficient obtained analytically from Lo and Oliver[5] to values obtained with the modified PMARC code (R=0.25)

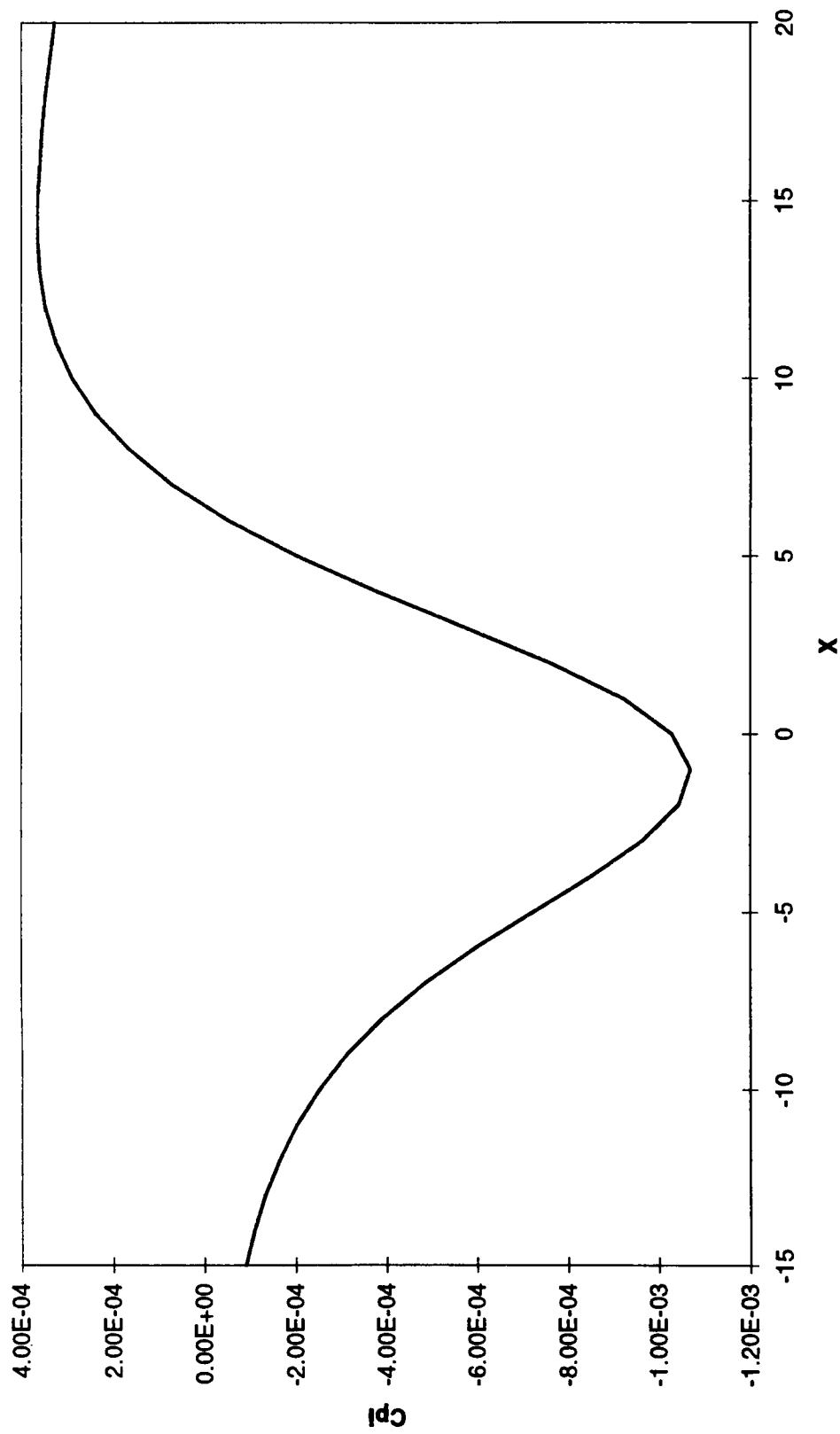


Figure 3.8 Plot of the interference pressure coefficient along the centerline for a wind tunnel with walls of porosity equal to 0.1111 (or $Q=0.1$)

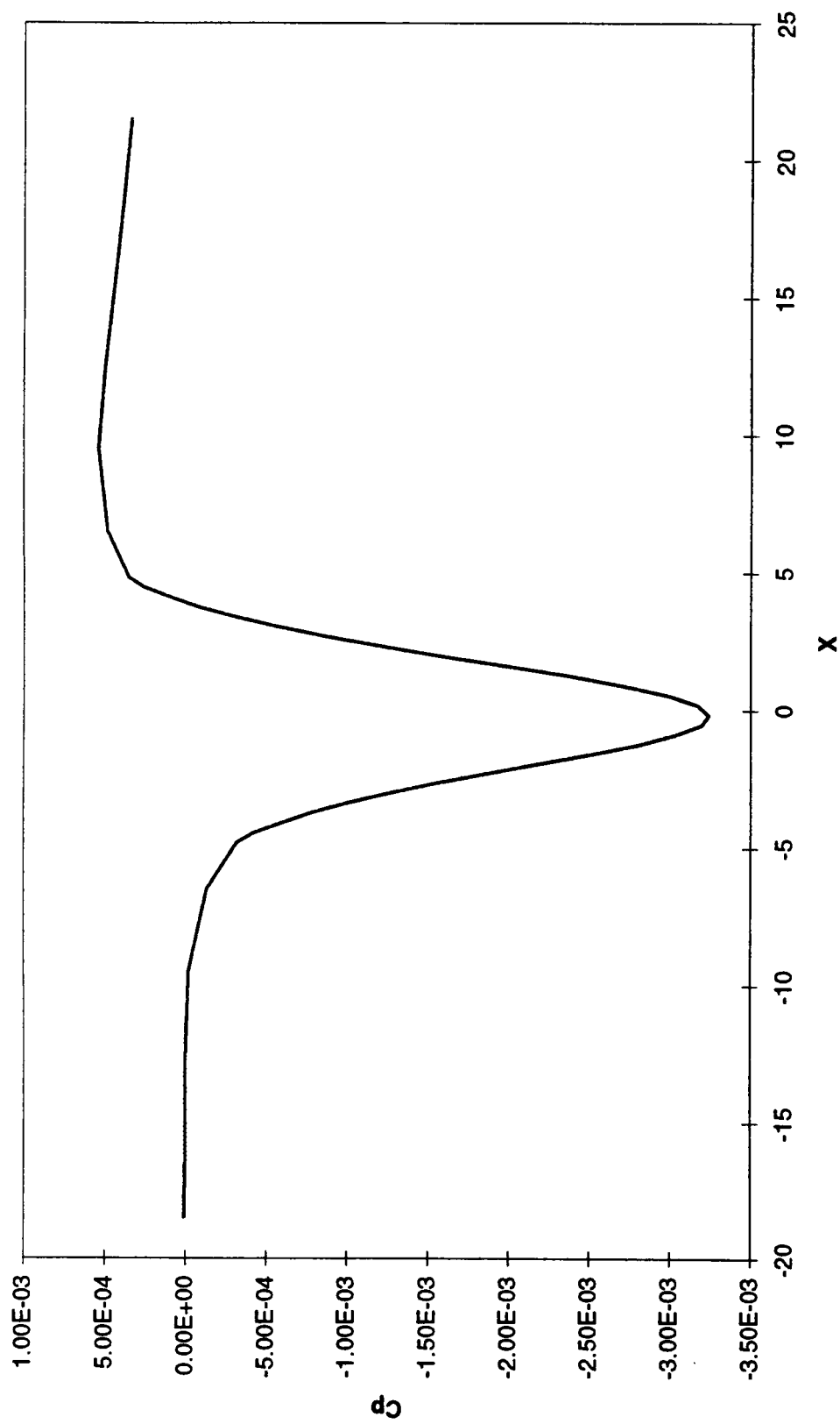


Figure 3.9 Plot of the pressure coefficient along the upper wall for a wind tunnel with walls of porosity equal to 0.1111 (or $Q=0.1$)

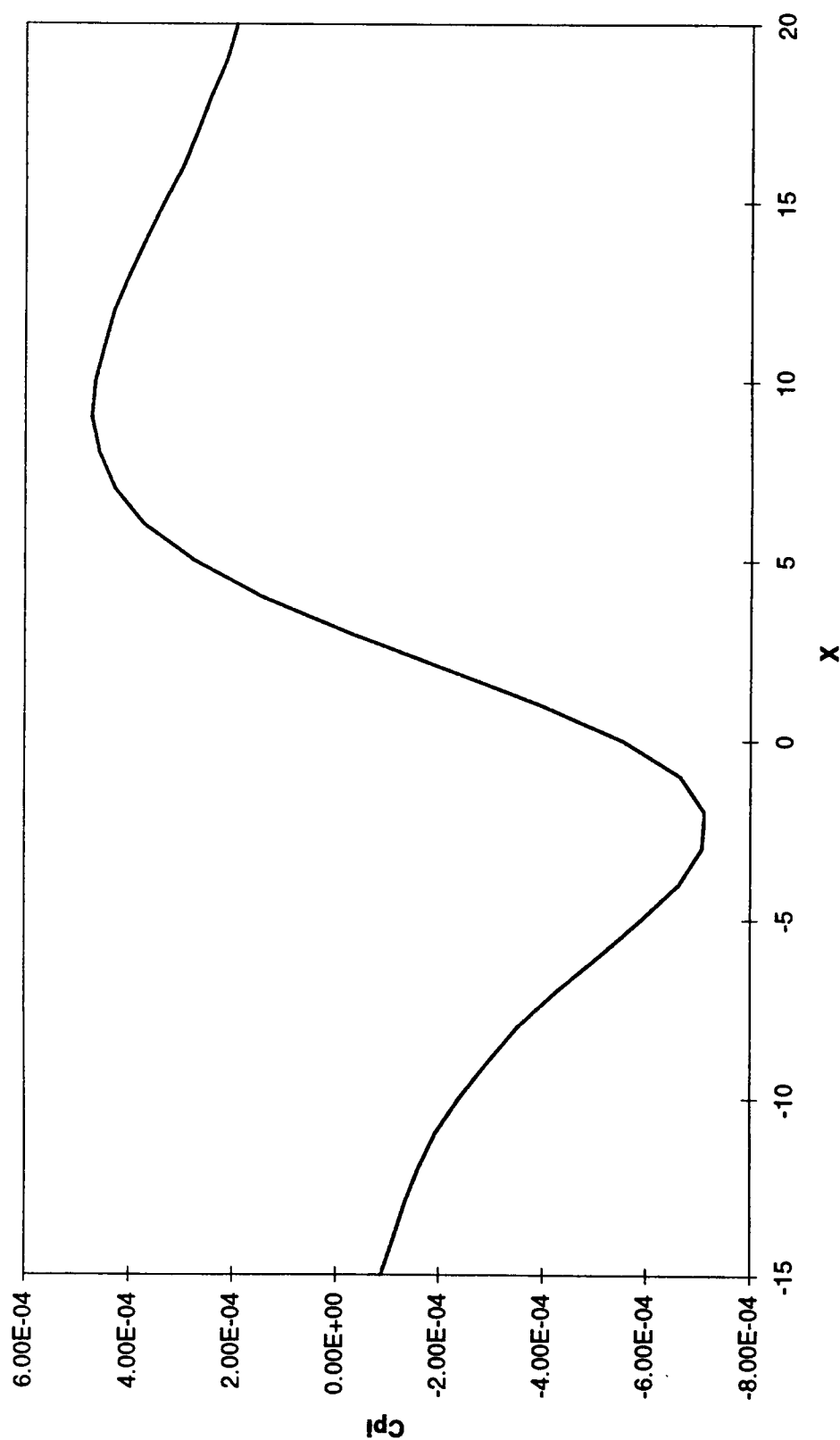


Figure 3.10 Plot of the interference pressure coefficient along the centerline for a wind tunnel with walls of porosity equal to 0.3(or $Q=0.23$) using no initialization values

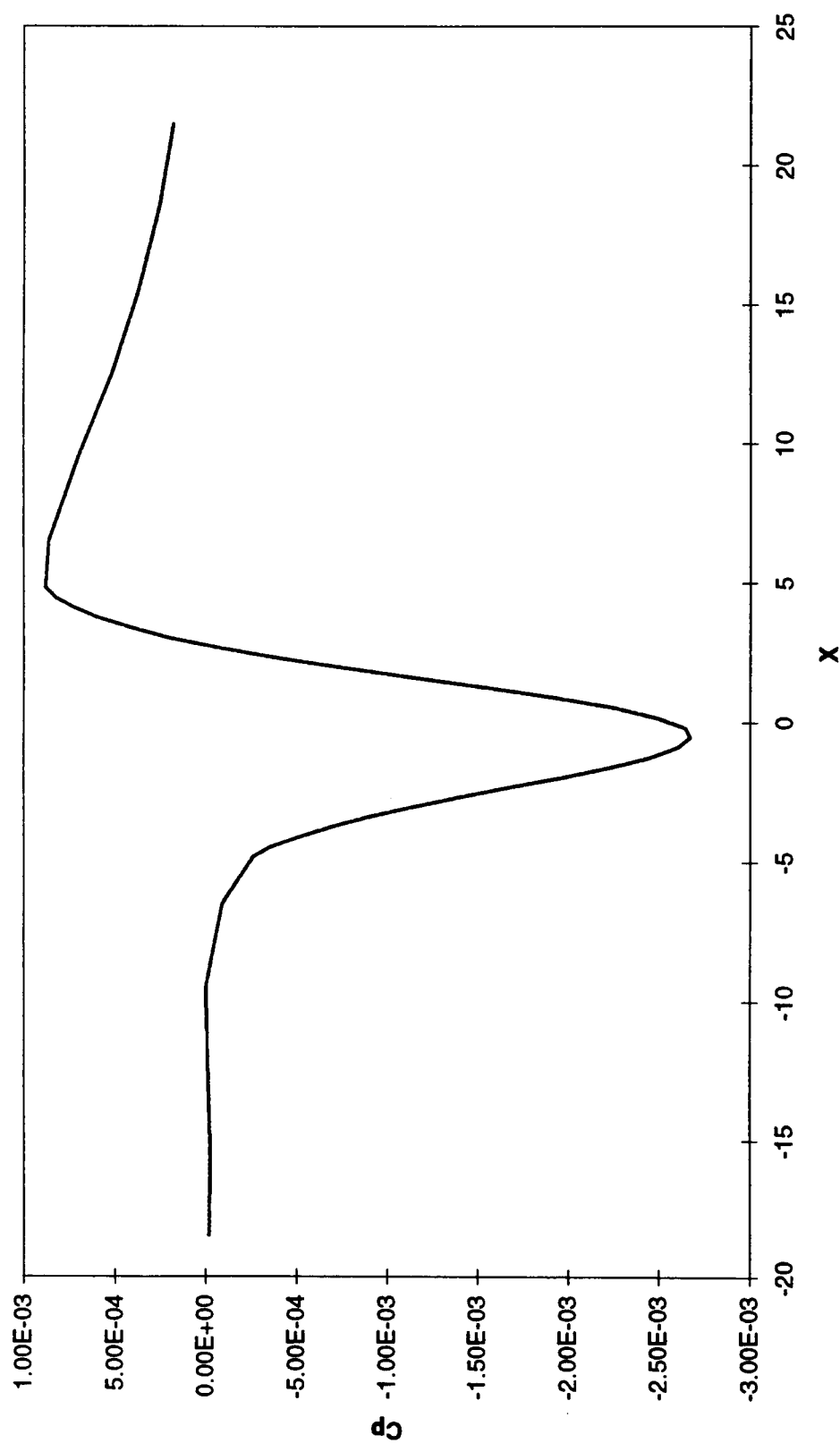


Figure 3.11 Plot of the pressure coefficient along the upper wall for a wind tunnel with walls of porosity equal to 0.3 (or $Q=0.23$) using no initialization values

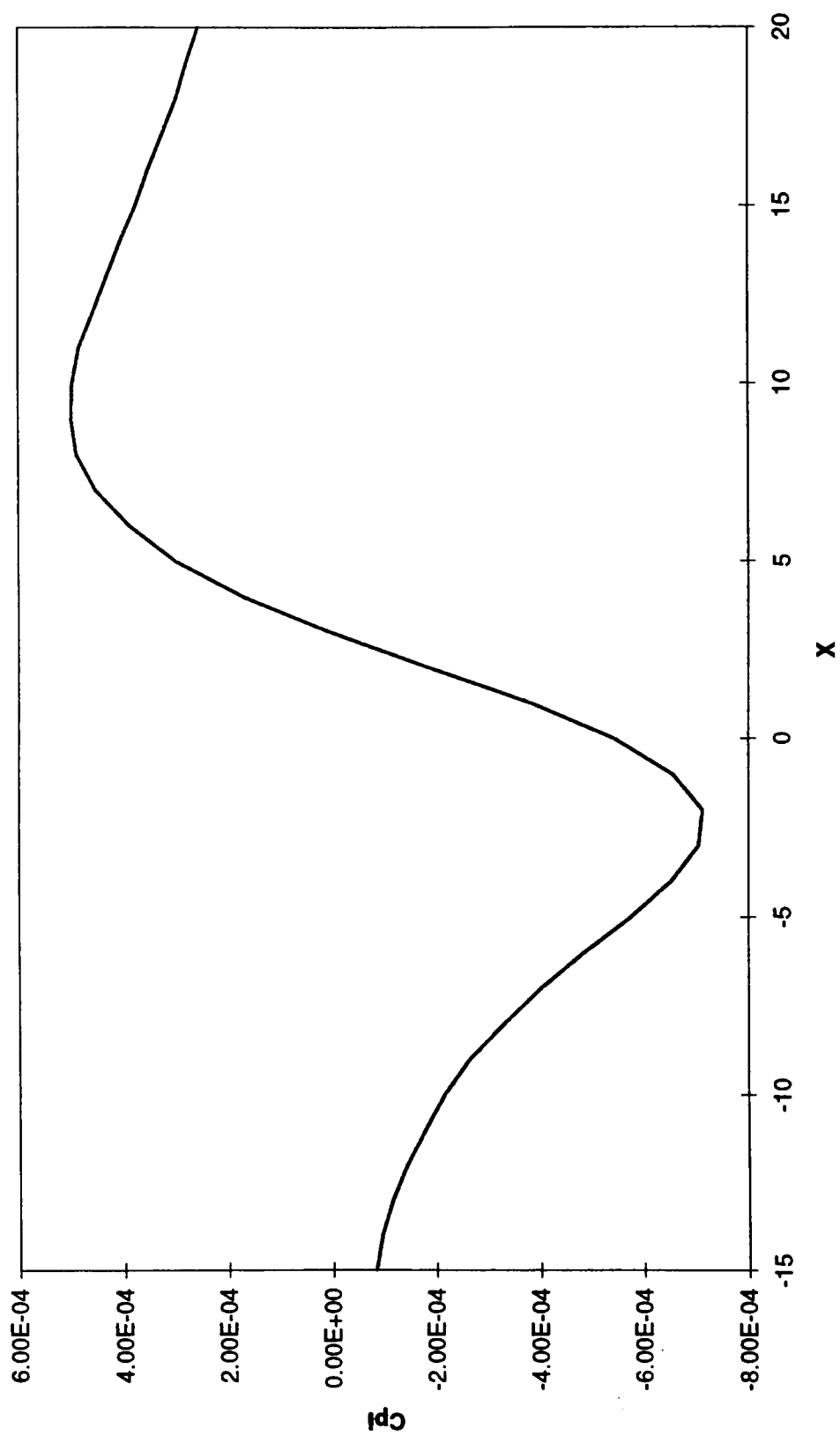


Figure 3.12 Plot of the interference pressure coefficient along the centerline for a wind tunnel with walls of porosity equal to 0.3 (or $Q=0.23$) using initialization values from $R=0.25$ case

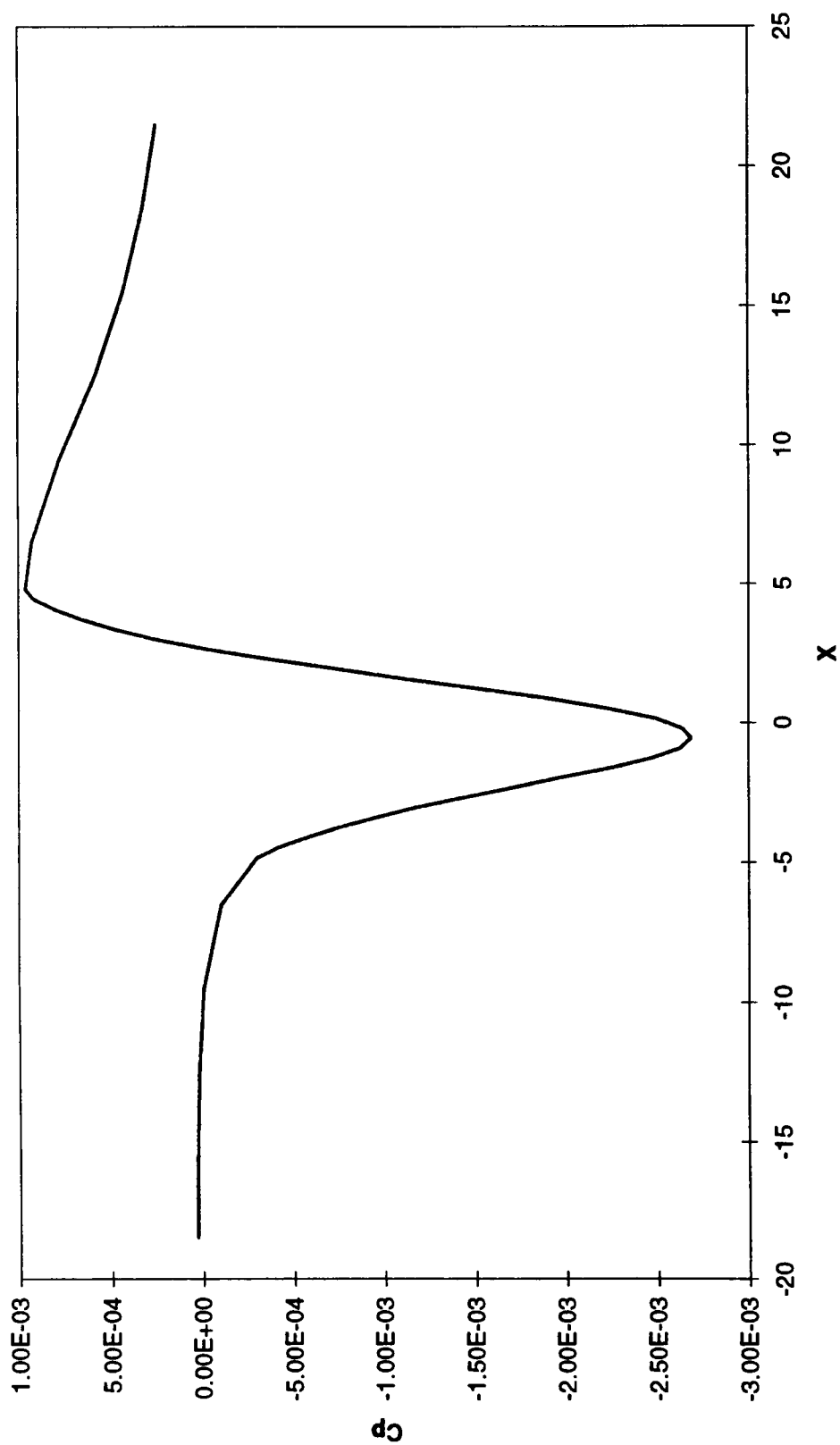


Figure 3.13 Plot of the pressure coefficient along the upper wall for a wind tunnel with walls of porosity equal to 0.3(or $Q=0.23$) using initialization values from $R=0.25$ case

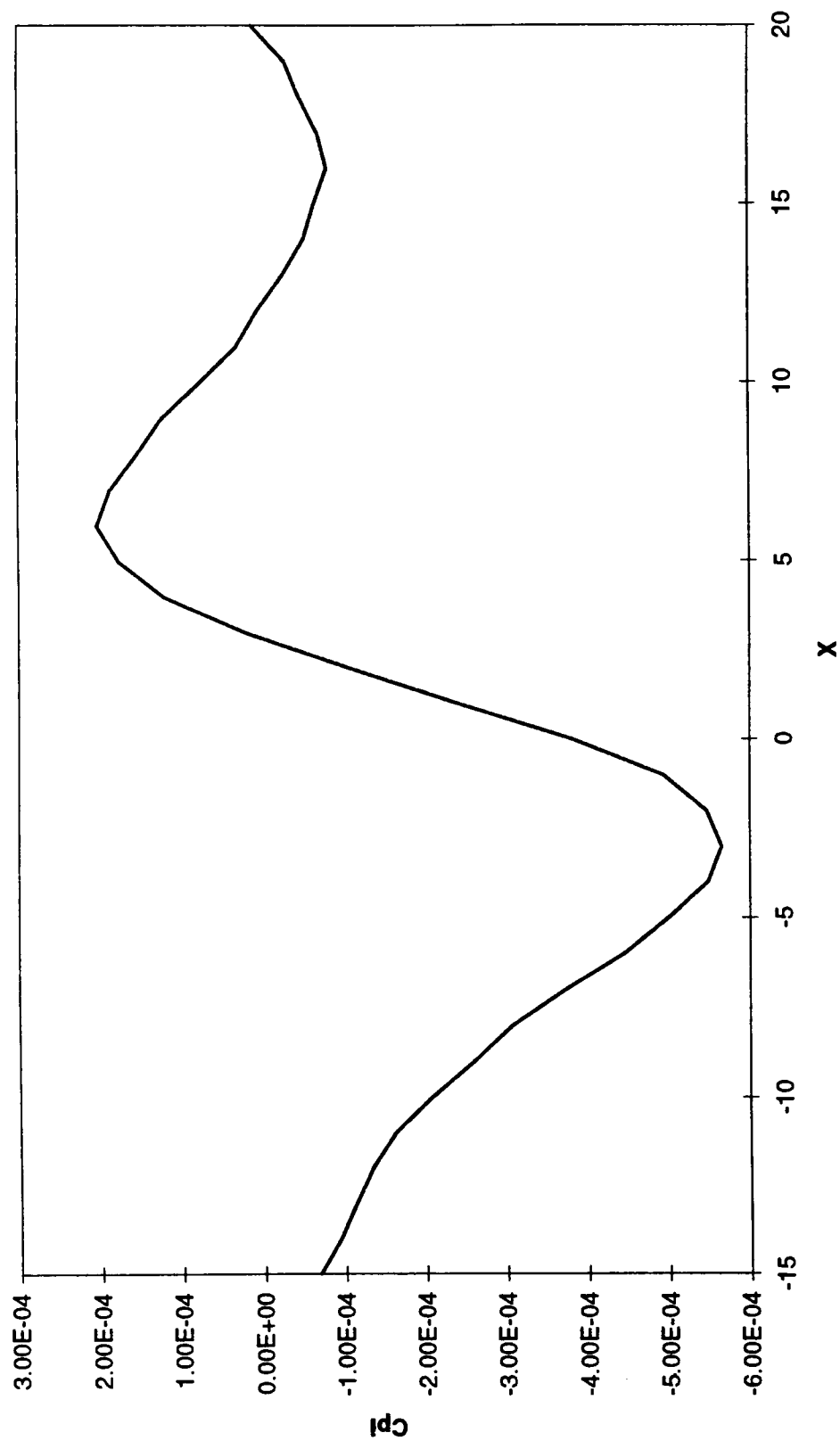


Figure 3.14 Plot of interference pressure coefficient along the centerline for a wind tunnel with walls of porosity equal to 0.43 (or $Q=0.3$) using initialization values from $R=0.25$ case

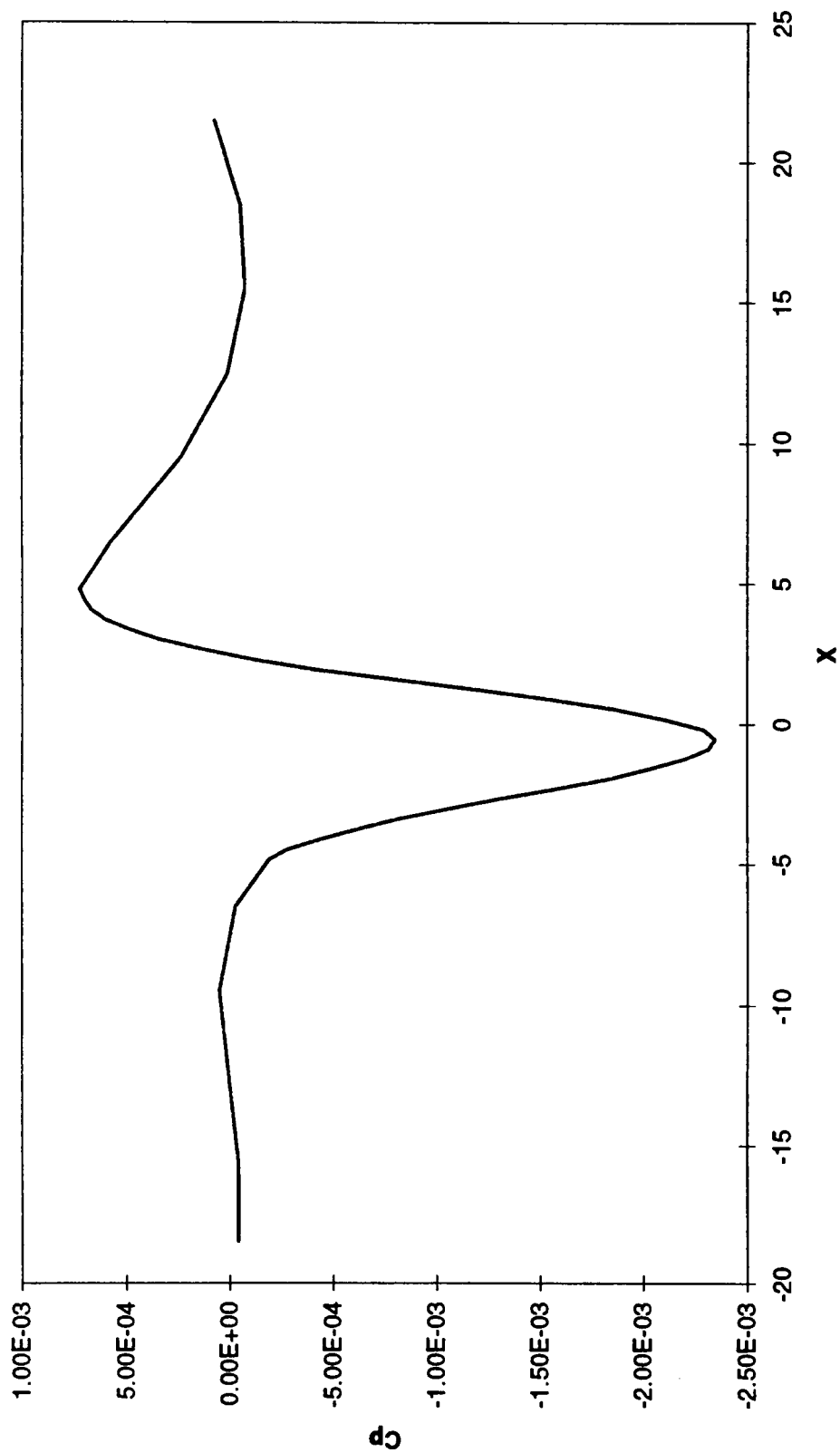


Figure 3.15 Plot of the pressure coefficient along the upper wall for a wind tunnel with walls of porosity equal to 0.43 (or $Q=0.3$) using initialization values from $R=0.25$ case

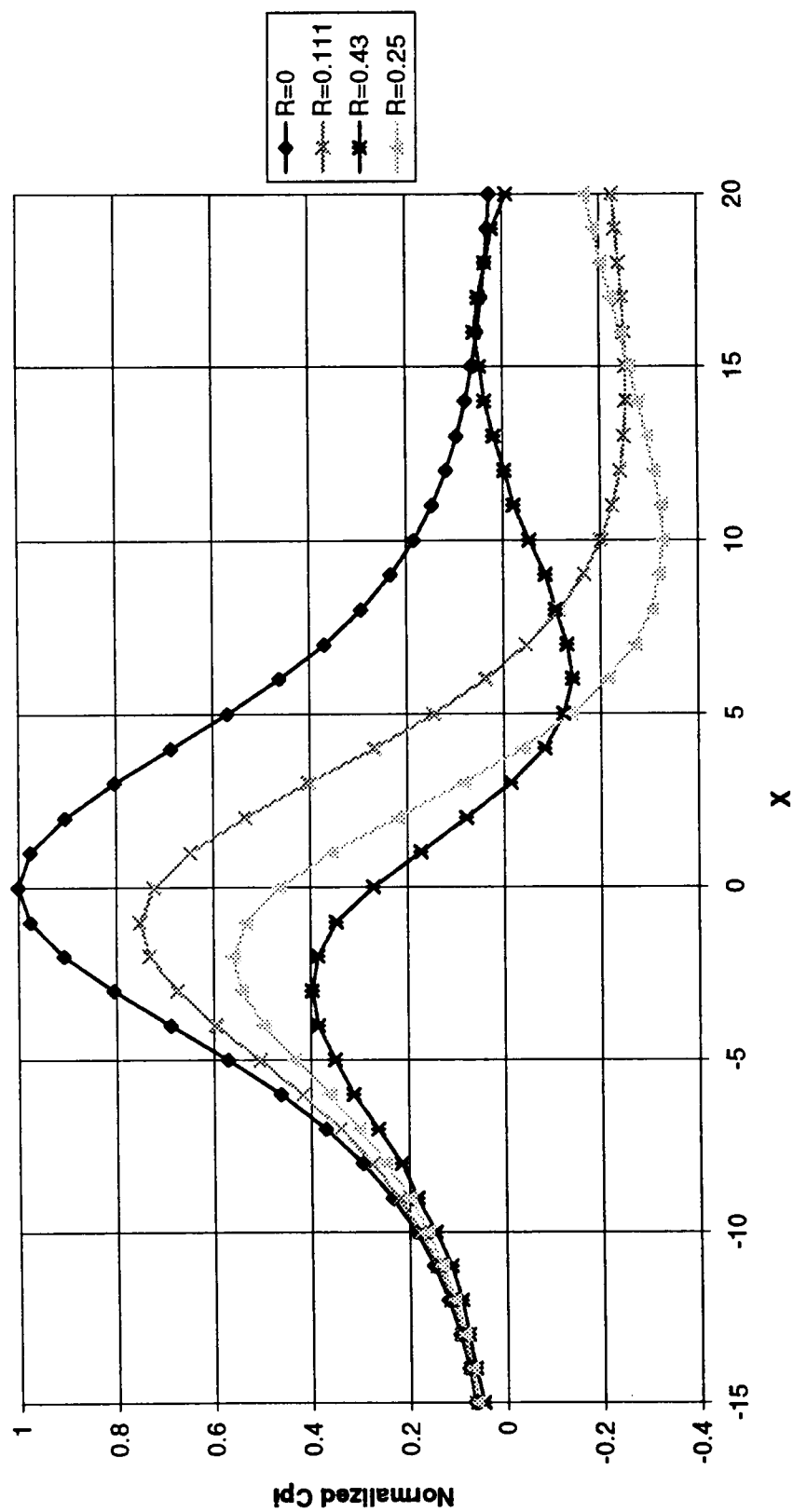


Figure 3.16 Distributions of normalized interference pressure coefficient along the test section for various uniform porosities ranging from $R=0$ (solid wall) to $R=0.43$ using a modified PMARC code

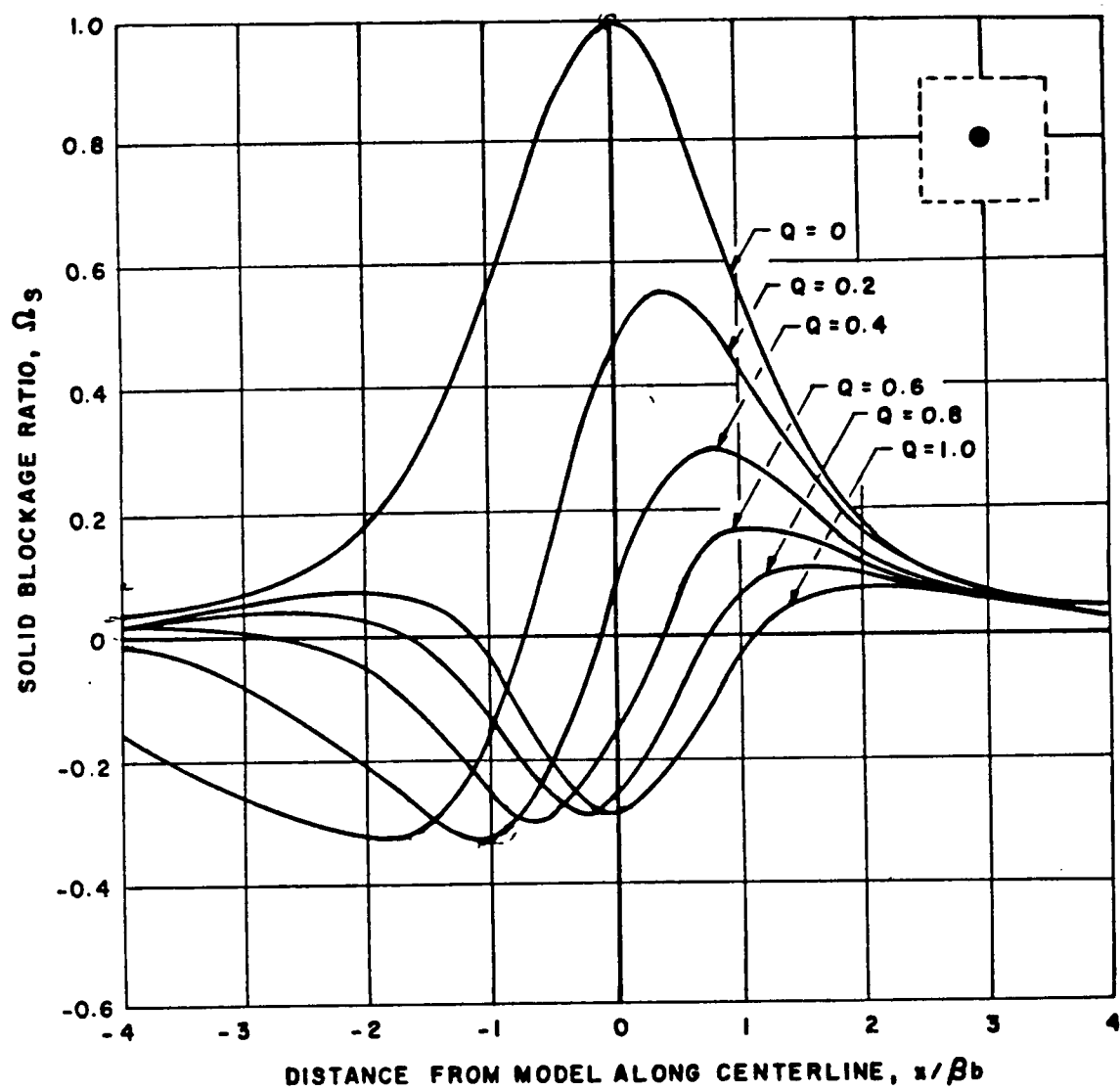


Figure 3.17 Plot of normalized interference pressure coefficient for a solid blockage at various porosities ranging from $Q=0$ (solid wall) to $Q=1$ (open wall) from Lo and Oliver[5]

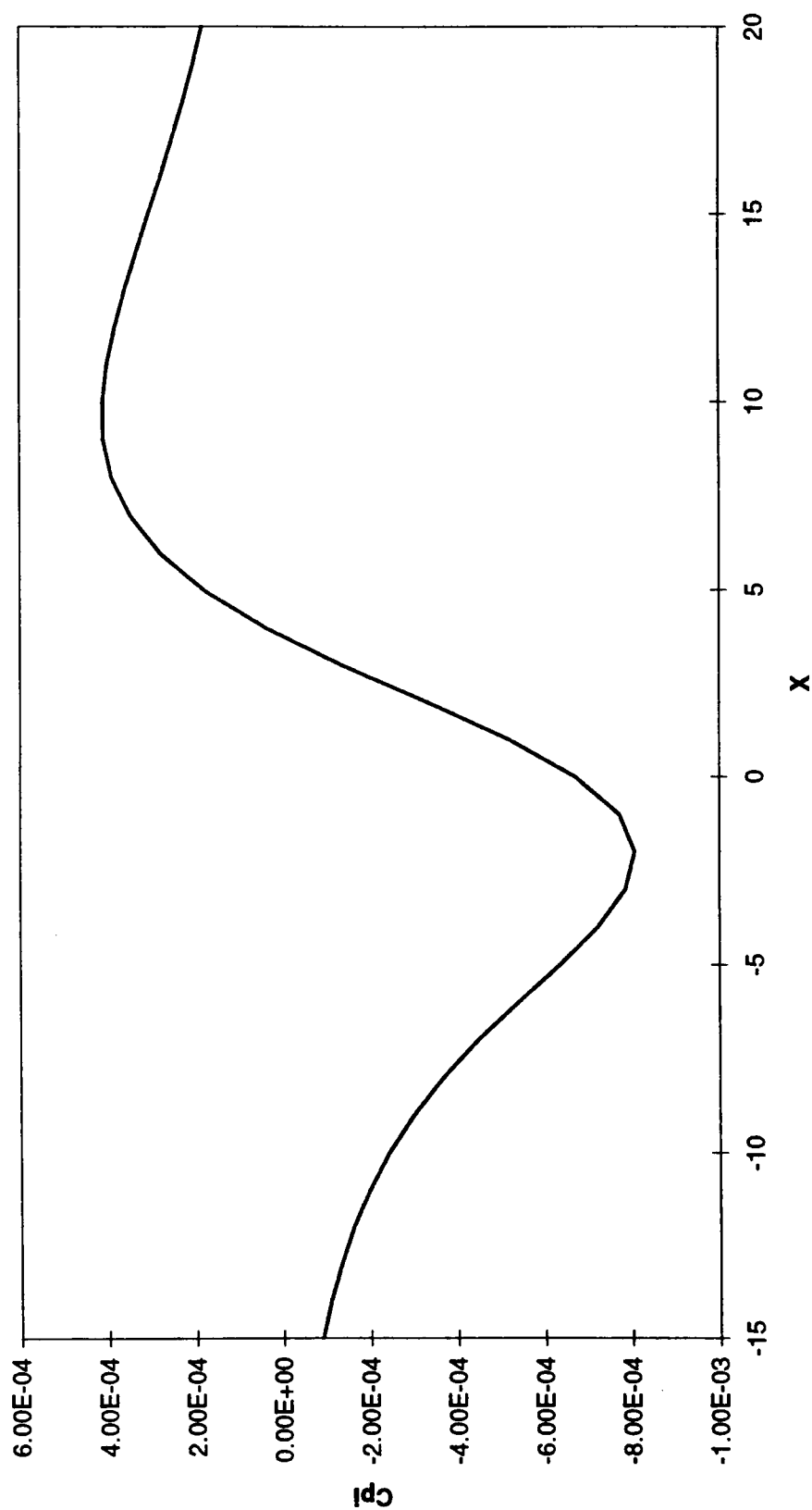


Figure 4.1 Plot of the interference pressure coefficient along the centerline for a perforated wall wind tunnel with distributed porosities of $R_1=0.18$, $R_2=0.25$, $R_3=0.3$ (try1h)

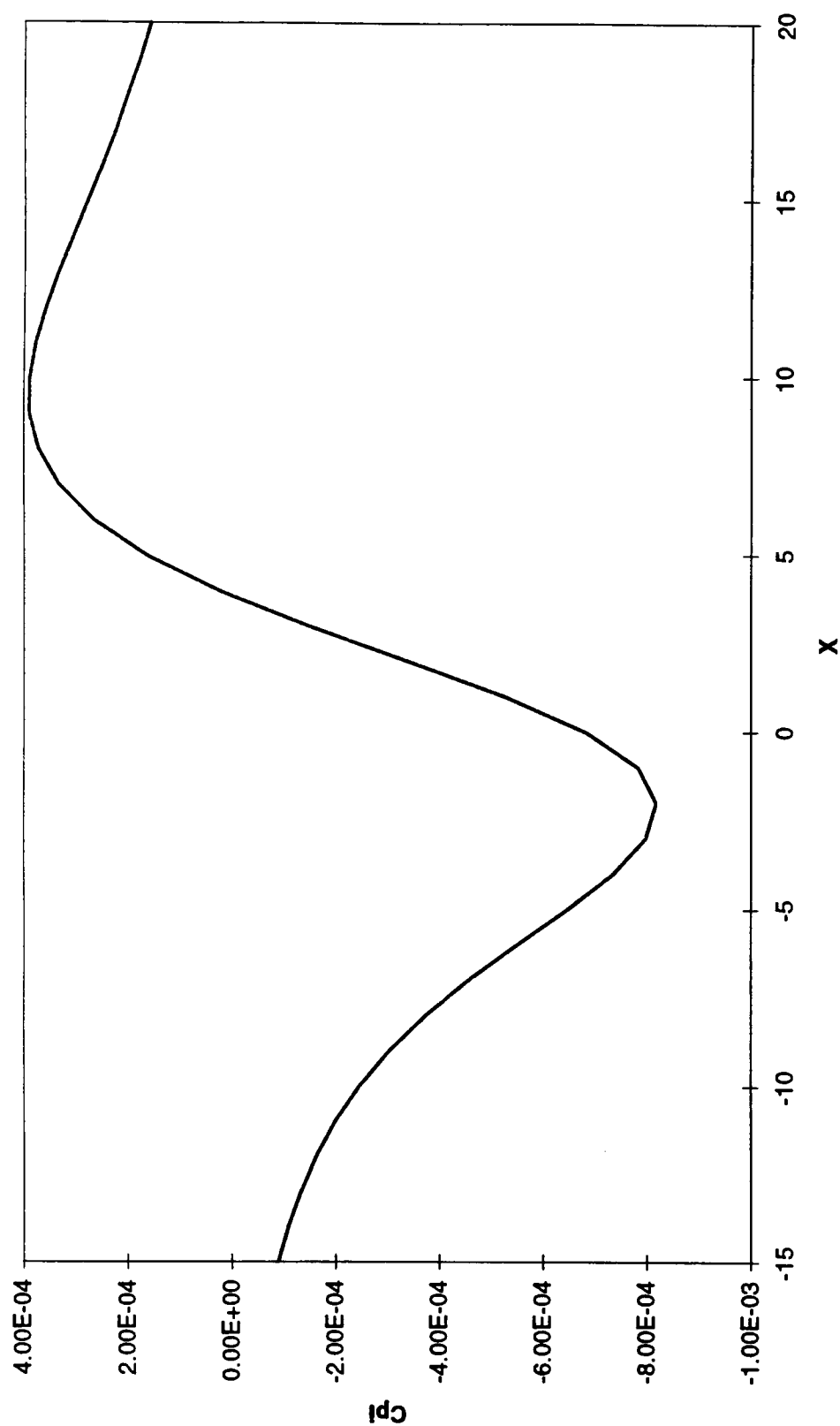


Figure 4.2 Plot of the interference pressure coefficient along the centerline for a perforated wall wind tunnel with varying porosities of $R_1=0.13$, $R_2=0.25$, $R_3=0.32$ (try1n)

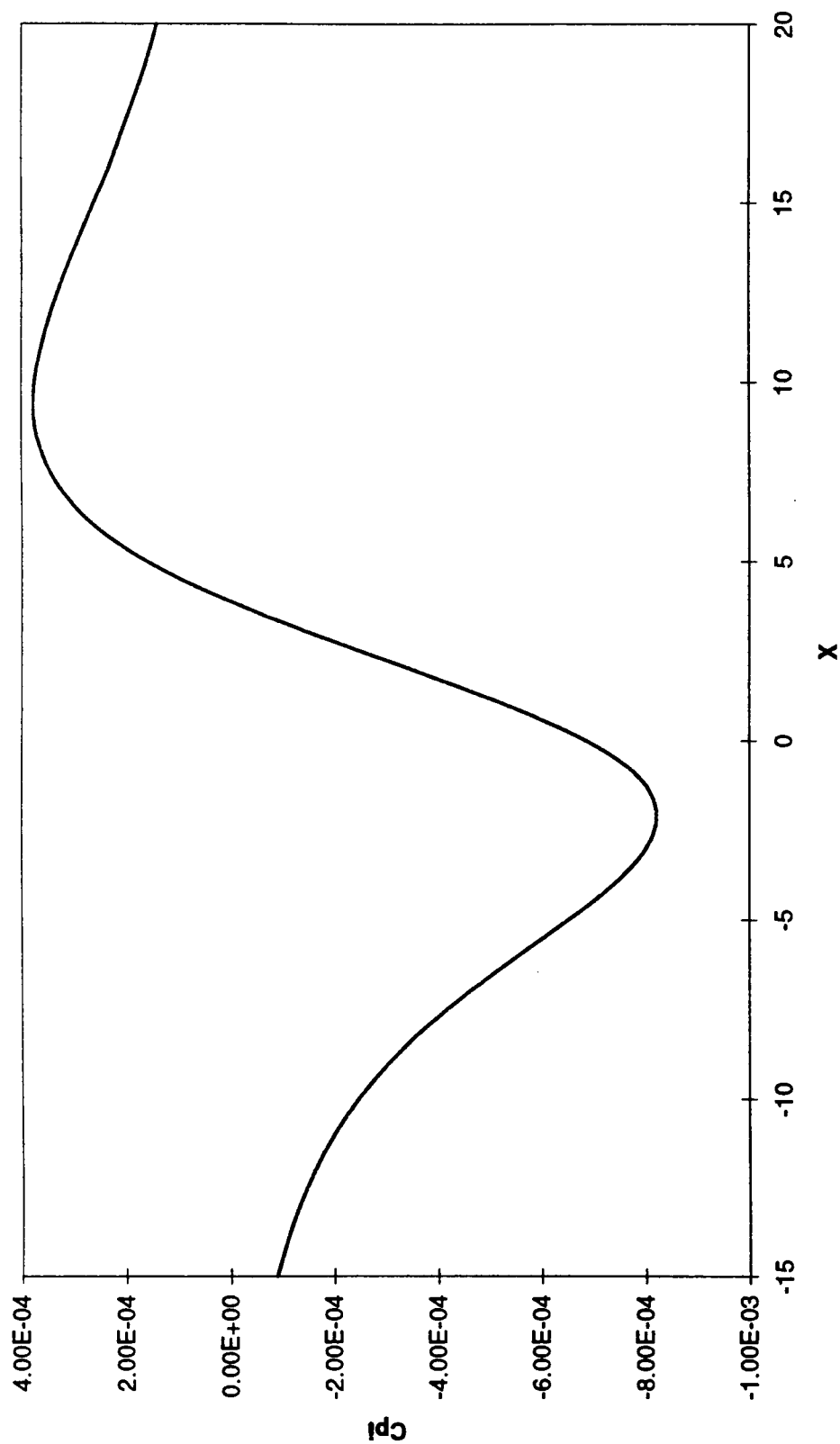


Figure 4.3 Plot of the interference pressure coefficient along the centerline for a perforated wall wind tunnel with distributed porosities of $R_1=0.11$, $R_2=0.25$, $R_3=0.33$ (try1o)

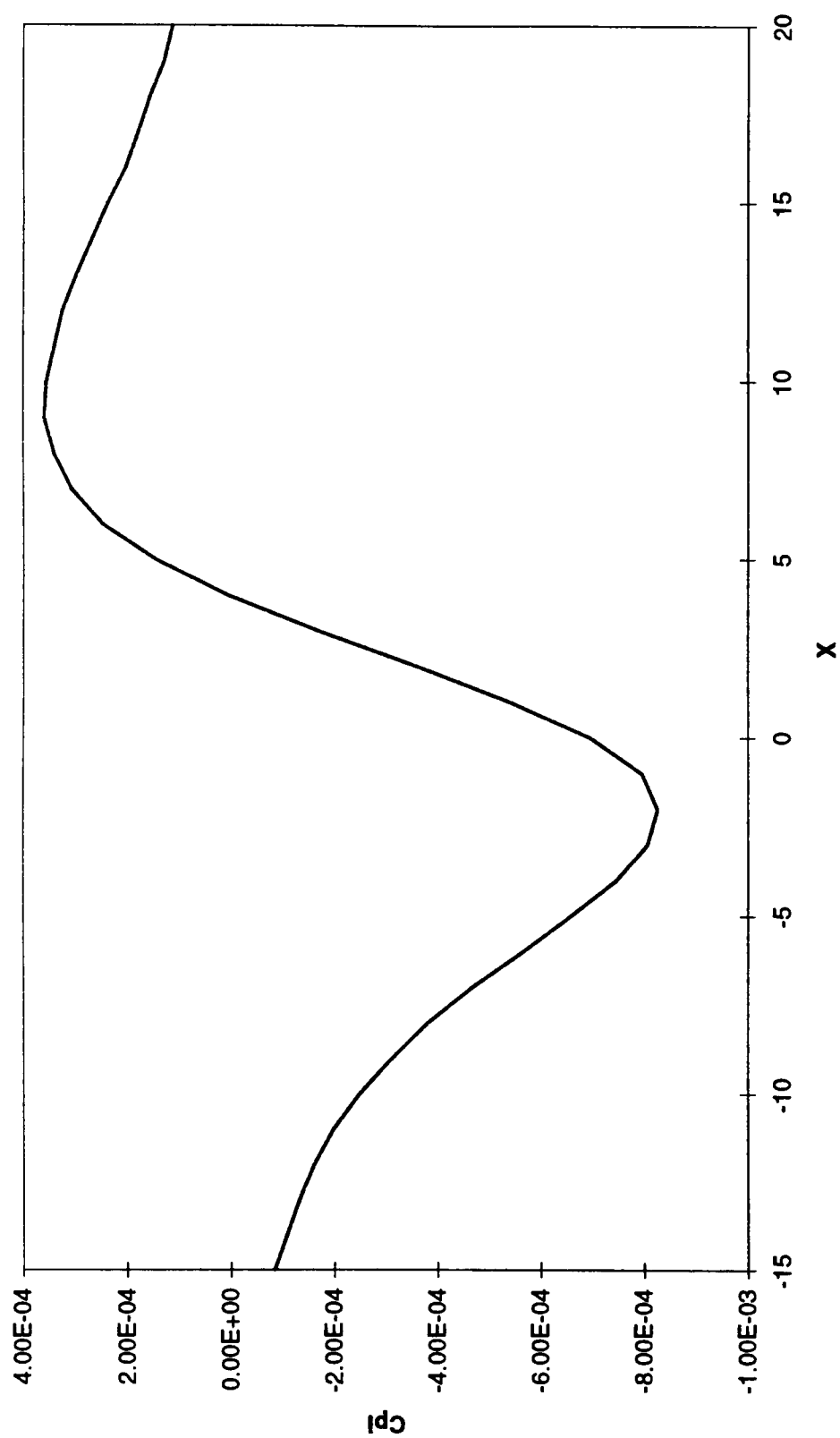


Figure 4.4 Plot of the interference pressure coefficient along the centerline for a perforated wall wind tunnel with distributed porosities of $R_1=0.08$, $R_2=0.25$, $R_3=0.34$ (try 1k)

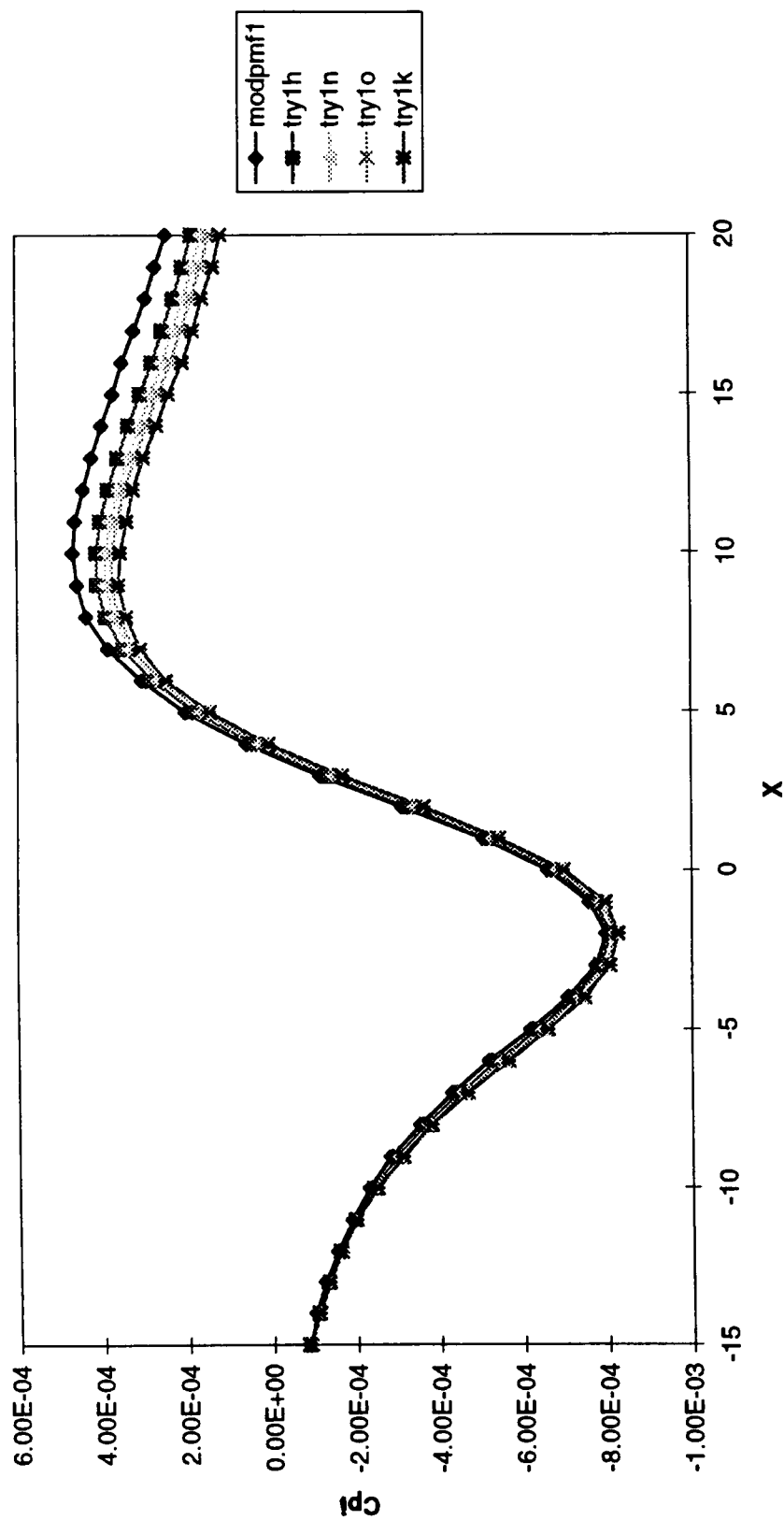


Figure 4.5 Comparison of the uniform porosity case (modpmf1, $R=0.25$) and the four cases with distributed porosities

VITA

Charles "Butch" Vision was born in St. Petersburg, Florida on July 27, 1971. He graduated from Gibbs Senior High School in St. Petersburg in 1989. He then transferred to St. Petersburg Junior College where he earned an Associate of Arts degree. He then continued his education at the University of Florida. In May 1994, he earned his Bachelor of Science in Mechanical Engineering. It was then that the University of Tennessee Space Institute called with a graduate research assistantship. Being too good of an offer to pass up, he moved to Tullahoma, Tennessee where he attended graduate school and finished in May 1996 with a Master of Science in Mechanical Engineering.

Charles is happily single and lives with a corn snake named Rasputin.