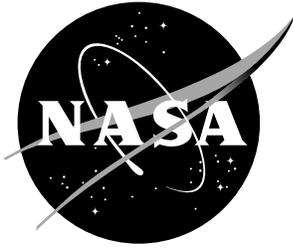


NASA/CR-2003-212157



# Source Term Model for an Array of Vortex Generator Vanes

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March 2003

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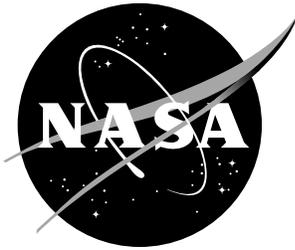
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## Abstract

A source term model was developed for numerical simulations of an array of vortex generators. The source term models the side force created by a vortex generator being modeled. The model is obtained by introducing a side force to the momentum and energy equations that can adjust its strength automatically based on the local flow. The model was tested and calibrated by comparing data from numerical simulations and experiments of a single low-profile vortex generator vane, which is only a fraction of the boundary layer thickness, over a flat plate. The source term model allowed a grid reduction of about seventy percent when compared with the numerical simulations performed on a fully gridded vortex generator without adversely affecting the development and capture of the vortex created. The source term model was able to predict the shape and size of the stream wise vorticity and velocity contours very well when compared with both numerical simulations and experimental data. The peak vorticity and its location were also predicted very well when compared to numerical simulations and experimental data. The circulation predicted by the source term model match the predictions of the numerical simulations.

## 1 Introduction

Low-profile vortex generating (VG) devices have shown significant improvement in turbofan engine-face distortion in the design of compact aircraft inlets [1]. Computational fluid dynamics (CFD) is a tool that can be used to predict the fan face distortion and in conjunction with experiments can be used to design new inlets. Before CFD can be used, researchers have to be sure that CFD analysis can model the complex flows associated with the vortices created by a VG. Allan et al. [2] have shown a comparison between a CFD analysis and experimental data of a low-profile vortex generator on a flat plate. Their results indicate that CFD analysis can accurately predict various aspects of the resulting vortex including size, shape, location, and decay. While the work conducted by Allan et al. was significant, the method used to model the VG has many drawbacks. In particular, the small size of the VG required very fine grids to model the VG and the region immediately surrounding the VG. The result was an increase in the number of grids required to model the entire flow and with an increase in grids comes an increase in computational time. As the number of VGs is increased from one to possibly twenty, a more efficient method must be used. Bender et al. introduced a source term model for modeling an array of VGs without gridding the VGs [3]. The model is obtained by introducing a side force to the momentum and energy equations that can adjust

its strength automatically based on the local flow. The user grids the rest of the flow replacing the VG with a boundary condition that models the side force created by the VG.

This report describes the implementation of a source term model for an array of VGs in the CFD software program called OVERFLOW version 1.8s [4] based on the method described by Bender et al. [3]. In addition, this report presents the results of CFD analysis utilizing the source term model on a low-profile VG oriented at ten degrees to the centerline of the initial flow on a flat plate. The results are compared to experimental results and CFD analysis with a gridded VG on the same 10° low-profile VG on a flat plate.

## 2 Numerical Method

The source term model was developed by Bender et al. [3], which describes vortex generator modeling for Navier-Stokes codes. The basic methodology of the model is to introduce a side force,  $\bar{L}_i$ , that is normal to the local flow and is parallel to the inlet surface. This side force is representative of the side force created by the VG being modeled. The final formulation for the side force is given by Equation 2.1.

$$\bar{L}_i = cS_{vg} \frac{\Delta V_i}{V_M} \rho (\bar{U} \cdot \hat{n}) (\bar{U} \times \hat{b}) \left( \frac{\bar{U}}{|\bar{U}|} \cdot \hat{t} \right) \quad 2.1$$

In equation 2.1,  $c$  is a calibration constant discussed later,  $S_{vg}$  is the planform area of the VG to be modeled,  $\bar{U}$  is the local velocity vector,  $(\Delta V_i)/V_M$  is the ratio of the cell volume to total volume of cells the source term is applied to,  $\rho$  is the density of the fluid, and  $\hat{b}$ ,  $\hat{n}$ , and  $\hat{t}$  are unit vectors that specify the orientation of the VG. Figure 2.1 shows a schematic of the orientation of these vectors given the angle of attack of the VG to the local flow,  $\alpha$ , and the tilt angle between the VG and the inlet surface,  $\phi$ . The components of the unit vectors are given by Equations 2.2 to 2.4.

$$b_1 = \cos(\phi)\cos(\alpha) \quad b_2 = \sin(\alpha)\cos(\phi) \quad b_3 = \sin(\phi) \quad 2.2$$

$$n_1 = \sin(\alpha)\sin(\phi) \quad n_2 = -\cos(\alpha)\sin(\phi) \quad n_3 = \cos(\phi) \quad 2.3$$

$$t_1 = \cos(\alpha)\sin(\phi) \quad t_2 = \sin(\alpha)\sin(\phi) \quad t_3 = \cos(\phi) \quad 2.4$$

The angle  $\phi$  is with respect to the flat plate and the angle  $\alpha$  is with respect to the plane perpendicular to the flat plate and parallel to the flow. These unit vectors are only for a VG on a flat plate and will

have to be modified for a VG on a curved surface. The computed side force is added to the discretized momentum and energy equations.

The source term model was implemented into the CFD code OVERFLOW version 1.8s [4] (See Appendix for Fortran 77 code). OVERFLOW solves the steady, compressible, Reynolds-Averaged Navier-Stokes (RANS) equations using the diagonal scheme of Pulliam and Chaussee [5]. The RANS equations are solved on structured grids using the overset grid framework of Steger et al. [6], which allows for complex geometries. The source term model is invoked in OVERFLOW by applying a boundary condition to a small group of cells containing the VG to be modeled. In particular, a row or several rows of cells that span the chord and the height of the VG are selected. For this study 6 cells were used to span the chord of the VG and 42 cells were used to span the height of the VG. The number of rows used was varied between 1, 3, and 11. The user also specifies the planform area,  $S_{vg}$ ; the angle of attack between the local flow and the VG,  $\alpha$ ; and the tilt angle between the VG and the inlet surface,  $\phi$ .

The source term model was tested by running simulations on a flat plate and implementing a source term boundary condition to model a low-profile VG. The grid for the flat plate used in this study is shown in Figure 2.2 and comprises a large, coarse block grid for the flat plate and a smaller, finer block grid for capturing the vortex for a total of 1,888,000 grid cells. A schematic of the VG being modeled is shown in Figure 2.3, which has a length to height ratio of approximately 7, a planform area of  $0.5772 \text{ mm}^2$ , a  $10^\circ$  angle of attack relative to the local flow, and a tilt angle of  $90^\circ$  to the inlet surface. To improve the convergence of the steady-state solution, both the low-Mach preconditioning and multigrid acceleration options of OVERFLOW were used. All simulations were run using the two-equation ( $\kappa$ - $\omega$ ) Shear-Stress Transport (SST) turbulence model of Menter [7]. The SST model was used because the study conducted by Allan et al. [2] indicate the SST model does a better job than the Spalart and Allmaras (SA) turbulence model [8] predicting the location, magnitude, and decay of the vortices being studied. All simulations were run at a freestream velocity,  $U_\infty$ , of 34 m/s.

OVERFLOW was compiled and run on a Compaq Alpha 500 MHz machine for this study. The total run time for each case was approximately 40 hours. The parallel version of OVERFLOW, developed by Jespersen [9], was not used for this study because the source term model needed to be tested on a single processor first. Future studies can utilize the parallel version of OVERFLOW to drastically reduce the computational time.

### 3 Results

The results of the source term model simulations were compared to a simulation of a gridded VG and experimental data on the VG being modeled. The source term model was calibrated before comparisons were made. To calibrate the model, Bender et al. [3] suggested that a calibration constant,  $c$ , be used to scale the side force in the source term model. In particular, Bender et al. suggested plotting the effects of the normalized, cross-stream kinetic energy,  $K$ , downstream of the VG as the calibration constant is increased. As the calibration constant is increased, the cross-stream kinetic energy downstream of the source term should asymptote to the cross-stream kinetic energy downstream of the gridded VG at the same location. The normalized, cross-stream kinetic energy is given by Equation 3.1.

$$K = \frac{\int_A \rho(v^2 + w^2) dA}{\int_A \rho u^2 dA} \quad 3.1$$

In Equation 3.1,  $u$ ,  $v$ , and  $w$  are the components of the local velocity vector,  $\bar{U}$ ,  $\rho$  is the density of the flow field, and  $A$  is the area of the cross-section over which the cross-stream kinetic energy is integrated. The asymptotic region of a cross stream kinetic energy plot is the region of interest, since the cross stream kinetic energy is no longer changing as the calibration constant is increased further. A total of 15 cases were run to establish the asymptotic region and to investigate the effects of varying the number of rows that span the chord and the height of the VG being modeled. Figure 3.1 shows the square root of the normalized, cross-stream kinetic energy,  $K^{1/2}$ , versus the calibration constant,  $c$ , at various grid cell widths or number of rows of the VG being modeled. The calibration constant was varied from  $c = 0.5, 1, 2, 5$  and  $10$  and the cell widths varied between  $1, 3,$  and  $11$ . The number of rows needed to model the VG will vary depending on the coarseness of the grid and can only be determined by calibration. In particular, once a value of a calibration constant causes the curve of Figure 3.1 to asymptote, the user may then modify the cell width until the asymptotic region matches the cross-stream kinetic energy of the gridded VG. In Figure 3.1, the cases with 3 grid cells wide asymptotes to the cross-stream kinetic energy of the gridded VG. The case with 3 grid cells wide and a calibration constant,  $c = 10$  will be used for comparison with experimental data and CFD data from the gridded VG.

The circulation,  $\Gamma$ , which characterizes the decay of the vortex strength, and the streamwise vorticity,  $\omega$ , were computed for the source term model by Equations 3.2 and 3.3 respectively.

$$\Gamma = \int_A \left( \frac{\partial v}{\partial z} - \frac{\partial w}{\partial y} \right) dA \quad 3.2$$

$$\omega = \frac{\partial v}{\partial z} - \frac{\partial w}{\partial y} \quad 3.3$$

In Equations 3.2 and 3.3,  $v$  and  $w$  are the components of the local velocity vector,  $\bar{U}$ ,  $y$  and  $z$  are the cross-stream directions perpendicular to each other and to the axial direction,  $x$ , and  $A$  is the area of the cross-section over which the circulation is integrated. Figure 3.2 shows a comparison of the positive circulation between the source term model, the experiment, and the gridded VG. The axial location,  $x$ , is nondimensionalized by the boundary layer thickness,  $\delta = 0.045$  m. The source term model compares very well with the gridded VG. Although, both the source term model and the gridded VG do not compare well with the experiment upstream, they compare well with each other. This comparison helps to validate the use of the source term model as an alternative to the fully gridded VG. The peak streamwise vorticity,  $\omega_{\max}$ , and its location are shown in Figure 3.3. The plots are also nondimensionalized by the boundary layer thickness,  $\delta = 0.045$  m. The source term predicts the vortex trajectory very well; details of peak vorticity are not resolved near the VG, but far away the effects are the same. Figures 3.4 and 3.5 show the streamwise velocity,  $u$ , and the streamwise vorticity,  $\omega$ , contours at various locations downstream from the VG. The source term model predicts the size and shape of both contours except at the streamwise velocity contour immediately downstream of the VG at  $x = 0.152$  m. The shape at this location is not as pronounced as both the experiment and the gridded VG.

The flow vector residual history is shown in Figure 3.6. The residual history is used to track the convergence of the CFD solution. A residual drop of several orders of magnitude is expected from the coarse solution to the fine solution of a converged solution. As shown in Figure 3.6, the solution has dropped four orders of magnitude for the block grid that captures the vortex and three orders of magnitude for the flat plate grid.

## 4 Conclusion

In general, the source term model predicted the size, shape, location, and decay of the streamwise vorticity and is a viable alternative to a fully gridded VG solution. The fully gridded solution used for comparison in this study comprised a total of 6,405,100 grid cells. The source term model realized a 70 percent reduction in grid cells without any significant drop in predicting the flow

field. While the source term model will never fully replace gridding the entire VG, it will substantially reduce the amount of cases run with a fully gridded VG. The source term model can be used to run the majority of cases and configurations of further interest can then be fully gridded for detailed study.

Future studies will include examining the effects on predicting the flow field by further grid reduction. In addition, there are plans for work on an inlet with the source term modeling several VGs, as well as expanding the model to predict the effects of synthetic jets.

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- [9] Jespersen, D. C., *Parallelism and OVERFLOW*, Tech. Report NAS-98-013, NASA Ames Research Center, Moffett Field, CA 23681-2199, October 1998.

## Figures

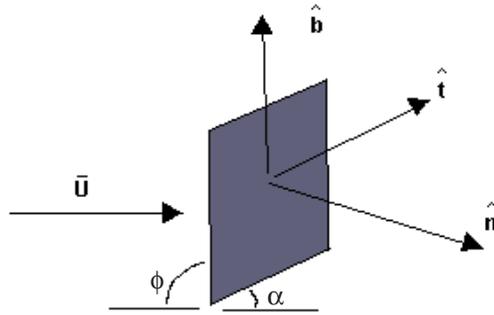


Figure 2.1. Schematic of orientation of unit vectors.

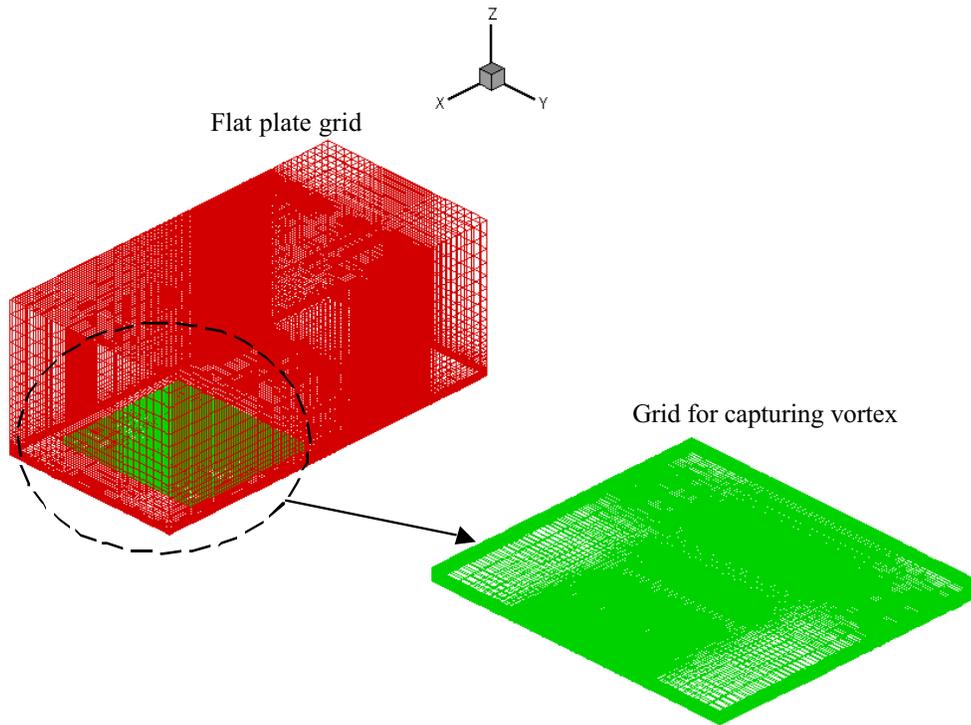


Figure 2.2. Overset grids for source term model.

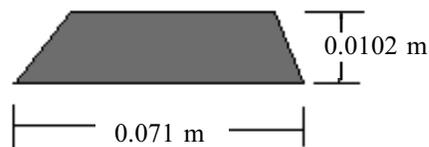


Figure 2.3. Schematic of vortex generator modeled

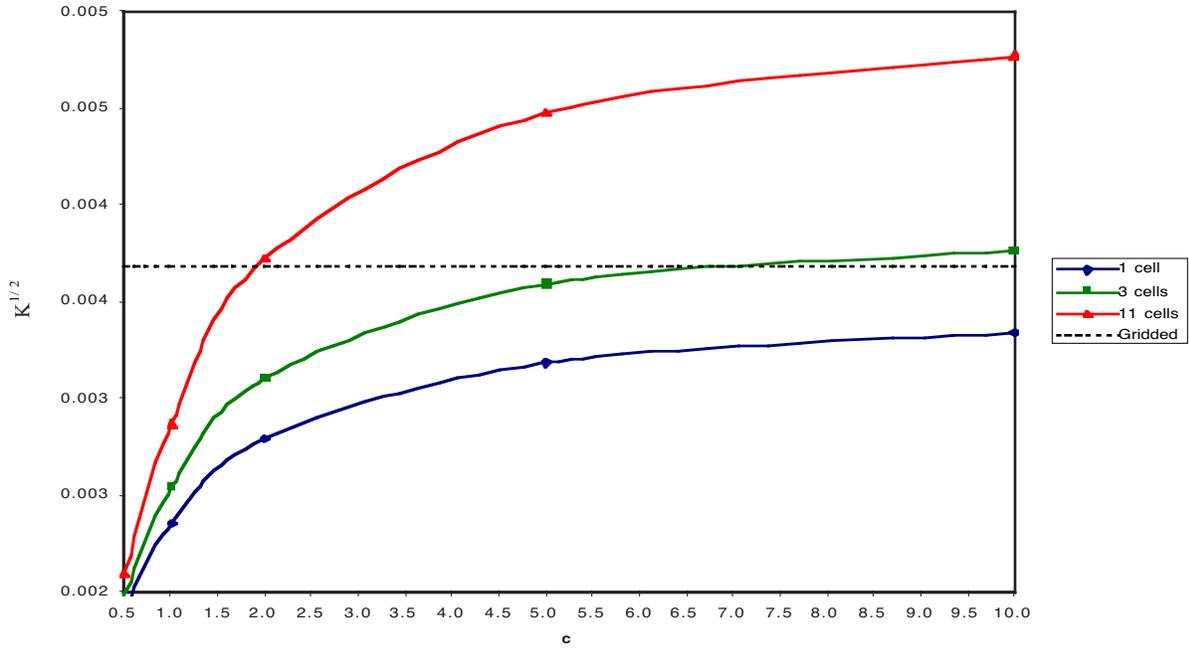


Figure 3.1. Square root of the normalized, cross-stream kinetic energy,  $K$ , versus calibration constant,  $c$ .

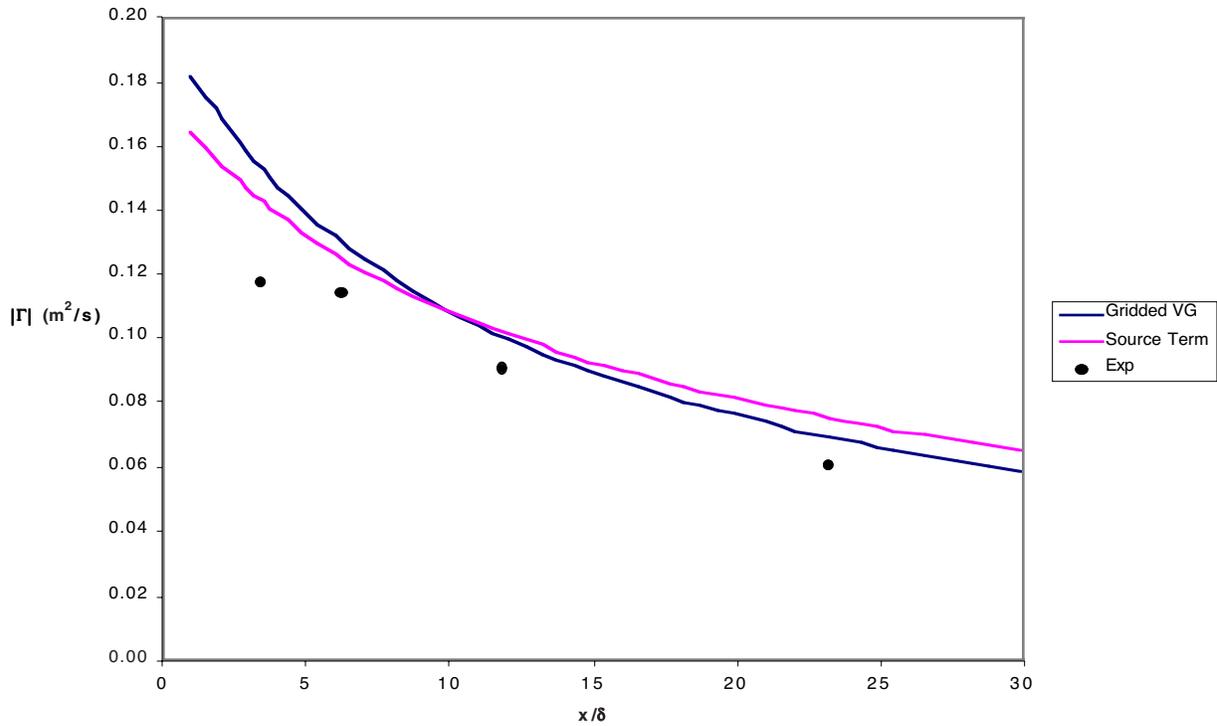


Figure 3.2. Circulation versus axial location.  $\delta = 0.045$  m.

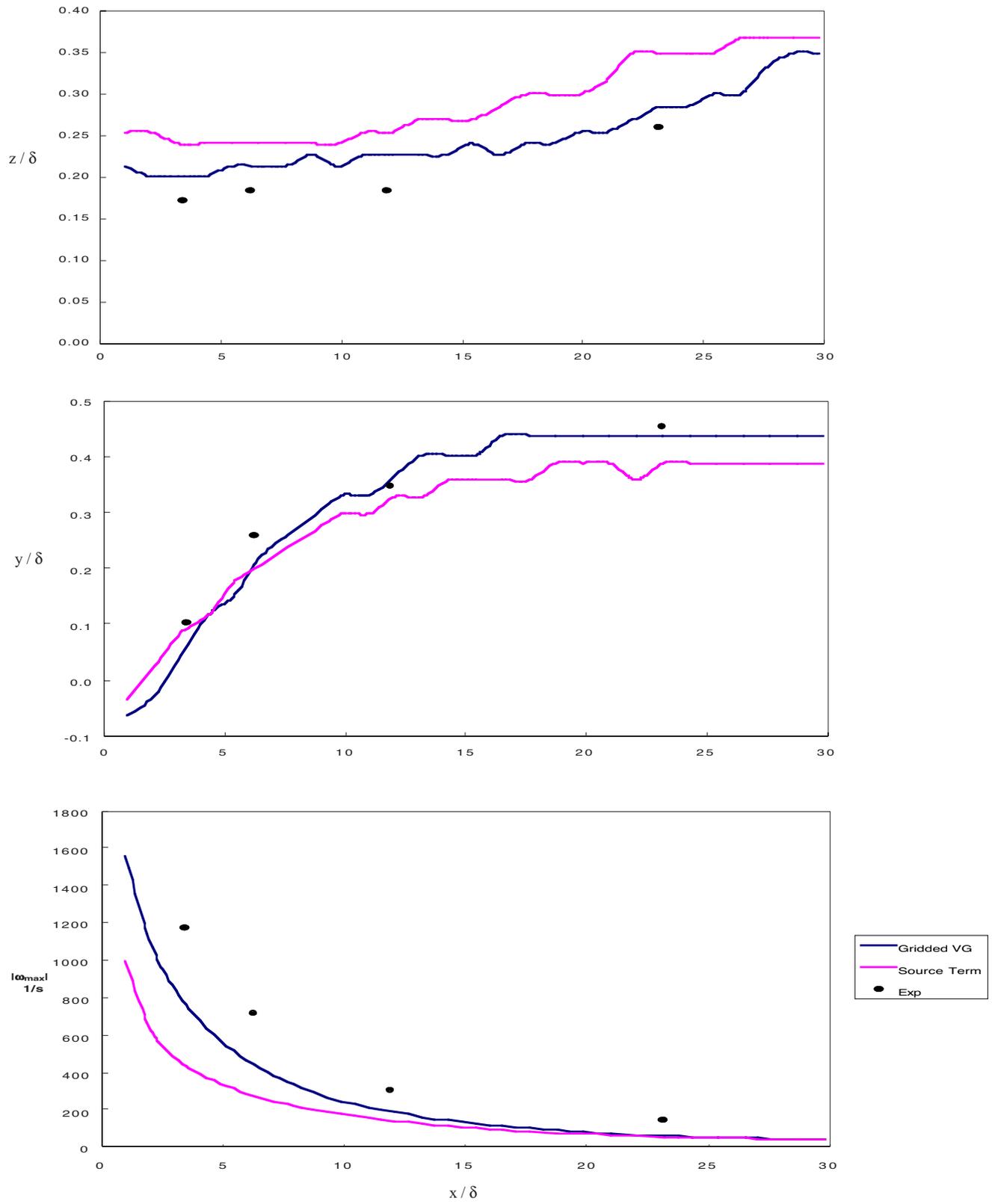


Figure 3.3. Location of the peak streamwise vortex versus axial location.  $\delta = 0.045$  m.

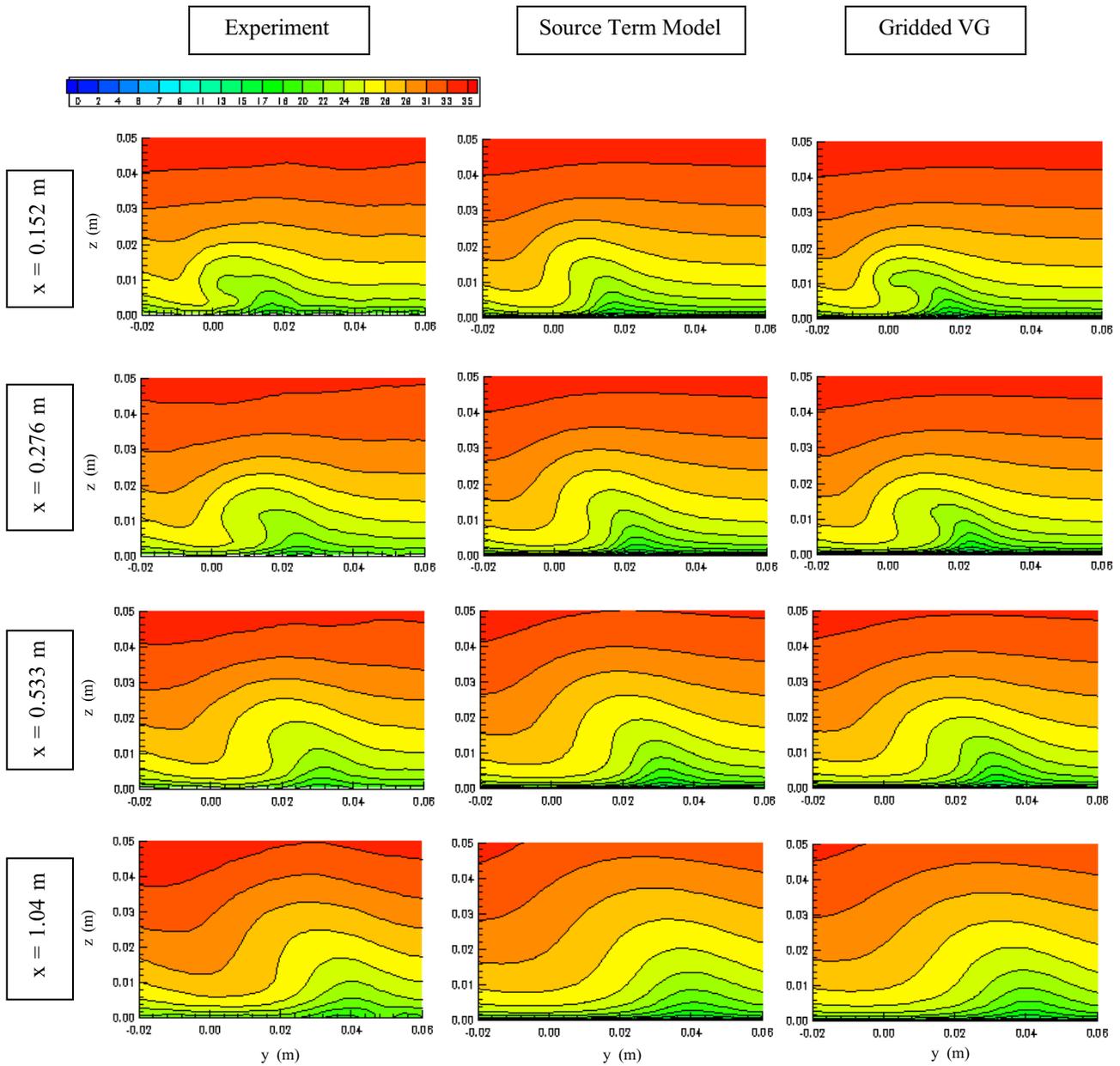


Figure 3.4. Streamwise velocity contours at various distances downstream from VG.

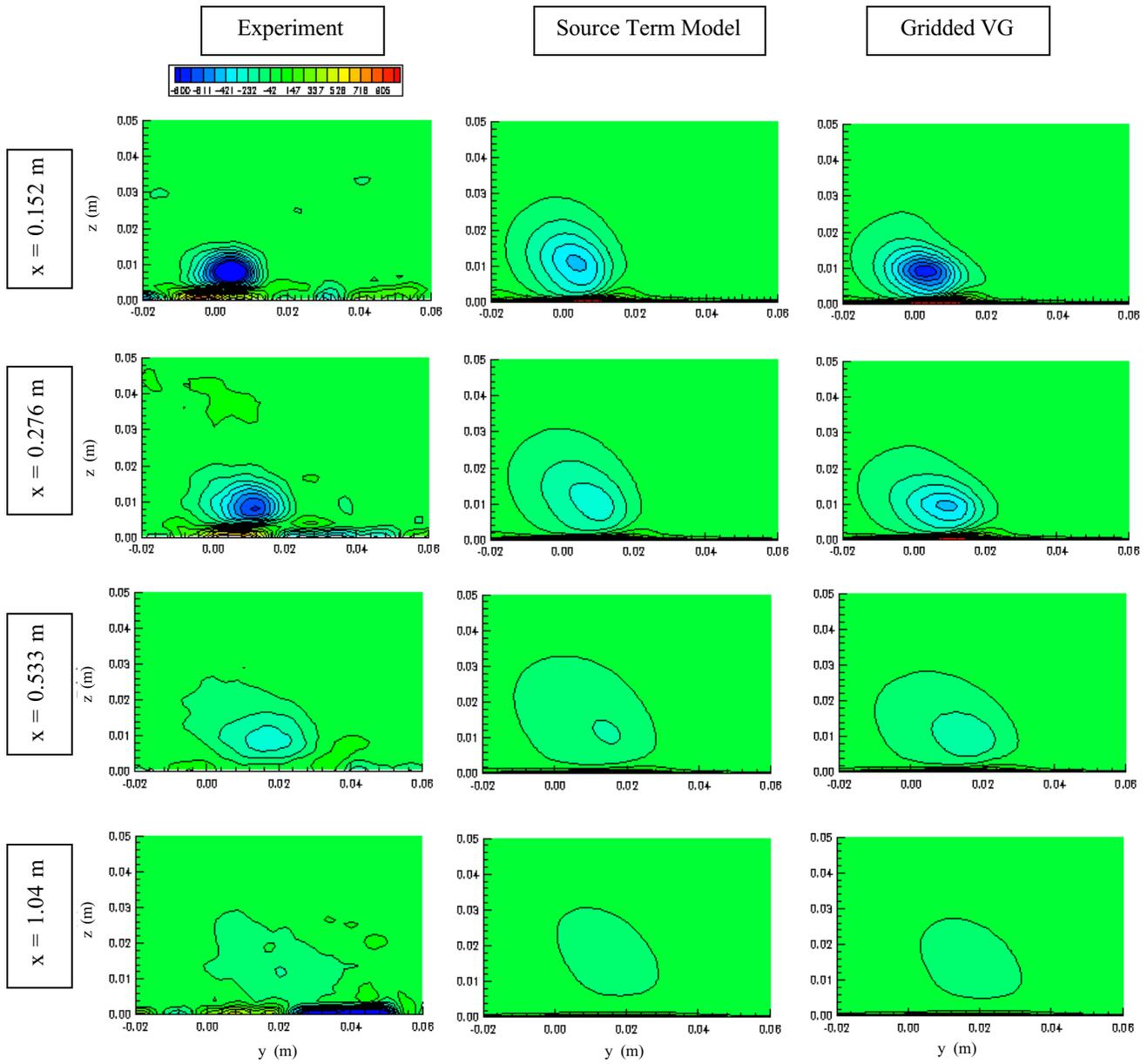


Figure 3.5. Streamwise vorticity contours

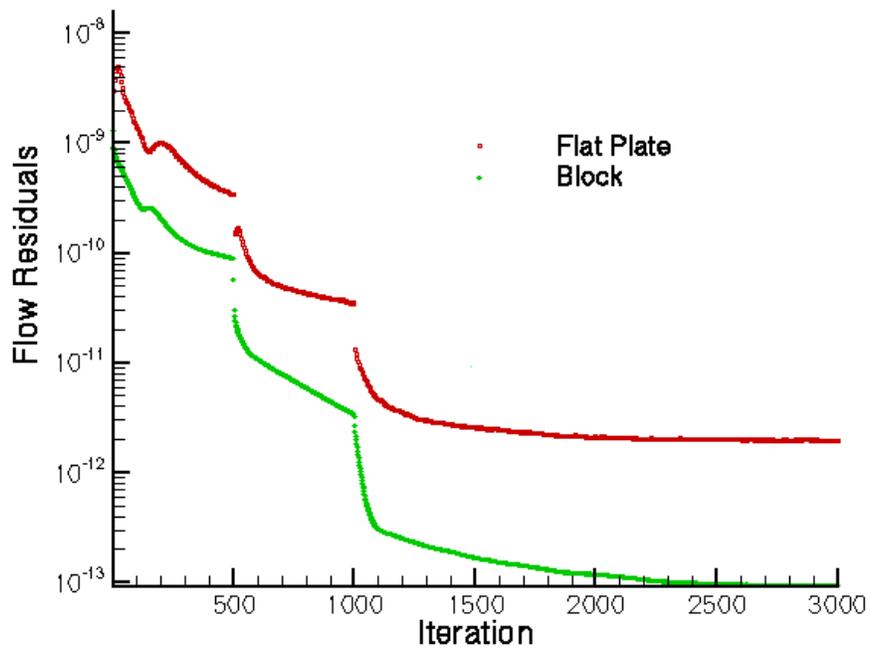


Figure 3.6. Flow residual history of flat plate and block capturing the vortex.

## Appendix – Fortran 77 Listing of Source Term Subroutine and Input Files

### Source Term Subroutine

```
c SUBROUTINE SOURCE TERM
*****
* Author:      Kenrick A. Waithe      *
* Date:        11/09/01                *
* Description: This program will calculate the source term that would      *
*              be created from a vortex generator. This source term        *
*              is applied to the cells where the generator would have      *
*              been located.          *
*****
      subroutine source(js,ks,ls,je,ke,le,jd,kd,ld,vol,q,nq,s)
      real vol(jd,kd,ld), q(jd,kd,ld,nq), s(jd,kd,ld,5)
      real sr(jd,kd,ld,5)
      real u(jd,kd,ld), v(jd,kd,ld), w(jd,kd,ld), rho(jd,kd,ld)
      real norm(jd,kd,ld), udotn(jd,kd,ld), uvecdott(jd,kd,ld)
      real n(3), t(3), b(3)
      real totvol, c, Svg, alpha, phi
      integer i,j,k,l

c Zero out total volume (totvol)
      totvol=0

c Read in VG properties

      open (1, FILE = 'vg.dat', STATUS = 'OLD')
      open (2, FILE = 'vg.out', STATUS = 'UNKNOWN')
      read (1,*) c, Svg,alpha, phi
      t(1)=(cosd(alpha))*(sind(phi))
      t(2)=(sind(alpha))*(sind(phi))
      t(3)=(cosd(phi))
      n(1)=(sind(alpha))*(sind(phi))
      n(2)=-cosd(alpha)*(sind(phi))
      n(3)=(cosd(phi))
      b(1)=(cosd(alpha))*(cosd(phi))
      b(2)=(sind(alpha))*(cosd(phi))
      b(3)=(sind(phi))
      write (2,*) "Unit Vectors t, n and b"
      write (2,*) (t(i),i=1,3)
      write (2,*) (n(i),i=1,3)
      write (2,*) (b(i),i=1,3)
      write (2,*) ""

c Start loop to calculate everything
      do j=js,je
         do k=ks,ke
            do l=ls,le

c Defining flow variables
```

```

rho(j,k,l)=q(j,k,l,1)
u(j,k,l)=q(j,k,l,2)/rho(j,k,l)
v(j,k,l)=q(j,k,l,3)/rho(j,k,l)
w(j,k,l)=q(j,k,l,4)/rho(j,k,l)
write (2,*) "Flow Velocity"
write (2,*) u(j,k,l),v(j,k,l),w(j,k,l)
write (2,*) ""

```

```

c Defining normal for velocity vector
norm(j,k,l)=sqrt((u(j,k,l)**2) +
& (v(j,k,l)**2) +
& (w(j,k,l)**2) )

```

```

c Defining total volume (totvol)
totvol=totvol+vol(j,k,l)

```

```

enddo
enddo
enddo

```

```

c Defining source terms

```

```

do j=js,je
do k=ks,ke
do l=ls,le

```

```

udotn(j,k,l)=u(j,k,l)*n(1) +
& v(j,k,l)*n(2) +
& w(j,k,l)*n(3)

uvecdott(j,k,l)=(1/norm(j,k,l))*(u(j,k,l)*t(1) +
& v(j,k,l)*t(2) +
& w(j,k,l)*t(3) )

```

```

c compute source terms

```

```

sr(j,k,l,2)=(c*Svg*(vol(j,k,l)/totvol) *
& rho(j,k,l)*udotn(j,k,l)*uvecdott(j,k,l) *
& (v(j,k,l)*b(3) - w(j,k,l)*b(2)) )
sr(j,k,l,3)=(c*Svg*(vol(j,k,l)/totvol) *
& rho(j,k,l)*udotn(j,k,l)*uvecdott(j,k,l) *
& (w(j,k,l)*b(1) - u(j,k,l)*b(3)) )
sr(j,k,l,4)=(c*Svg*(vol(j,k,l)/totvol) *
& rho(j,k,l)*udotn(j,k,l)*uvecdott(j,k,l) *
& (u(j,k,l)*b(2) - v(j,k,l)*b(1)) )

```

```

c add source terms to other momentum and energy equations

```

```

s(j,k,l,2)=s(j,k,l,2) + sr(j,k,l,2)
s(j,k,l,3)=s(j,k,l,3) + sr(j,k,l,3)
s(j,k,l,4)=s(j,k,l,4) + sr(j,k,l,4)
s(j,k,l,5)=s(j,k,l,5) + (0.5*((sr(j,k,l,2)*u(j,k,l))+
& (sr(j,k,l,3)*v(j,k,l)) +
& (sr(j,k,l,4)*w(j,k,l))))

```

```

c Print out source terms after adding vg source to them
  write (2,*) "Source Terms after adding VG source"
  write (2,*) s(j,k,l,2), s(j,k,l,3), s(j,k,l,4)
  write (2,*) ""
  write (2,*) ""

      enddo
    enddo
  enddo
close(1)
return
end

```

## Input Files

### vg.dat for c = 0.5:

```

C Svg alpha phi
0.5 .0000555 10 90

```

### vg.dat for c 1:

```

C Svg alpha phi
1 .0000555 10 90

```

### vg.dat for c = 2:

```

C Svg alpha phi
2 .0000555 10 90

```

### vg.dat for c = 5:

```

C Svg alpha phi
5 .0000555 10 90

```

### vg.dat for c = 10:

```

C Svg alpha phi
10 .0000555 10 90

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14. ABSTRACT A source term model was developed for numerical simulations of an array of vortex generators. The source term models the side force created by a vortex generator being modeled. The model is obtained by introducing a side force to the momentum and energy equations that can adjust its strength automatically based on a local flow. The model was tested and calibrated by comparing data from numerical simulations and experiments of a single low-profile vortex generator vane, which is only a fraction of the boundary layer thickness, over a flat plate. The source term model allowed a grid reduction of about seventy percent when compared with the numerical simulations performed on a fully gridded vortex generator without adversely affecting the development and capture of the vortex created. The source term model was able to predict the shape and size of the stream wise vorticity and velocity contours very well when compared with both numerical simulations and experimental data.					
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