Numerical and Experimental Evaluations of the Flow Past Nested Chevrons

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Nomenclature

d = screen wire diameter
g_s = edge condition (see Fig. 2)
k = presssure drop coefficient, $= 2\ (P_{\text{upwind}} - P_{\text{downwind}})/\rho U_0^2$ (note that k_s is for screen and V_n replaces U_0)
L = length of the extension wall (see Fig. 2)
s_c = spacing between chevrons (see Fig. 2)
$\tilde{u}$ = rms of the streamwise velocity fluctuations
U_0 = approach velocity
V_n = normal velocity component at the screen
w_c = characteristic chevron dimension (see Fig. 2)
x,y = streamwise and transverse coordinates
δt^* = nondimensional time step for the calculations, $= U_0 \delta t / w_c$

Abstract

THE use of computer simulations in the service of fluids engineering calculations is a developing area of activity. The present communication contributes to this development by recording a successful use of vortex dynamics for the computation of the pressure drop past a planar array of chevron-shaped obstructions. It was initially estimated that these obstructions, which were under consideration for acoustical attenuation of engine test noise in the 24.4×36.6 m^2 (80×120 ft^2) tunnel at the NASA Ames Research Center, would provide an acceptable pressure drop. A simulation of the flow (executed by the third author) predicted a loss coefficient k 8–10 times larger than that estimate. An ensemble of results, similar to those shown in Fig. 1, were used to compute the loss coefficient k. These calculations stimulated a brief experimental program[1] to assess the measured loss coefficient for the same flow geometry.

The experiments supported the numerical (but not the ad hoc) estimates; hence, the plan to use the chevrons was canceled and this decision completed the technological portion of the investigation. The fluid dynamic issues that have been raised by these independent efforts are not fully resolved. This synoptic should serve as a stimulus for their further consideration.

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The calculations were performed using the two-dimensional vortex method applied by Spalart[2] to cascades of airfoils in a study of rotating stall. (This program is available for public use in the United States; interested parties can contact the NASA Ames Research Center.) It is a spatially periodic version of an earlier method of Spalart and Leonard.[3] Its ability to treat abritrary geometries without conformal mappings or

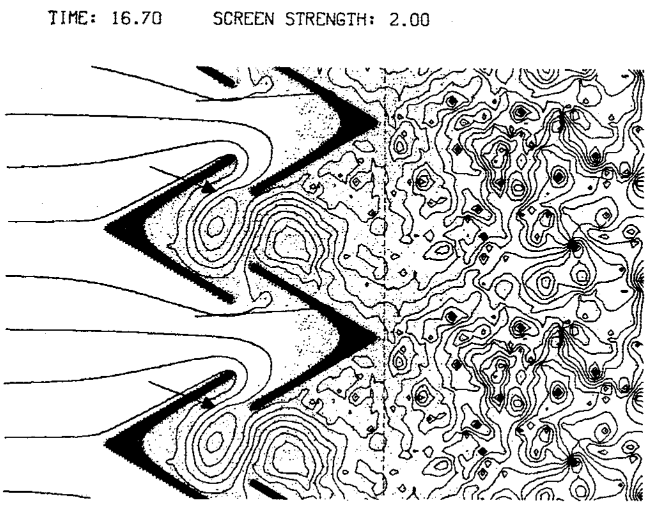
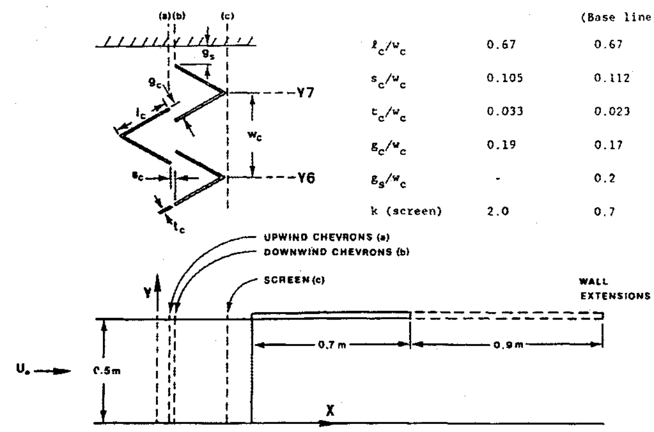


Fig. 1 One realization of the flow past a set of chevrons (note: $k = 86$).



	Calculation	Experiment (Base line)
ℓ_c/w_c	0.67	0.67
s_c/w_c	0.105	0.112
t_c/w_c	0.033	0.023
g_c/w_c	0.19	0.17
g_s/w_c	-	0.2
k (screen)	2.0	0.7

Fig. 2 Definition sketch for the experiment.

image vortices was a major asset for the present application. Vortices are released along the solid boundaries at each time step to enforce the boundary conditions. Viscous effects are otherwise neglected. The development of the primary boundary layers is computed by integral methods. The dashed line in Fig. 1 represents the fine mesh screen $k_s = 2$) that was to be included with the chevrons. Note that the screen is modeled as a resistive force (per unit length), $\delta F = -\hat{i} k_s (\rho V_n^2/2)\,\delta_y$, in the momentum equation. The curl operation, applied to this equation, yields $(k\rho V_n^2/2)$ as a source term in the vorticity transport equation; vorticity was introduced at the screen face in accord with this expression.

The sharp edges and high local velocities made the chevron geometry numerically demanding. The number of vortices was about 2000 and the nondimensional step δt^* was 0.002. Up to 10,000 time steps were needed to establish the flow and collect averages. Periodic boundary conditions and one pair of chevrons were included in the calculation; the domain is shown twice in Fig. 1 for clarity. The dots are the vortices and the lines are instantaneous streamlines. The arrows are instantaneous force vectors. One can see large vortices forming between the chevrons.

The time-averaged loss coefficient k was about 86 for the chevrons plus the screen. [Preliminary results from the numerical calculations (unrecorded) suggested only a small contribution to the k value from the screen.] A control volume, which extends from the region upstream of the chevrons to a downstream location where the mean velocity is again uniform and equal to U_0, shows that

$$k = \frac{2\Delta p}{\rho U_0^2} = \frac{\overline{3\acute{u}^2}}{U_0^2} + \frac{\overline{\acute{v}^2}}{U_0^2} + \frac{\overline{\acute{u}^3}}{U_0^3} + \frac{\overline{\acute{u}\acute{v}^2}}{U_0^3} \qquad (1)$$

for the numerical calculation. The large k value, therefore, suggests that quite large disturbance levels exist downstream of the assembly.

The experiments were executed in the 50×80 cm^2 primary flow opening of the single stream shear layer facility at Michigan State University (MSU).[4] Unlike the laterally "unbounded" calculations (laterally periodic boundary conditions), the experimental configuration was required to select an arbitrary edge condition g_s. This value, and a comparison of the MSU and Ames values are presented in Fig. 2. The values shown are nominal; fabrication irregularities resulted in the specific dimensions documented in Ref. 1. The interchevron spacing s_c was adjusted by means of spacers; the specific values are shown in Table 1.

The final module in the assembly provided for a screen just aft of the downwind set of chevrons. When the screen alone was placed in the tunnel, a pressure drop coefficient of $k = 0.07$ was obtained. The mean and rms velocites were determined using conventional hot-wire anemometry at a streamwise distance of 30 w_c for the two larger s_c values. (Note, however, that the rms values are based on the velocity, not the voltage, time series values.) The pressure drop was evaluated using the static pressure taps of a pitot-static probe that was moved from a location of $\simeq 2w_c$ upwind of the chevron's centerline to $\simeq 32 w_c$ downwind of the chevron face. The experimental results are presented in Table 1. The associated Reynolds number value is given as $R_e = w_c\, U_0/\nu \simeq 1.1 \times 10^4$.

Table 1 Pressure drop coefficient and fluctuating intensity[a]

s_c/w_c	0.0563	0.1125	0.169	No chevrons
Screen, k	86	82	57	0.70
No screen, k	—	62	—	—
Screen, $100 \times \tilde{u}/U_0$	25	25	26	—
No screen, $100 \times \tilde{u}/U_0$	—	26	—	—

[a] $\tilde{u}$ values were obtained at $s/w_c = 30$ and $W_c U_0/\nu = 1.1 \times 10^4$.

Note that there is no Reynolds number in the numerical simulation.

An interesting attribute of the flowfield was revealed by a survey with a wool tuft. Specifically, the region downwind of chevron 6 (see Fig. 2) was "stalled," whereas the air was clearly moving in the streamwise direction for the balance of the region downwind of the chevrons. The stalled region terminated just upwind of the extension wall termination for both the 70 cm ($L/w_c = 12.5$) and the 160 cm ($L/w_c = 28.6$) cases. The values of Table 1 were not, however, sensitive to the L/w_c value. It is inferred that this physical effect is similar to the flow nonuniformities that are observed downwind of a large solidity screen.

A noteworthy attribute of the experiments is the large effect of the screen, $k = 62$ vs 82 for the no-screen/screen cases. It is inferred that this net effect reflects the very large (cf U_0) local velocities as the flow finds its way through the narrow passages defined by the chevrons. The nonlinear dependence of k upon (s_c/w_c) is of interest in this regard and it is clearly significant that $\tilde{u}/U_0$ is nominally a constant for this wide range of conditions.

The entire pressure drop, for the numerical calculations, is represented by the terms of Eq. (1). If $\overline{\acute{u}^2} \simeq \overline{\acute{v}^2}$ and if the third-order terms are neglected, then $\acute{u}^2/U_0^2 \simeq 22$. This is dramatically different from the value of 0.063 suggested by the experiments. The latter value reflects the presence of viscous dissipation that is absent in the numerical results.

The provocative result, which invites further study, is the ability of such a numerical scheme to represent the production of turbulent kinetic energy in terms of the vorticity source terms. Clearly, a more sophisticated model would have to be incorporated if the effect of the screen were also to be accurately modeled.

Acknowledgment

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