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Asymmetric Distortion Generation in a Variable Height Annulus

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Abstract

POROUS screens were placed in the compressor intake to create quasisteady pressure maldistributed inlet flows. This study was aimed at creating a single-lobe circumferential sine-wave velocity profile with no radial components at the compressor inlet. A method relating screen blockage to predicted velocity levels was devised. The method yields velocity levels close to those for which the screen was designed.

Contents

Quasisteady pressure maldistributed compressor inlet flows are normally created during testing by the inclusion of porous screens in the compressor intake, but interactions between a row of compressor rotor blades and upstream placed screens in such experiments can alter the shape of the generated distortion.[1] Suppression of this effect may be realized by remote positioning of the screen upstream of the compressor leading-edge plane. Often, an intake may not be a constant annulus, so flow differences between the compressor leading-edge plane and the plane of the screen call for differences in the screen design whose generated distortion is itself modified in passing through the annulus to the compressor.

The aim of this study was to present to a compressor inlet a single-lobe circumferential sine-wave velocity profile with no radial components, the distortion being generated remotely upstream in a duct dissimilar to the annulus at the compressor intake. Based upon small perturbation assumptions, a method of screen design is proposed which superimposes a generated distortion upon the undistorted potential flow solution of the developed annulus. The example used was a bellmouth and nose-bullet sited coaxially close to the compressor leading-edge plane and separated only by a short length of the constant height annulus. The screen was set at the bellmouth intake, perpendicular to the axial direction.

While this example used symmetrical ducting, the principles involved could be applied to a nonsymmetrical installation.

Analytical Model

It was assumed that the flow was inviscid, leading to constant stagnation pressure along streamlines ahead of and behind the screen, except at the screen itself where there was a discontinuity in stagnation pressure governed by the equation:

$$\Delta P = \tfrac{1}{2}\rho K v_x^2$$

where

K = resistance coefficient of the screen
v_x = flow velocity in the axial direction
ρ = average air density

Using a small perturbation approach, it was assumed that the flow was not disturbed ahead of the screen either by being deviated to a different meridional plane or, by using the continuity equation, was the velocity ahead of the screen altered by the screen blockage.

In the case studied it was desired to create a circumferential sine-wave velocity distortion in the flow, so the vorticity resulting from such a pressure distribution was also convected along the same streamline paths. This transport pattern was repeated in every meridional plane where it will be seen it was necessary to impose a gradation of stagnation pressure. Appealing to Crocco's equation then, there was a nonhomentropic rotational flow following a symmetrical streampath.

The annulus was divided radially at the rotor inlet plane into 10 equal area annuli with 11 boundaries, 2 of which were duct walls and were considered as stream surfaces.

The boundaries were given by:

$$r_j = r_i\, j(v^2 - 1)(z+1)^{-\frac{1}{2}} + 1$$

and the center of gravity of each stream annulus by:

$$r_m = (r_o^2 - r_i^2)(m - 0.5)(z+1)^{-\frac{1}{2}} + r_i^2$$

where:

r_j = radius of jth streamline
r_i = inner radius of the duct parallel section
r_o = outer radius of the duct parallel section
r_m = radius at stream tube center of gravity
j = jth streamline away from inner wall
z = total number of streamlines
m = stream tube number (1 = near hub)
$x = r_o / r_i$

Working against the direction of airflow, successive lines of equipotential, sited orthogonally to the stream surfaces, were erected in the bellmouth volume. Maintaining continuity within each annulus and knowing that flow must be orthogonal to the line of equipotential, the stream surfaces were uniquely defined by the equation:

$$(A_i V_i)_{a,b\ldots} = (A_j V_j)_{a,b\ldots}$$

for the streamline/potential line intersections, *i,j*... in the streamtubes *a,b*.... Since the lines of equipotential were not planar, the resulting velocity at the point in the flow was a function of *x* and *r*.

For practical reasons the desired continuously varying blockage was approximated by discrete steps defined radially by intersections between resulting mapped stream surfaces

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and the bellmouth inlet plane. These segments were subdivided into nine elements at 10 deg intervals in the circumferential direction. Assuming that within each annular segment the velocity was constant at the plane of the screen and the mass flow weighted velocity was at the center of gravity of the segment being selected, the problem was reduced to calculating the circumferential and radial variation in screen resistance coefficient.

Allowing for streamline circumferential displacement, a 100 deg sector angle sine-wave was specified whose maximum axial velocity depression was:

$$V/V_{FS}=0.72 \quad \text{yielding} \quad V/V_{FS}=0.86+0.14\cos(\pi\theta/50) \tag{1}$$

From McCarthy[2]

$$V/V_{FS}=1-\frac{N(1+X)}{(1+X^3)^{2/3}}\left[\frac{1+6X^3}{6X^2}-\gamma_0\right] \tag{2}$$

where $\gamma_0=1.866$ as calculated from continuity. Equation (2) with Eq. (1) yielded the resistance coefficient $K=K(\theta)$ which could be represented by a multisegment step distribution.

Since the screen approach velocity V_{REF} varied radially, the screen pressure drop, constant radially, called for a radial change in the screen resistance coefficient given by:

$$K'=K\left[\frac{V_{\mathrm{REF}}}{V'_{\mathrm{REF}}}\right]^2 \quad \text{for } \Delta P'_\theta=\Delta P_\theta$$

The K values were thus modified at all radial stations.

Screen Construction

Having evaluated the variation of K required it was necessary to establish the associated screen geometries. Weighardt[3] related K to screen geometry by:

$$K=\frac{CS}{(1-S)^2}$$

where

$S=2(d/m)-(d/m)^2$
d = wire diameter
m = mesh pitch for square mesh
$C=C(R_e)$ = loss coefficient
R_e = Reynolds number

At low Reynolds number Weighardt used the relationship:

$$C=6(R_e)^{-1/3} \qquad R_e=V_{\mathrm{REF}}d/[(1-s)v]<10^3$$

Cornell[4] extended this to higher Reynolds numbers:

$$C=0.8 \text{ if } 10^3<R_e<10^4$$

These were used in the present work with blending in the range $300<R_e<1000$.

For a particular, known approach velocity, R_e and hence K were determined for available mesh sizes. Multiple layups were used where necessary assuming that the final value of K was a summation of all individual K values.[2,5] For very high blockage, a perforated plate was used covering the perforations with tape as necessary, resistance coefficients being derived from Cornell.[4] The resulting screen is defined in Fig. 1.

Screen Calibration

Measurements were made behind the screen in a plane 12 cm ahead of the rotor leading edge at nine equidistant radial stations.

Stagnation and static pressure were nondimensionalized:

$$C_P=(P-P_{FS})/(P_{FS}-p_{FS}), \quad C_p=(p-p_{FS})/(P_{FS}-p_{FS})$$

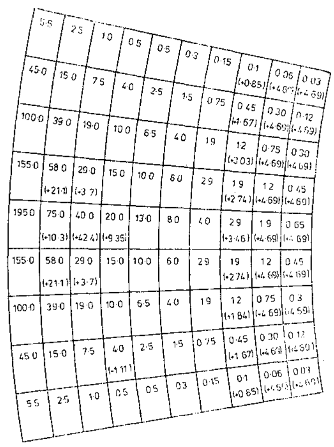

Fig. 1 *K* distribution plus modifications for screen.

where

P = local stagnation pressure
p = local static pressure
P_{FS} = freestream stagnation pressure
p_{FS} = freestream static pressure

Stagnation pressure variation with θ showed that toward the inner wall the stagnation pressure drop, while sinusoidal in shape, was markedly lower than predicted. Static pressure in the same traverse was higher but the resultant velocity distribution indicated reasonable agreement with the design velocity profile. At the midheight position, the stagnation pressure drop was generally close to the design value. The static pressure distribution, being much higher, yielded velocity levels lower than those designed. Approaching the annulus outer wall a lower stagnation pressure drop than that designed for was measured in the midscreen region and an uneven distribution of static pressure led to a rather uneven velocity profile.

To improve the measured disturbance, modifications in the resistance coefficient used are shown bracketed in Fig. 1. The resultant distortion was almost entirely within acceptance limits of ±5% on velocity ratio.

Conclusion

In attempting to produce a distortion of specified characteristics and intensity, a method relating screen blockage to predicted velocity levels at upstream stations in a duct was devised. The major simplifying assumption that flow was always maintained in its meridional plane, while not correct and in consequence probably the main source of inaccuracy, nevertheless resulted in flow characteristics close enough to design to require only minor modifications generally in the original design of the screen. Resulting errors in both stagnation and static pressure were found, in their influence upon velocity, to be largely self-compensating, yielding velocity levels close to those for which the screen was designed.

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