arclength) for the complete angle-of-attack range from −6 to 14 deg; a long run of laminar flow is not present. But for a C_l above 1.5, the drag increase for the other two airfoils is significant, whereas the HG airfoil continues with moderately increasing drag up to a maximum lift coefficient of 1.95. Whereas the NLF airfoil reaches its $C_{l\max}$ at $C_d = 0.025$, the HG airfoil reaches its $C_{l\max}$ at a C_d of 0.016.

Plots of the airfoil endurance parameter, $C_l^{3/2}/C_d$, for the three airfoils are shown in Fig. 3. The Wortmann and HG airfoils reach identical maximum values of about 165, whereas the NLF airfoil reaches a slightly higher value of 175. But note that the other two airfoils peak at $C_l = 1.55$, whereas the HG airfoil peaks at $C_l = 1.85$. Therefore, an endurance UAV with the HG airfoil would be able to remain aloft comparably to others with FX or NLF airfoils but at a significantly higher lift coefficient and therefore lower speed (or identical speed with less wing area). Within the limits of the assumptions of the Breguet endurance equation, where the engine/propeller characteristics are not being treated, a loitering ability may be maximized using the airfoil with the higher lift coefficient at the same value of endurance parameter.

A long run of laminar flow is not necessarily an important requirement for all aircraft designs. To maximize an endurance capability, a tradeoff of increased drag at low-lift values for reduced drag at very high-lift conditions may be beneficial.

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Constant Swirl Angle Inlet Guide Vanes

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Nomenclature

m = velocity profile exponent — defined in text
n = polytropic exponent
RH,RT = hub and tip radius, respectively
r = radial coordinate
U = upstream and uniform axial velocity
u, v_r, v_θ = axial, radial, and tangential velocity components, respectively
x,y = dummy variables
γ = ratio of specific heats
μ = defined in text; $\mu = 1$ for isentropic flow
ω = angular velocity of a compressor rotor

Subscripts
1, 2 = upstream and downstream, respectively

Received Oct. 27, 1989; revision received March 5, 1990.

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Introduction

WIND-TUNNEL compressors can benefit from the use of variable inlet guide vanes. This is especially true if the drive is constant speed and/or the compressor or fan is fixed pitch. When inlet guide vanes are used, it is desirable to make at least some part of the vane system structurally rigid, usually connecting a nose fairing to the drive section ducting. The trailing-edge sections of the support vanes can be made movable with a simple flap arrangement. The inlet guide vane system can therefore consist of a simple untwisted symmetric airfoil section with plain flaps at the aft 40 or 50% of the chord. NASA Ames is considering such a geometry for the modification of existing wind tunnels. If the chord and thickness of the airfoils are increased in proportion to the radial station, the vanes will have a constant solidity. Neglecting secondary effects, such as the radially increasing vane chord Reynolds number, a constant turning angle (swirl angle) of the flow should result. A solution for the axial and tangential velocity distributions is presented. The analysis is restricted to the case of a frictionless and incompressible flow with a uniform and axial velocity upstream of the inlet guide vane system.

Analysis

The energy equation may be combined with the radial equilibrium equations upstream and downstream of a rotor (or stator) to yield the equation[1]

$$u_2\frac{du_2}{dr_2} - u_1\frac{du_1}{dr_1} = (\mu-1)\left[\frac{v_{\theta1}{}^2}{r_1} - \frac{v_{\theta2}{}^2}{r_2}\right] + \left[\frac{v_{\theta1}}{r_1} - \omega\right]\frac{d(v_{\theta1}r_1)}{dr_1} - \left[\frac{v_{\theta2}}{r_2} - \omega\right]\frac{d(v_{\theta2}r_2)}{dr_2} \tag{1}$$

where μ is given by $\mu = (\gamma/n)[(n-1)/(\gamma-1)]$, and $\mu = 1$ for isentropic flow. For Eq. (1), the radial velocity contribution has been neglected according to

$$v_r^2 \ll u^2 + v_\theta^2$$

For the inlet guide vane, $\omega = 0$. The inlet velocity is taken as axial and uniform ($u = U$). If the vane loss is assumed small, $\mu = 1$ (isentropic), the throughflow equation reduces to

$$u_2\frac{du_2}{dr_2} = \frac{v_{\theta2}}{r_2}\frac{d(v_{\theta2}r_2)}{dr_2} \tag{2}$$

Inlet guide vanes with a constant solidity and constant flap chord to total chord ratio should produce a nearly uniform

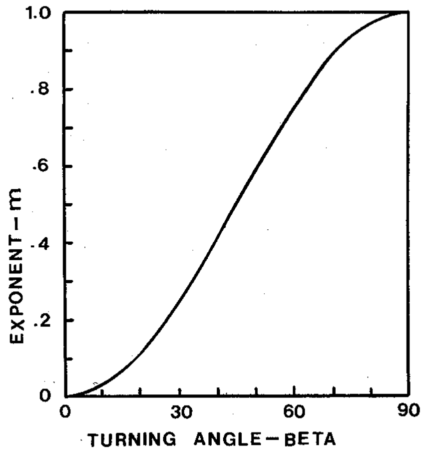

Fig. 1 Velocity exponent *m*.

turning of the flow (constant swirl angle):

$$\tan\beta_2 = \frac{v_{\theta 2}}{u_2} = \text{const} \qquad (3)$$

Solution of Eq. (2) is discussed in Ref. 1 for the cases of a potential vortex and solid rotation. Reference 2 gives a generalized solution in terms of the stream function and shows that for small swirl, the swirl distribution approximates a constant swirl velocity.

To solve Eq. (2) with the constraint in Eq. (3), the following change of variable is made:

$$r_2 v_{\theta 2} = x, \quad u_2^2 = 2y$$

The transformed differential relation becomes

$$\frac{\mathrm{d}y}{y} = -2\tan^2\beta_2\left(\frac{\mathrm{d}x}{x}\right)$$

Integrating the above equation for constant turning angle and transforming back to the original coordinates yields

$$u_2(r_2)^m = C \qquad (4)$$

where

$$m = \tan^2\beta_2/(1+\tan^2\beta_2), \qquad C = \text{const}$$

Equation (4) is valid for compressible flow. For application to wind-tunnel inlet guide vane systems, the radial variation of density is usually acceptably small so that the radial density variation can be neglected in the evaluation of the constant C.

$$\int_{RT_1}^{RH_1} u_1(2\pi r_1 \mathrm{d}r_1) = \int_{RT_2}^{RH_2} u_2(2\pi r_2 \mathrm{d}r_2)$$

For a duct with constant inner and outer radius and uniform upstream axial velocity

$$u_1 = \text{const} = U, \quad RT_1 = RT_2 = RT, \quad RH_1 = RH_2 = RH$$

$$C = U\left[\frac{RT^2 - RH^2}{RT^{2-m} - RH^{2-m}}\right]\left(\frac{2-m}{2}\right)$$

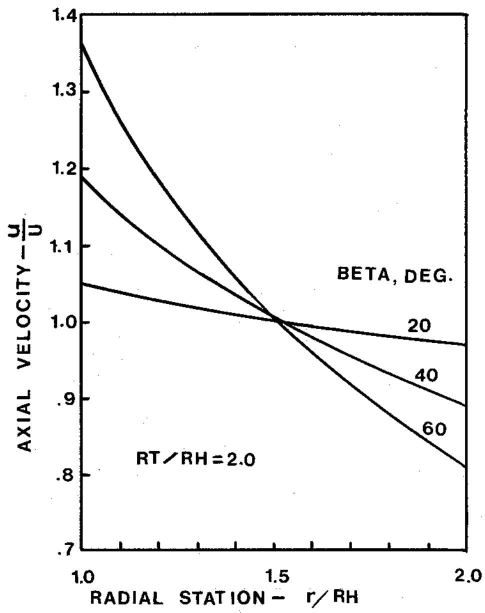

Fig. 2 Axial velocity *u*.

resulting in

$$\frac{u_2}{U} = \left[\frac{1-(RH/RT)^2}{(RH/RT)^m - (RH/RT)^2}\right]\left(\frac{2-m}{2}\right)\left(\frac{RH}{r_2}\right)^m$$

and

$$\frac{v_{\theta 2}}{U} = \frac{u_2}{U}\tan\beta_2 \qquad (5)$$

Results and Discussion

As an application to wind-tunnel fans, the desired turning angle would usually be 20 deg or less. For the 20-deg turn angle, the exponent m is about 0.1 (see Fig. 1). With a typical tip to hub ratio of 2.0 and the 20-deg turn angle, Fig. 2 shows an axial velocity variation of about 8%. For a 10-deg turn angle, the exponent m is about 0.03, and the axial profile is, for all practical purposes, constant. In wind-tunnel applications, a uniform swirl angle with an almost constant axial profile allows flow control similar to a variable pitch fan. One recent use, dictated by acoustical studies, is to obtain the same tunnel test section speed with varied fan speeds.

Conclusion

Constant swirl angle inlet guide vanes may be used to increase the operating envelope of a wind-tunnel compressor. The constant swirl angle feature may be obtained by using flapped inlet guide vanes having a constant flap chord percentage in conjunction with a constant solidity. The constant solidity results in a guide vane geometry having vane chord proportional to radius. For small turning angles, the axial velocity variation is small and the tangential velocity is nearly constant. For large turning angles, the tangential and radial velocity components both approach an inverse radius relationship.

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