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Utilization of Propagating Stall in a Cascade of Vanes

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Nomenclature

C_p $= (p_1 - p_3)/(\frac{1}{2}\rho u_1^2)$
p = static pressure
t = time
u = x component of flow velocity
v = y component of flow velocity
V_p = stall propagation velocity relative to cascade
x = direction of u_1
y = (normal to x) direction parallel to frontal plane of cascade, positive in the direction of stall propagation
α = vane setting angle relative to u_1
ρ = density

Subscripts

1 = far upstream of cascade
2 = inlet to cascade
3 = outlet from cascade
x,y,t = partial derivatives with respect to x, y, t
Also see Fig. 1.

Introduction

IN the operation of compressors it has often been observed that, when the angle of attack of the rotor vanes becomes too large (e.g., as a result of an excessive reduction of the oncoming flow velocity), the flow in the rotor passages stalls in a number of regions, each encompassing a number of blades. These stalled regions rotate relative to the rotor at an angular velocity which is normally lower than that of the rotor and of the opposite sign.

The mechanism of rotating stall may be qualitatively explained as follows.

Consider an annular cascade of vanes exposed to a flow at an angle only slightly lower than their critical (stalling) angle of attack. If a perturbation causes a local increase of the angle of the flow relative to one or more vanes, flow separation (with an attendant reduction of mass flow rate) occurs in the affected passages and fluid is consequently diverted upstream of the inlet to the neighboring passages. This modification of the nearfield causes the approach angle to increase beyond the critical angle on one side and to decrease on the other side of the stalled region (Fig. 2). Thus the occurrence of stall moves to the region where the angle of attack has increased, while the originally stalled region becomes unstalled. A steady state is soon established whereby the stalled region, comprising a fixed number of passages, propagates through the cascade at a constant rate. In an annular cascade, a number of evenly spaced and steadily propagating stall zones are formed in this manner.

Rotating stall is most undesirable in compressors because it causes a deterioration of performance and flow fluctuations which may lead to blade failure. On the other hand, it has been suggested[1] that stall propagation through a stationary cascade of vanes may be used to advantage in the generation of the laterally moving jets of cryptosteady-flow thrust augmenters[2,3] and energy separators.[4] To this end, the primary fluid would be made to issue into the interaction space through a cascade in which propagating stall would be promoted, rather than inhibited, through appropriate design. If the vanes are so sharp-edged that their stalling angle is very low and so closely spaced that the flow is substantially stopped in the stalled passages, the fluid issuing through the unstalled passages will form a pattern similar to that of jets issuing through laterally moving orifices.

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Analysis

For the purpose of estimating the magnitude of the "equivalent rotor peripheral speeds" that can be achieved in this manner, the annular blade row is approximated in the present analysis—as it is in all available analyses of rotating stall (e.g., Refs. 5-9)—by an infinite two-dimensional cascade, with compressibility effects neglected.

The cascade considered here is stationary, with its frontal plane perpendicular to the direction of u_1 (the undisturbed flow velocity at upstream infinity). The vanes are thin and closely spaced flat plates, so that α is a very small angle and the flow through the cascade can be assumed to be completely stopped in the stalled regions and substantially unimpeded in the unstalled regions. It is also assumed that: 1) the approaching flow is irrotational, 2) the depth of the approaching flow in proximity to the cascade inlet is uniform, and 3) a steady and steadily propagating stall pattern is established.

At the cascade inlet, the dynamical equation of motion, the continuity equation, and the condition of irrotationality give

$$v_{t_2} + u_2 v_{x_2} + v_2 v_{y_2} = -(1/\rho) p_{y_2} \quad (1)$$

$$u_{x_2} = -v_{y_2} \quad (2)$$

and

$$v_{x_2} = u_{y_2} \quad (3)$$

respectively. Furthermore, treating the vane spacing as if it were infinitesimal, the stall pattern is stationary in a coordinate system moving in the positive y direction at the velocity

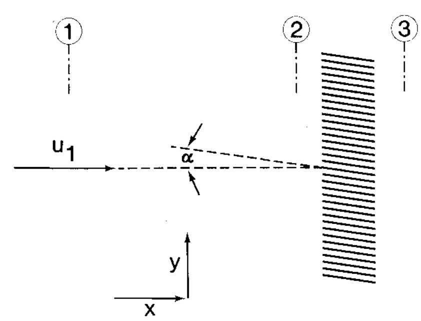

Fig. 1 Schematic of arrangement.

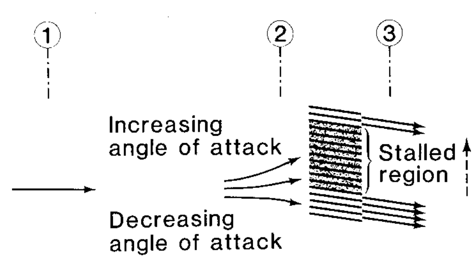

Fig. 2 Stall propagation.

V_p. Thus,

$$v_{t_2} = -V_p v_{y_2} \tag{4}$$

Equations (1-4) yield

$$V_p = v_2 - \frac{1}{u_{x_2}}\left(\frac{1}{\rho}p_{y_2} + u_2 u_{y_2}\right) \tag{5}$$

Since the stall pattern is steady, it is enough to calculate V_p at one point of it. Somewhere in front of the unstalled region, p_2 is a minimum $(p_2 \simeq p_3)$, hence $p_{y_2}=0$, $u_2 \simeq u_1(1+C_p)^{1/2}$, and, α being very small, $v_2 \simeq -u_2\alpha$. Also, at the same point, $du_2/dy = u_{x2}\ (dx/dy) + u_{y2} = 0$, hence $u_{y2}/u_{x2} = -dx/dy \simeq -\alpha^{-1}$. Then, Eq. (5) yields

$$V_p \simeq u_2[-\alpha + (1/\alpha)] \simeq (u_1/\alpha)(1+C_p)^{1/2} \tag{6}$$

By continuity, assuming (as above) $u_2=0$ in the stalled zones and $u_2 = u_1(1+C_p)^{1/2}$ in the unstalled ones, the jet-to-total area ratio at the cascade exit is $(1+C_p)^{-1/2}\ (\simeq u_1/\alpha V_p)$.

Equation (6) is consistent with the results of considerably more detailed analyses[5-9] and provides a measure of the stall propagation velocities that can be achieved in this manner.

Conclusions

The results obtained here show that the utilization of propagating stall through a stationary high-solidity cascade of vanes having a low stalling angle might permit the attainment of very high "equivalent rotor peripheral speeds." For example: with a jet-to-total area ratio of 0.40, a critical angle of 6 deg, and an approach velocity (u_1) of 12 m/s (40 ft/s), the equivalent rotor peripheral speed would turn out to be about 286 m/s (938 ft/s).

It is also to be noted that the cascade, being stationary, need not be annular. It could, indeed, be looped in other shapes, thereby making it possible to utilize the rotary-jet method of flow induction in asymmetric spaces.

Acknowledgment

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Effects of Drive Slots on Parachute Performance

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Introduction

A COMMON adaptation of parachute canopy design is by the provision of cutouts or "drive slots" in the canopy surface. This is done to reduce oscillations during descent, purportedly resulting from the introduction of a horizontal component to the resultant velocity. Drive slots vary in number, size, and disposition around the canopy on an apparently empirical basis. An investigation was therefore conducted into the effects of such slots on aerodynamic characteristics and descent performance. The basic canopy chosen for this study was the GQ Aeroconical parachute, a virtually imporous 20 gore nylon canopy with a flight diameter d of 5.18 m. The manufacturer's standard drive slot configuration is two slots, 108 deg displaced in planview, each replacing the outer two panels of a five block-panel gore as shown in Fig. 1. Aerodynamic characteristics of the Aeroconical canopy were derived from wind-tunnel tests on rigid and fabric models conducted at various Reynolds numbers. Data from tests on a rigid model at 1/7 full-scale Reynolds number were input into a modified version of an existing flight performance prediction computer program,[1] enabling flight behavior in two dimensions to be predicted. Flow visualization tests were conducted in a vertical working section water tunnel to determine the mass flux through the slots. Full-scale validation drop tests were conducted at the Royal Aircraft Establishment at Cardington, England, for four different canopy-payload configurations.

Analysis

A two-dimensional representation of the canopy-store system is shown in Fig. 2. The resultant aerodynamic force R is conveniently expressed in terms of either the lift L and drag D, respectively perpendicular and parallel to the relative velocity V_R, or the normal force N and tangential force T, respectively perpendicular and parallel to the parachute's z axis. From test data, the magnitude of R and its moment M about any specified point, such as the center of gravity G, are known. Thus the line of action of R is determined. In Fig. 3 a set of aerodynamic coefficients (C_N, C_T, and C_{MG}, where M_G is the aerodynamic moment about G), nondimensionalized with respect to d and V_R, are presented as a function of angle of attack α, for rigid canopy models tested in air at 1/7 full-scale Reynolds number ($Re = 3.4\times10^5$ based on d). From consideration of the similarities between the C_N/α and the C_{MG}/α curves in Fig. 3, it is apparent that over a relevant range of angles of attack, C_T has a minor effect on C_{MG}. Hence, the center of pressure cp lies close to the z axis. The generality of this conclusion, which is stated in the second revised USAF Parachute Handbook,[2] is confirmed by aerodynamic characteristics obtained from wind-tunnel tests on seven different types of parachutes conducted by Doherr.[3]

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