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.

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References

[1] Foa, J.V., "Pressure Exchange," *Applied Mechanics Reviews*, Vol. 11, Dec. 1958, pp. 655-657.

[2] Hohenemser, K.H., "Preliminary Analysis of a New Type of Thrust Augmenter," *Proceedings of the 4th U.S. National Congress of Applied Mechanics*, ASME, New York, 1962, pp. 1291-1299.

[3] Hohenemser, K.H., "Flow Induction by Rotary Jets," *Journal of Aircraft*, Vol. 3, Jan.-Feb. 1966, pp. 18-24.

[4] Foa, J.V., "Cryptosteady-Flow Energy Separation," *Journal of Fluids Engineering*, Vol. 95, Ser. I, No. 4, Dec. 1973, pp. 513-518.

[5] Emmons, H.W., Pearson, C.E., and Grant, H.P., "Compressor Surge and Stall Propagation," *Transactions of ASME*, Vol. 77, April 1955, pp. 455-469.

[6] Sears, W.R., "Rotating Stall in an Axial Compressor," *Zeitschrift für Angewandte Mathematik und Physik*, Vol. 6, No. 6, 1955, pp. 429-455.

[7] Marble, F.E., "Propagation of Stall in a Compressor Blade Row," *J.A.S.*, Vol. 22, 1955, pp. 541-554.

[8] Fabri, J. and Siestrunck, R., "Rotating Stall in Axial-Flow Compressors," *J.A.S.*, Vol. 24, 1957, pp. 805-812.

[9] Stenning, A.H., "Rotating Stall and Surge," *Journal of Fluids Engineering*, Vol. 102, March 1980, pp. 14-20.

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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 ($Re = 3.4 \times 10^5$ 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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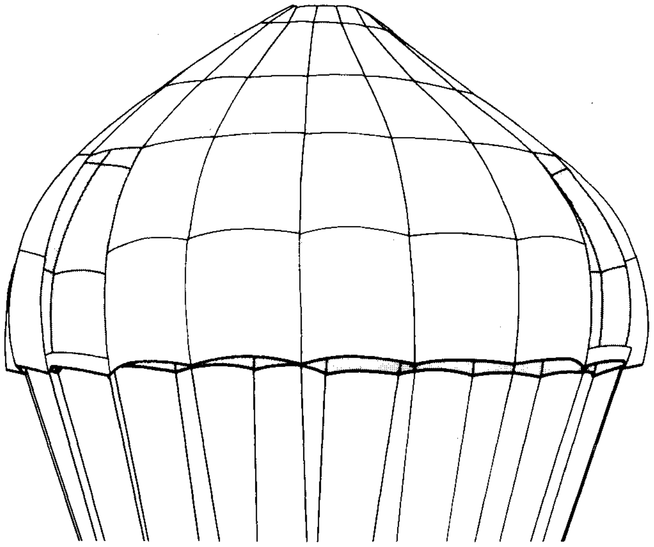

Fig. 1 GQ Aeroconical parachute canopy.

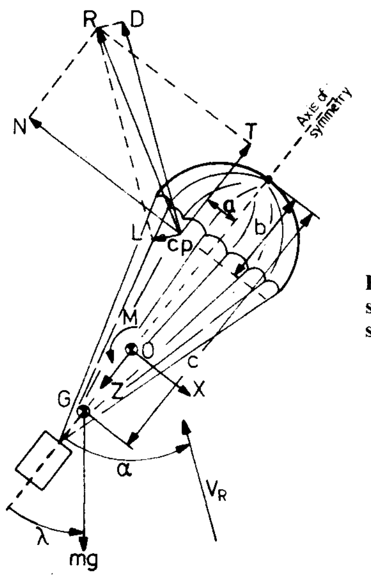

Fig. 2 Parachute system in two dimensions.

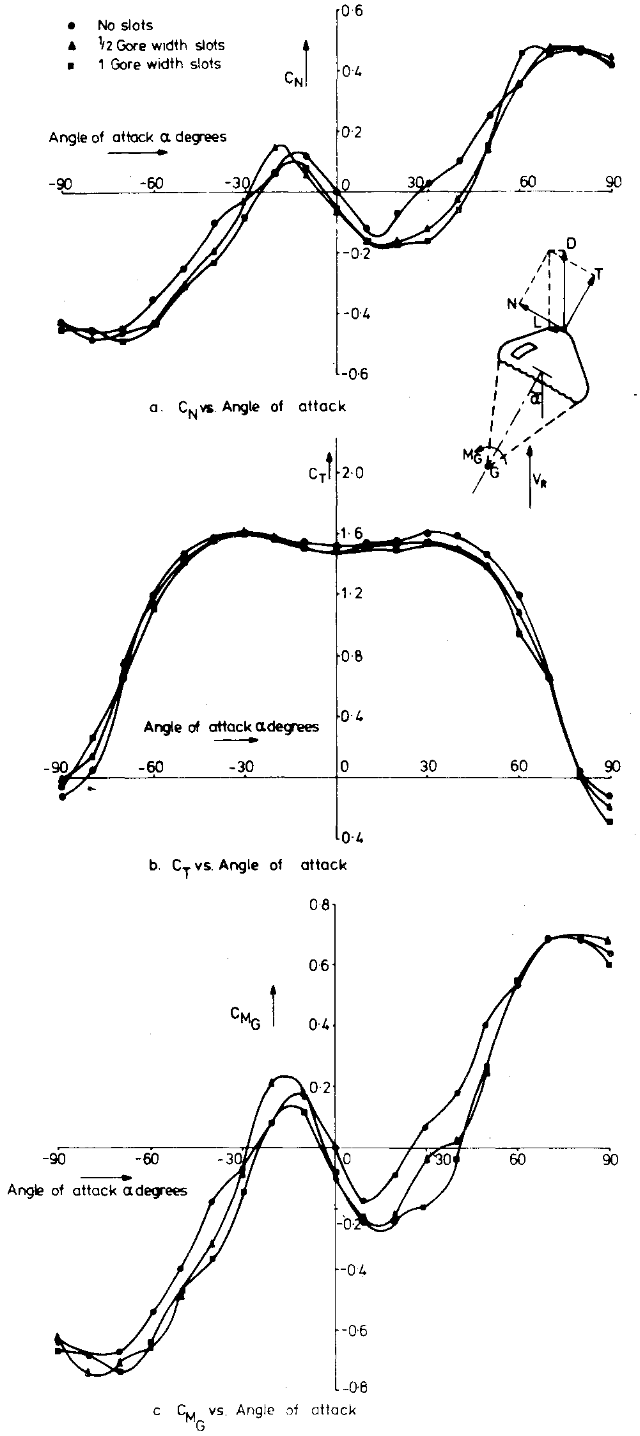

Fig. 3 Aerodynamic coefficients vs angle of attack for Aeroconical parachute.

Referring to Fig. 2, for equilibrium,

$$N = mg\sin\lambda$$

$$T = mg\cos\lambda$$

$$M_G = N(c-b) - Ta = 0$$

where mg is the gravitational force acting on the system. Considering cp to lie virtually on the z axis, these equilibrium equations reduce to

$$M_G = 0 \simeq N(c-b)$$

$$\therefore N \simeq 0$$

$$\therefore \lambda \simeq 0$$

$$\therefore T \simeq mg$$

Thus, since $\lambda \simeq 0$, a parachute in equilibrium will fly with its z axis approximately vertical. For static stability, $dC_{M_O}/d\alpha$, where O is the mass center of the descending system, must be positive. Mass here includes the mass of the volume of air accelerating with the system. Thus O is not coincident with G. However, when the system is statically stable not only is the contribution of mg to M_O small but when $dC_{M_O}/d\alpha$ is greater than zero, so is $dC_{M_G}/d\alpha$. Since G is a more clearly defined point than O it is convenient to define this static stability criterion in terms of G.

From Fig. 3c, there are two discrete angles of attack in each case where the parachute could fly in equilibrium and in a statically (though not necessarily dynamically) stable state. Because of the force imparted by the jet of air through the slots, the canopy with drive slots will be restricted to seeking the positive value of equilibrium angle of attack α_e. In Ref. 1 it is stated that, "... the only position of real interest in considering parachute or parachute-load system stability, is that about a zero-degree angle of attack." But, by the provision of drive slots, the parachute is induced to fly at a

Table 1 Flight performance of Aeroconical parachute

	No slots	Half gore width slots	Full gore width slots (standard configuration)
α_e, deg	29	41	43
C_T	1.60	1.50	1.48
V_R, m/s	8.4	8.7	8.8
V_h, m/s	4.1	5.7	6.0
V_v, m/s	7.3	6.6	6.4

Table 2 Comparison of results

	Analytical predictions	Full scale computer predicted	Full scale trials (wind corrected)
α_e, deg	43	42	39
V_R, m/s	6.8	6.6	7.4
V_h, m/s	4.6	4.4	4.6
V_v, m/s	5.0	4.8	5.7

positive angle of attack at which both M_0 is zero and $dC_{M0}/d\alpha$ is positive. Thus descent is both in equilibrium and statically stable.

Under these conditions, reducing the resultant velocity of the equilibrium system into its characteristic components of horizontal (or "drive") velocity V_h and vertical (or "descent") velocity V_v, the effects of different drive slot configurations on the GQ Aeroconical canopy are compared in Table 1. The values of α_e and C_T are taken from Fig. 3. V_R is derived from the equation for C_T where $T=mg$. For computational purposes, the total all-up-weight of the canopy-store system is taken as 150 kg, the flight diameter as 5.18 m and the density of air as constant at 1.19 kg/m^3 in each case.

Effects of Drive Slots

Provision of drive slots affects the parachute performance in two ways. First, drive slots constrain the flight path to the plane through the axis of symmetry about which the slot configuration is symmetric. Second, this introduction results in improved dynamic stability because the parachute continuously flies at an angle of attack at which $dC_{MG}/d\alpha$ is positive, a condition which does not occur in the absence of slots.

The mechanisms by which drive slots affect the canopy can be appreciated by considering the forces acting on a control volume formed between imaginary surfaces immediately outside and inside the canopy. Two types of force are present, the first arising from the pressure of the air acting on the canopy, and the second being the rate of change of momentum of the air jet through the drive slots.

The first has been idealized by assuming that the pressure over the canopy is approximately uniform and further assuming that by cutting away part of the canopy to form the slot no change results in the pressure distribution over the remainder of the canopy. The idealization is a crude approximation and, although acceptable for small slots cut in conventional canopies, becomes less valid as the ratio of slot area to canopy area is increased. Considering the effectiveness of the slot to result entirely from cutting away part of the load bearing canopy surface gives, for slots of between ½ and 1½ gore widths, at the equilibrium angle of attack, a good estimate for C_T but underestimates C_N by approximately 50%.

The rate of change of momentum of the air jet through the slot has been determined for a rigid model canopy in free flight in a vertical working section water tunnel by using hydrogen bubble flow visualization techniques. Provided Reynolds numbers are similar, ratios of velocities around a model under these conditions will be identical to those around a parachute descending in air. The ratio of mean flow velocity through the drive slots to the descent velocity was observed to be approximately 1.2. Knowing this value, the effect of the airflow through the drive slots has been evaluated. At an angle of attack of 30 deg the effects on C_T and C_N are of the same order as those of the pressure distribution, thus the total effect of the idealizations considered is to overestimate the change in C_T caused by the drive slots but to give a fair estimate of the change in C_N. The most likely cause of the overestimate in C_T is the error resulting from the assumption that the pressure distribution over the rest of the canopy is unchanged when a drive slot is cut into it. To suggest that a drive slot is effective solely because of the jet of air flowing through it is thus an oversimplification; a part of its effectiveness results from having cut away unwanted aerodynamic force-producing surface, thus altering the magnitude of the normal force coefficient.

Results

Visual observations of full scale test drops accord well with the analysis just described. In Table 2, flight performance predictions for a GQ Aeroconical parachute with the standard drive slot configuration and an all-up-weight of 90 kg made from the relationships described in Analysis are compared with computer predictions using the Tory-Ayres model and results from a full scale test drop (trial number V892916D) conducted by the Admiralty Underwater Weapons Establishment at Helston, England, on March 30, 1977. Full scale trial values correspond to steady-state descent and are corrected to account for a mean wind of 10 m/s at 180 deg measured at the time of the test.

Results show that the two prediction models overestimate α_e by approximately 9% and underestimate V_R by approximately 9%. This discrepancy probably arises from having conducted wind-tunnel tests using rigid models resulting in an overestimation of drag.

Conclusions

The introduction of drive slots does not drastically alter the basic shapes of the aerodynamic coefficient curves. Rather, drive slots induce the parachute to seek a preferred nonzero equilibrium angle of attack. In so doing, it is the mere existence of these slots that is critical. Their shape and disposition is of secondary importance since their effect on aerodynamic characteristics is small.

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References

[1] Tory, A.C. and Ayres, R.M., "Computer Model of a Fully-Deployed Parachute," *Journal of Aircraft*, Vol. 14, July 1977, pp. 675-679.

[2] "Performance of and Design Criteria for Deployable Aerodynamic Decelerators," Air Force Flight Dynamics Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson AFB, Ohio, ASD-TR-61-579, Dec. 1963.

[3] Doherr, K.-F., "Dreikomponetenmessungen an Fallschirmmodellen zur Ermittlung der statischen Stabilität," DFVLR München, DLR FB 68-50, March 1968.