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AUTOROTATION FOR SURVIVAL IN A DISABLED FIXED WING LIGHT AIRCRAFT

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SUMMARY Autorotation as a means of surviving mid air disablement of a fixed wing light general aviation aircraft, has been studied. Results of scale model tests are reported. A survivable descent rate is predicted for full scale, provided weight is reduced and the centre of gravity lies within limits beyond which spin is not possible.

LIST OF SYMBOLS

a	inflow velocity decrement through windmilling rotor disc, fraction of V
A	frontal area of rotor disc, πR^2
AR	aspect ratio of wing: span b /chord c of half wing, or b/c of full wing
b	aircraft full span $= 2\,s$
B	number of blades in rotor, i.e. number of half wings
c	wing chord; mean aerodynamic chord of wing
C	coefficient, e.g. $C_W = W/\rho(\Omega R)^2 A$; $C_T = T/\rho(\Omega R)^2 A$; $C_{D_R} = D/\frac{1}{2}\rho V^2 A$
D	drag; diameter of rotor $= 2\,R$
I	moment of inertia, Mr^2
J	tip advance ratio, $V/\Omega R = \bar{V}/\bar{\Omega}$
L	lift force $= W$ in equilibrium descent
M	mass of vehicle
r	radius of gyration
R	tip radius of rotor
RN	Reynolds number, $\rho V_R c/\mu$
s	semi wing span
S	semi wing area $= sc$
T	rotor axial thrust, $T = W$ in equilibrium descent
V	vertical descent velocity
W	weight $= Mg$
x,y,z	spatial co-ordinates
ρ	air density, 1.23 kgm^{-3}
σ	rotor disc solidity, $Bc/\pi R$
ϕ_a	advance angle, $\tan\phi_a = J$
θ,ϕ,ψ	pitch, roll, yaw
Ω	angular velocity of rotation $\dot{\psi}$

Subscripts:	D_R	rotor drag
	L,D,T,W	lift, drag, thrust, weight
	R	relative
	t	tip
	T	terminal
	x,y,z	axes
Superscripts:	$-$	dimensionless
	$\sim$	mean value

INTRODUCTION

Light general aviation aircraft, which are critically disabled in the air by such action as bird strike, mid air collision, violent turbulence, lightning strike or fire, can be expected to enter a high speed diving motion at a rate of descent ($> 30\,\text{ms}^{-1}$) from which survival of the occupants is unlikely.

Assuming that at least one half of the wing structure remains attached to the cockpit enclosure a simple means of reducing rate of descent is to generate a spinning, helicopter-like, rotor motion. The corresponding "windmill brake state" of autorotation will dissipate height potential energy more slowly than a free fall.

Typical undercarriage design rates of descent are about $4\,\text{ms}^{-1}$ for naval aircraft. Parachitists land at about $7\,\text{ms}^{-1}$. Millicer [1978] specifies for crashing aircraft $12\,\text{ms}^{-1}$ as marginally survivable and $18\,\text{ms}^{-1}$ as unsurvivable in a vertical descent. Therefore vertical descent rates of $\leqslant 10\,\text{ms}^{-1}$ are desirable although much higher rates may be survivable in a crashworthy cockpit.

In the early days of flying, accounts are given of crashes in flat spins from which the pilot walked away. Such machines were characterised by low wing loading ($\sim 25\,\text{kgm}^{-2}$ or 6 lb/ft^2), relatively low moment of inertia in pitch (small ineffective tail planes or tail arms), and frequently, low static stability implying aft c.g. positions. All these favour flat spins.

Now consider the light general aviation aircraft: Cessna 172, [(normal all up mass, 1044 kg/wing area, 16.4 m^2) = wing loading, 64 kgm^{-2}]. As a result of mid air disablement, assume that the wing on one side only remains. In order to reduce wing loading as far as possible, it is further assumed that all non essential components (engine, propeller, fuel, wheels, rear fuselage) are discarded (Fig. 1).

The spinning behaviour of the capsule and the effect of c.g. position has been investigated in model tests.

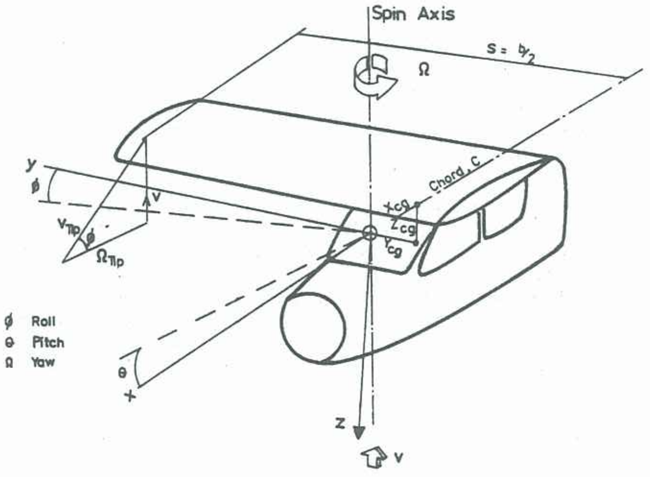

Figure 1 Autorotating capsule

TABLE 1 CESSNA 172 CAPSULE - GEOMETRY AND MASS CHARACTERISTICS

Semi span	s	m	5.4		Mass	M	kg	427 (4185 N)
Semi wing area	S	m^2	8.1		Inertia	I_x , I_y , I_z	kgm^2	565, 160, 640
Wing chord	c	m	1.5		Rad. of gyr.	$\frac{r_x}{s} , \frac{r_y}{c} , \frac{r_z}{s}$	-	0.24, 0.43, 0.22
Aspect ratio	AR	-	3.6		CG	$\frac{x}{c}, \frac{y}{s}, \frac{z}{c}$	% from l.e. of m.a.c.	25% aft, 7% outboard, 65% below
Solidity	$\sigma = \frac{Bc}{\pi R}$	-	0.09		Wing loading	M/S	kgm^{-2}	53 (11 lb/ft^2)

MODEL TEST PARAMETERS

Flexibility in choice of model mass, inertia and geometry scales conflicts with the demands imposed by aerodynamics for the equality of full scale and model force coefficients (such as C_W) and Reynolds number (such as RN_t). It is not possible to satisfy the latter requirement for viscous force similitude in air tests on small scale models. If the flow over any part of the body is separated, there may be less "scale effect" - or RN - penalty for attempting to simulate the tests on small models. This will depend on the fidelity of similar local flow angles which in turn depends on similarity distribution of mass and inertia. But in regions of attached flow boundary layer simulation is not possible.

Nevertheless, preservation of similarity of force coefficients can be interpreted as requiring:

$$\bar{V} = \frac{V}{\sqrt{W/\rho S}} \quad \text{and} \quad \bar{\Omega} = \frac{\Omega R}{\sqrt{W/\rho S}}$$

Hence also advance ratio $J = V/\Omega R = \bar{V}/\bar{\Omega}$ is a similarity parameter, as are $\bar{V}, \bar{\Omega}$ the normalised linear and rotational speeds.

In terms of the geometry and mass characteristics of the C172 capsule (Table 1), $\sqrt{W/\rho S} \cong 20\ ms^{-1}$. If V is to be $\leqslant 10 ms^{-1}$, $\bar{V}$ is required to be $\leqslant 0.5$. By comparison, $V_T \sim 40\ ms^{-1}$ and $\bar{V}_T = 2$. If the vertical descent velocity V is to be reduced to $10\ ms^{-1}$ for a given configuration, a different and large energy dissipation mechanism is needed. A high speed motion can be generated in a horizontal plane by a flat spin about the vertical axis. Unlike current aircraft in a steep spin at a high rate of descent ($\sim V_T$), it is necessary to induce a flat spin with the wing chord line near the horizontal, by generating high spin rates. The corresponding value of J will therefore be low ($0 < J << 1$).

An initial estimate of the value of J can be made if it is assumed that the energy stored in rotation $\Sigma \frac{1}{2} I \Omega^2$ is to be comparable to the kinetic energy of vertical descent $\frac{1}{2} MV^2$. Assuming that most rotational energy is due to rotation in yaw and $\frac{1}{2} MV^2 = \Sigma \frac{1}{2} I \Omega^2 = \frac{1}{2} M {r_z}^2 \Omega^2$, then $r^2{}_z \Omega^2 = V^2$. But $r_z/s = 0.22$ and $s \cong R$, so $V \cong \frac{1}{4} \Omega R$ or $J \cong \frac{1}{4}$, and the corresponding advance angle $\phi_a = 14°$.

Again it could be argued that the rate of energy dissipation by spinning should, if the wing is stable, be comparable to that in a free fall, $\alpha {V_T}^3 C_D$. Taking the whole wing as acting at 3/4 radius at velocity V ($= \Omega R$) with lift/drag ratio (L/D), its drag power dissipation is proportional to $V^3 (C_L/(L/D))$ which is to be taken equal to ${V_T}^3 C_D$. Thus for $C_D = 1 = C_L = L/D$, $\underset{\sim}{V} = V_T$. But we require $\underset{\sim}{V} = (1/3) V_T = 10 ms^{-1}$. With $V = (3/4) V_t$, $J = V/V_t = V/(4/3)V = V/(4/3)V_T = \frac{1}{4}$.

These rough estimates can be comapred with the experimental data for helicopter rotor autorotation of Gessow and Myers [1952]. Whereas momentum disc theory [Hartmann, 1973] itself precicts a limit of $7\ ms^{-1}$ corresponding to a slipstream $2a = 1$, a $\bar{V}$ of 0.35, and a rotor disc drag coefficient $C_{D_R} = (DR/\frac{1}{2}\rho V^2 A)$ of 2, experiments on helicopter rotors give $C_{D_R} \cong 1.1$ at a blade loading $C_T/\sigma = 0.01$. If this is the case, then $V = 8.2\ ms^{-1}$, $\Omega R = 77\ ms^{-1}$ and $J = 0.11$. The corresponding dimensionless velocities are $\bar{V} = 0.41$ and $\bar{\Omega} = 3.9$. Also $V/\sqrt{W/\rho A} = 1.9$ which is just on the borderline between the windmill brake state (> 2) and the vortex ring state (< 2). In the event that typical helicopter rotor action is not generated and that much of the wing remains stalled, the operating point will move into the windmill brake state. V can be expected to rise, ΩR to fall and J to increase.

In summary, successful autorotation requires a low value of $J \sim 0.1\text{-}0.2$. A low rate of descent $\cong 10\ ms^{-1}$ also requires a low wing loading ($\cong 50\ kgm^{-2}$). Even though model tests cannot satisfy RN, they can be expected to reveal trends caused by c.g. movement, and to define spin boundaries. If the model length scale is L, the mass scale is L^3, time scale $L^{-\frac{1}{2}}$ and velocity scale $L^{\frac{1}{2}}$ for tests in air.

MODEL TESTS

A range of model sizes have been tested (Table 2).

Unlike other models, 1/12 and 1/15 scale models have not generated many data points. In drop tests they required considerable height to spin up (> 30 m) and were unmanageable in a 3 m square spinning tunnel. However, like the smaller scale models, they demonstrated c.g. boundaries for spin, self starting, and inverted, as well as upright, spin attitudes. Stable spins were successful in a spin tunnel for 1/30 and 1/60 scale models. The seeds were drop tested. Typical results are in Table 3.

The results of Mills [1974] and Miller [1980] are given in Fig. 2 and the c.g. boundaries for spin in Fig. 3. Betts [1975] conducted controlled tests to examine the effect of moment of inertia. These confirmed the benefit of larger r_z/s than 0.22 of the full scale C172, although larger values would be difficult to achieve on the prototype. Miller [1980] investigated coning angles on the 1/30 scale model, Fig. 3. A straightforward strip integration by Heller [1981] of the equations of motion in 4 degrees of freedom: 3 moments and the z-force equation, solved the unknowns J, θ, ϕ and Ω. Observed model behaviour allowed the assumption that the spin axis passed through the c.g. Aerodynamic data at the appropriate RN was used for the NACA 2412 section of the C172.

DISCUSSION AND CONCLUSION

It is noted that deliberate autorotation of a light aircraft caught in a hopeless situation might also be an option to avoid disaster. In this case both half wings can be used and would confer a wing loading reduced by 50% and therefore a descent rate reduced by up to 30% [Mills, 1974] of that for a half wing.

Descent rates predicted from model tests for the full size C172 half wing capsule lie between 12 and 23 ms^{-1}. The RN of the rotor tip for these tests was between 2000 and 90000 and therefore lies well below that for full scale $\sim 5 \times 10^6$. A calculation at full scale RN

TABLE 2 MODEL DIMENSIONS

Model	Span	Mass	Length Scale	Mass Scale	c.g.		R. of G.	Aspect Ratio	Solidity	Tip RN	Reference
					Chord	Span					
	s	m	L	$\sim L^3$	x/c	y/s	r_z/s	AR	σ	RN_t	
	m	kg	-	-	%	%	-	-	-	-	
Hakea gibbosa seed	0.025	0.00005	200	204^3	50	20-35	0.08	4	0.08	1800	Mills
Sycamore maple seed	0.031	0.0004	180	220^3	25	30-35	0.17	5	0.08	2000	Mills
1/60 scale C172	0.09	0.0043	60	46^3	15-30	8-16	~0.3	3.30	0.10	10000	Miller
1/30 scale C172	0.18 0.185	0.0222 0.020	30	27^3 28^3	10-40	5-30	~0.3 0.25-0.4	3.3	11	30000	Miller Betts
1/15 scale C172	0.37	0.12	15	15^3	25	10	~0.3	3.3	11	90000	Hartmann
1/12 scale C172	0.46	0.16	12	14^3	14-68	6-14	~0.3	3.3	11	120000	Jakob
Full scale C172	5.5	427	1	1	25	7		3.3	0.10	5×10^6	-

TABLE 3 TYPICAL PERFORMANCE (see Fig. 2)

Model	Descent Velocity	Rotational Speed	Ref. Vel.	-	-	-	Predicted Full Scale C172 Capsule			Coning Angle	Reference
	V	Ω	$\sqrt{W/\rho S}$	$\bar{V}$	$\bar{\Omega}$	J	V	Ω	ϕ_a	ϕ	
	ms^{-1}	rpm	ms^{-1}	-	-	-	ms^{-1}	rpm	deg	deg	
Hakea gibbosa seed	1.2	400	1.6	0.7	0.7	1	14	24	45°	30-40°	Mills, 1974
Sycamore maple seed	0.9	600	1.3	0.7	0.78	0.9	14	27	42°	5-10°	Mills, 1974
1/60 scale	4.5	~400	4	1.15	1.0	1.15	23	35	49°	-	Miller, 1980
1/30 scale	4	~500	5	0.8	2.0	0.4	16	69	22°	60°	Miller, 1980
1/15 scale	3	~250	5	0.6	2.0	0.3	12	70	17°	-	Hartmann, 1973 Jakob, 1974
1/12 scale	4	190	5	0.8	1.6	0.5	16	65	27°	-	Jakob, 1974
Full scale	-	-	20	0.5	2.5	0.2	10	87	11°	20°	Heller, 1981
Helicopter rotor	-	-	~10	0.41	3.9	0.11	82	77	6°	~5°	Gessow & Myers

however predicts a lower descent rate of 10 ms^{-1} which is somewhat higher than for helicopter rotors in autorotation at about 8 ms^{-1}. The corresponding rotational speed for the C172 capsule is predicted to be about 90 rpm and coning angle 20°, for the centre of gravity at 25% m.a.c. and 7% outboard from the centreline. Model tests indicate that there can be expected to be a useful range of c.g. positions for stable autorotation.

The predicted descent rate of the capsule is low enough for human occupants to survive the final impact.

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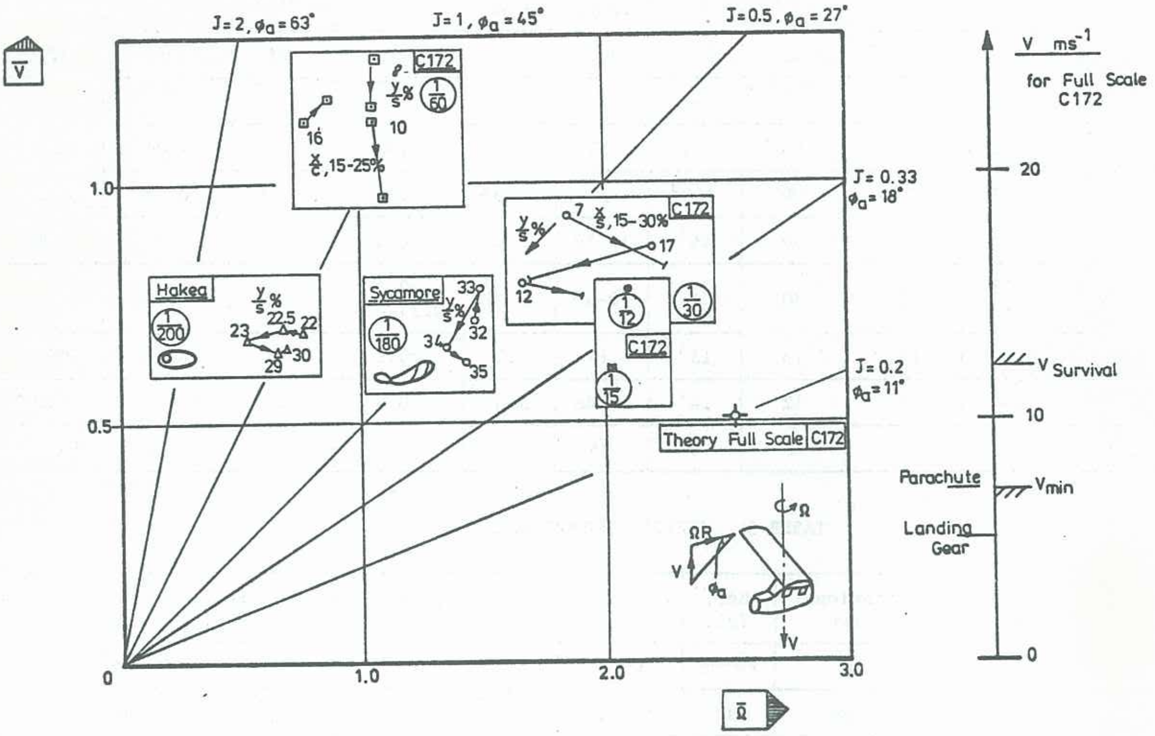

FIGURE 2: Test Results

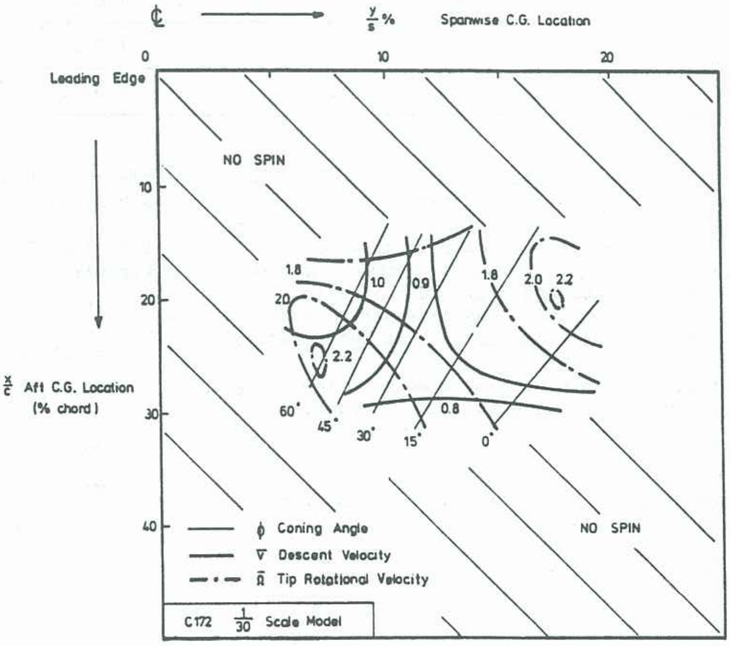

FIGURE 3: Spin Boundaries