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Power Failure Near to the Ground in Near Hovering Flight

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Preamble

The requirement for a helicopter to make a safe power off landing is that it has sufficient kinetic energy in the rotor. A simple example of this type of manoeuvre, or flare, is given below in the case of an engine power failure when the helicopter is hovering close to the ground.

If the helicopter is near to the ground when the power failure occurs, it is impossible for the pilot to establish a steady descent condition and to complete a conventional autorotative landing. The pilot can, in this case only, use the kinetic energy stored in the rotor at the instant of engine failure to reduce the rate of descent, and the rotor controls, particularly the collective pitch lever, are held in position. The safety of the landing will then depend on one or both of the following two factors:-

- The maximum descent velocity which the landing gear and fuselage can absorb.

- The minimum permissible rotor speed which can be tolerated without the blade coning angle becoming excessive. As the flare is initiated the rotor is in a high thrust and low rotational speed condition. If the rotor speed is too low, then the blade flapping will become uncontrolled with the inevitable catastrophic consequences.

Nomenclature

Variable	Description
T	Rotor Thrust
W	Helicopter Weight
y	Descent Height from Power Failure (T=0)
g	Acceleration due to Gravity
J	Polar Moment of Inertia of the Main Rotor
Ω	Rotor Speed
Q_S	Shaft Torque Input from the Engine(s)
Q_A	Aerodynamic Torque
Ω_0	Rotor Speed at Instant of Engine Failure
Q_0	Aerodynamic Torque at Instant of Engine Failure
y_{BRICK}	Descent Height of Freely Falling Object

Method

The height from which this type of descent can be safely made is analysed as follows:-

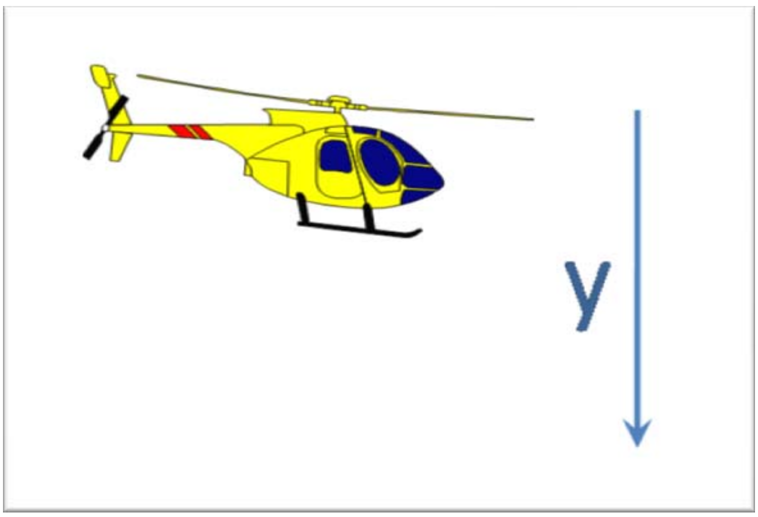

Figure 1

The equation of vertical motion is-

$$\ddot{y} = g\left(1 - \frac{T}{W}\right) \tag{1}$$

Rotor rotation equation:-

$$J\dot{\Omega} = Q_s - Q_a \tag{2}$$

Immediately before the power failure we have:-

$$Q_s = Q_a$$
$$\dot{\Omega} = 0 \tag{3}$$

When the power fails:-

$$Q_s = 0$$
$$J\dot{\Omega} = -Q_a \tag{4}$$

It is a reasonable assumption that the rotor thrust, T, and the rotor torque, Q, vary with the square of the rotor speed, Ω, whence:-

$$T = W\left(\frac{\Omega}{\Omega_0}\right)^2 \tag{5}$$

and

$$Q_a = Q_0 \left(\frac{\Omega}{\Omega_0} \right)^2 \qquad (6)$$

Substitution of (7) in (4) gives:-

$$J\dot{\Omega} = -Q_0 \left(\frac{\Omega}{\Omega_0} \right)^2 \qquad (7)$$

Now if we define:-

$$\overline{\Omega} = \frac{\Omega}{\Omega_0} \qquad (8)$$

Equation (7) becomes:-

$$\dot{\Omega} = -\frac{Q_0}{J}\overline{\Omega}^2$$

$$\frac{d\overline{\Omega}}{dt} = -\frac{Q_0}{J\,\Omega_0}\overline{\Omega}^2 \qquad (9)$$

and (1) becomes:-

$$\ddot{y} = g\left(1 - \overline{\Omega}^2\right) \qquad (10)$$

Now if we define:-

$$\alpha = \frac{Q_0}{J\,\Omega_0} \tag{11}$$

Equation (9) reduces to:-

$$\frac{d\overline{\Omega}}{dt} = -\alpha\,\overline{\Omega}^{\,2} \tag{12}$$

With the boundary condition of =1 at t=0, the solution is:-

$$\overline{\Omega} = \frac{1}{1+\alpha\,t} \tag{13}$$

Substituting this result into (1) gives:-

$$\ddot{y} = g\left(1 - \frac{1}{(1+\alpha\,t)^2}\right) \tag{14}$$

Which, with the boundary conditions y(0)=(0)=0, gives:-

$$\dot{y} = g\,t + \frac{g}{\alpha}\cdot\frac{1}{(1+\alpha t)} - \frac{g}{\alpha}$$

$$= \frac{g\alpha t^2}{(1+\alpha t)} \qquad (15)$$

and:

$$y = \frac{1}{2}g\,t^{2} + \frac{g}{\alpha^{2}}\ln(1+\alpha\,t) - \frac{g}{\alpha}t \qquad (16)$$

Comparison with Freely Falling Object

To give a comparison of the effectiveness of this manoeuvre, consider an object, a brick say, falling under gravity. If y_{BRICK} is the height loss in the same time t then we have:-

$$y_{BRICK} = \frac{1}{2} g\, t^2 \tag{17}$$

Whence expressing the height loss of the helicopter compared to the brick we have the ratio:-

$$\begin{aligned} \frac{y}{y_{BRICK}} &= 1 + \frac{2}{\alpha^2 t^2} \ln(1 + \alpha\, t) - \frac{2}{\alpha\, t} \\ &= \alpha\, t \left(\frac{2}{3} - \frac{1}{2} \alpha\, t + \ldots\ldots \right) \end{aligned} \tag{18}$$

y/y_{BRICK} is the distance which the helicopter falls compared to the distance which a body (brick) falling freely under 1g acceleration would have fallen in the same time.

It can be seen that via the α term outside of the bracket, the higher the polar moment of inertia of the rotor (J) and the normal operating rotor speed (Ω_0) the greater will be the difference between y and y_{BRICK} and the better will be its flare performance.

Example

Variable	Value
J	10,000 kg.m^2
Ω_0	21.8 rads/sec
Q_0	68807 N.m

An example using these results is presented in Figures 2, 3 and 4. The rotor speed at the instant of power failure is 21.8 rads/sec. The figures show the effect of increasing polar inertia of the rotor. Figure 2 shows the rotor speed decay, 3 the vertical velocity increase, and 4 the height loss. The basic conclusion is that this manoeuvre can only be contemplated for a limited time. If the polar inertia of 10,000 kg.m^2 is selected, a time 2 seconds reduces the rotor speed to 61% of normal, a vertical velocity of 8 m/s both of which are severe situations.

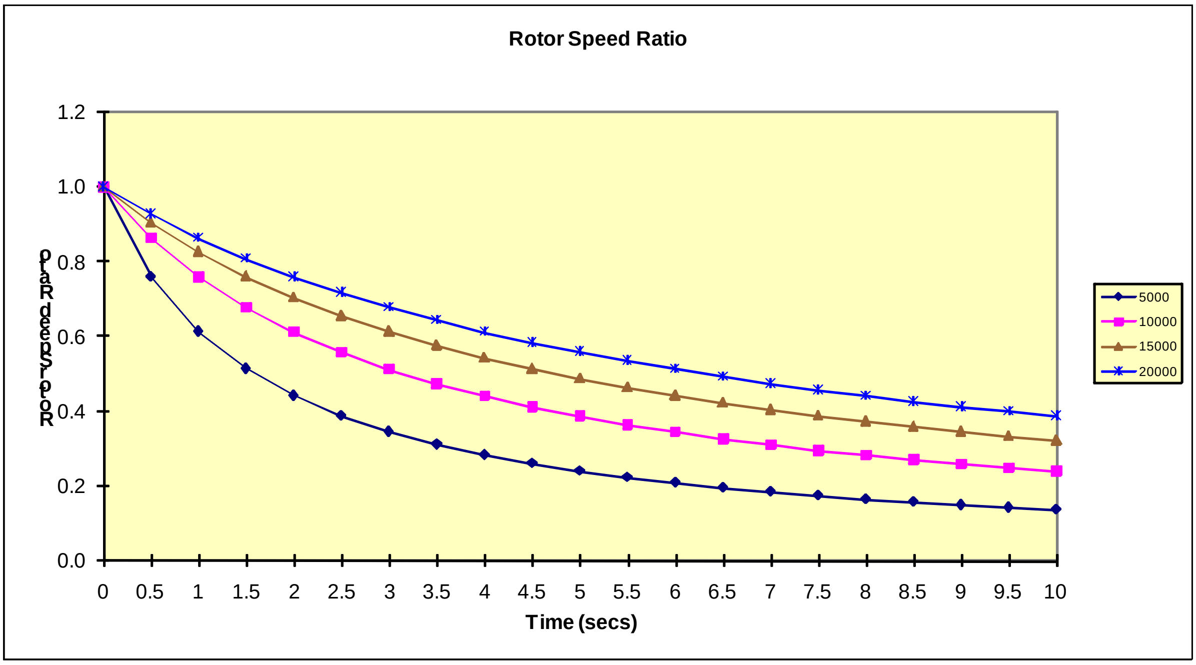

Figure 2

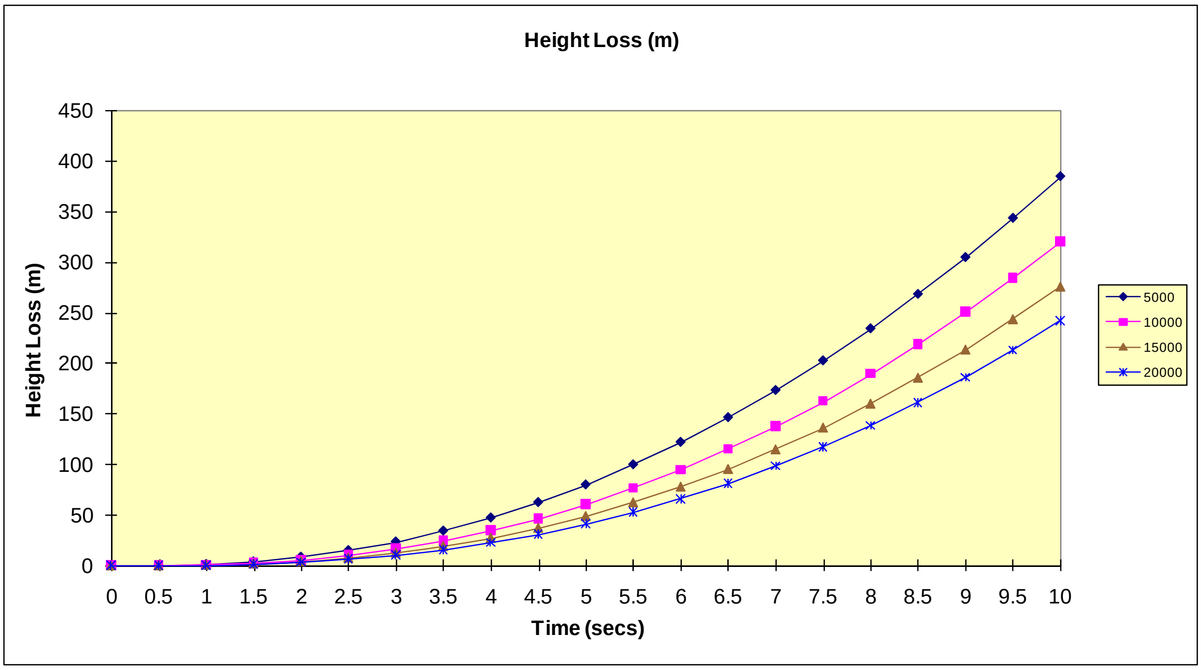

Figure 3

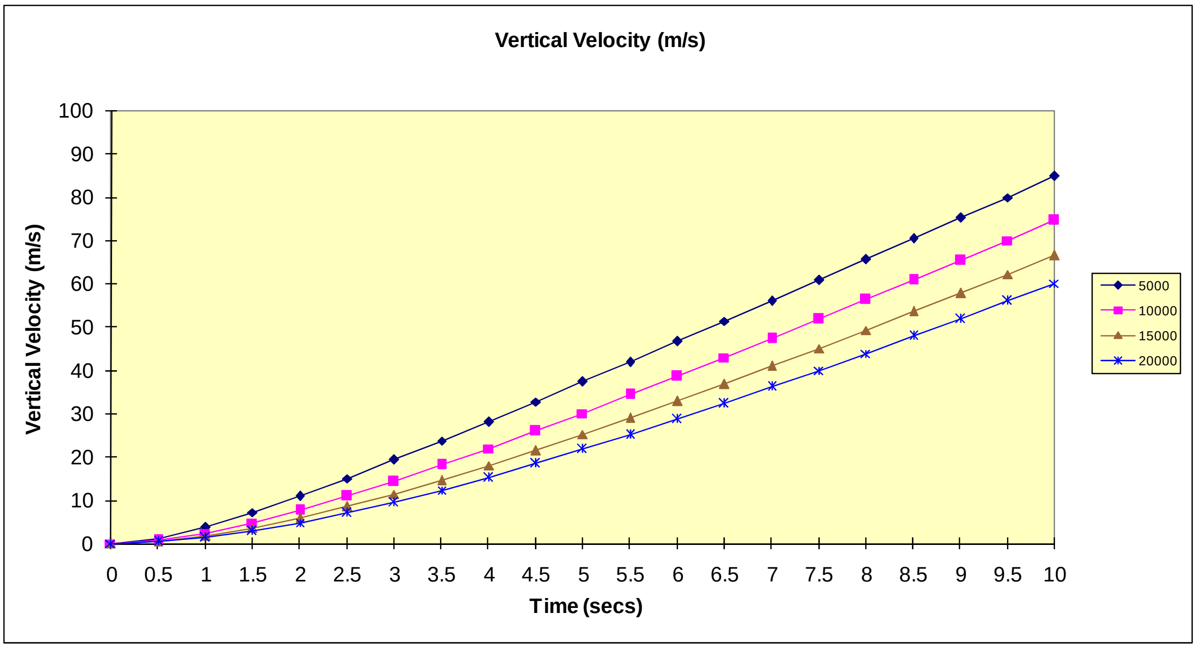

Figure 4

Addendum – Descent Starting from Reduced Rotor Speed

The above analysis applies to descent from a steady hover. However, the situation can be modified to starting from a different rotor speed to that of a steady hover. The α term refers to the pitch angle settings and these are assumed to remain at the steady hover value.

The initial rotor speed is now defined to be Ω_1, from which we find:

$$\overline{\Omega}_1 = \frac{\Omega_1}{\Omega_0} = \frac{1}{\gamma} \tag{19}$$

With the revised boundary condition of at t=0, the solution is now:-

$$\overline{\Omega} = \frac{1}{\gamma + \alpha t} \tag{20}$$

Substituting this result into (1) gives:-

$$\ddot{y} = g\left(1 - \frac{1}{(\gamma + \alpha t)^2}\right) \tag{21}$$

Which, with the same boundary conditions y(0)=(0)=0, now gives:-

$$\dot{y} = g\,t + \frac{g}{\alpha\gamma}\cdot\frac{1}{\left(1+\dfrac{\alpha}{\gamma}t\right)} - \frac{g}{\alpha\gamma}$$

$$= \frac{gt}{(\gamma+\alpha t)}\left\{\alpha t + \frac{\gamma^2 - 1}{\gamma}\right\} \qquad (22)$$

and:

$$y = \frac{1}{2}g\,t^2 + \frac{g}{\alpha^2}\ln\left(1+\frac{\alpha}{\gamma}t\right) - \frac{g}{\alpha\gamma}t \qquad (23)$$