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Power Failure Near to the Ground in Near Hovering Flight (Multi - Engined)

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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. This note extends the analysis of SJN – A – 010 to include multi-engined cases where one or more engines fail.

As before, if the helicopter is near to the ground when the engine(s) 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, together with the remaining engine power (*if available*) 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 three 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.

- The number of engines left operating.

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
N	No. of Engines Installed
N_F	No. of Engines Failing
α	Terms used in the analysis
γ	

Method

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

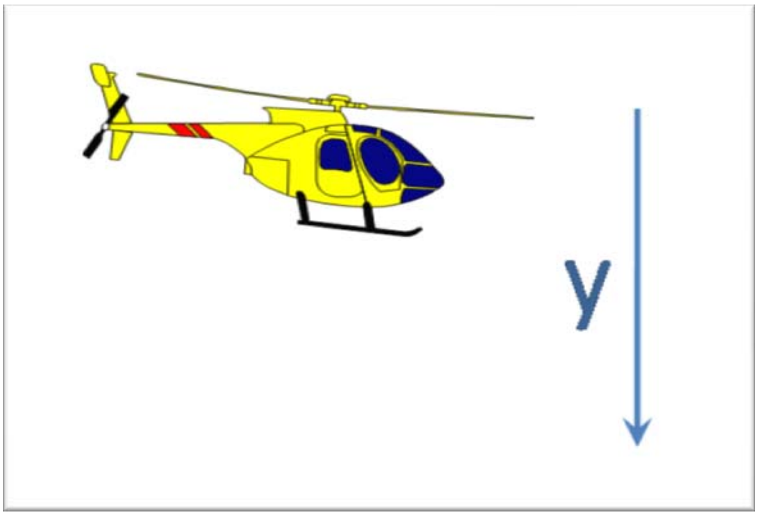


Figure 1

The equation of vertical motion is-

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

Rotor rotation equation:-

$$J\dot{\Omega} = Q_s - Q_a \qquad (2)$$

Immediately before the power failure we have:-

$$Q_s = Q_a$$
$$\dot{\Omega} = 0 \qquad (3)$$

When the engine(s) fails:-

$$Q_s = \left\{ \frac{N - N_F}{N} \right\} Q_a$$
$$J\dot{\Omega} = Q_s - Q_a \qquad (4)$$

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:-

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

and

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

If we define the following parameter:

$$\gamma = \sqrt{\left\{ \frac{N - N_F}{N} \right\}} \qquad (7)$$

Substitution of (6) in (4) gives:-

$$J\dot{\Omega} = \gamma^2 Q_0 - Q_0 \left(\frac{\Omega}{\Omega_0} \right)^2 \tag{8}$$

Now if we define:-

$$\overline{\Omega} = \frac{\Omega}{\Omega_0} \tag{9}$$

Equation (8) becomes:-

$$\dot{\Omega} = \frac{Q_0}{J}\left(\gamma^2 - \overline{\Omega}^{\,2}\right)$$

$$\frac{d\overline{\Omega}}{dt} = \frac{Q_0}{J\Omega_0}\left(\gamma^2 - \overline{\Omega}^{\,2}\right) \tag{10}$$

and (1) becomes:-

$$\ddot{y} = g\left(1 - \overline{\Omega}^{\,2}\right) \tag{11}$$

Now if we define:-

$$\alpha = \frac{Q_0}{J\,\Omega_0} \qquad (12)$$

Equation (9) reduces to:-

$$\frac{d\overline{\Omega}}{dt} = \alpha\left(\gamma^2 - \overline{\Omega}^{\,2}\right) \qquad (13)$$

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

$$\overline{\Omega} = \gamma \left\{ \frac{\frac{(\gamma+1)}{(\gamma-1)} e^{2\gamma\alpha t} - 1}{\frac{(\gamma+1)}{(\gamma-1)} e^{2\gamma\alpha t} + 1} \right\}$$

$$= \gamma \left\{ \frac{(\gamma+1) e^{\gamma\alpha t} - (\gamma-1) e^{-\gamma\alpha t}}{(\gamma+1) e^{\gamma\alpha t} + (\gamma-1) e^{-\gamma\alpha t}} \right\}$$

$$= \gamma \left\{ \frac{\gamma \tanh(\gamma\alpha t) + 1}{\gamma + \tanh(\gamma\alpha t)} \right\} \qquad (14)$$

$$= \gamma \coth(\gamma\alpha t + \phi)$$

Where:

$$\tanh(\phi) = \gamma \qquad (15)$$

Substituting this result into (1) gives:-

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

$$= g\left\{\left(1-\gamma^2\right) - \gamma^2 \operatorname{cosech}^2(\gamma\alpha t + \phi)\right\} \qquad (16)$$

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

$$\dot{y} = g\left\{\left(1-\gamma^2\right)t - \frac{1}{\alpha} + \frac{\gamma}{\alpha}\coth\left(\gamma\alpha t + \phi\right)\right\} \quad (17)$$

and:

$$y = g\left\{\frac{\left(1-\gamma^2\right)t^2}{2} - \frac{t}{\alpha} + \frac{1}{\alpha^2}\ln\left[\frac{\sinh\left(\gamma\alpha t+\phi\right)}{\sinh\left(\phi\right)}\right]\right\}$$

(18)

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:-

$$y_{BRICK} = \frac{1}{2} g\, t^{2} \tag{19}$$

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

$$\begin{aligned} \frac{y}{y_{BRICK}} &= 1 - \gamma^{2} + \frac{2}{\alpha^{2} t^{2}} \ln\left[\frac{\sinh\left(\gamma\alpha t + \phi\right)}{\sinh\left(\phi\right)}\right] - \frac{2}{\alpha\, t} \\ &= 1 - \gamma^{2} - \frac{\gamma^{2}}{\sinh^{2}\left(\phi\right)} \ldots\ldots\ldots \end{aligned} \tag{20}$$

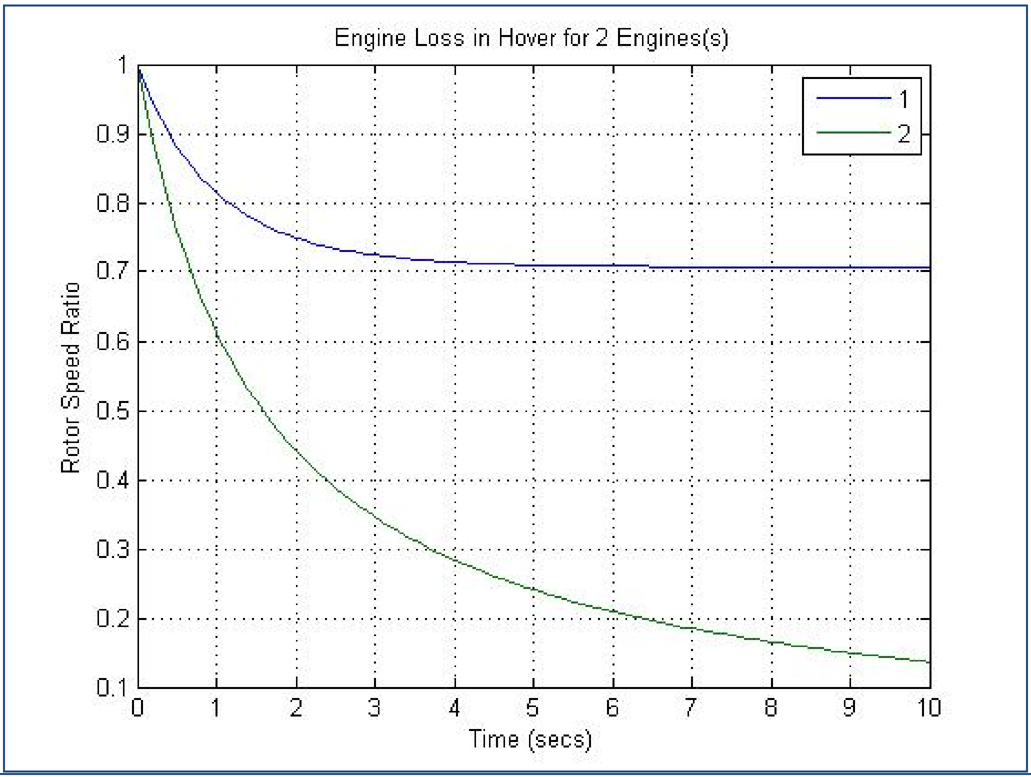
y/y_{BRICK} is the distance which the helicopter falls compared to the distance which a body (brick) falling freely under 1g acceleration would have fallen in the same time.

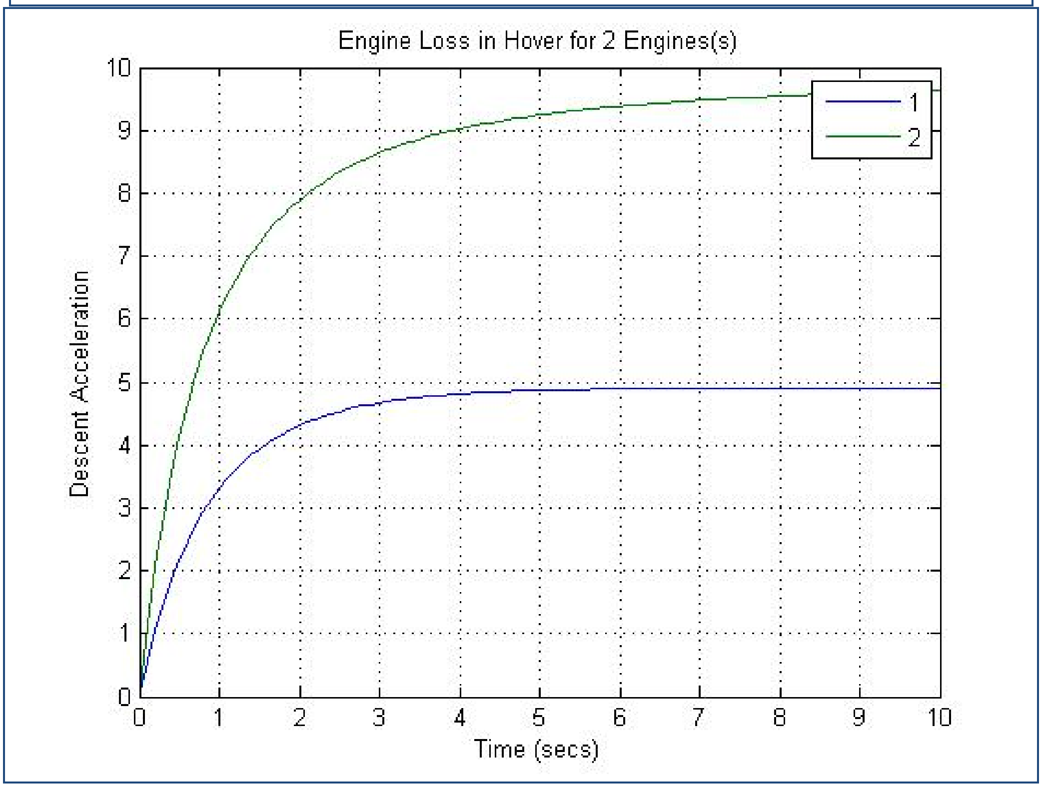
Example

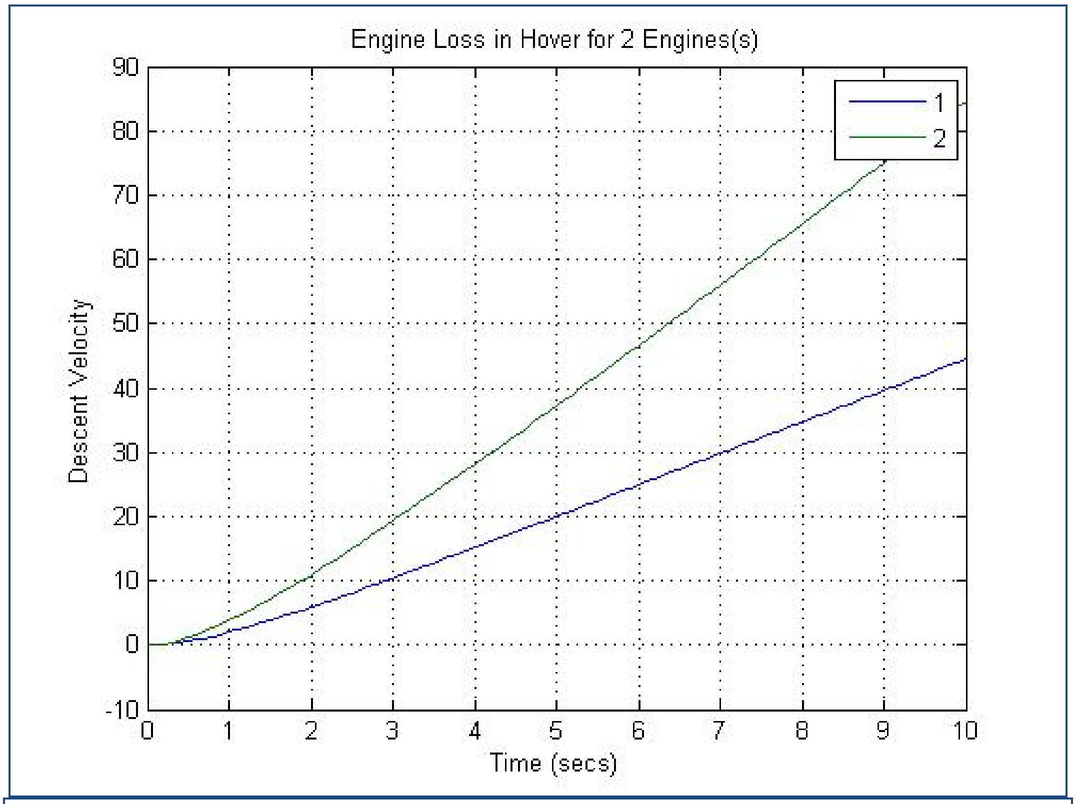
Variable	Value
J	5000kg.m^2
Ω_0	21.8 rads/sec
Q_0	68807 N.m

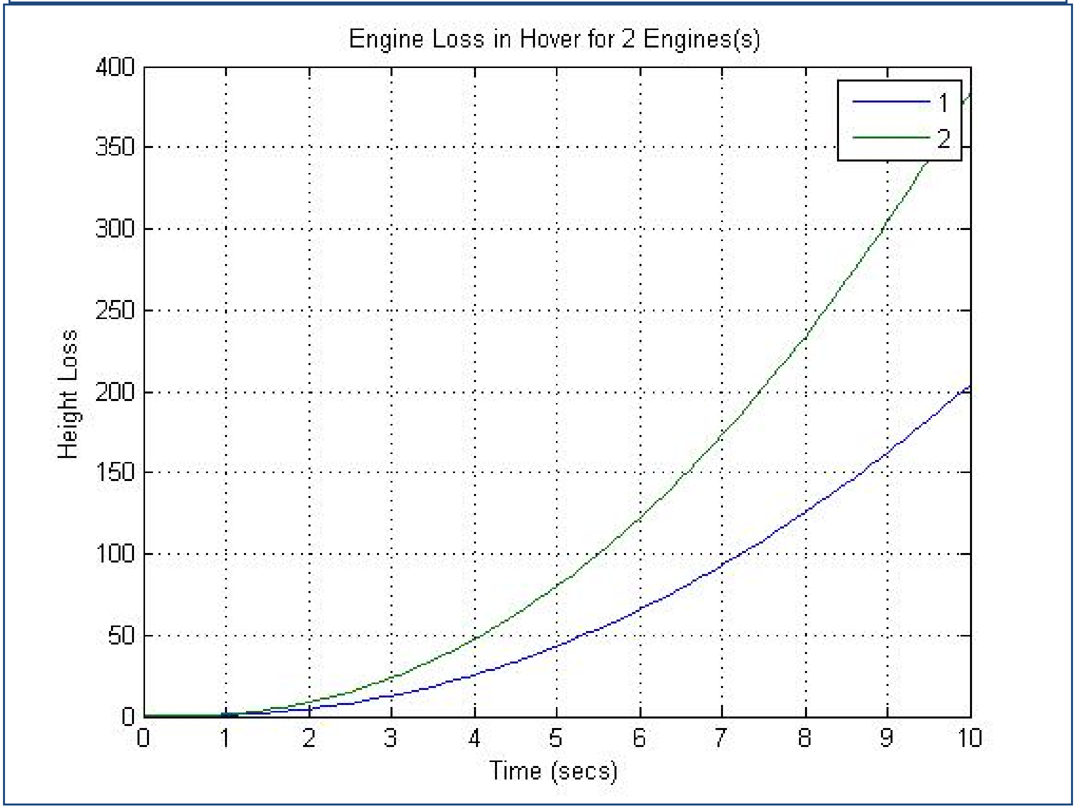
An example using these results is presented in the following Figures. The rotor speed at the instant of power failure is 21.8 rads/sec. The figures show the effect of increasing the number of engines failing.

Number of Engines = 2

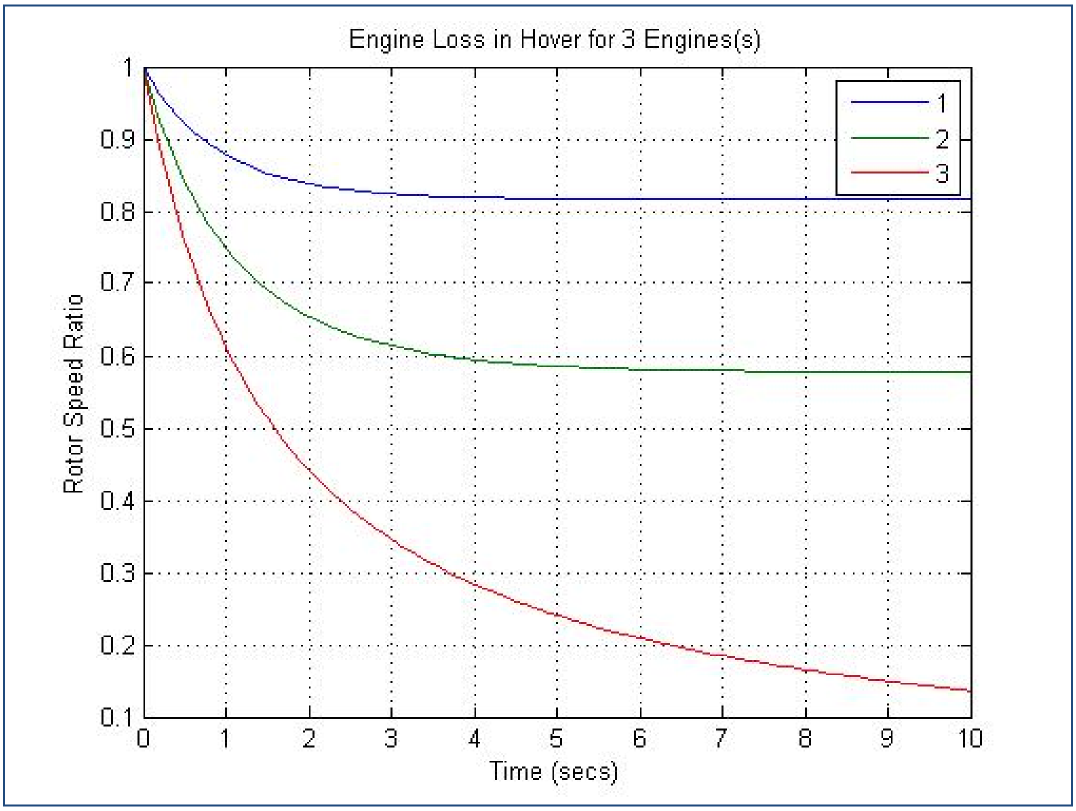


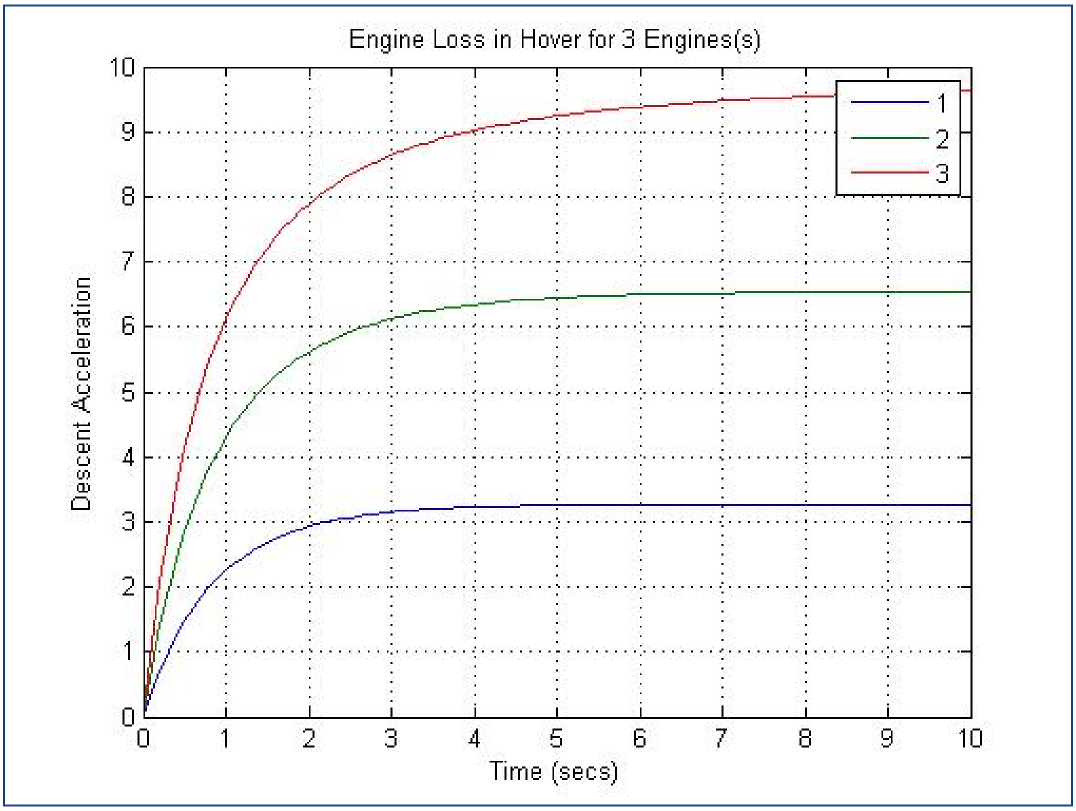


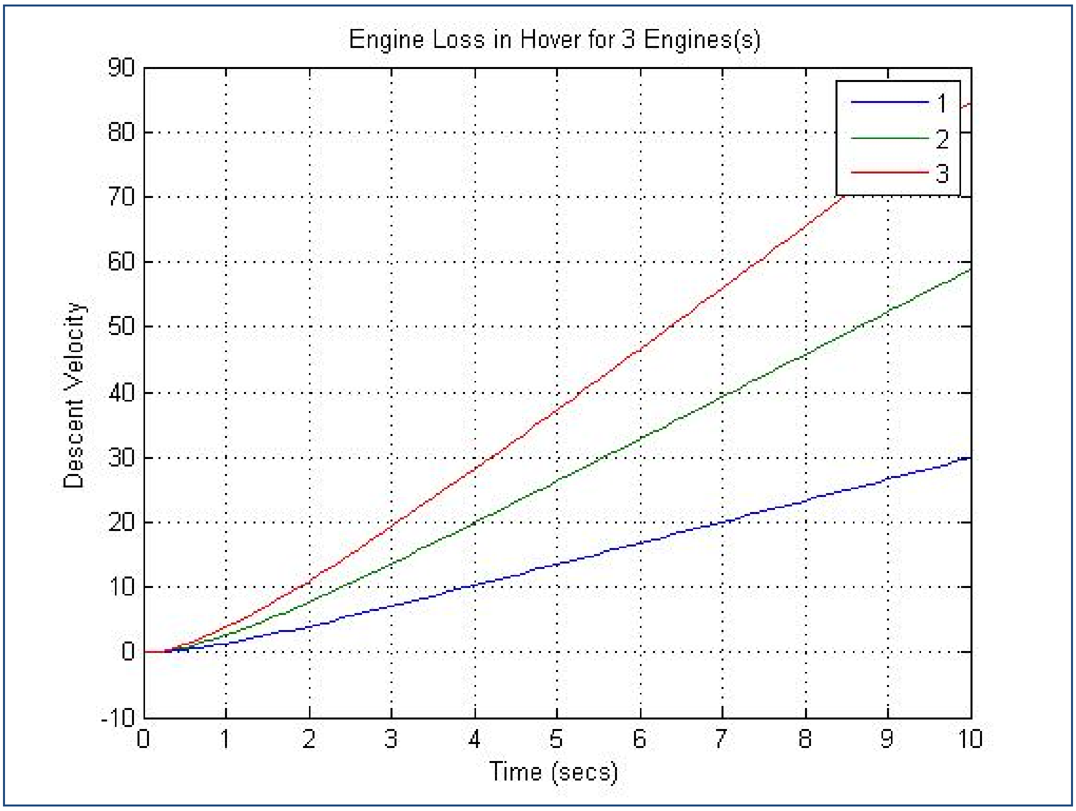

Engine Loss in Hover for 2 Engines(s)
Descent Velocity
Time (secs)
1
2
90
80
70
60
50
40
30
20
10
0
-10
0
1
2
3
4
5
6
7
8
9
10

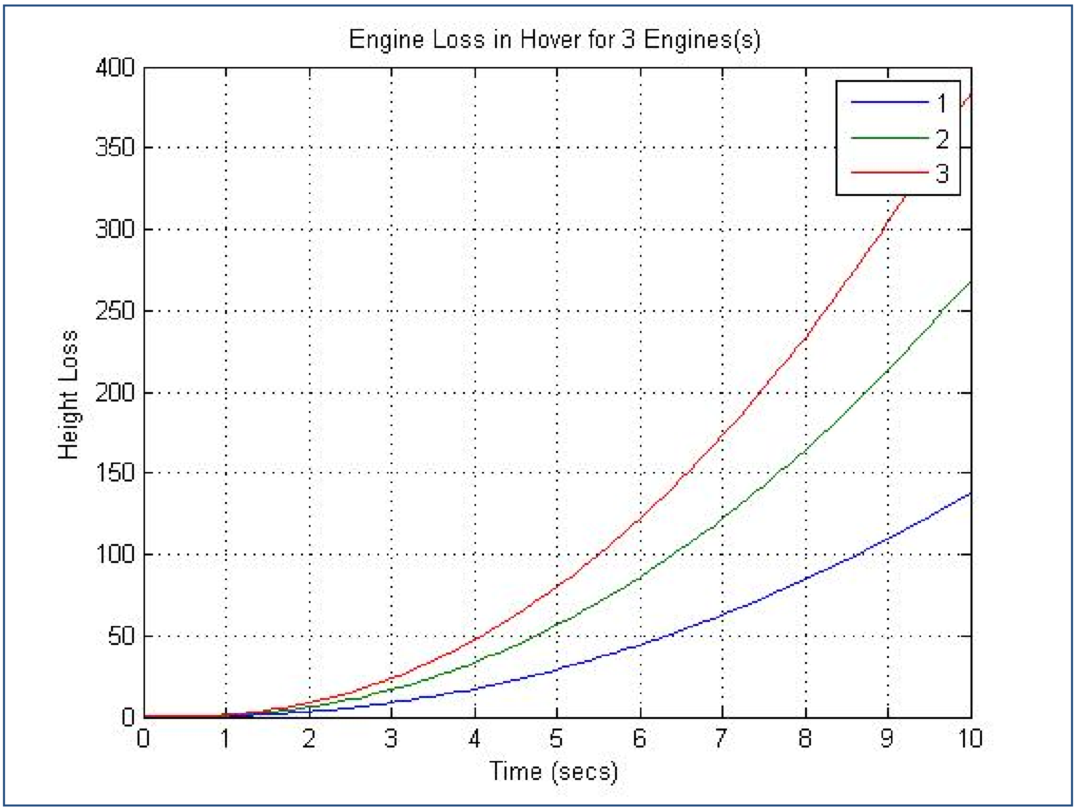

Engine Loss in Hover for 2 Engines(s)
Height Loss
Time (secs)
1
2
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10

Number of Engines = 3




Engine Loss in Hover for 3 Engines(s)
Descent Acceleration
Time (secs)
1
2
3
0
1
2
3
4
5
6
7
8
9
10


Engine Loss in Hover for 3 Engines(s)
Descent Velocity
Time (secs)
1
2
3
-10
0
10
20
30
40
50
60
70
80
90


Engine Loss in Hover for 3 Engines(s)
Height Loss
Time (secs)
1
2
3
0
50
100
150
200
250
300
350
400
0
1
2
3
4
5
6
7
8
9
10