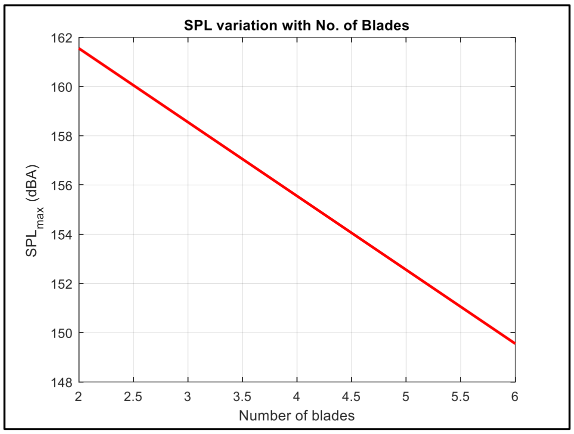
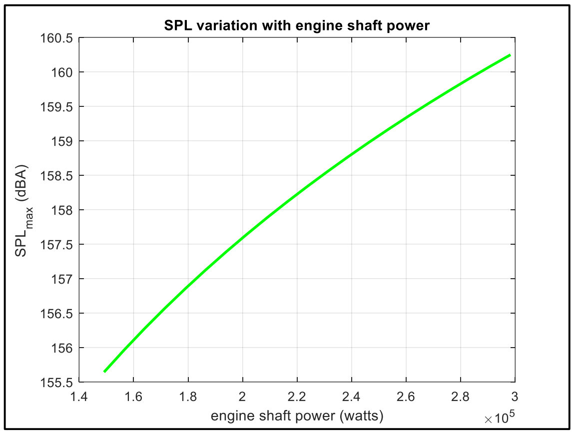
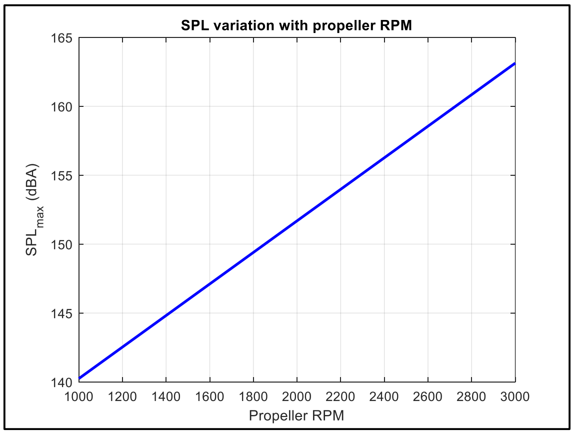
1. Sensitivity Analysis of the Empirical Model

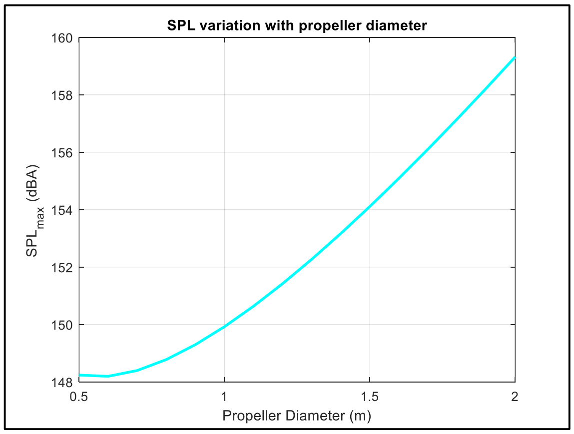
The following is a sensitivity analysis for the empirical model for propeller noise taken from Chapter 12 of the textbook "Elements of Aviation Acoustics" by G.J.J Ruijgrok. The propeller noise equation is given as:

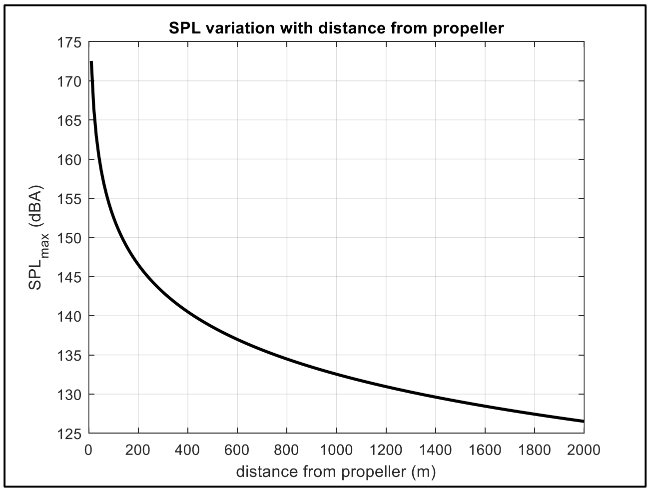
$$SPL_{max}(r) = 83.4 + 15.3 \log P_{br} - 20 \log D + 38.5\, M_t - 3(B-2) + 10 \log N - 20 \log r$$









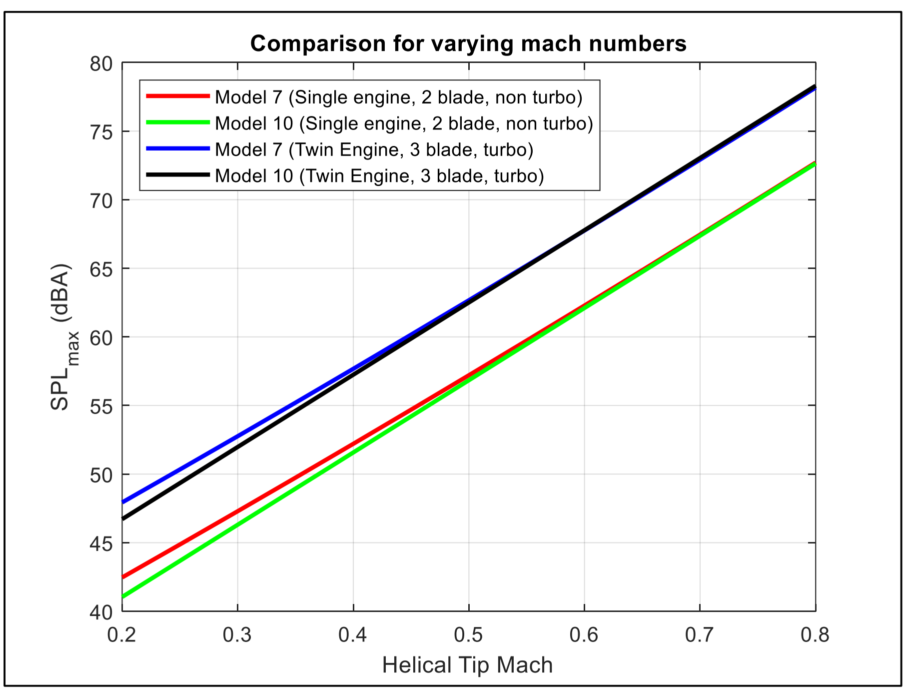


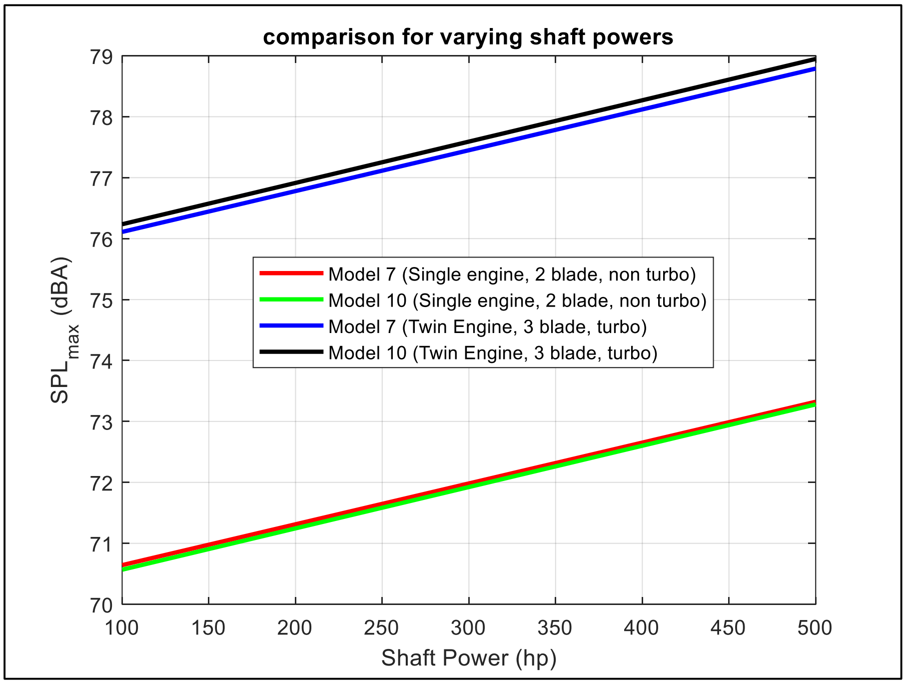
2. Input Identification of Regression Analysis Based Sound Models

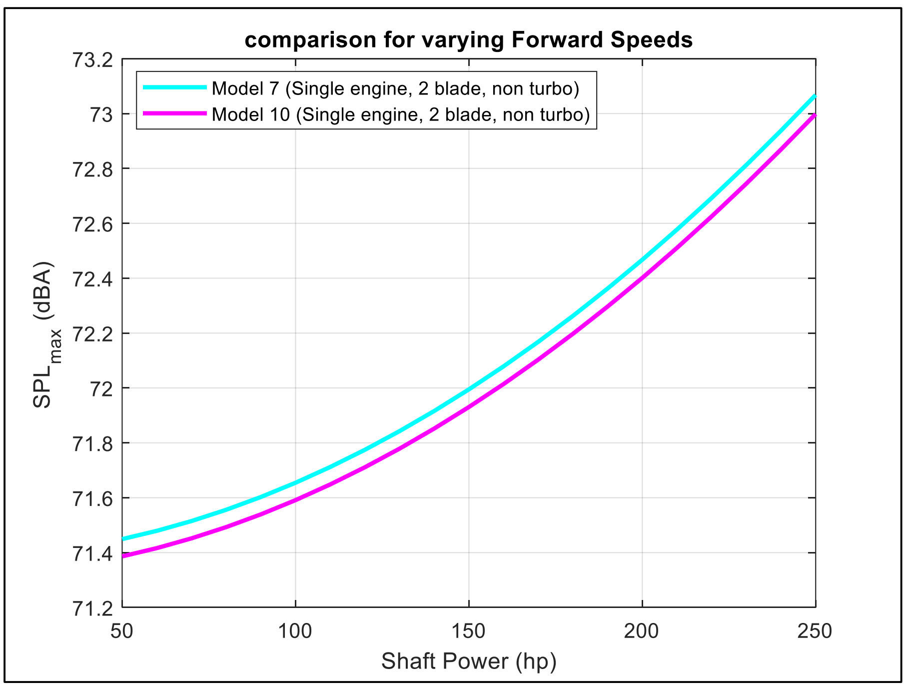
Following table identifies the different inputs to the several flyover sound models delineated in the technical study "The Development of a Flyover Noise Prediction Technique Using Multiple Linear Regression Analysis" by Cessna Aircraft Co.

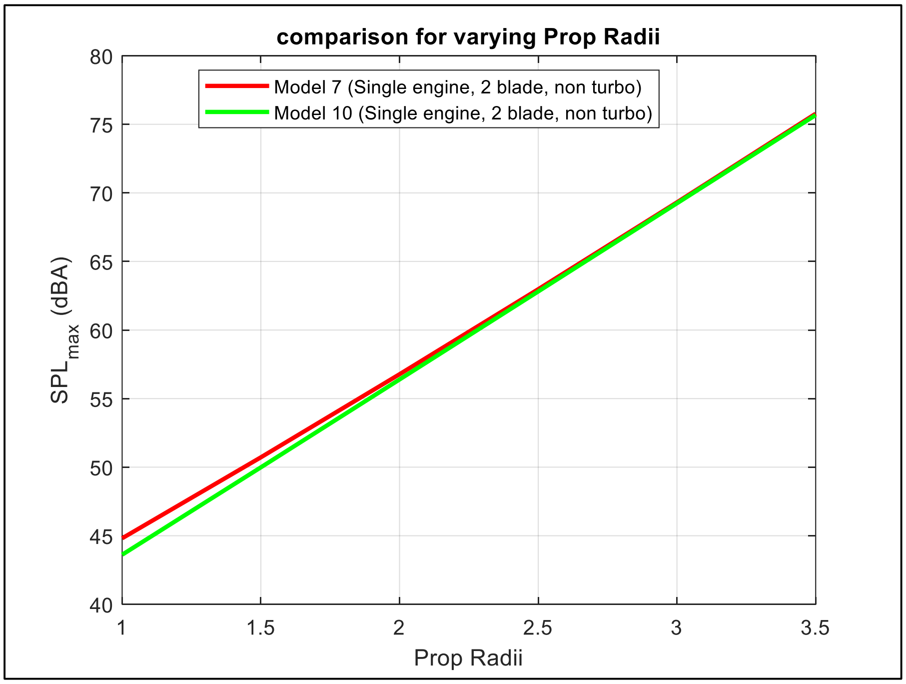
Model Number:		**1**	**2**	**3**	**4**	**5**	**7**	**8**	**9**	**10**
Parameter	**Unit**									
Helical Mach	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Shaft HP	Hp						✓	✓	✓	✓
Helical Mach Squared	-						✓			
Two or Three Blades ?	-			✓			✓	✓		✓
Turbocharger Enabled?	-						✓	✓		✓
Single or Twin engine?	-						✓			✓

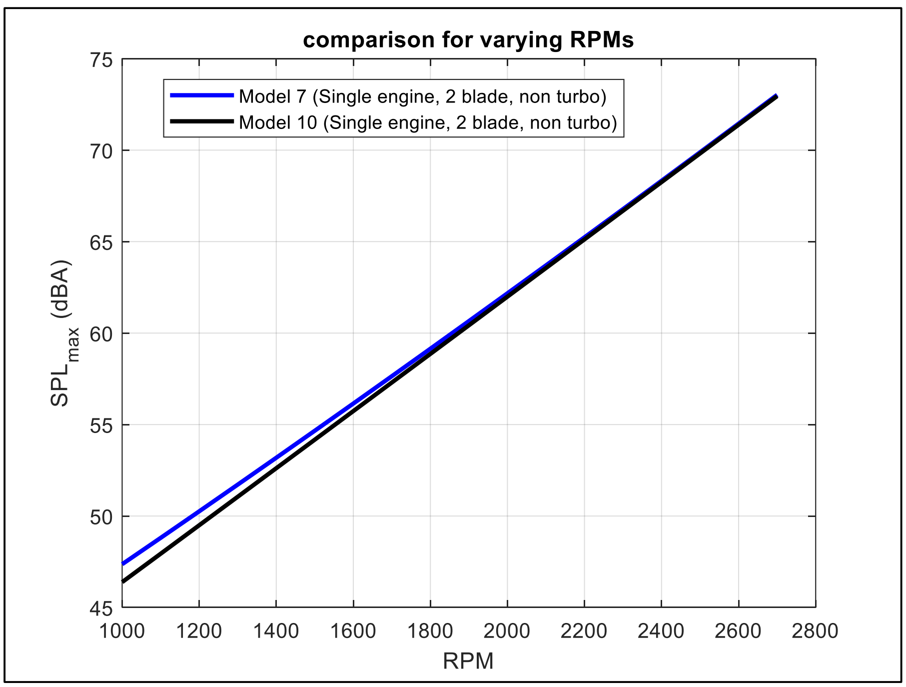
2.1 Comparison between Models 7 and 10




comparison for varying shaft powers
79
78
77
76
75
74
73
72
71
70
SPL$_{max}$ (dBA)
100
150
200
250
300
350
400
450
500
Shaft Power (hp)
Model 7 (Single engine, 2 blade, non turbo)
Model 10 (Single engine, 2 blade, non turbo)
Model 7 (Twin Engine, 3 blade, turbo)
Model 10 (Twin Engine, 3 blade, turbo)


comparison for varying Forward Speeds
73.2
73
72.8
72.6
72.4
72.2
72
71.8
71.6
71.4
71.2
SPL$_{max}$ (dBA)
50
100
150
200
250
Shaft Power (hp)
Model 7 (Single engine, 2 blade, non turbo)
Model 10 (Single engine, 2 blade, non turbo)





3. Codes for both Models

3.1 Empirical Model

```
clc;clear;close all
%For this code, let us use the data from Chapter 14 examples of Gudmundson
%The model has been taken from Ref 18 - "Elements of aviation Acoustics"
```

```
%Starting with the piston engine noise:
n = 2600;%engine rotational speed in RPM
N = 4;%number of cylinders
f_c = n/120;%cylinder firing frequency
f_e = (N*n)/120;%exhaust firing frequency
% According to Reference 61, the overall A-weighted level of the exhaust
noise
% of an unmuffled piston engine at 150 m sideline can be estimated by:
P_br = 310*745.7;%engine shaft power, watts
L_A = 8 + (14*log10(P_br)) %dBA
%Using data in Gudmundson - An airplane is powered by a two-bladed propeller
%whose diameter is 76 inches is driven by a 310 BHP engine

%Then moving on to propeller noise:
% For the prediction of far-field propeller noise, the following expres sion
for the
% maximum sound pressure level can be used:
B = 3;%number of blades per propeller
n_p = 2600;%propeller rotational speed (rpm)
D = 1.9304;%propeller diameter (m)
r = 50;%distance from propeller (m)
c = 340;%speed of sound(m/s)
M_t = (pi*D*n_p)/(60*c);%tip mach number
SPL_max = 83.4 + (15.3*log10(P_br)) - (20*log10(D)) + (38.5*M_t) + ...
          (-3*(B - 2)) + (10*log10(N)) - (20*log10(r))

%Sensitivity Analysis for the propeller model
%First we will vary each input parameter indvidually to check its impact on
%the sound level while keeping the other inputs constant.

%Sensitivity to Number of Blades
figure(1)
B_set = [2, 3, 4, 5, 6];
SPL_max_B = 83.4 + (15.3.*log10(P_br)) - (20.*log10(D)) + (38.5.*M_t) + ...
          (-3.*(B_set - 2)) + (10.*log10(N)) - (20.*log10(r))
plot(B_set,SPL_max_B,'r','LineWidth',2);grid on
xlabel('Number of blades');ylabel('SPL_{max} (dBA)');title('SPL variation
with No. of Blades')

%Sensitivity to Engine Horse Power
figure(2)
P_br_set = [200:10:400].*745.7;%watts
SPL_max_P_br = 83.4 + (15.3.*log10(P_br_set)) - (20.*log10(D)) + (38.5.*M_t)
+ ...
          (-3.*(B - 2)) + (10.*log10(N)) - (20.*log10(r))
plot(P_br_set,SPL_max_P_br,'g','LineWidth',2);grid on
xlabel('engine shaft power (watts)');ylabel('SPL_{max} (dBA)');title('SPL
variation with engine shaft power')

%Sensitivity to Propeller RPM i.e. tip mach
figure(3)
n_p_set = 1000:100:3000
M_t_set = (pi.*D.*n_p_set)./(60.*c);%tip mach number
SPL_max_n_p = 83.4 + (15.3.*log10(P_br)) - (20.*log10(D)) + (38.5.*M_t_set) +
...
          (-3.*(B - 2)) + (10.*log10(N)) - (20.*log10(r))
```

```
plot(n_p_set,SPL_max_n_p,'b','LineWidth',2);grid on
xlabel('Propeller RPM');ylabel('SPL_{max} (dBA)');title('SPL variation with
propeller RPM')

%Sensitivity to Propeller Diameter i.e. also affects tip mach
figure(4)
D_set = 0.5:0.1:2;%propeller diameter (m)
M_t_set_2 = (pi.*D_set.*n_p)./(60.*c);%tip mach number
SPL_max_D = 83.4 + (15.3.*log10(P_br)) - (20.*log10(D_set)) +
(38.5.*M_t_set_2) + ...
          (-3.*(B - 2)) + (10.*log10(N)) - (20.*log10(r))
plot(D_set,SPL_max_D,'c','LineWidth',2);grid on
xlabel('Propeller Diameter (m)');ylabel('SPL_{max} (dBA)');title('SPL
variation with propeller diameter')

%Sensitivity to distance From Propeller
figure(5)
r_set = 0:10:100;%distance from propeller (m)
SPL_max_r = 83.4 + (15.3.*log10(P_br)) - (20.*log10(D)) + (38.5.*M_t) + ...
          (-3.*(B - 2)) + (10.*log10(N)) - (20.*log10(r_set))
plot(r_set,SPL_max_r,'k','LineWidth',2);grid on
xlabel('distance from propeller (m)');ylabel('SPL_{max} (dBA)');title('SPL
variation with distance from propeller')
```

3.2 Regression Models

```
%Following are the regression based models from the paper:
%   "The Development of a Flyover Noise Prediction Technique Using Multiple
%   Linear Regression Analysis"
clc;clear variables;close all
%Defining the State Conditions at different altitudes
%specifying all of the altitudes
alt_ft = 1000:1000:35000;
alt_m = alt_ft * 0.3048;
%Temp in K, Sound Speed in m/s, Pressure in Pa, rho(h) in kg/m3
[T_si,a_si,P_si,rho_si] = atmoscoesa(alt_m);
%converting atmospheric values to english uni`ts
T_eng = 1.8*T_si;%rankine
a = 3.28084*a_si;%ft/s
P = 0.02088547*P_si;%lb/ft^2
rho = 0.00194032*rho_si;%slugs/ft^3

%MODEL # 1 - (Single Engine Aircraft)
X_1 = 0.79;%Helical Mach
Y_1 = 12.7506 + (75.6219*X_1);%dBA

%MODEL # 2 - (Twin Engine Aircraft)
X_2 = 0.78;%Helical Mach
Y_2 = 25.99 + (65.0586*X_2);%dBA

%MODEL # 3 - (Single and Twin Engine)
X_3_1 = 0.78;%Helical Mach
X_3_2 = 0;% 0 for single and 1 for double prop
Y_3 = 13.2314 + (75.0445*X_3_1) + (4.3295*X_3_2);%dBA
```

```
%MODEL # 4 - (Single Engine Aircraft)
X_4 = 0.78;%Helical Mach
Y_4 = 86.7697 + (137.8972*X_4);%dBA

%MODEL # 5 - (Single Engine Aircraft)
X_5 = 0.78;%Helical Mach
Y_5 = 60.8837 + (0.00481*X_5);%dBA

%MODEL # 6 - ILLEGIBLE

%MODEL # 8 - (Single Engine Aircraft)
X_8_1 = 250;%BHP
X_8_2 = 0.78;%Helical Mach
X_8_3 = 0;%0 for 2 blade, 1 for 3 blade
X_8_4 = 0;%0 for non-turbo, 1 for turbo
Y_8 = 30.5646 + (0.00942*X_8_1) + (49.9636*X_8_2) + (2.4494*X_8_3) +
(0.4552*X_8_4);

%MODEL # 9 - (Twin Engine Aircraft)
X_9_1 = 250;%BHP
X_9_2 = 0.78;%Helical Mach
Y_9 = 5.2566 + (0.01428*X_9_1) + (84.2969*X_9_2);

%MODEL # 10 -
X_10_1 = 250;%BHP
X_10_2 = 0.78;%Helical Mach
X_10_3 = 0;%0 for 2 blade, 1 for 3 blade
X_10_4 = 0;%0 for non-turbo, 1 for turbo
X_10_5 = 0;%0 for single engine, 1 for twin engine
Y_10 = 28.8194 + (0.00678*X_10_1) + (52.6543*X_10_2) + (2.8333*X_10_3)...
       + (0.2603*X_10_4) + (2.5742*X_10_5);

%MODEL # 7 - (Sing and Twin Engine Aircraft)
X_7_1 = 250;%BHP
X_7_2 = 0.78;%Helical Mach
X_7_3 = X_7_2^2;%Helical Mach Squared
X_7_4 = 0;%0 for 2 blade, 1 for 3 blade
X_7_5 = 0;%0 for non-turbo, 1 for turbo
X_7_6 = 0;%0 for single engine, 1 for twin engine
Y_7 = 31.3920 + (0.0067*X_7_1) + (46.1576*X_7_2) + (4.2376*X_7_3) + ...
      (2.5981*X_7_4) + (0.2577*X_7_5) + (2.6106*X_7_6);

%COMPARISONS BETWEEN MODELS 7 & 10

%Helical Tip Mmach Variance Comparison:
%Single engine (250 hp), 2 blade, non turbo
figure(1)
M_hel_Set = 0.2:0.05:0.8;
Y_7_Mach_1 = 31.3920 + (0.0067.*250) + (46.1576.*M_hel_Set) +
(4.2376.*(M_hel_Set.^2)) + ...
      (2.5981.*0) + (0.2577.*0) + (2.6106.*0);
Y_10_Mach_1 = 28.8194 + (0.00678*250) + (52.6543*M_hel_Set) + (2.8333*0)...
       + (0.2603*0) + (2.5742*0);
%Twin Engine, 3 blade, turbo
```

```
Y_7_Mach_2 = 31.3920 + (0.0067.*250) + (46.1576.*M_hel_Set) +
(4.2376.*(M_hel_Set.^2)) + ...
      (2.5981.*1) + (0.2577.*1) + (2.6106.*1);
Y_10_Mach_2 = 28.8194 + (0.00678*250) + (52.6543*M_hel_Set) + (2.8333*1)...
       + (0.2603*1) + (2.5742*1);
plot(M_hel_Set,Y_7_Mach_1,'r','LineWidth',2);grid on;hold on
plot(M_hel_Set,Y_10_Mach_1,'g','LineWidth',2)
plot(M_hel_Set,Y_7_Mach_2,'b','LineWidth',2);
plot(M_hel_Set,Y_10_Mach_2,'k','LineWidth',2)
xlabel('Helical Tip Mach');ylabel('SPL_{max} (dBA)');title('comparison for
varying mach numbers')
legend('Model 7 (Single engine, 2 blade, non turbo)', 'Model 10 (Single
engine, 2 blade, non turbo)',...
       'Model 7 (Twin Engine, 3 blade, turbo)', 'Model 10 (Twin Engine, 3
blade, turbo)','Location','NorthWest')
xlim([0.2 0.8])

%Shaft Horse Power Variance Comparison:
%Mach 0.78, 2 blade, non turbo
figure(2)
M_hel_Set = 0.78;
Power_Set = 100:10:500;%hp
Y_7_Power_1 = 31.3920 + (0.0067.*Power_Set) + (46.1576.*M_hel_Set) +
(4.2376.*(M_hel_Set.^2)) + ...
      (2.5981.*0) + (0.2577.*0) + (2.6106.*0);
Y_10_Power_1 = 28.8194 + (0.00678.*Power_Set) + (52.6543.*M_hel_Set) +
(2.8333.*0)...
       + (0.2603.*0) + (2.5742.*0);
%Twin Engine, 3 blade, turbo
Y_7_Power_2 = 31.3920 + (0.0067.*Power_Set) + (46.1576.*M_hel_Set) +
(4.2376.*(M_hel_Set.^2)) + ...
      (2.5981.*1) + (0.2577.*1) + (2.6106.*1);
Y_10_Power_2 = 28.8194 + (0.00678*Power_Set) + (52.6543*M_hel_Set) +
(2.8333*1)...
       + (0.2603*1) + (2.5742*1);
plot(Power_Set,Y_7_Power_1,'r','LineWidth',2);grid on;hold on
plot(Power_Set,Y_10_Power_1,'g','LineWidth',2)
plot(Power_Set,Y_7_Power_2,'b','LineWidth',2);
plot(Power_Set,Y_10_Power_2,'k','LineWidth',2)
xlabel('Shaft Power (hp)');ylabel('SPL_{max} (dBA)');title('comparison for
varying shaft powers')
legend('Model 7 (Single engine, 2 blade, non turbo)', 'Model 10 (Single
engine, 2 blade, non turbo)',...
       'Model 7 (Twin Engine, 3 blade, turbo)', 'Model 10 (Twin Engine, 3
blade, turbo)','Location','NorthWest')

%Setting up comparisons via models 7 and 10 w.r.t Diameter, RPM, and Speed
%Assuming configuration through all comparisons to be -> 250 hp, 2 blade, non
turbo
%forward velocity of 50 ft/s if unvaried, Diameter of 6.33333 ft if unvaried
%Forward Speed:
figure(3)
alt = 1;
R = 6.3333/2; %ft
RPM = 2600;%rpm
RPM_rads = RPM*0.1047198;%rad/s
```

```
V_forward = 50:10:250;%ft/s
V_hel_2 = sqrt((V_forward.^2) + ((RPM_rads.*R).^2));
M_hel_Set_2 = V_hel_2./a(alt)
Y_7_Forward = 31.3920 + (0.0067.*250) + (46.1576.*M_hel_Set_2) +
(4.2376.*(M_hel_Set_2.^2)) + ...
      (2.5981.*0) + (0.2577.*0) + (2.6106.*0);
Y_10_Forward = 28.8194 + (0.00678*250) + (52.6543*M_hel_Set_2) +
(2.8333*0)...
       + (0.2603*0) + (2.5742*0);
plot(V_forward,Y_7_Forward,'c','LineWidth',2);grid on;hold on
plot(V_forward,Y_10_Forward,'m','LineWidth',2)
legend('Model 7 (Single engine, 2 blade, non turbo)',...
       'Model 10 (Single engine, 2 blade, non turbo)')
xlabel('Shaft Power (hp)');ylabel('SPL_{max} (dBA)');title('comparison for
varying Forward Speeds')

%Prop Diameter
figure(4)
R_set = (2:1:7)./2; %ft
RPM = 2600;%rpm
RPM_rads = RPM*0.1047198;%rad/s
V_forward = 50;%ft/s
V_hel_3 = sqrt((V_forward.^2) + ((RPM_rads.*R_set).^2));
M_hel_Set_3 = V_hel_3./a(alt)
Y_7_Rad = 31.3920 + (0.0067.*250) + (46.1576.*M_hel_Set_3) +
(4.2376.*(M_hel_Set_3.^2)) + ...
      (2.5981.*0) + (0.2577.*0) + (2.6106.*0);
Y_10_Rad = 28.8194 + (0.00678*250) + (52.6543*M_hel_Set_3) + (2.8333*0)...
       + (0.2603*0) + (2.5742*0);
plot(R_set,Y_7_Rad,'r','LineWidth',2);grid on;hold on
plot(R_set,Y_10_Rad,'g','LineWidth',2)
legend('Model 7 (Single engine, 2 blade, non turbo)',...
       'Model 10 (Single engine, 2 blade, non turbo)')
xlabel('Prop Radii');ylabel('SPL_{max} (dBA)');title('comparison for varying
Prop Radii')

%Propeller RPM
figure(5)
R_set = 6.33333/2; %ft
RPM_set = 1000:100:2700;%rpm
RPM_rads = RPM_set.*0.1047198;%rad/s
V_forward = 50;%ft/s
V_hel_4 = sqrt((V_forward.^2) + ((RPM_rads.*R_set).^2));
M_hel_Set_4 = V_hel_4./a(alt)
Y_7_RPM = 31.3920 + (0.0067.*250) + (46.1576.*M_hel_Set_4) +
(4.2376.*(M_hel_Set_4.^2)) + ...
      (2.5981.*0) + (0.2577.*0) + (2.6106.*0);
Y_10_RPM = 28.8194 + (0.00678*250) + (52.6543*M_hel_Set_4) + (2.8333*0)...
       + (0.2603*0) + (2.5742*0);
plot(RPM_set,Y_7_RPM,'b','LineWidth',2);grid on;hold on
plot(RPM_set,Y_10_RPM,'k','LineWidth',2)
legend('Model 7 (Single engine, 2 blade, non turbo)',...
       'Model 10 (Single engine, 2 blade, non turbo)')
xlabel('RPM');ylabel('SPL_{max} (dBA)');title('comparison for varying RPMs')
```