An Intermittent-Combustion General Aviation Aircraft Engine Exhaust Noise prediction Algorithm

Hiroko Tada
Embry-Riddle Aeronautical University - Daytona Beach

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Hiroko Tada

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THESIS COMMITTEE:

Dr. Howard V. L. Patrick
Chair

Dr. Donald T. Higdon
Member

Dr. Allen Ormsbee
Member

Program Chair, MASE Program

Department Chair, Aerospace Engineering

Date

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ABSTRACT

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From an environmental point of view, the reduction of aircraft noise has become an important factor recently. There are two factors that make airplane noise: propeller noise and engine noise. This report puts emphasis on only the engine noise in order to begin understanding what airplane engine exhaust noise is. At first, the engine exhaust noise is comprehended using the Dobrzynski's engine noise theory. Next, a discussion about an Embry-Riddle Aeronautical University (ERAU) engine system, engine exhaust system configurations, and microphone setting standards that show the ERAU engine system exhaust noise data. Finally, an Intermittent-Combustion (IC) General Aviation (GA) aircraft engine exhaust noise prediction algorithm using FORTRAN code is compiled. The predicted noise level by this algorithm is compared with the actual airplane engine noise data. Consequently, the results from this algorithm can serve to modify the propulsion system and to design the engine noise reduction system.

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List of Symbols

A_d	:	Cross-section area with diameter d, m^2
A_r	:	Spherical surface area with radius r, m^2
c	:	Speed of sound, m/s
d	:	Exhaust pipe diameter, m
EFF	:	Engine firing frequency
f	:	Fundamental firing frequency, Hz
f_c	:	Center frequency of one-third octave-band, Hz
f_D	:	Doppler effect characteristic frequency, Hz
f_l	:	Lower limit frequency of one-third octave-band, Hz
f_M	:	Characteristic engine firing frequency, Hz
f_m	:	Middle frequency, Hz
f_{rpm}	:	Frequency of tonal noise at engine rotational speed rpm, Hz
f_u	:	Upper limit frequency of one-third octave-band, Hz
H	:	Airplane altitude, m
k	:	Wave number, $k = f/c$
$L_{A,max}$	:	Engine A-weighted overall sound pressure level at maximum engine rotational speed, dBA
$L_{A,norm}$	:	Normalized engine A-weighted overall sound pressure level, dBA
L_{AP}	:	Predicted engine A-weighted overall sound pressure level, dBA
$L_{AP,max}$	:	Predicted engine A-weighted overall sound pressure level at maximum engine rotational speed, dBA
$L_{AP,S}$	:	Predicted engine A-weighted overall sound pressure level with sound level meter setting at slow response, dBA
M_v	:	Mach number, $M_v = v/c$
N	:	Engine rotational speed, rpm
N_0	:	Reference level for engine rotational speed, 100 rpm
N_{max}	:	Maximum engine rotational speed, rpm
n_{cyl}	:	Number of engine cylinders
n_r	:	Number of engine piston rotation per second
OD	:	Outside diameter of tube, m
OASPL	:	Overall sound pressure level, dB

P : Engine power, hp

$\overline{P}$: Non-dimensional sound pressure

P_0 : Reference level for engine power, 10 kW

P_{max} : Maximum engine power, hp

$\widetilde{p}$: Sound pressure, Pa

p_{act} : Actual sound pressure, Pa

p_{ref} : Reference level for sound pressure, 20×10^{-6} Pa

$\overline{p}_{rpm}^{\,2}$: Mean-square value of sound pressure, Pa^2

$\overline{p}_{rpm,OA}^{\,2}$: Mean-square value of overall sound pressure, Pa^2

$\widetilde{Q}$: Volume flow rate, m^3/s

$\widetilde{Q}_{max}$: Maximum volume flow rate, m^3/s

r : Sound wave path distance, m

r' : Actual sound wave path distance, m

rps : Engine-shaft revolutions per second

S : Strouhal number, $S = f_{rpm} d / \widetilde{v}$

SPL : Sound pressure level, dB

SPL_{non} : Non-dimensional sound pressure level, dB

$SPL_{non}*$: Non-dimensional sound pressure level with engine rotational speed correction, dB

SPL_{rpm} : Sound pressure level at certain engine rotational speed, dB

t : Time, s

V : Engine displacement volume, m^3

v : Airplane speed, m/s

$\widetilde{v}$: mean fluid speed, m/s

x : x-coordinates of airplane at time t

y : y-coordinates of airplane at time t

α : Sound attenuation coefficient, 0.1 dB/100 m

ΔL_A : Sound pressure level difference between two at different engine rotational speed, dB

$\Delta L_{A,alt}$: Sound pressure level correction by airplane altitude difference, dB

$\Delta L_{A,rpm}$: Sound pressure level correction by engine rotational speed difference, dB

ΔL_{atn} : Sound pressure level correction by air attenuation, dB

$\Delta(\Delta L_A)$: Sound pressure level correction by Doppler effect, dB

ΔSPL : Sound pressure level correction by spectral line resolution, dB

Δt : Sound traveling time between sound source and microphone, s

Δx : Airplane traveling distance between the time Δt, m

ϕ : Sound radiation angle, deg

ϕ' : Actual sound radiation angle, deg

γ : Flight path angle, deg

ρ : Air density, kg/m^3

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Since the first airplane was invented in the early 1900's, airplane technology has developed dramatically. Two of the most important characteristics of airplanes are the wing profile and engine capabilities. Today, however, airplane noise must also be considered from an environmental point of view. Small propeller driven intermittent-combustion (IC) general aviation (GA) aircraft do not produce as much noise as larger commercial and business turbojet and turbofan airplane, but their operation at small airports near residential areas does create a noise pollution problem. In order to solve this problem, it is necessary to understand the characteristic of airplane noise and to study how to diminish the noise pollution.

1.2 Definition of Airplane Engine Noise

Generally, airplane noise is created by the movement of air over the airplane fuselage, wing. engine, and so on, but for IC GA aircraft the propeller and engine exhaust are the main noise sources [1]. The noises from these sources do not have the same magnitude, i.e. the propeller noise comprises 80 % of the airplane noise.

Air movement caused by the rotation of the propeller creates the propeller noise. The exact propeller blade geometry and blade tip speed are the main factors in the variation of the magnitude of propeller noise. The noise radiation from an airplane propeller has been predicted based upon Farassaf's [2] solution of the Ffowcs-Williams/Hawkings equation. This prediction derives the sound pressure variation with time as a function of blade thickness and the aerodynamic loading on the blade.

Airplane engine noise is generated by air movement from the exhaust pipe. The magnitude of this noise is a function of the engine rotational speed and power. However, airplane engine noise cannot easily be predicted theoritically as with propeller noise, since measuring air pressure and air speed at the end of the exhaust pipe is very difficult. Therefore, it is impossible to calculate the air fluctuation at that point. Also from an empirical standpoint, the airplane engine noise cannot be measured by itself because it is only a minor part of the total airplane noise. As a result, it is very difficult to compile an aircraft engine noise prediction algorithm.

1.3 Objective of the Research

The purposes of this report are to understand the characteristics of engine exhaust noise, to modify the normalization based upon Dobrzynski's theory [3]*, and to compile an IC GA aircraft engine exhaust noise prediction algorithm. To accomplish these goals, a special engine performance evaluation system incorporating a dynamometer is developed. In order to measure engine exhaust noise by itself, the dynamometer takes the place of the propeller in applying a load to the engine. The advantage of using this system is that the engine noise can be measured exclusively without having to conduct an airplane flight. Therefore, the resulting noise data can be used to compile the IC GA

* Mark Valon, a former ERAU student, translated this reference from German to English, which is unpublished.

aircraft engine exhaust noise algorithm. This algorithm will be able to estimate the noise of existing and future propulsion systems and evaluate the impact of configuration changes on the propulsion system noise. Consequently, the results from this algorithm can serve to modify the propulsion system and to design the engine exhaust noise reduction system.

CHAPTER 2

BACKGROUND

2.1 Experimental Report

In the 1940's Davis and Czarnecki performed an experimental investigation of the exhaust noise from a series of exhaust mufflers installed on a typical six-cylinder light airplane engine, mounted on a ground dynamometer stand [4,5]. This was a very innovative way to measure engine noise exclusively. The results showed that the muffler lowered the engine exhaust noise by about 5 –10 dB. Most of the sound energy in the exhaust was found to be concentrated at low frequencies, especially at the fundamental firing frequency, where the sound pressure level (SPL) was the loudest.

The quietest audible sound corresponds to a root-mean-square sound pressure about 20×10^{-6} Pa $(20\mu\text{Pa})$. On the other hand, the loudest one corresponds to a root-mean-square sound pressure 200 Pa. Because of the wide range of sound pressure of human interest, a decibel level (dB) is used to report the sound magnitude. The decibel level is defined as ten times the base-ten logarithm of a power ratio [6].

Human perception of loudness varies depending on the frequency of a sound. Noise with most of its energy concentrated around the frequency 1 kHz is perceived as louder than noise of equal energy concentrated at lower and higher frequencies than 1 kHz. Frequency weighting takes typical human response into account when all of the audible frequency components of a noise sample are to be described by a single number.

The sound pressure level concerning the human hearing response is called A-weighted SPL whose unit is dBA. On the other hand, the SPL without human response is called non-weighted SPL, which is shown in dB.

The report by Jones [7] included data from a Piper Cherokee Lance (a two-blade constant speed propeller driven airplane). The noise was measured during level fly over and take-off. This noise data showed that the take-off noise levels were 3 to 4 dBA higher than the level fly over noise levels. This effect was believed to result from unsteady propeller blade loading when the airplane was at a high angle of attack during take-off/climb-out as opposed to level flight.

2.2 Noise Prediction Algorithm

Magliozzi compiled an airplane propeller and engine noise prediction algorithm for developing noise reduction equipment in the 1970's. This is called the Hamilton Standard algorithm [8]. This algorithm allows for estimates of GA aircraft propulsion system noise and includes the effects of muffling the engine exhaust.

Dobrzynski also compiled an airplane noise prediction algorithm [3]. Dobrzynski normalized the IC GA aircraft engine exhaust noise using eleven different airplane noise data sets. This normalization allows for the calculation of the overall sound pressure level (OASPL) of any type of engine with any engine rotational speed. In his report, however, it is mentioned that engine mufflers do not effect the engine exhaust noise.

2.3 Muffler Effect

Pegg and Hilton stated that mounting a muffler onto the air frame would reduce engine exhaust noise. The report [9] included the evaluation of five different acoustic performances of exhaust mufflers for a helicopter reciprocating engine. The results showed that the maximum OASPL reduction was 8 dB during level fly over noise measurement. In other words, it is clear, from experimentation, that the muffler is effective at reducing the engine exhaust noise.

CHAPTER 3

THEORY

3.1 Dobrzynski's Engine Noise Theory and Normalization

The purpose of Dobrzynski's airplane noise normalization is to estimate the overall sound pressure level (OASPL) of any type of intermittent-combustion (IC) general aviation (GA) aircraft with any engine rotational speed. His approach is based upon empirical data, which includes take-off and level flight noise recordings of eleven different IC GA aircraft. These aircraft characteristics: aircraft type, aircraft engine type, engine configurations, are shown in Table 1. Each aircraft noise recording is normalized and formulated with the following steps.

The IC GA aircraft noise is dominated by propeller and engine noise. Propeller noise is a function of the exact propeller blade geometry, rotational speed and free stream speed. Consequently, it is possible to determine the details of the spectral distribution of propeller noise using the Ffowcs-Williams/Hawkings equation [2]. In Dobrzynski's report, the engine noise levels, which are given in Figure 8 of his report, are calculated by subtracting the predicted propeller noise levels from the total airplane noise levels at maximum engine power, which are measured in advance. These noise levels, which are the sound pressure level (SPL) in the A-weighted decibels for various aircraft, are given in Table 1.

Table 1 Propulsion Sound Pressure Level Data of 11 Airplanes

Aircraft		Engine							SPL	
Type	#	Type	Max. Power [kW]	Max. RPM [rpm]	Number of cylinder	Number of cycle	Engine displacement [dm^3]	Number of engine	L_A [dBA]	$L_{A,norm}$ [dBA]
FFA-AS-202-15	1	LY-320-E2A	110	2500	4	4	5.20	1	64.3	55.3
PA-28-180B	2	LY-360-A4A	132	2700	4	4	5.92	1	67.8	57.8
Cessna F152	3	LY-O-235-N2C	81	2550	4	4	3.85	1	62.8	55.7
PA-38-112	4	LY-O-235-L2C	82	2600	4	4	3.85	1	62	54.9
Mooney M 20K	5	Con. TSIO-360 MB	155	2700	6	4	5.90	1	67.8	56.9
Beech B 200	6	P&W PT 6A-42	625	2000	-	-	-	2		
PA-34-220T	7	Con. L/TSIO-360 KB	147	2600	6	4	5.90	2	65	54.3
Cessna 182 Q	8	Porche PFM 3200 NO3	165	5300	6	4	3.20	1	66.3	56.2
DR-400-180R	9	LY-O-360-A3A	132	2700	4	4	5.92	1	65	55.0
SF 25 C Falke	10	Limb. L 2000 EA	59	3450	4	4	2.00	1	58.9	54.3
GROB G 109 B	11	Grob G 2500	66	3000	4	4	2.50	1	62.8	57.2

The noise that comes from an engine consists of many different parts: mechanical, combustion, exhaust, to name a few. In addition, the engine noise depends on the engine system itself. A change in the diameter of the exhaust pipe or in the type of muffler mounted on the engine will alter the exhaust noise. Therefore, not only are the characteristics of the sound components important, but the characteristics of the engine system are as well. In Dobrzynski's research, it is shown that engine noise is dominated by exhaust noise, and is assumed to be a monopole source. The exhaust noise, which originates as a pulsating air movement inside the engine cylinder, has a monopole sound source at the exhaust exit whose radiation is a result of a fluctuation in the volume flow rate. Therefore, the magnitude of the engine noise is related to the engine system and operating parameters.

Since a monopole has a spherically symmetric directivity characteristic, the sound pressure, $\tilde{p}$, radiated by a monopole source is calculated using the following equation:

$$\tilde{p} = \frac{\rho A_r}{4\pi r}\frac{\partial \tilde{Q}}{\partial t} \tag{1}$$

where ρ is air density, A_r is the spherical surface area with radius r. This equation indicates that the change of the volume flow rate with respect to time, $\frac{\partial \tilde{Q}}{\partial t}$ is very significant. The volume flow rate is the engine displacement volume, V, multiplied by the engine rotational speed, N. Therefore, the maximum volume flow rate, Q_{max}, is:

$$\tilde{Q}_{max} \sim V \cdot N_{max} \tag{2}$$

where N_{max} is the maximum engine rotational speed. According to Sass [10], for combustion engines the maximum engine power, P_{max}, is given by the following:

$$\frac{P_{max}}{V} \sim N_{max} \cdot (\text{Combustion Pressure}) \tag{3}$$

In other words, the key parameter for maximum engine power is the maximum engine rotational speed, since the combustion pressure is constant for each engine. Combining Eqs. (2) and (3) results in the following equation for maximum volume flow rate without using the engine displacement:

$$\tilde{Q}_{max} \sim (N_{max})^{E1} \left(\frac{P}{N_{max}} \right)^{E2} \tag{4}$$

where E1 and E2 are empirical constants which will be explained later. The reason maximum engine parameters are used is that all engine noise can be based on the noise at maximum engine power as shown in Fasold [11]. As a result, the sound pressure is calculated from Eqs. (1) and (4), simply using two parameters: engine power and engine rotational speed. In Dobrzynski's approach, the SPL of any type of IC engine can be normalized according to the following equation:

$$L_{A,norm} = L_{A,max} - 10\log\left(\frac{N_{max}}{N_0} \right)^{E1} - 10\log\left(\frac{P_{max}/N_{max}}{P_0/N_0} \right)^{E2} \tag{5}$$

where $L_{A,max}$ is engine A-weighted OASPL at maximum engine rotational speed, and N_0 and P_0 are the reference levels for engine rotational speed and engine power, which are 100 rpm and 10 kW respectively. The three unknown constants, $L_{A,norm}$, E1, and E2 are empirical numbers which are derived from actual airplane noise data. The operating conditions, for which this equation is valid, are a source distance of 1000-ft and a ground microphone setting.

To derive these unknown constants, Dobrzynski collected noise data from eleven airplanes (see Table 1). All noise data were measured using the ground microphone setting (discussed later). Since airplane noise is the sum of engine and propeller noise, it is assumed that the engine noise level can be calculated by subtracting the predicted propeller noise level from the entire radiated noise level of the airplane, which is labeled as $L_{A, max}$. In Dobrzynski's theory, two constants, E1=1.0 and E2=1.4, are used. Using these two numbers and $L_{A, max}$, the normalized engine A-weighted OASPL, $L_{A, norm}$, can be calculated. Table 1 shows $L_{A, norm}$ and the maximum power of each engine and Figure 1 shows the $L_{A, norm}$ plots depend upon the maximum engine power respectively. In most of the plots, $L_{A, norm}$ is close to 56.3 dBA. In other words, the results of empirical data analysis provided data necessary for the normalization procedure used in Eq. (5).

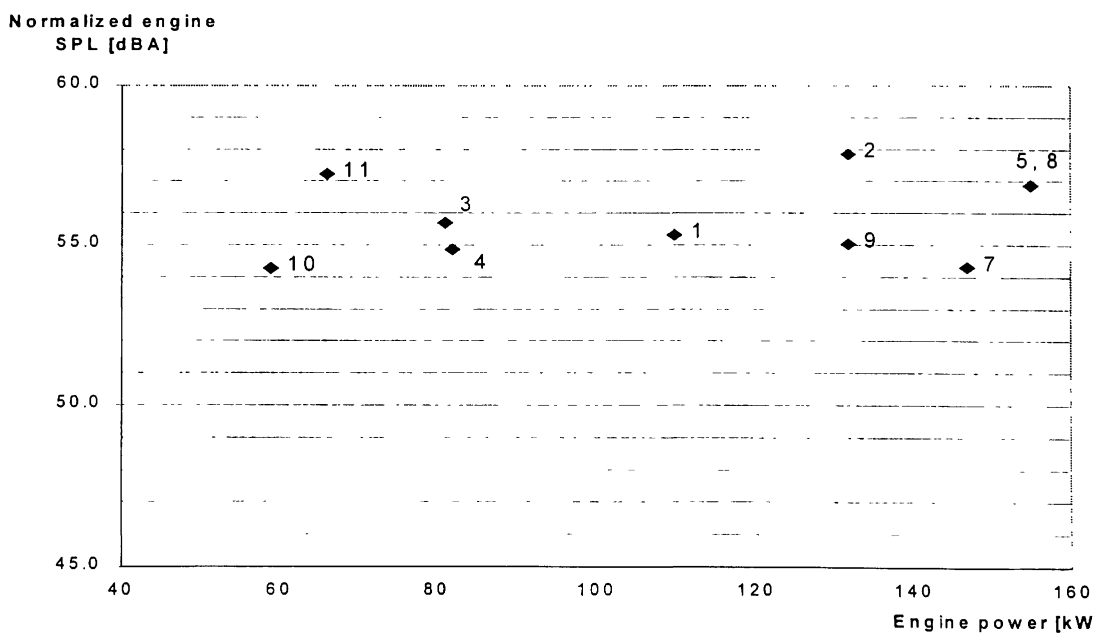


Figure 1 Normalized Sound Pressure Level Dependent upon Engine Maximum Power

However, in his research, Dobrzynski calculated a value of 51.9 dBA for $L_{A,\,norm}$, which is 4.4 dBA lower than the figure of 56.3 dBA determined from the plots. In this report, 56.3 dBA is used as the normalized engine OASPL in the development of the engine noise prediction algorithm. The predicted engine A-weighted OASPL at maximum engine speed is given by:

$$L_{AP,\max} = 56.3 + 10\log\left(\frac{N_{\max}}{N_0}\right) + 14\log\left(\frac{P_{\max}/N_{\max}}{P_0/N_0}\right) \tag{6}$$

The subscript P in $L_{AP,max}$ denotes the predicted SPL.

3.2 Correction Factors

Correction factors are necessary in Eq. (6) concerning the following headings:

1) A sound pressure correction factor must be used if the actual engine rotational speed is below the maximum. This correction factor is a function of the ratio of the engine rotational speed to the maximum engine rotational speed. Since engine exhaust noise is generated by a monopole source, the SPL correction value for engine rotational speed difference, $\Delta L_{A,rpm}$, is a function of the fourth power of the engine rotational speed ratio as given below.

$$\Delta L_{A,rpm} = 10\log\left(\frac{N}{N_{\max}}\right)^4 \tag{7}$$

2) A change in altitude causes a change in engine exhaust noise OASPL, $\Delta L_{A,alt}$. The SPL correction by a airplane altitude difference is a function of the ratio of altitude to reference altitude, 1000-ft, and is based upon the assumption of spherical expansion,

i.e. the acoustic pressure is inversely proportional to distance from the sound source.

$$\Delta L_{A,alt} = -10\log\left(\frac{r'}{1000}\right)^2 \tag{8}$$

where r' is the actual sound wave path between the noise source and microphone in feet.

3) When measuring fly-over noise, the Doppler effect must be considered. A diagram showing the position of the airplane with respect to the observer is given in Figure 2. The observer is at the origin (0,0) and the airplane is (x,y) at time t. The airplane passes the point (0,H) with constant speed, v, and flight path angle, γ. The sound wave path distance is respected by r, and $v\Delta t$, which is defined as the actual sound wave path distance divided by speed of sound, $|r'|/c$, is the time for the sound wave

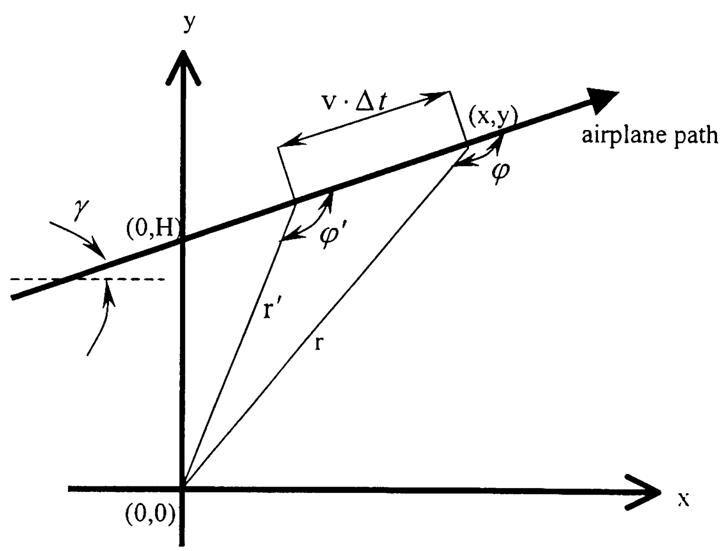


Figure 2 View of Observer and Airplane

to reach the observer. The airplane is at the following point, t seconds later:

$$x = (v\cos\gamma)t \tag{9}$$

$$y = H + (v\sin\gamma)t \tag{10}$$

The sound wave path distance, r, and the sound radiation angle, ϕ, can be shown using x and y:

$$|r| = \sqrt{(x^2 + y^2)} \tag{11}$$

$$\phi = \gamma + \cos^{-1}\left(-\frac{x}{|r|}\right) \tag{12}$$

where the flight path angle γ is positive during climb and negative during descent. Therefore, sound traveling time between sound source and microphone, Δt, is modified as:

$$\Delta t = \frac{|r'|}{c} = \frac{\Delta x}{v\cos\gamma} \tag{13}$$

The airplane travels a distance of $v \cdot \Delta t$ in the amount of time between the initial radiation of the sound waves off the airplane and the reception of these waves by the observer. The actual sound path, r', and the corresponding true radiation angle, ϕ', are calculated as follows:

$$|r'| = \frac{-M_v x + \left[y^2\left(1 - M_v^{\ 2}\right) + x^2\right]^{1/2}}{1 - M_v^{\ 2}} \tag{14}$$

$$\phi' = \gamma + \cos^{-1}\left(M_v \cos\gamma - \frac{x}{|r'|}\right) \tag{15}$$

where M_v is the Mach number of the aircraft, i.e. $M_v = v/c$. These relationships are required for estimating the sound reduction due to the Doppler effect, which is shown as $\Delta(\Delta L_A)$. The Doppler effect causes the frequency distortion between the source and observer. The Doppler effect characteristic frequency is given by:

$$f_D = \frac{f_M}{1 - M_v \cos\phi'} \tag{16}$$

where f_M is the characteristic engine firing frequency. This number for a 4-cycle engine is give by following equation:

$$f_M = \frac{n_{cyl}}{2}\frac{N}{60} \tag{17}$$

where n_{cyl} is the number of engine cylinders. Moreover, the frequency distortion also changes the A-weighted radiation signal, according to the following equation:

$$\frac{d}{df}(\Delta L_A) = \frac{1}{f_m}\left[50.91 - 22.71(\log f_m) + 2.229(\log f_m)^2\right] \tag{18}$$

$$f_m = \frac{f_M + f_D}{2} \tag{19}$$

where f_m is the middle frequency for the A-weighted function. Finally, the SPL correction by the Doppler effect is given by:

$$\Delta(\Delta L_A) = (f_D - f)\frac{d}{df}(\Delta L_A) \tag{20}$$

4) When a sound wave travels great distances, the surrounding air absorbs some of the wave's energy. This phenomenon is called air attenuation and this SPL correction by air attenuation is indicated by ΔL_{atm}. This can be calculated using the Doppler effect characteristic frequency f_D and the actual sound wave path $|r'|$ following the guidelines of ISO 3891 [12]. This reference indicates that at a temperature range of

10 - 40 °C and a relative humidity range of 10 - 100 %, a sound attenuation coefficient α is 0.1dB/100m.

As a result, Eq. (6) is modified by the correction factors given by Eqs (7), (8), and (20) and ΔL_{atm}, and the predicted engine A-weighted OASPL of any type of engine at any engine rotational speed, L_{AP} is calculated by the following equation:

$$L_{AP} = L_{A,norm} + 10\log\left(\frac{N_{max}}{N_0}\right) + 14\log\left(\frac{P_{max}/N_{max}}{P_0/N_0}\right) + 40\log\left(\frac{N}{N_{max}}\right) - 20\log\left(\frac{r'}{1000}\right) + \Delta(\Delta L_A) + \Delta L_{atm} \quad (21)$$

where $L_{A.norm}$ is 56.3 dBA, N_0 is 100 rpm, and P_0 is 10 kW.

6.3 Example

Reproduced in Figure 3 noise from an example in Dobrzynski's report [3] is the predicted airplane. The far-field airplane radiated noise in A-weighted decibels with respect to 20 μPa is plotted as a function of time in seconds, for the Mooney M 20K during 65% of maximum powered level flight at an altitude of 1000-ft. This engine noise is measured with the sound level meter (SLM) setting at slow response.

Inspection of Figure 3 reveals that the predicted total aircraft noise is represented by the solid curve, the propeller noise is indicated by the long dashed lines, and the engine noise is represented by the short dashed lines. The total airplane noise is obtained from the sum of the propeller and engine noise components. The maximum engine noise is about 65 dBA and occurs when the aircraft is nearly directly overhead, i.e. at time zero. It is important to note that this single engine powered aircraft is at a level flight speed of

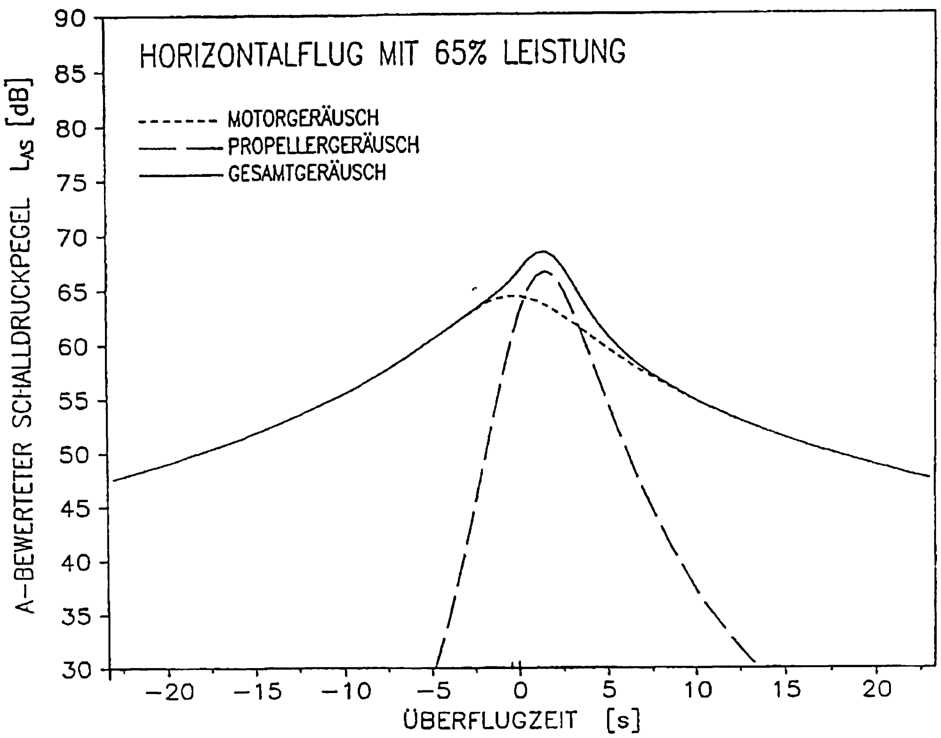


Figure 3 Example for Prediction of Sound Emission for a Mooney M 20K during Level Flight at 65% Maximum Power and Altitude of 1000-ft

243.7 ft/s and 65% of maximum power, i.e. at an engine delivered power of 101 kW at an engine rotational speed of 2,338 rpm.

Let us use Eq. (21) to predict engine A-weighted OASPL with a SLM at slow response, $L_{AP,S}$. The subscript S in $L_{AP,S}$ denotes the SLM setting at slow response. Eq. (21) is repeated here for calculation purposes.

$$L_{AP,S} = L_{A,norm} + 10\log\left(\frac{N_{max}}{N_0}\right) + 14\log\left(\frac{P_{max}/N_{max}}{P_0/N_0}\right) + 40\log\left(\frac{N}{N_{max}}\right) - 20\log\left(\frac{r'}{1000}\right) + \Delta(\Delta L_A) + \Delta L_{atm} \quad (21)$$

where $L_{A\,norm}$ is 56.3 dBA, N_0 is 100 rpm, and P_0 is 10 kW. As mentioned before, the engine rotational speed N is 2,338 rpm, engine power P is 101 kW and altitude H is

1000-ft.

The maximum level is easily calculated because t is zero. Therefore, x is zero resulting in a ϕ' of 90°, and then $|r'|$ is equal to the altitude H of 1000-ft. Because ϕ' is 90° the Doppler correction $\Delta(\Delta L_A)$ correction is zero and the atmospheric attenuation is 0.3 dB, which is calculated by the following equation:

$$\begin{aligned} \Delta L_{atm} &= \alpha \cdot |r'| \\ &= (0.1\,\text{dB}/100\,\text{m}) \cdot 1000 \cdot (0.3048\,\text{m/ft}) \\ &= 0.3\,\text{dB} \end{aligned}$$

Substituting the corresponding values into Eq. (21) we have:

$$\begin{aligned} L_{AP,S} &= 56.3 + 10\log\left(\frac{2700}{100}\right) + 14\log\left(\frac{155/2700}{10/100}\right) \\ &\quad + 40\log\left(\frac{2338}{2700}\right) - 20\log\left(\frac{1000}{1000}\right) + 0 - 0.3 \\ &= 64.4\,\text{dBA} \end{aligned}$$

This value of $L_{AP,S}$ at time zero is essentially identical to the value indicated in Figure 3.

Let us arbitrarily take a time t of -7.5-second, which constitutes a time during approach, i.e. 7.5-second before the aircraft is directly overhead. Using Eq. (9) to determine x and noting that the climb angle γ is zero and therefore y is 1000-ft we have:

$$\begin{aligned} x &= (v\cos\gamma)t \\ &= 243.7 \cdot \cos 0 \cdot |-7.5| \\ &= -1828.2\,\text{ft} \end{aligned}$$

Assuming the speed of sound is 1115.5 ft/s, the flight Mach number M_V is:

$$\begin{aligned} M_v &= v/c \\ &= 243.7/1115.5 \\ &= 0.218 \end{aligned}$$

The actual sound wave path is given by Eq. (14) and is calculated as follows:

$$
\begin{aligned}
|r'| &= \frac{-M_v x + \left[y^2\left(1-M_v^{\,2}\right)+x^2\right]^{1/2}}{1-M_v^{\,2}} \\
&= \frac{-0.218\cdot(-1828.2)+\left[1000^2\cdot\left(1-0.218^2\right)+1828.2^2\right]^{1/2}}{1-0.218^2} \\
&= 2554.5\ \text{ft}
\end{aligned}
$$

The actual radiation angle ϕ' is calculated from Eq.(15):

$$
\begin{aligned}
\phi' &= \gamma + \cos^{-1}\left(M_v \cos\gamma - \frac{x}{|r'|}\right) \\
&= 0 + \cos^{-1}\left(0.218\cdot\cos(0) - \frac{(-1828.2)}{2554.5}\right) \\
&= 21\ \text{deg}
\end{aligned}
$$

Next the characteristic engine firing frequency is calculated using Eq. (17) while noting that the Mooney uses a 6-cylinder engine:

$$
\begin{aligned}
f_M &= \frac{n_{cyl}}{2}\frac{N}{60} \\
&= \frac{6}{2}\cdot\frac{2338}{60} \\
&= 116.9\ \text{Hz}
\end{aligned}
$$

The Dopler effect characteristic frequency is given by Eq. (16):

$$
\begin{aligned}
f_D &= \frac{f_M}{1-M_v \cos\phi'} \\
&= \frac{116.9}{1-0.218\cdot\cos(21)} \\
&= 146.7\ \text{Hz}
\end{aligned}
$$

Next the middle frequency is determined using Eq. (19):

$$
\begin{aligned}
f_m &= \frac{f_M + f_D}{2} \\
&= \frac{116.9 + 146.7}{2} \\
&= 131.8\ \text{Hz}
\end{aligned}
$$

The first derivative of the A-weighting function is given by Eq. (18):

$$
\begin{aligned}
\frac{d}{df}(\Delta L_A) &= \frac{1}{f_m}\left[50.91 - 22.71(\log f_m) + 2.229(\log f_m)^2\right] \\
&= \frac{1}{131.8}\left[50.91 - 22.71 \cdot \log(131.8) + 2.229(\log 131.8)^2\right] \\
&= 0.0970
\end{aligned}
$$

It is now necessary to determine the difference in the SPL associated with the Doppler frequency shift given by Eq. (20):

$$
\begin{aligned}
\Delta(\Delta L_A) &= (f_D - f)\frac{d}{df}(\Delta L_A) \\
&= (146.7 - 116.9) \cdot 0.0970 \\
&= 2.89\ \text{dB}
\end{aligned}
$$

Finally, the atmospheric SPL correction, ΔL_{atm}, is calculated by estimating the sound attenuation coefficient α to be 0.1 dB per 100 m from Reference [11], that is given by the relation:

$$
\begin{aligned}
\Delta L_{atm} &= \alpha \cdot |r'| \\
&= (0.1\ \text{dB/100 m}) \cdot 2554.5 \cdot (0.3048\ \text{m/ft}) \\
&= 0.78\ \text{dB}
\end{aligned}
$$

Substituting all of these appropriate values into Eq. (21) we have:

$$\begin{aligned} L_{AP,S} &= 56.3 + 10\log\left(\frac{2700}{100}\right) + 14\log\left(\frac{155/2700}{10/100}\right) \\ &\quad + 40\log\left(\frac{2338}{2700}\right) - 20\log\left(\frac{2254.5}{1000}\right) + 2.5 - 0.8 \\ &= 59.3\,\text{dBA} \end{aligned}$$

This $L_{AP,S}$ value of 59.3 dBA at time –7.5 second is essentially identical to the level determined by inspecting the curve in Figure 3 at a time of –7.5 seconds. These two comparisons at time zero and –7.5 second show that the algorithm depicted in Eq. (21) adequately predicts the airplane OASPL versus time curve depicted in Figure 3.

CHAPTER 4

ENGINE NOISE TEST FACILITY

4.1 Embry-Riddle Aeronautical University Aircraft Engine Noise Test Facility

Embry-Riddle Aeronautical University (ERAU) developed an aircraft engine noise test facility (ENTF) for evaluating intermittent-combustion (IC) general aviation (GA) aircraft engine exhaust noise free of propeller noise. Because there is no propeller in this installation, the noise is generated in free of propeller noise, which is shown in Figure 4. A Lycoming O-320 D1D aircraft engine and an AW hydraulic dynamometer are mounted on this engine system. This engine is an IC GA aircraft 4-stroke 4-cylinder engine, also the maximum engine power is 160 hp at 2700 rpm at standard sea-level

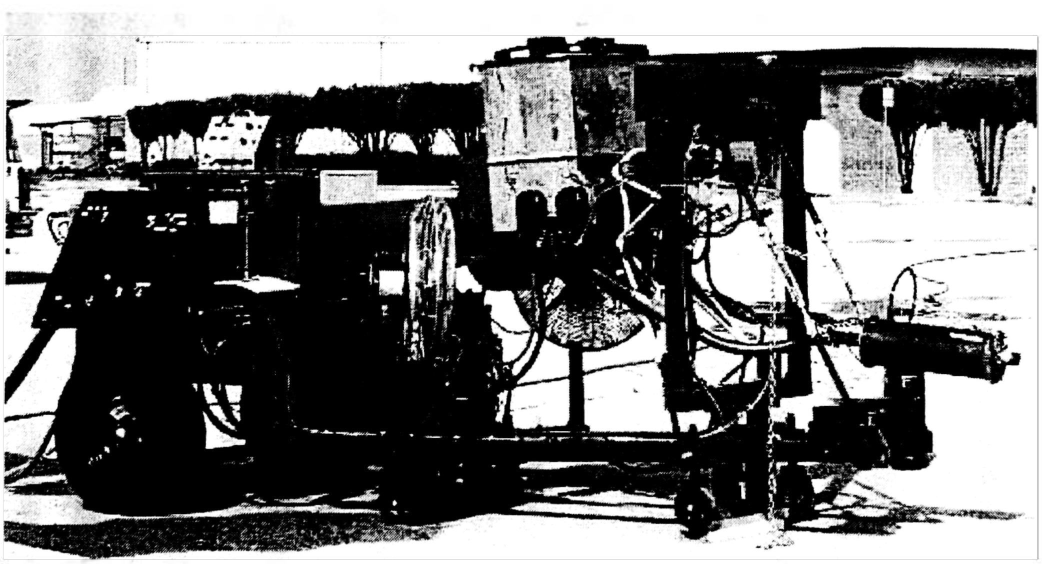


Figure 4 Embry-Riddle Aeronautical University Aircraft Engine Noise Test Facility

condition. The dynamometer takes the place of the propeller in applying a load to the engine. A detailed description of this facility and its capabilities are given in Reference [13].

The advantage of using this system is that the engine exhaust noise can be measured exclusively without having to conduct an airplane flight. Generally, since propeller noise dominates the radiated noise while the airplane is flying, it is difficult to measure the engine exhaust noise independently. Therefore, this engine system is very useful for establishing an empirical aircraft engine exhaust noise prediction algorithm.

4.2 Location

The ERAU ENTF is located in a parking lot at ERAU, which is an area sufficiently far from buildings, so that there is no acoustic pressure reflection, i.e. no

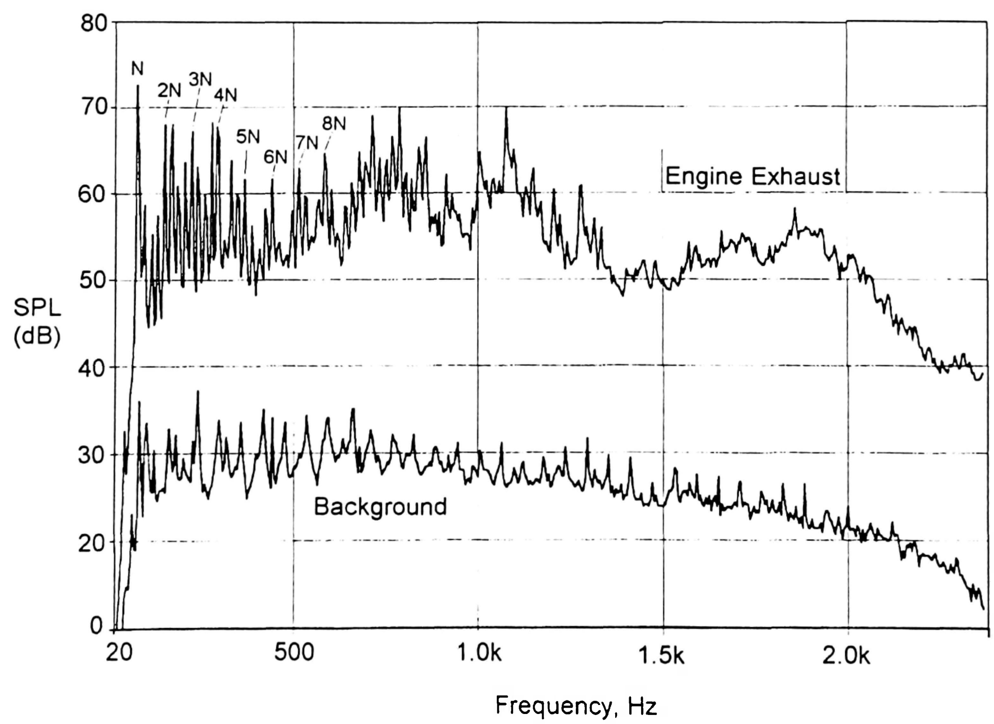


Figure 5 Noise Spectrum 1 (Background Noise)

reverberation effect. This test location results in acoustic measurements, which is performed with the microphone laid down on the hard asphalt surface of the parking lot. Acoustic measurements are performed on Saturday and on Sunday so that the parking lot is free of automobiles. In Figure 5, the background noise spectrum, whose overall sound pressure level (OASPL) is 69 dB, is shown. The background noise includes the noise of the cooling fans mounted on the ENTF as well as environmental noise. Normally the OASPL of the Lycoming O-320 D1D aircraft engine is more than 90.0 dB, which is 20.0 dB higher than the background noise. As a result, the background noise does not have an influence on the engine exhaust noise itself.

CHAPTER 5

INSTRUMENTATION AND MEASUREMENT PROCEDURE

5.1 Noise Measurement Standards

There are three microphone settings for aircraft noise measurement:

1) Ground microphone setting: According to the International Civil Aviation Organization (ICAO) noise measurement standard, the microphone has to be set upside-down, the membrane part is 7-mm above a cylindrical shaped flat white aluminum plate, 75-cm in diameter and 3-mm inch thick (Figure 6). The ICAO noise measurement standard is employed for take-off and level flight aircraft noise measurement.

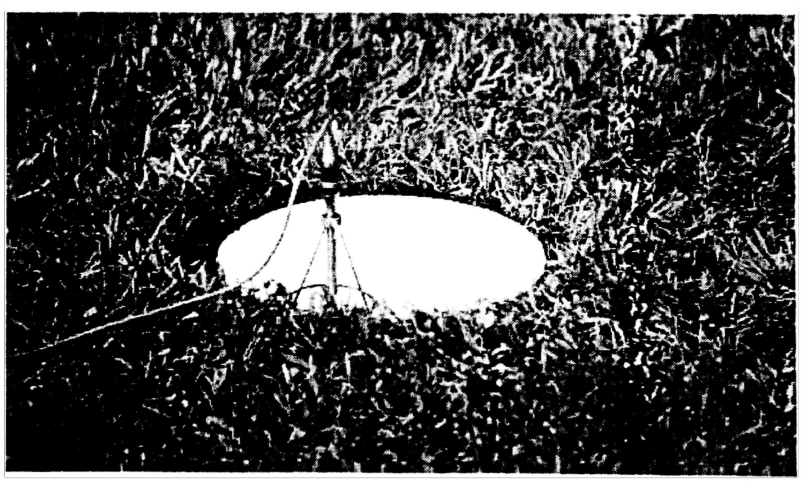


Figure 6 Ground Microphone Setting (ICAO)

2) 4-ft high microphone setting: The FAA-FAR-36 standard requires that the microphone is mounted on a 4-ft (1.2-m) high tripod in the free-field (Figure 7). The sound pressure level (SPL) measured using the ICAO microphone arrangement is 6 dB higher than the free-field measurement, which is measured using the FAA-FAR-36 microphone arrangement, because of acoustic pressure doubling due to the reflecting hard surface. Since the acoustic pressure reflection patterns from the ground surface as the aircraft passes overhead is complex, there is no simple method for relating measured SPL to free-field measurement.

Figure 7 4-ft high Microphone Setting (FAA-FAR-36)

3) Laid down microphone setting: This microphone setting modifies the ICAO microphone for static noise measurement. The microphone is set to lay on an asphalt surface (Figure 8). This setting is designed to measure static noise, and allows a more accurate measurement of higher frequency noise. A detailed description of this microphone setting is given in Reference [14].

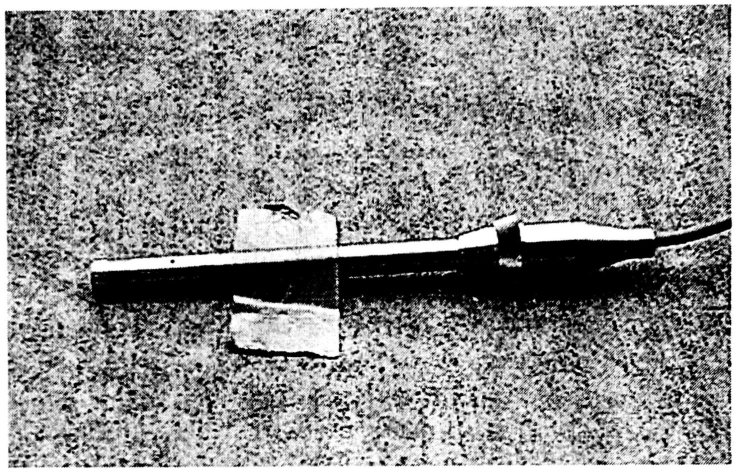
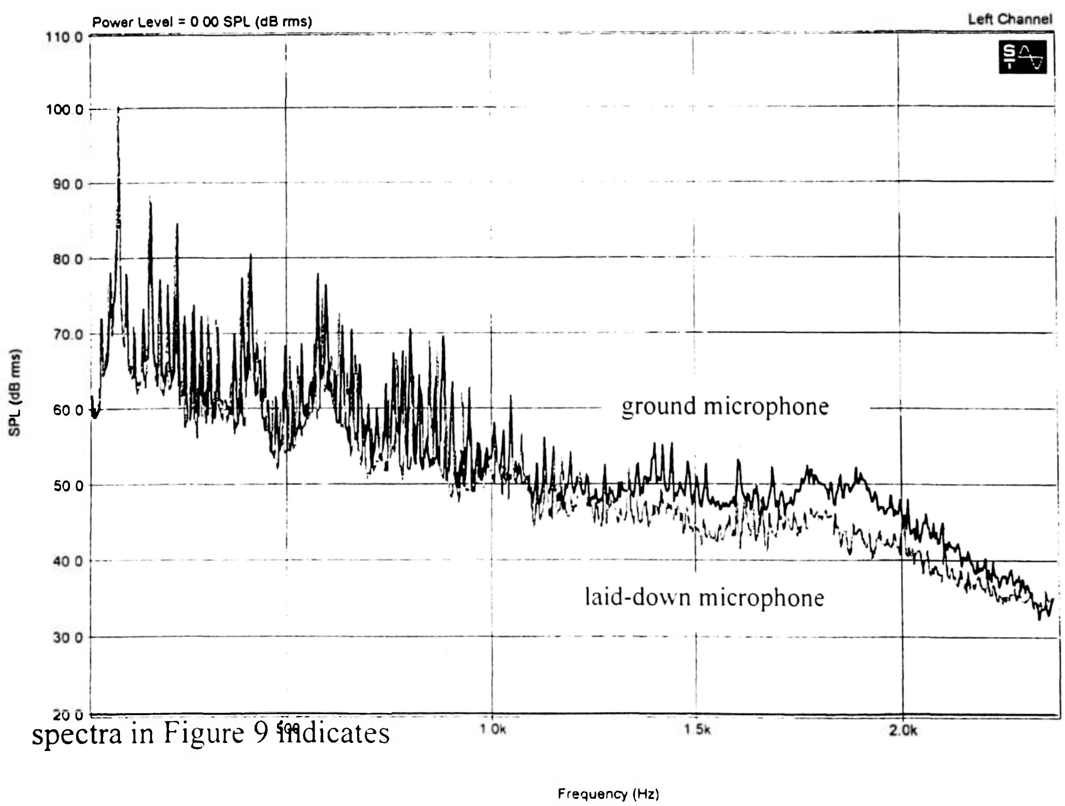


Figure 8 Laid-Down Microphone Setting

For this report the laid-down microphone setting is chosen because the SPL is measured from a static noise source instead of a moving source like an airplane fly by.



spectra in Figure 9 indicates

Figure 9 Noise Spectrum 2
(Ground and Laid-Down Microphone setting)

Figure 9 shows two sound spectra which are the engine noise measured by the ground microphone setting and by the laid-down microphone setting. Obviously the ground microphone setting's spectrum has a higher SPL at a high frequency range. By comparing the OASPL, there is no difference between the two numbers, because the engine noise is dominated by the lower frequency noise more than the higher one. Inspection of the noise spectra in Figure 9 indicates that at frequencies greater than about 1.2 kHz, the ground microphone spectrum is about 3-dB greater than the laid-down microphone spectrum. This SPL difference compare well with the measurements repeated in Reference [14].

The noise measurement are to be carried out under the following atmospheric conditions:

1) There may be no precipitation.
2) The relative humidity may not be higher than 90 percent or lower than 30 percent.
3) The ambient temperature may not be above 95 °F or 36 °F at 4-ft (1.2-m) above the ground.
4) The reported wind may not be above 10-kts and cross wind may not be above 5-kts at four feet, using a 30 second average.
5) There are no other anomalous meteorological conditions that would significantly affect the noise level of the airplane when the noise is recorded at the measuring points specified by the certification authority.

5.2 Microphone Settings

The Brüel & Kjær precision integrating sound level meter (SLM) with model 2230 microphone is used for measuring the engine exhaust noise. The SLM settings are given as follows:

1) FSD: Select the overlapping measuring range. Note that the "OVERLOAD" mark (the black triangle mark) never shows up on the microphone screen during noise measurement. If it does, slide up the FSD switch.
2) ALL-MAX./MIN.-Pause : Select a "RESET" choice. In this report, "All" is chosen, which resets the whole reading in the SLM when the RESET button is pressed.
3) FREQ. WEIGHTING : Select the frequency weighting. In this report, "Lin. $\cap$ " is chosen, which constitutes linear weighting from 20 Hz to 20 kHz. Another "Lin." setting designates linear weighting from 10 Hz to 50 kHz.
4) EXT. FILTER : Select the external filter socket, either set or by-passed. In this report, "Out" is chosen.
5) SOUND INCIDENCE : Select sound incidence weighting. When the "Frontal" setting is chosen, the free field 0° incidence response of the microphone is un-weighted. While the frequency response of the microphone is weighted to obtain a flat random incidence frequency response when the "Random" setting is chosen.
6) DISPLAY : Select the sound pressure level (SPL) mode. In this report, SPL is chosen.
7) TIME WEIGHTING : Select the time weighting. In this report, "F" (fast) time weighting is chosen.
8) DETECTOR : Select the value of the SPL.

The SLM signal is connected to the computer for digital data recording. The microphone face is placed flat onto the ground surface (Figure 8) normal to the exhaust pipe end. This recording distance is used to assume that far-field measurements are assured. The microphone is calibrated for every noise measurement using a Brüel & Kjær calibrator of 94.0 dB at 1 kHz.

5.3 Computer Noise Analyzer

For data analysis the Fast Fourier Transform (FFT) spectral analysis computer software program, Spectra PRO, is used. This spectrum analyzing program is used to convert a signal from the time domain to the frequency domain (time–vs.–frequency). A frequency domain display is known as a spectrum, which shows the sound pressure level (SPL) versus frequency. The engine exhaust noise is recorded and analyzed using Spectra PRO for determining the frequency spectrum. This spectral software program also calculates the OASPL of the signal as well as applying the A-weighting function.

CHAPTER 6

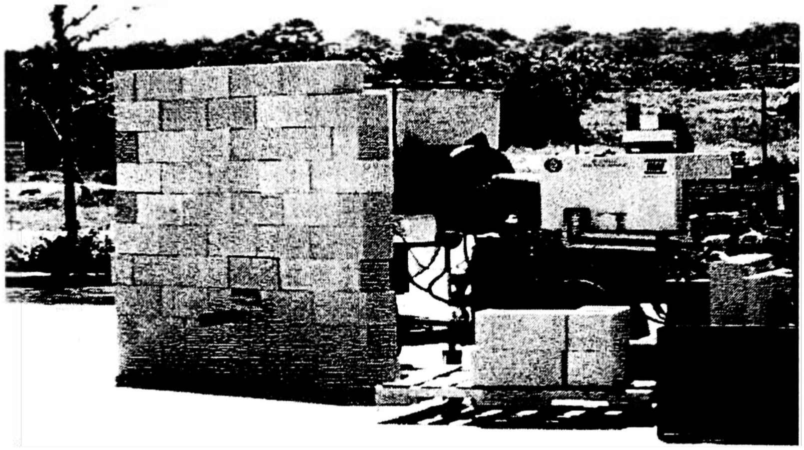
RESULTS

6.1 Engine Exhaust System Configuration

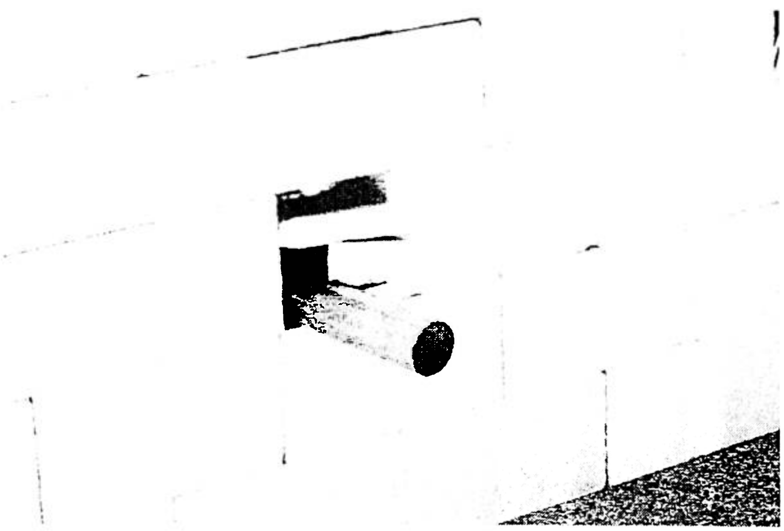
To determine the best engine exhaust system configuration for the ERAU aircraft engine noise test facility (ENTF), the following comparisons are investigated.

1) Comparison with and without concrete block wall:

Technically, engine noise includes engine exhaust noise and engine mechanical noise, as previously mentioned. To eliminate the engine mechanical noise, a wall made using 40 8-in by 16-in concrete blocks is shown in Figure 10-(a). A 4-ft long pipe extension, beyond the normal exhaust termination, is extended through the wall by approximately 6-in as shown in Figure 10-(b). Only the exhaust pipe passes through the block wall. Two noise spectra are shown in Figure 11, with and without the concrete block wall and both with a 4-ft pipe extension. Comparison of both reveals that the first tonal noise sound pressure level (SPL) with the wall is greater than without. In the frequency range of 500 – 1000 Hz, the SPL with the wall is also noisier than without. As a result, the concrete block wall does not have any effect on reducing the engine mechanical noise. In fact, the noise spectra is more intense with the wall because of sound reflection from the wall. Based upon this comparison, it is concluded that the mechanical engine noise is negligible compared to the engine exhaust noise.



(a)



(b)

Figure 10 Exhaust System View 1 (with Concrete Block Wall)
(a) Whole view
(b) Square Hole on the Concrete Block Wall

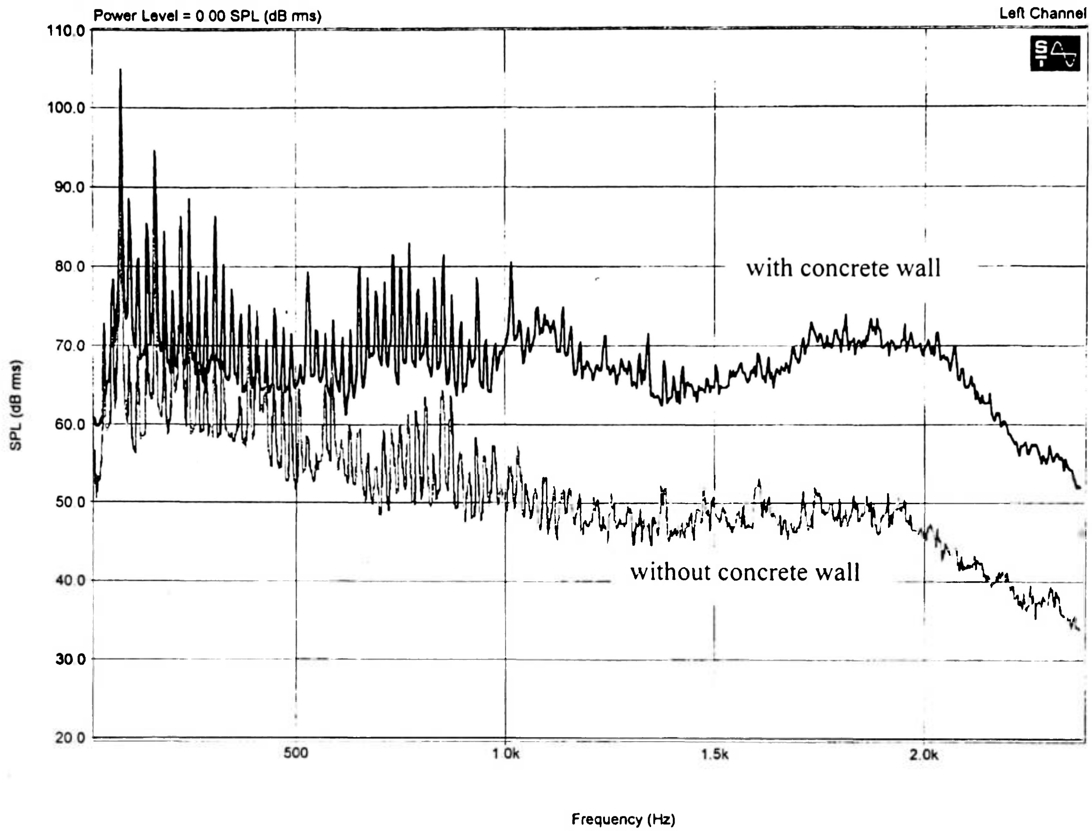


Figure 11 Noise Spectrum 3
(with/without Concrete Block Wall and 4-ft Pipe Extension)

2) Comparison with and without a 4-ft pipe extension beyond normal exhaust type termination:

The same 4-ft pipe extension as the previous comparison is used to evaluate the effect of the additional exhaust length. Figure 12 shows two spectra labeled with and without pipe extension. The overall sound pressure level (OASPL) with the 4-ft pipe extension is 13 dBA smaller than without one. It is clear from this figure that the sound pressure level (SPL) is reduced in all frequency ranges, especially by 10 dB at the first tonal noise. A simple straight pipe has a significant affect reducing engine exhaust noise. A Reynolds number calculation indicates that fully established turbulent pipe flow exists in the exhaust pipe. A literature search reveals that there is significant dissipation of acoustic pressure that is frequency dependent, in turbulent pipe flow [15].

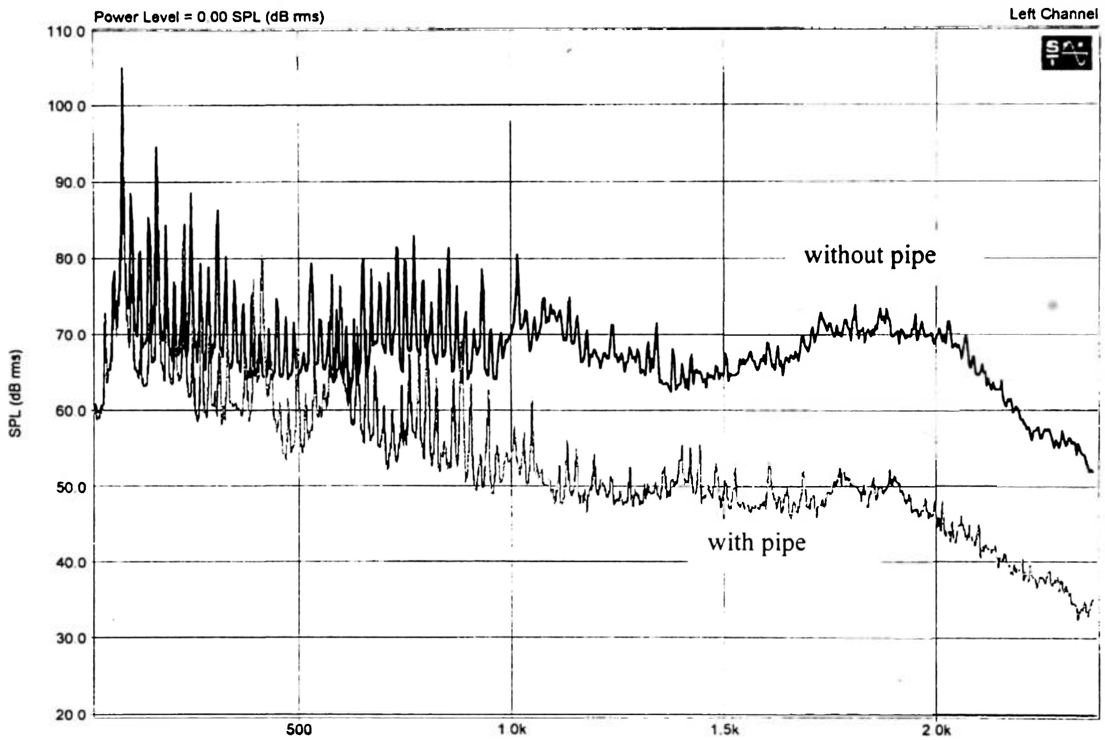


Figure 12 Noise Spectrum 4 (with/without 4-ft Pipe Extension)

3) Comparison between Y-shaped corrugated pipe and Y-shaped smooth pipe collectors:

Two exhaust headers shown in Figure 13 and a Y-shaped collector are joined to the ENTF as an exhaust system. The exhaust headers from the number two and four (port side) engine cylinders are brought together in a two-to-one collector and lead to the rear of the engine. These components are clearly visible in Figure 13. The number one and three engine cylinders on the starboard side are brought together in a similar manner. The collector is barely visible in the right side of Figure 13.

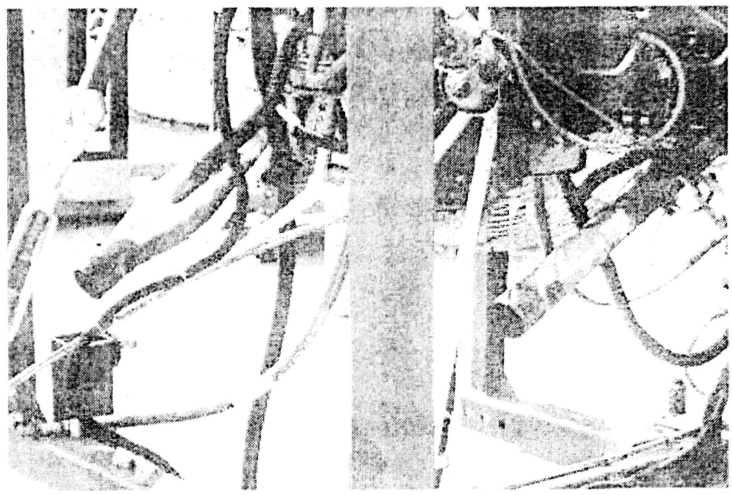


Figure 13 Exhaust System View 2 (Engine Exhaust Headers)

The two headers are then collected together into a single exhaust exit pipe using corrugated Y-shaped pipe as shown in Figure 14. This pipe is bent along a large radius on both sides. The headers and the bent part of the Y-shaped pipe are made of one and three quarter inch outside diameter (OD) pipe with one-sixteenth inch wall thickness. The 4-in long pipe, which is attached to the end of Y-shaped pipe, is 2-in OD with similar wall thickness.

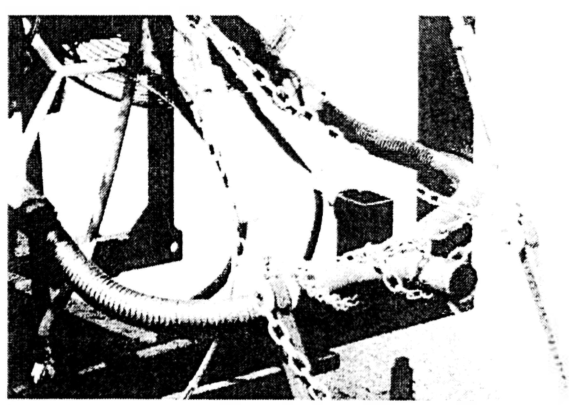


Figure 14 Exhaust System View 3 (Corrugated Y-shaped Pipe)

The inside surface of the corrugated Y-shaped pipe, however, is very rough. Therefore, it creates complicated air flow with excess turbulence generated by the flow over the rough surface. To avoid this problem, the corrugated Y-shaped pipe is modified with a smooth one shown in Figure 15. Both the corrugated and smooth pipe are the same length and configuration. The collision of two air flows inside the Y-shaped pipe also creates an air mixture. To ensure that air flow remains steady throughout this mixture, an additional length of straight pipe is needed. A 2-in OD and 13 ½-in long extension is added to the pipe exit shown in Figure 15. A comparison of the noise spectra of the air flow through the corrugated and smooth Y-shaped pipe is shown in Figure 16. Inspection of Figure 16 indicates that the far-field exhaust noise spectrum with the corrugated Y-shaped collector pipe is significantly larger in magnitude than for the smooth one, and at all frequencies. This spectra comparison indicates the turbulent flow field inside the corrugated pipe adversely affects the engine exhaust radiated noise.

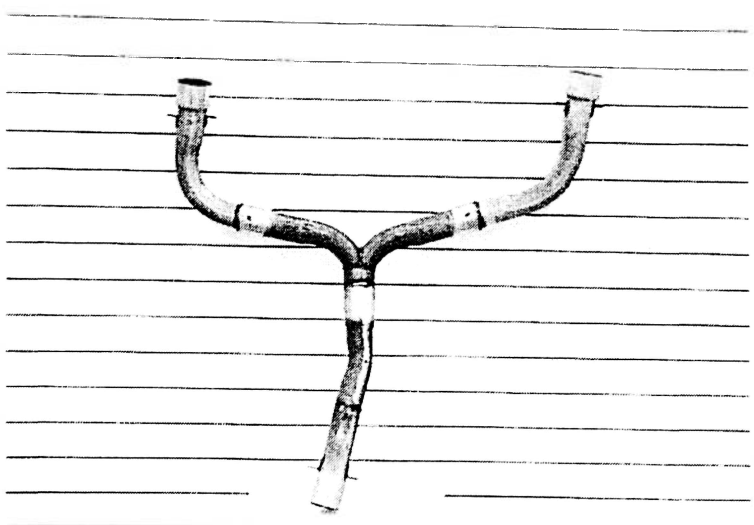


Figure 15 Exhaust System View 4 (Smooth Y-shaped Pipe)

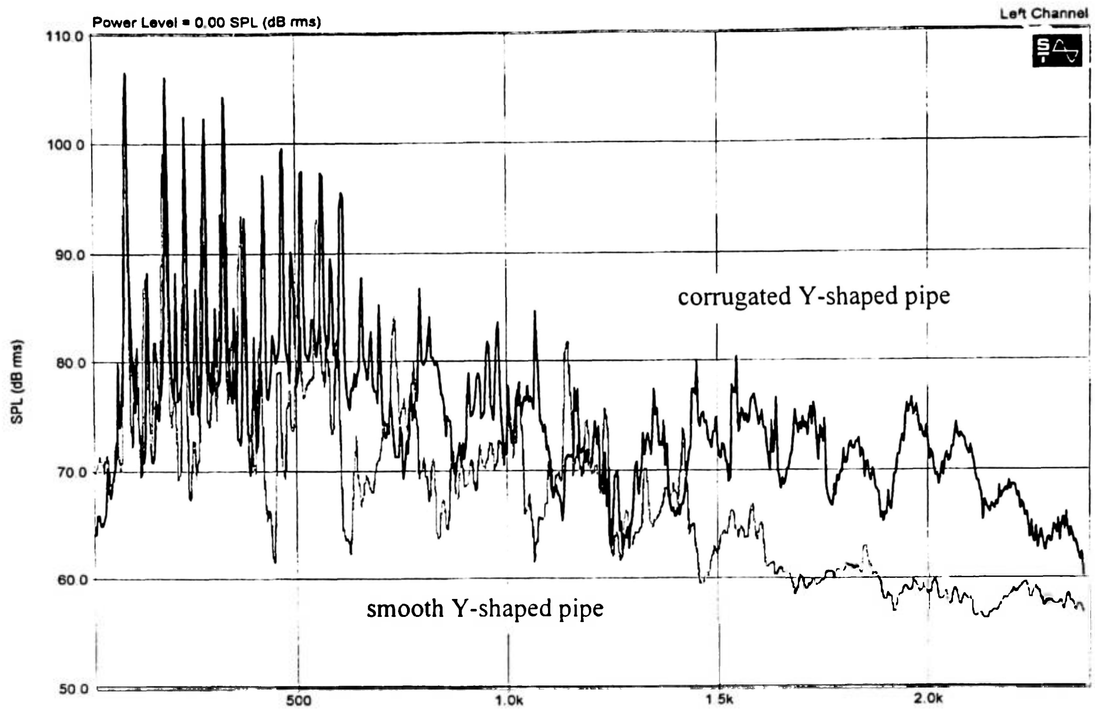


Figure 16 Noise Spectrum 5 (Corrugated and Smooth Y-shaped Pipe)

6.2 Engine Exhaust Noise Directionality Test

Directionality engine exhaust noise measurements are made using the ENTF with the Lycoming 0-320 D1D aircraft engine and Cessna 172 standard muffler shown in Figure 17. Inspection of this figure shows the muffler labeled as item 1 and the risers labeled item 2 through 5. The muffler is mounted just below the engine of the ENTF. For the noise measurements reported using the Cessna 172 standard muffler there are no elements inside the muffler, i.e. the muffler consists of only an expansion chamber.

Based upon defining the horizontal azimuthal angle as zero in the forward direction along the propeller shaft centerline, and 90^0 in the direction normal to the muffler exhaust exit, laid-down microphone (Reference [13]) is set at 50-ft and angles of 30^0, 45^0, 60^0, 90^0, 120^0, 135^0, and 150^0. The engine is evaluated using a partial throttle setting at a nominal

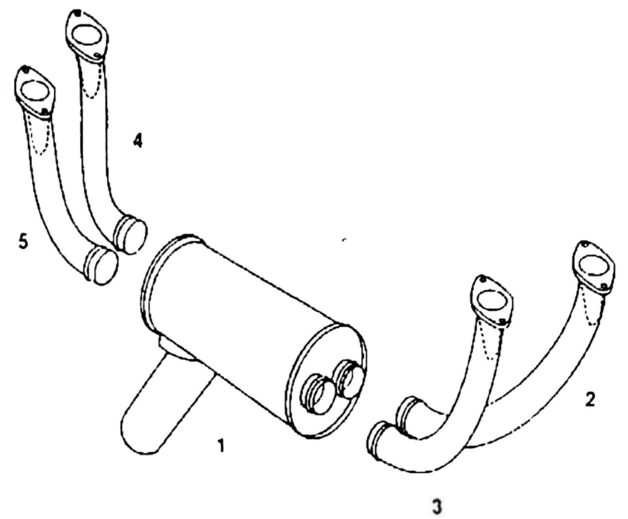


Figure 17 Exhaust System View 5 (Cessna 172 Standard Muffler)

power of 101 hp at 2,710 rpm. Engine power settings vary by plus/minus 1 hp and plus/minus 10 rpm. The non-weighted and A-weighted overall sound pressure level (OASPL) at the various horizontal azimuthal angles are presented in Table 2. Inspection of this table indicates that the non-weighted OASPL varies by 2 dB and A-weighted by 2 dBA with the larger values occurring near the 90^0 position.

This OASPL variation is indicative of only minor directionality characteristics and within experimental error, therefore it is reasonable to state that the engine exhaust far-field radiated noise directionality is spherical, i.e. a monopole source. This conclusion is consistent with the monopole sound source conclusion assumed by Dobrzynski (Reference [3]). Because

Table 2 OASPL with Cessna 172 Exhaust System at 50-ft, 101 hp and 2,710 rpm

Angle	30^0	45^0	60^0	90^0	120^0	135^0	150^0
SPL [dB]	101	101	103	103	102	101	101
SPL [dBA]	91	90	91	92	92	91	91

the acoustic pressure is doubled using a laid-down microphone, the OASPL measurements reported are 6 dB greater than in a free acoustic field.

6.3 Engine Noise Analysis

In this paper, any engine sound pressure level (SPL) is assumed to be based upon the SPL at the maximum engine rotational speed, and Dobrzynski's normalization, given by Eq. (21), is assumed to hold true. An engine rotational speed change causes a frequency shift and an engine power change causes a SPL magnitude shift. Using the ERAU ENTF with the exhaust pipe discussed earlier, the engine noise is recorded at the maximum engine rotational speed. In this measurement, the engine rotational speed is recorded as 2740 rpm instead of as 2700 rpm. Consequently, the maximum engine rotational speed is based upon the engine rotational speed of 2740 rpm.

The non-weighted noise spectrum of engine exhaust noise with the smooth Y-shaped pipe in a frequency range of 20 – 11k Hz, is given by Figure 18-(a), at 160 hp and 2740 rpm. The non-weighted overall sound pressure level (OASPL) is 104.4 dB and the A-weighted OASPL is 98.4 dBA. In the frequency range between 20 - 1500 Hz, tonal noise dominates the engine noise, and Figure 18-(b) gives the spectrum over this frequency range. In the same spectrum at frequencies greater than 1500 Hz, the curve line is smooth in shape. The noise in this higher frequency range is due to jet exhaust noise which is random in nature, and is often referred to as broad-band noise. Consequently, the engine noise can be separated into two different types of noise: low frequency tonal noise and high frequency broad-band noise.

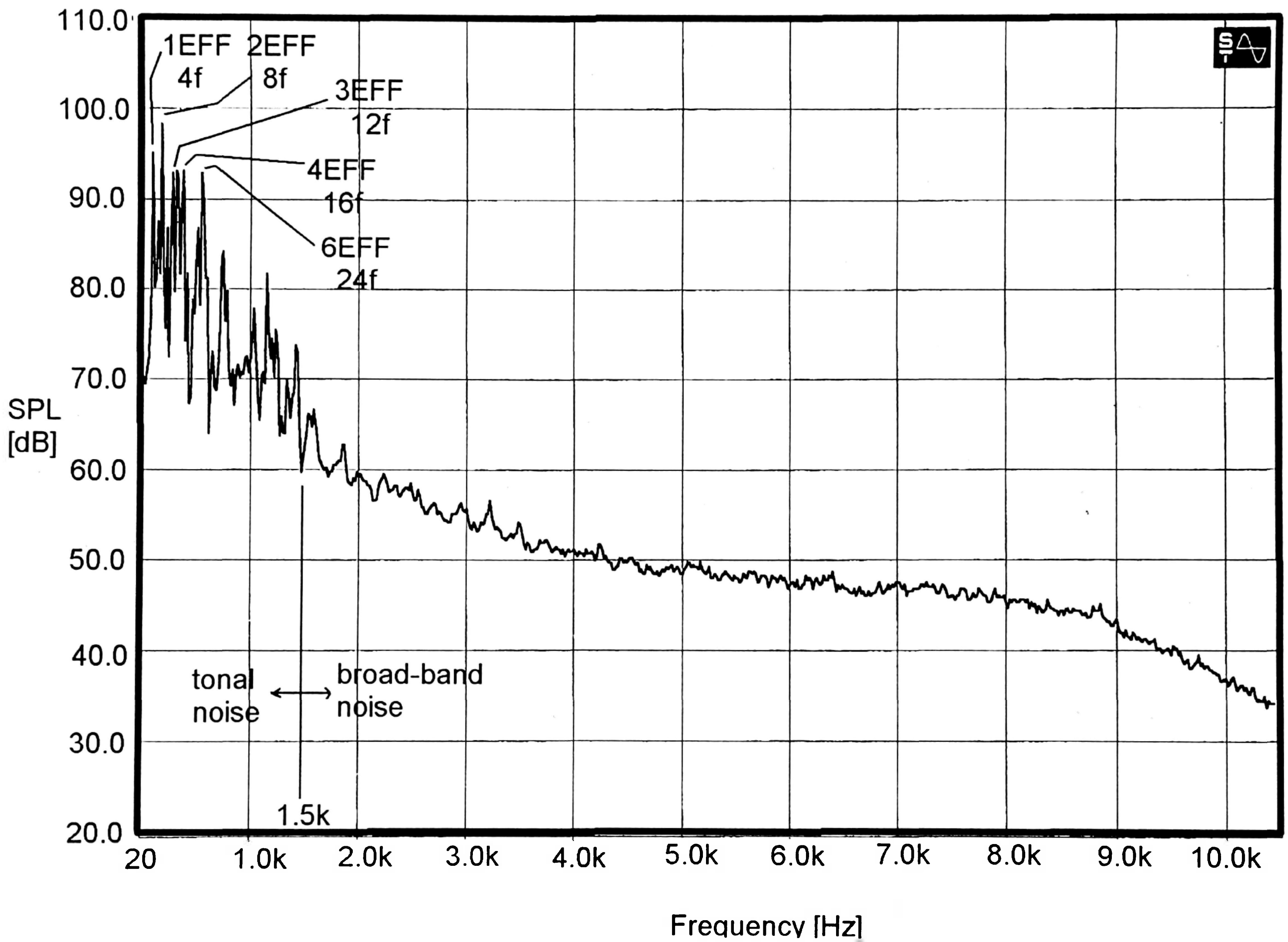


Figure 18-(a) Noise Spectrum 6 (Lycoming O-320 D1D Aircraft Engine Noise with Smooth Y-shaped Pipe, 2740 rpm) , Frequency Range 20 – 11k Hz

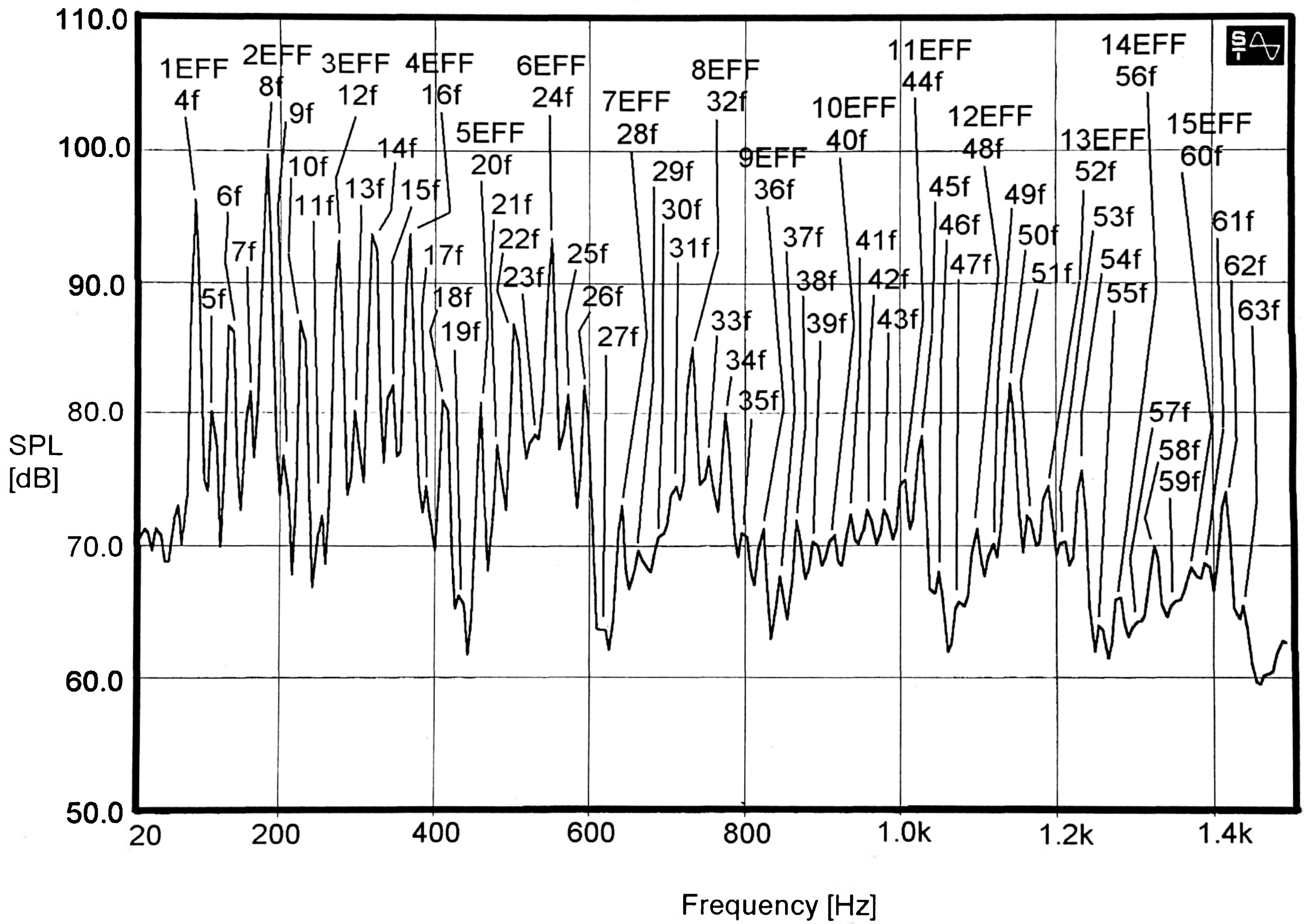


Figure 18-(b) Noise Spectrum 6 (Lycoming O-320 D1D Aircraft Engine Noise with Smooth Y-shaped Pipe, 2740 rpm), Frequency Range 20 – 1500 Hz

Figure 18-(b) demonstrates the range where the noise is dominated by tonal noise, and these tonal noise can be labeled using the following non-dimensional frequencies:

1) Fundamental Firing Frequency (f) gives how many times one engine piston completes a full cycle of motion in a second. The following equation calculates f.

$$f = \frac{1}{n_r}\frac{N}{60} \tag{22}$$

where n_r is 2 for a 4-cycle engine or 1 for a 2-cycle engine.

2) Engine Firing Frequency (EFF) shows how many times engine pistons complete a full cycle of motion in a second. EFF can be calculated from f multiplied by the number of the engine cylinder (piston) like the following equation:

$$EFF = n_{cyl} \cdot f = \frac{n_{cyl}}{n_r} \cdot \frac{N}{60} \tag{23}$$

where n_{cyl} is the number of cylinders.

3) Engine-shaft Revolutions per Second (rps) gives how many times engine-shaft rotates in a second. Since the gear ratio between the engine-shaft and the propeller-shaft is one, the number of the propeller rotation in a second is the same as rps, which is calculated using the following equation:

$$rps = \frac{N}{60} \tag{24}$$

This non-dimensional frequency, rps, is used in predicted noise spectrum.

The relationship among three non-dimensional frequencies is written as:

$$1EFF = \frac{n_{cyl}}{n_r} rps \tag{25}$$

Since the Lycoming O-320 D1D is a 4-stroke 4-cylinder engine, EFF is calculated to be 91.3 Hz at 2740 rpm. Harmonics of EFF occur at 2EFF (182.6 Hz), 3EFF (273.9 Hz), etc.

Each cylinder fires every two revolutions resulting in a fundamental firing frequency f of 22.8 Hz. Therefore, f tones occur at f and multiple of f. Inspection of the Figure 18-(b) spectrum reveals these f tones where EFF is equal to 4f, i.e. the primary engine firing frequency EFF occurs at four times the Fundamental Firing Frequency f. Harmonics of EFF are composed of multiple of 4f, i.e. 2EFF is 8f, 3EFF is 12f, etc. Further, review of this spectrum reveals the noise is dominated by EFF tones, with 2EFF being the most intense. It is interesting to note that the 14f tone is at the same levels as the 3EFF and 4EFF tones. In general, even numbered f tones tend to be more intense than odd numbered f tones. For example, the 6f tone is more intense than adjoining 5f or 7f tones, and 14f tone is considerably more intense than adjoining 13f and 15f tones. Detailed discussion of engine f tones for IC GA aircraft engine is given in References [1, 16].

It is necessary to perform frequency and magnitude shift of the tones to predict these characteristics for using in the engine noise prediction algorithm. To calculate the tonal noise SPL at different engine rotational speed a couple of corrections are needed. One is the SPL magnitude correction that is the same as Eq. (7), since the tonal noise has a monopole sound source and the tonal noise SPL are dependent upon the fourth power of engine rotational speed. Another correction is for the shift of each tone's frequency. Each frequency of tonal noise is dependent upon the engine rotational speed, and is calculated using Eq. (23). Therefore, the sound frequency and SPL at different engine rotational speed, f and SPL_{rpm} individually, are given by:

$$f_{rpm} = \frac{N}{2740} f_{2740} \tag{26}$$

$$SPL_{rpm} = SPL_{2740} + 40\log\frac{N}{2740} \tag{27}$$

For example, according to Figure 18-(b), the frequency and SPL of the first EFF at 2740 rpm is 91.3 Hz and 96.2 dB. These numbers change to 80.0 Hz and 93.9 dB of the first EFF at 2400 rpm by the calculation using Eqs. (26) and (27).

The broad-band noise is separated into four parts and formulated. There is, however, a discrepancy that must be considered. The Spectra PRO program analyzes a broad-band noise using a certain frequency band, which is called the spectral line resolution. Therefore, the broad-band noise SPL shown in the Spectra PRO spectrum is higher than the actual one. The SPL correction by spectral line resolution is given by the following equation:

$$\Delta SPL = 10\log(\text{spectral line resolution}) \tag{28}$$

In this noise spectrum, 5.383 Hz is used as the spectral line resolution, i.e. $\Delta \text{SPL} = 7.31\,\text{dB}$. This correction is not necessary for the tonal SPL because all of the tonal noise energy in at a specific frequency. Using this correction, the broad-band noise levels are approximated as follows:

At maximum power of 160 hp at 2740 rpm, the broad-band noise SPL on a single Hz bandwidth is assumed to be a constant 54.1 dB over the frequency range of 20 – 1500 Hz, i.e. Eq. (29) where SPL_{2740} constitutes the broadband SPL at 2740 rpm.

$$SPL_{2740} = 54.1\,\text{dB} \tag{29}$$

Over the frequency range of 1.5 – 4 kHz the broad-band noise SPL is given by Eq. (30).

$$SPL_{2740} = -\frac{8.6}{2000} f_{2740} + 60.6\,\text{dB} \tag{30}$$

Eq. (31) represents the broad-band noise SPL over the frequency range of 4 – 9 kHz.

$$SPL_{2740} = -\frac{7.1}{5000} f_{2740} + 49.1\,\text{dB} \tag{31}$$

Finally, the broad-band noise SPL over the frequency range 9 – 11 kHz is given by Eq. (32)

$$SPL_{2740} = -\frac{7.0}{1000} f_{2740} + 99.2\,\text{dB} \tag{32}$$

The SPL in decibels (dB) is calculated from the ratio of the root mean square values of actual sound pressure, p_{act}, to the reference sound pressure, p_{ref}, as showing Eq. (33). In this report, the square of this pressure ratio is mean square value of sound pressure, which is noted as $\overline{p}_{rpm}^{\ 2}$.

$$SPL_{rpm} = 10\log\left(\frac{p_{act}}{p_{ref}}\right)^2 = 10\log\left(\overline{p}_{rpm}^{\ 2}\right) \tag{33}$$

where p_{act} is the actual sound pressure and p_{ref} is the reference level for sound pressure, which is 20×10^{-6} Pa.

One-third octave-band analysis is used to derive the broad-band noise SPL spectrum [6]. As the name implies, one-third octave-bands are formed by dividing each octave band into three parts. The standardized one-third octave-band limit and center frequencies are given in Table 3. Since the broad-band noise has a quadrupole noise source, the SPL correction factor is the eighth power of the engine rotational speed ratio instead of the fourth power, is used in Eq. (7) for the tonal noise. Lighthill [17] shows that broad-band noise associated with turbulent jet mixing is a quadrupole source, which scales as the eighth power of jet speed and the exhaust pipe exit jet flow speed is proportional to engine rotational speed, i.e. rpm.

Table 3 Standardized One-Third Octave-Band Limits and Center Frequencies [Hz]

LOWER f_l	CENTER f_c	UPPER f_u
18	20	22.4
22.4	25	28
28	31.5	35.5
35.5	40	45
45	50	56
56	63	71
71	80	90
90	100	112
112	125	140
140	160	180
180	200	224
224	250	280
280	315	355
355	400	450
450	500	560
560	630	710
710	800	900
900	1000	1120
1120	1250	1400
1400	1600	1800
1800	2000	2240
2240	2500	2800
2800	3150	3550
3550	4000	4500
4500	5000	5600
5600	6300	7100
7100	8000	9000
9000	10000	11200

When calculating the overall sound pressure level (OASPL), the mean square sound pressure, $\overline{p}_{rpm}^{\,2}$, must be summed – not the sound pressure levels. Therefore, Eqs. (29) - (32) must be put into a form to directly calculate $\overline{p}_{rpm}^{\,2}$ At this time, it is necessary to change the frequency range since the border frequencies of each range are dependent upon the engine rotational speed, N

The frequency range 20 – 1500 Hz is changed to $\frac{20 \cdot N}{2740}$ $\frac{1500 \cdot N}{2740}$ Hz, and Eq. (29) is rewritten as Eq (29)*

$$\overline{p}_{rpm}^{\,2} = 10^{(-22.09)} \times (N)^8 \qquad (29)^*$$

---

* Asterisk mark on Eqs (29)* through (32)* denotes that these equations are modified from Eqs (29) through (32)

Eq. (30) over the frequency range 1.5 – 4 kHz is changed to Eq. (30)* over the frequency range $\frac{1.5 \cdot \mathrm{N}}{2740}$ - $\frac{4 \cdot \mathrm{N}}{2740}$ kHz.

$$\overline{p}_{rpm}^{\ 2} = 10^{\left(-1.178\frac{f_{rpm}}{N} - 21.44\right)} \times (N)^8 \tag{30*}$$

Eq. (31) with the frequency range 4 – 9 kHz can be rewritten as Eq. (31)* over the frequency range $\frac{4 \cdot \mathrm{N}}{2740}$ $\frac{9 \cdot \mathrm{N}}{2740}$ kHz.

$$\overline{p}_{rpm}^{\ 2} = 10^{\left(-0.389\frac{f_{rpm}}{N} - 22.60\right)} \times (N)^8 \tag{31*}$$

Finally, over the frequency range 9 – 11 kHz, Eq. (32) is changed to Eq. (32)* with the frequency range $\frac{9 \cdot N}{2740}$ - $\frac{11 \cdot N}{2740}$ kHz.

$$\overline{p}_{rpm}^{\ 2} = 10^{\left(-1.918\frac{f_{rpm}}{N} - 17.58\right)} \times (N)^8 \tag{32*}$$

The overall sound pressure between the frequency range of the one-third octave-bands is calculated using the following equation:

$$\overline{p}_{rpm\,OA}^{\ 2} = \int_{f_l}^{f_u} \overline{p}_{rpm}^{\ 2} df \tag{34}$$

where f_l is the lower limit frequency of the one-third octave-band analysis standard frequency range and f_u is the upper limit frequency.

6.4 IC GA Aircraft Engine Exhaust Noise Prediction Algorithm

Based upon Eqs. (27) and (29)* through (32)*, the engine SPL prediction FORTRAN code is compiled.

The inputs are:

1) engine type
2) engine rotational speed

The outputs are:

1) engine power in horse power (hp)
2) non-weighted and A-weighted one-third octave-band broad-band noise SPL and broad-band noise OASPL
3) non-weighted and A-weighted tonal noise SPL up to 1500 Hz
4) non-weighted and A-weighted engine noise OASPL for entire spectrum

The flow chart which shows a visualized noise prediction algorithm is given in Appendix A-1 and the actual FORTRAN code is given in Appendix A-2.

This program can include the data of six different engine types, which are indicated by engine type (ET) 1 though 6. The data of the Lycoming O-320 D1D aircraft engine is denoted by ET=1, the data of the Lycoming O-360 A-series aircraft engine is denoted as ET=2, and the data of the Lycoming O-320 D1D aircraft engine with a Cessna 172 standard muffler is denoted as ET=3.

The Lycoming O-360 A-series is a 4-stroke 4-cylinder engine. The rated maximum engine power is 180 hp at 2700 rpm. This engine is not acoustically evaluated and a method of predicting its noise spectrum is required. However, it is clear that the Lycoming O-360 A-series reaches 160 hp at 2200 rpm, and Lycoming O-320 D1D achieves 160 hp at 2700 rpm, both at standard sea-level conditions. Since both are 4-stroke 4-cylinder aircraft engines, the following assumption is made: both engine noise spectra at 160 hp are exactly the same. The result is the Lycoming O-360 A-series tonal noise SPL at 2700 rpm is modified to the following from the Lycoming O-320 D1D at 2740 rpm:

$$SPL_{2,2700} = SPL_{1,2740} + 40\log\frac{2700}{2200} \tag{35}$$

where $SPL_{2,2700}$ is the SPL of the Lycoming O-360 A-series at 2700 rpm and $SPL_{1,2740}$ is of the Lycoming O-320 D1D at 2740 rpm. The first subscript indicates an engine type and the second one indicates an engine rotational speed. The next equation gives the SPL of the Lycoming O-360 A-series at any engine rotational speed:

$$SPL_{2,N} = SPL_{2,2700} + 40\log\frac{N}{2700} \tag{36}$$

The Lycoming O-360 A-series aircraft engine broad-band noise SPL at 2700 rpm is modified as follows:

$$SPL_{2,2700} = 61.3\,\text{dB} \quad \text{for the frequency range 20 - 1500 Hz} \tag{37}$$

$$SPL_{2,2700} = -\frac{8.6}{2000} f_{2,2700} + 67.7\,\text{dB} \quad \text{for the frequency range 1.5 - 4 kHz} \tag{38}$$

$$SPL_{2,2700} = -\frac{7.1}{5000} f_{2,2700} + 56.2\,\text{dB} \quad \text{for the frequency range 4 - 9 kHz} \tag{39}$$

$$SPL_{2,2700} = -\frac{7.0}{1000} f_{2,2700} + 106.3\,\text{dB} \quad \text{for the frequency range 9 - 11 kHz} \tag{40}$$

The equations for calculating the Lycoming O-360 A-series engine noise mean-square sound pressure, $\overline{p}_{2,rpm}{}^{2}$, at any engine rotational speed is modified from Eqs. (37) through (40) and the frequency ranges of each equation are also changed.

$$\overline{p}_{2,rpm}{}^{2} = 10^{(-21\ 33)} \times (N)^{8} \qquad (37)^{*}$$

$$\text{for the frequency range } \frac{20 \cdot N}{2700} - \frac{1500 \cdot N}{2700} \text{ Hz}$$

$$\overline{p}_{2,rpm}{}^{2} = 10^{\left(-1\ 161\frac{f_{2\ rpm}}{N} - 20\ 68\right)} \times (N)^{8} \qquad (38)^{*}$$

$$\text{for the frequency range } \frac{1.5 \cdot N}{2700} - \frac{4 \cdot N}{2700} \text{ kHz}$$

$$\overline{p}_{2,rpm}{}^{2} = 10^{\left(-0\ 383\frac{f_{2\ rpm}}{N} - 21\ 83\right)} \times (N)^{8} \qquad (39)^{*}$$

$$\text{for the frequency range } \frac{4 \cdot N}{2700} - \frac{9 \cdot N}{2700} \text{ kHz}$$

$$\overline{p}_{2,rpm}{}^{2} = 10^{\left(-1\ 890\frac{f_{2\ rpm}}{N} - 16\ 82\right)} \times (N)^{8} \qquad (40)^{*}$$

$$\text{for the frequency range } \frac{9 \cdot N}{2700} - \frac{11 \cdot N}{2700} \text{ kHz}$$

Eqs. (36) and (37)* through (40)* are used in the noise prediction algorithm.

The Cessna 172 standard muffler, which is shown in Figure 17, is mounted at the ERAU engine noise test facility on a Lycoming O-320 D1D aircraft engine. The engine

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* Asterisk mark on Eqs. (37)* through (40)* denotes that these equations are modified from Eqs. (37) through (40)

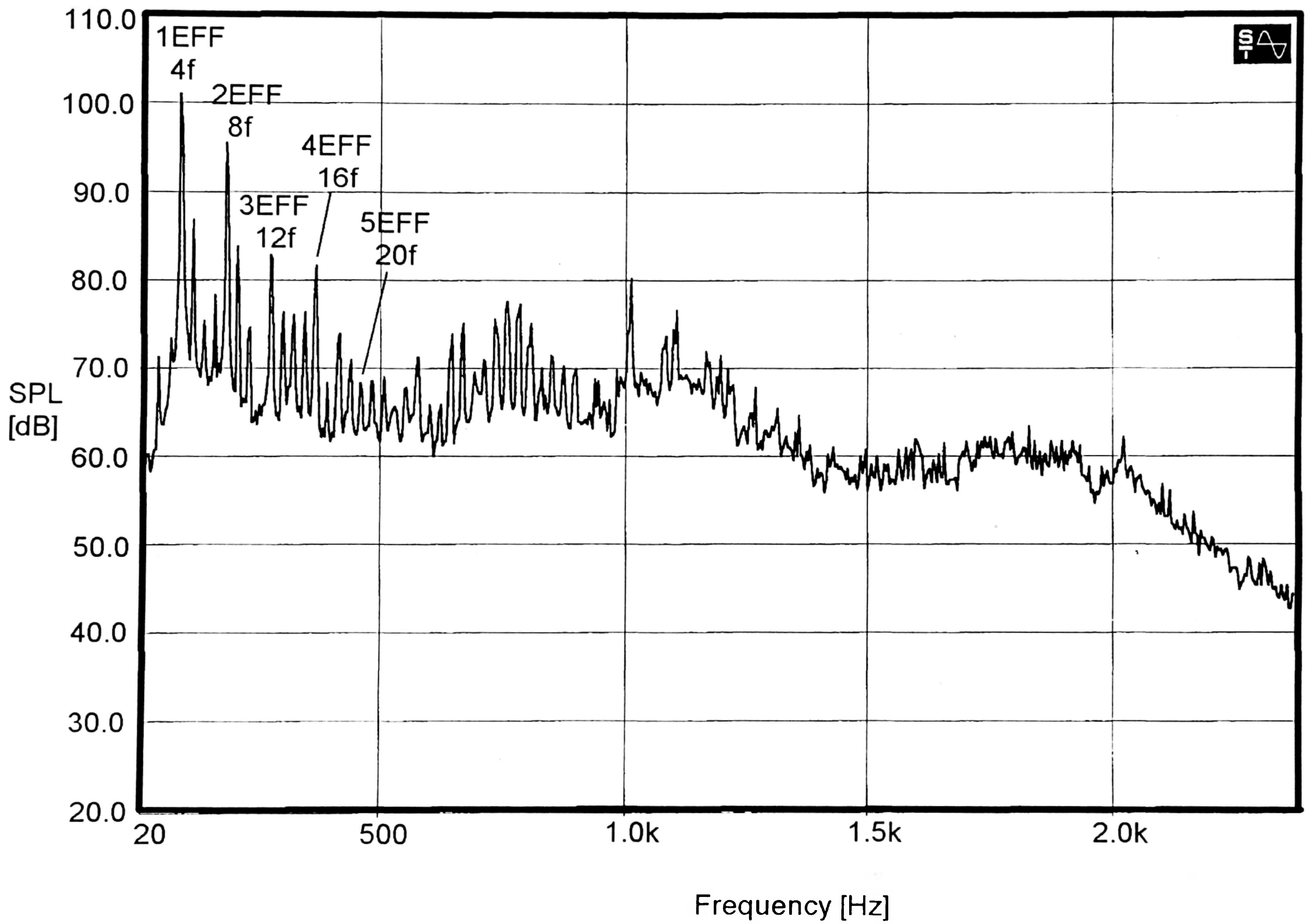


Figure 19-(a) Noise Spectrum 7 (Lycoming O-320 D1D Aircraft Engine **Noise with Cessna 172 Standard** Muffler, 2750 rpm), Frequency Range 20 – 2375 Hz •

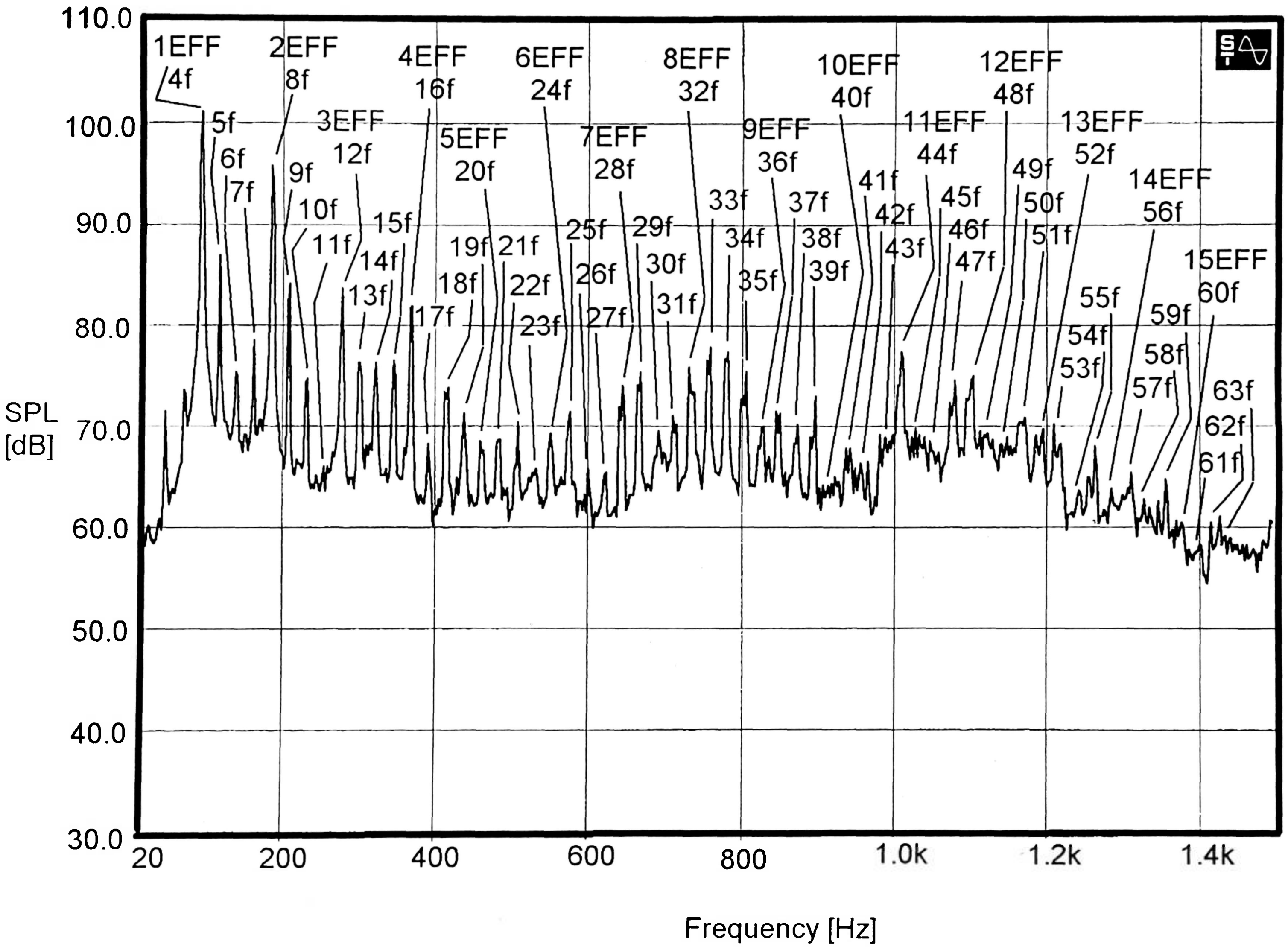


Figure 19-(b) Noise Spectrum 7 (Lycoming O-320 D1D Aircraft Engine Noise with Cessna 172 Standard Muffler, 2750 rpm), Frequency Range 20 – 1500 Hz

noise is recorded at 147 hp and 2750 rpm. The engine exhaust noise is measured at a distance of 50-ft from the exhaust exit normal to engine shaft centerline. This spectrum whose frequency range is 20 – 2375 Hz is given by Figure 19-(a). Generally, the broad-band noise data can be corrected from the spectrum whose frequency range 20 – 10 kHz. For that reason, the same data from the Lycoming O-320 D1D aircraft engine broad-band noise, which is shown by Figure 18-(a), is used as the data for the same engine as the Cessna 172 standard muffler. Figure 19-(b) shows the spectrum over the frequency range 20 – 1500 Hz, and the tonal noise data is corrected from this spectrum.

6.5 Comparison of Estimated and Measured SPL for the Lycoming O-320 D1D Aircraft Engine Exhaust Noise

The engine exhaust noise prediction algorithm is developed for use in the Advanced General Aviation Transport Experiments (AGATE) General-Aviation (GA) total aircraft noise prediction algorithm. Other members of the AGATE acoustic Work Task Group rather than ERAU developed the aircraft propeller noise prediction algorithm. To estimate the entire airplane noise, both the engine noise and propeller noise prediction algorithms are added together. This combination of algorithms results in the requirement that engine tones being predicted on a per Hertz (Hz) bases, i.e. one Hertz bandwidth, and the broad-band noise given in one-third octave bands as shown in Figure 20. Note that SPL of engine tones represented in Figure 20 are shown with these peak values connected together because of the plotting process. It is further required that the noise spectrum be given in terms of engine rotational speed as revolutions per second, i.e. rps. This transformation at engine rotational speed as 2740 rpm results in 1 rps as

45.7 Hz, in fundamental firing frequency f as 22.8 Hz, which is equal to 0.5 rps, and in engine firing frequency (EFF) as 91.3 Hz, which is equal to 2 rps. This transformation result is mentioned in Eqs. (22) through (25).

Comparing the predicted sound pressure level (SPL) for the IC GA airplane engine exhaust noise prediction algorithm and the actual airplane engine noise data, as well as Dobrzynski's normalization, confirms the accuracy of the FORTRAN noise prediction algorithm. The estimated OASPL of Lycoming O-320 D1D aircraft engine at 147 hp and 2740 rpm is 104.4 dB (97.6 dBA). This data sheet is given in Appendix B-1 and the spectrum is shown in Figure 20. This predicted spectrum is very close to the actual airplane engine SPL, which is shown in Figure 18-(a). It is important to note that the broadband spectrum in terms of 1/3 octave bandwidth while the tonal spectrum is in one Hz bandwidth. It can be stated that the actual noise data translated to the FORTRAN code very well.

Before comparing, Dobrzynski's normalization expressed in Eq. (21), has to be changed because of the test configuration difference. In this report, the static noise measurement is used instead of fly-over noise measurements. For that reason, the Doppler effect and the air attenuation can be ignored. The distance between the exhaust pipe end and the microphone is fixed at 50-ft. For the case with no Doppler nor air attenuation effects, Eq. (21) is modified as:

$$\begin{aligned} L_{AP} = L_{A,norm} + 10\log\left(\frac{N_{max}}{N_0}\right) + 14\log\left(\frac{P_{max}/N_{max}}{P_0/N_0}\right) \\ + 40\log\left(\frac{N}{N_{max}}\right) + 20\log\left(\frac{r'}{1000}\right) \end{aligned} \tag{41}$$

where $L_{A.\,norm}$ is 56.3 dBA, N_0 is 100 rpm, and P_0 is 10 kW.

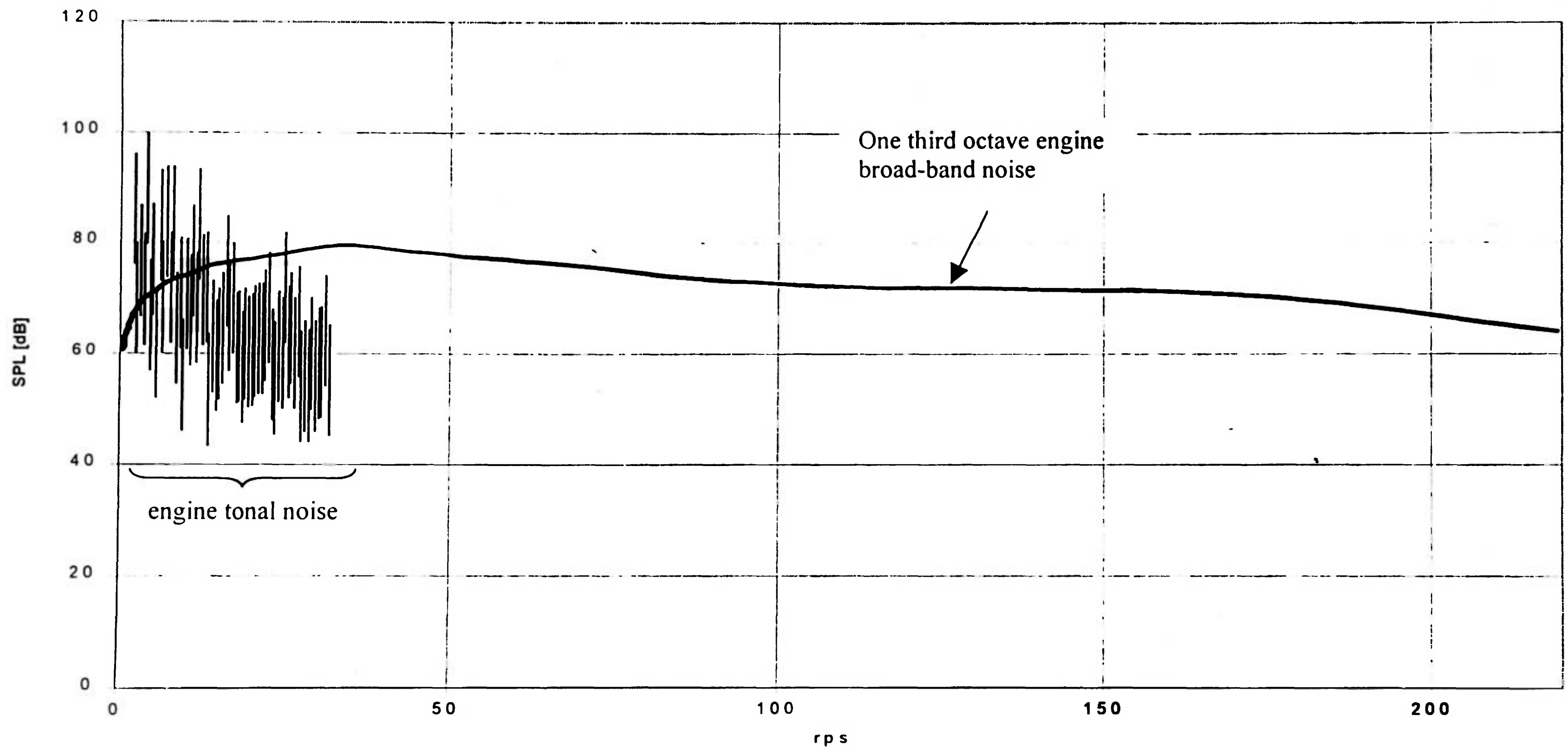


Figure 20 Predicted Noise Spectrum 1 (Lycoming O-320 D1D Aircraft Engine Noise with Smooth Y-shaped Pipe, 2740 rpm)

This modified Dobrzynski normalization relationship gives the L_{AP} (OASPL) of 92.4 dBA for the Lycoming O-320 D1D engine OASPL at 147 hp and 2740 rpm, which is 6 dBA lower than predicted for the OASPL by the noise prediction algorithm presented in Figure 20. In the predicted noise spectrum rps is used as x-axis. This gives the same non-dimensional frequency as the propeller noise. Although a 6 dBA difference is very significant, it is important to note that the OASPL presented is for an exhaust system with no muffler installed. Dobrzynski concluded in Reference [3] that mufflers had little effect on the magnitude of airplane exhaust noise. In other words, his airplane noise data should probably include a 6 dBA muffler effect. This investigation determined that the Cessna 172 aircraft with the standard muffler reduced engine noise significantly. Dobrzynski included the Cessna 172 with standard muffler data in his OASPL prediction method. Consequently, it is reasonable that there is a 6 dBA increase in the OASPL of engine exhaust noise without a muffler relative to when a muffler is installed.

To verify the noise prediction algorithm, engine noise data at 146 hp and 2450 rpm is used, where the OASPL is 102.4 dB (94.7 dBA). This data sheet is given in Appendix B-2 and the predicted spectrum is presented in Figure 21. The measured engine exhaust noise spectrum presented in Figure 22, gives an OASPL of 103.7 dB (96.0 dBA), which is 1.3 dB (1.3 dBA) greater than the predicted OASPL as given in Figure 20. This small difference is considered negligible. Dobrzynski's normalization relation predicts an OASPL of 90.6 dBA, which is 4.1 dBA lower than the predicted A-weighed OASPL. This larger difference is attributed to muffler effect. Therefore, it is reasonable to state that the noise prediction algorithm being presented in this investigation works well.

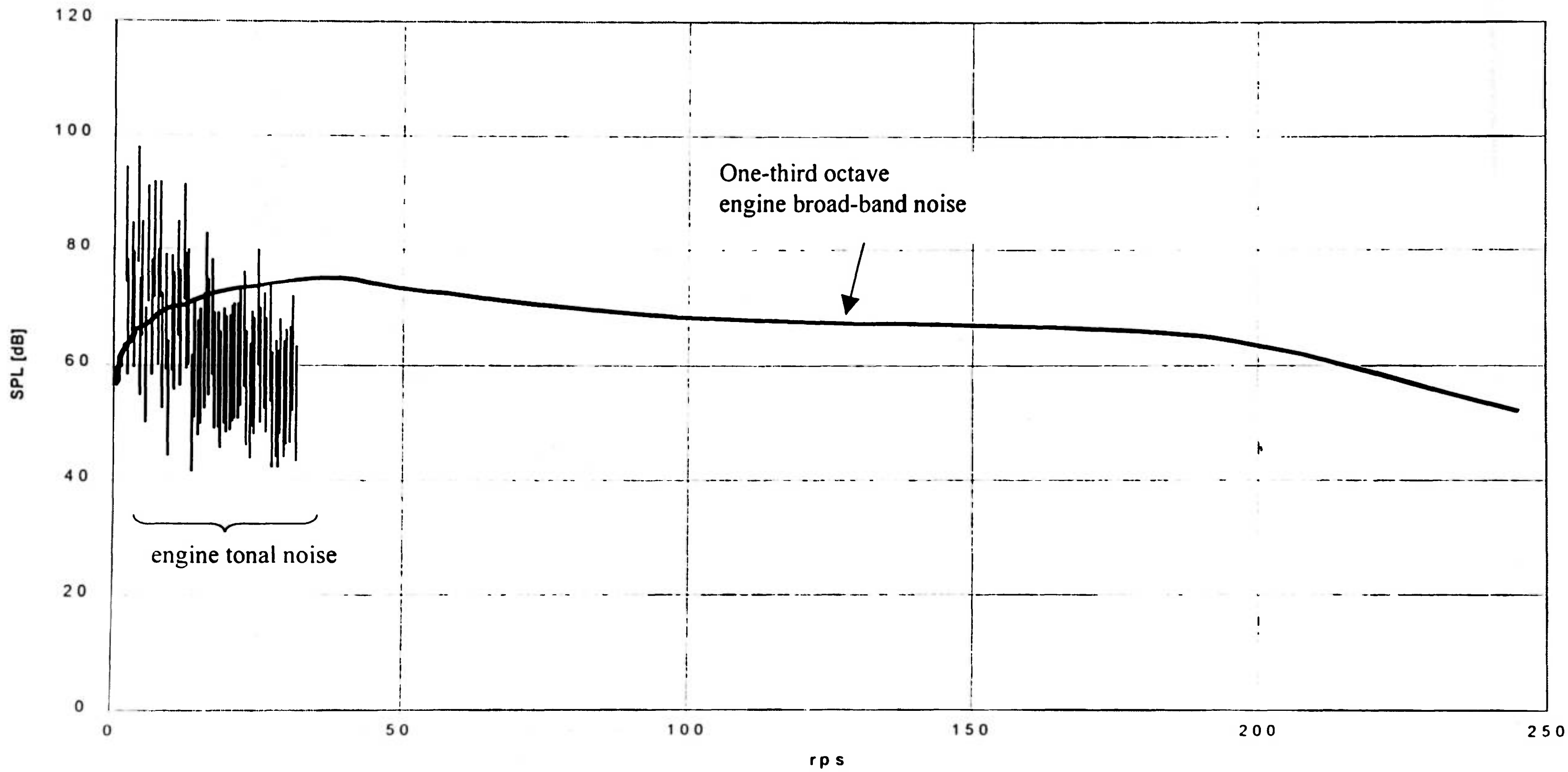


Figure 21 Predicted Noise Spectrum 2 (Lycoming O-320 D1D Aircraft Engine Noise with Smooth Y-shaped Pipe, 2450 rpm)

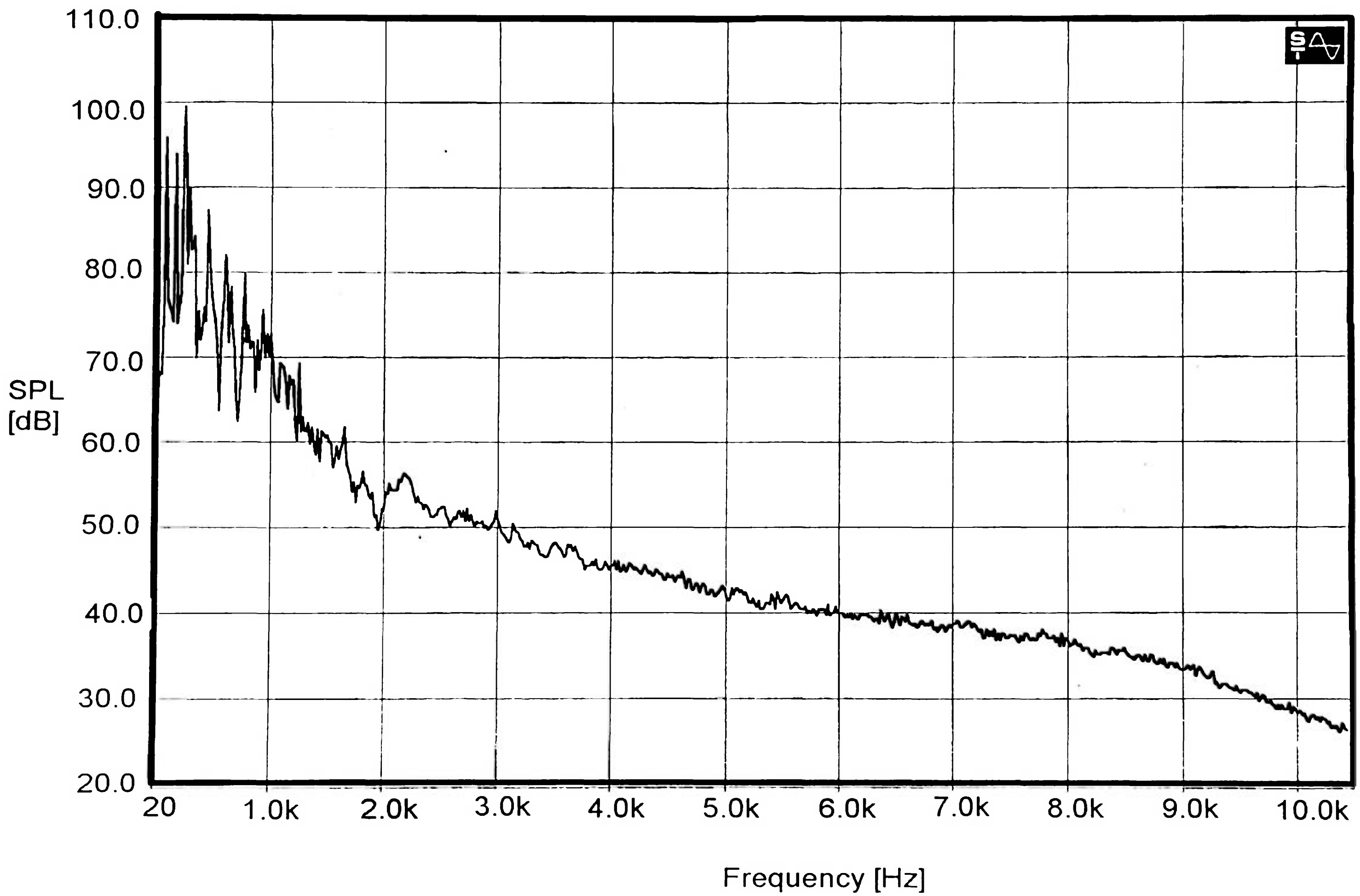


Figure 22 Noise Spectrum 8 (Lycoming O-320 D1D Aircraft Engine Noise **with Smooth Y-shaped pipe,** 2450 rpm, Frequency Range 20 – 11k Hz)

Although it is necessary to collect more engine exhaust noise data to validate the power spectrum predicted by the algorithm.

6.6 Estimated Power Spectrum for the Lycoming O-360 A-series Aircraft Engine Exhaust Noise

The Lycoming O-360 A-series aircraft engine exhaust noise is predicted without experiment validation using the engine noise test facility (ENTF). The predicted OASPL of this engine at 160 hp and 2700 rpm at standard sea-level conditions (maximum rated) based on Eq. (41) is 108.1 dB (101.7 dBA). Appendix B-3 presents the estimated engine noise power spectrum data sheet, and this spectrum is presented in Figure 23. This OASPL is 3.7 dB (3.3 dBA) greater than the Lycoming O-320 D1D aircraft engine at the same engine rotational speed.

Dobrzynski's normalization based on Eq. (41) gives 93.1 dBA, which is only 1.0 dBA greater than the Lycoming O-320 D1D at the same engine power and rotational speed. Between the Lycoming O-320 and O-360, there is a 20-hp maximum engine power difference at maximum rated power of 2700 rpm and standard sea-level conditions. According to the actual measured engine noise data for the Lycoming O-320 D1D versus the predicted level, the OASPL difference of 2.0 dB is created by the engine rotational speed increase from 2450 rpm to 2750 rpm, with engine powers of 148 hp and 161 hp respectively. However, Dobrzynski's normalization shows only 1.0 dBA increase because of the additional 20-hp is too low. This comparison indicates that the engine noise prediction algorithm, which gives 3.7 dB (3.3 dBA) as the OASPL difference, predicts reasonable levels.

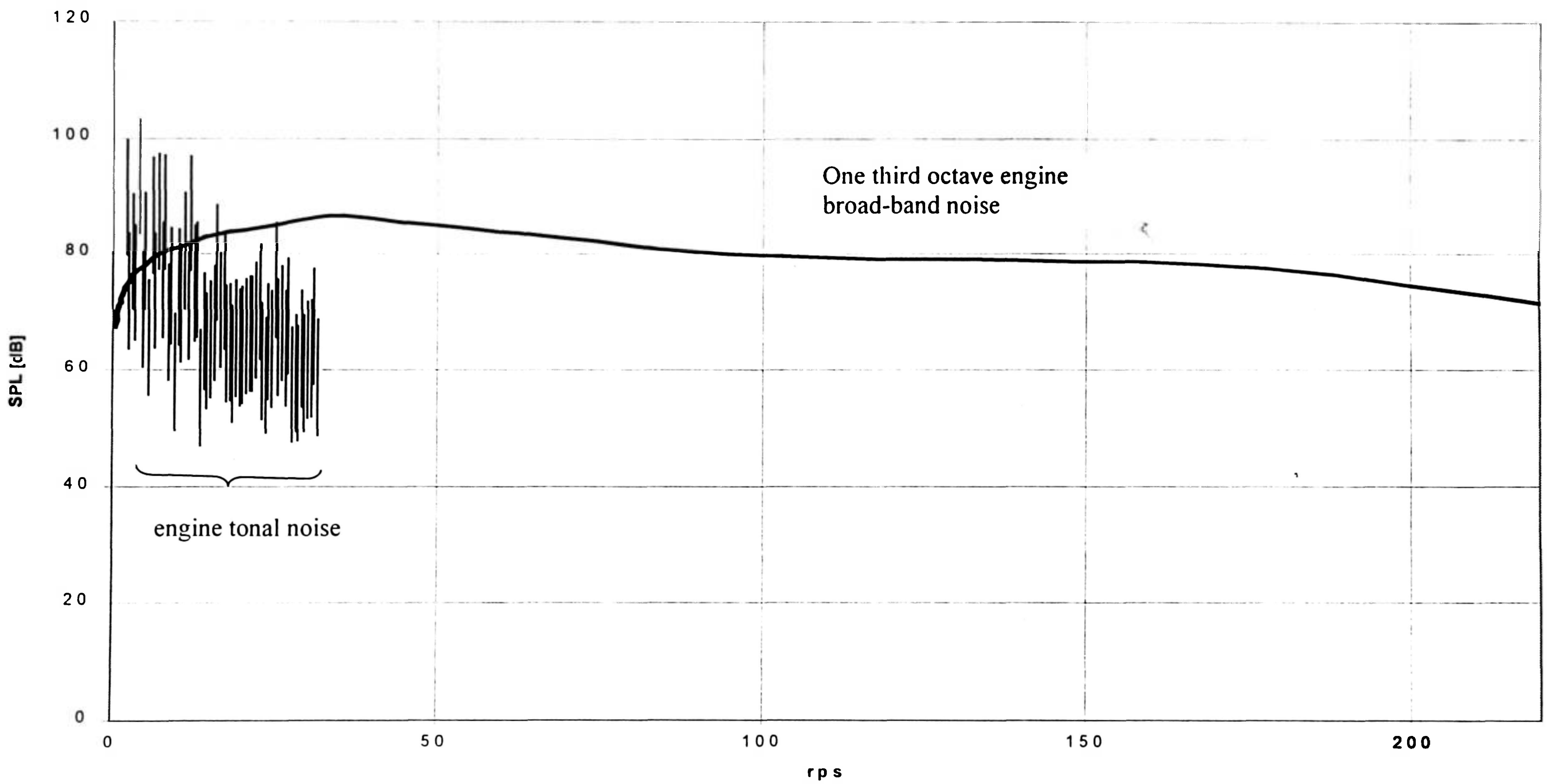


Figure 23 Predicted Noise Spectrum 3 (Lycoming O-360 A-series Aircraft Engine Noise, 2700 rpm)

6.7 Estimated Power Spectrum for the Lycoming 320 Engine Exhaust Noise with Cessna 172 Standard Muffler

The predicted engine exhaust noise of the Cessna 172 standard muffler mounted on the Lycoming O-320 D1D aircraft engine is predicted and the power spectrum data sheet is given in Appendix B-4 for 162.3 hp at 2750 rpm. According to this predicted data, the OASPL is 104.0 dB and is presented in Figure 24. This predicted spectrum represents an OASPL that is 0.7 dB lower than the OASPL based upon the measured spectrum presented in Figure 19-(a). This comparison validates the prediction with the Cessna 172 muffler at maximum rated power at standard sea-level conditions.

To validate the accuracy of this engine noise prediction algorithm with the Cessna muffler installed, a comparison is made at 124 hp and 2590 rpm. Shown in Figure 24 is the measured engine exhaust noise at these conditions with an OASPL of 103.4 dB. Inspection of Figure 25-(a) shows the measured spectrum from 20 Hz to 2375 Hz, which gives a good view of the high frequency broadband noise. In part (b) of this figure, the spectrum from 20 Hz to 1000 Hz is presented, which gives a blown up view on the low frequency engine tones. The data sheet for the predicted power spectrum for 124 hp and 2590 rpm is given in Appendix B-5, predicting an OASPL of 103.6 dB, which is almost identical to the measured value. This comparison reveals that the engine noise prediction algorithm for the Lycoming O-320 aircraft engine with Cessna 172 standard muffler installed is very accurate.

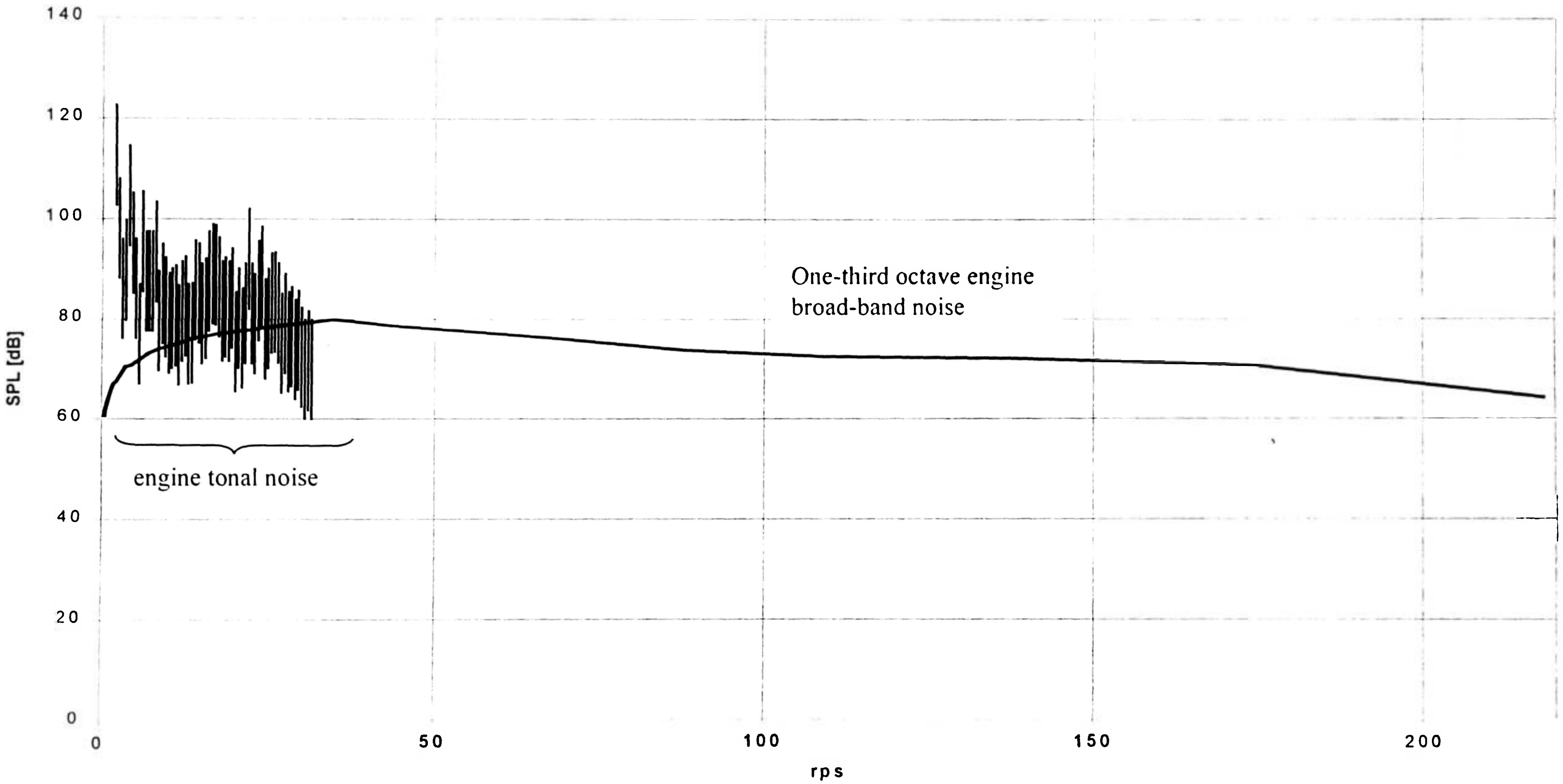
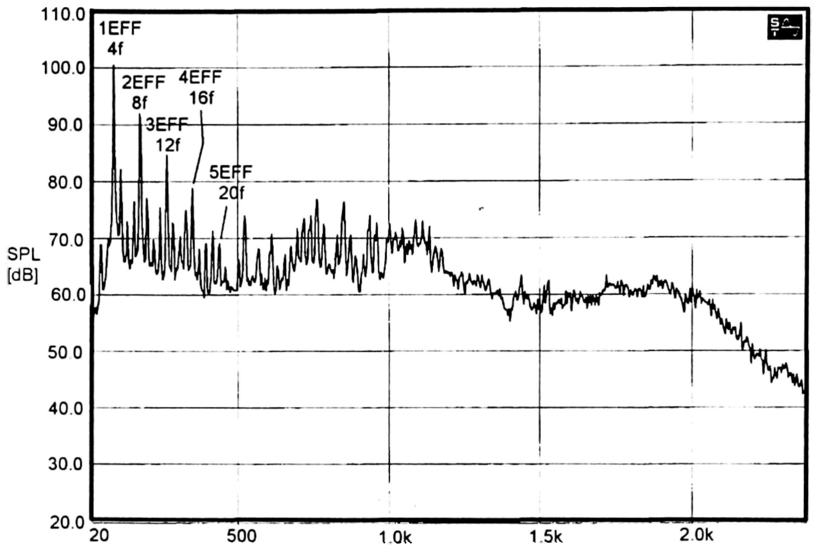
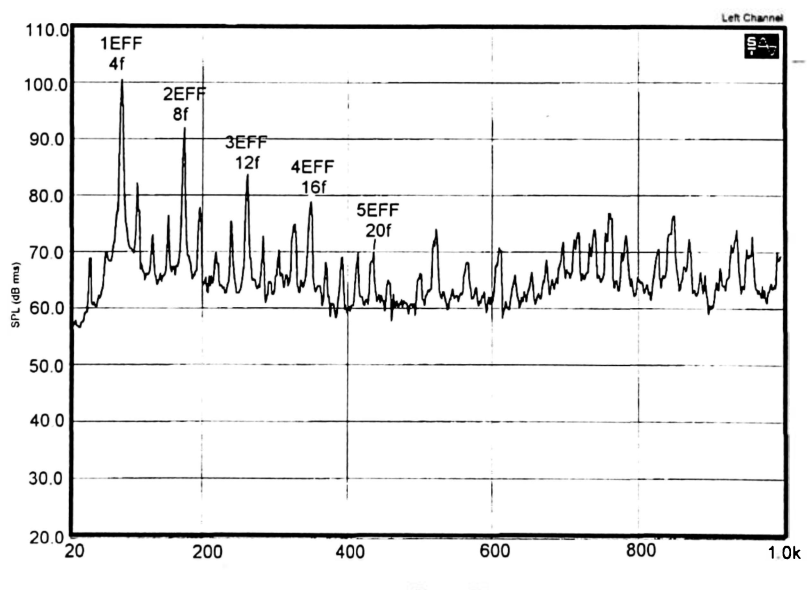


Figure 24 Predicted Noise Spectrum 4 (Lycoming O-320 D1D **Aircraft Engine Noise** with Cessna 172 Standard Muffler, 2740 rpm)



(a)



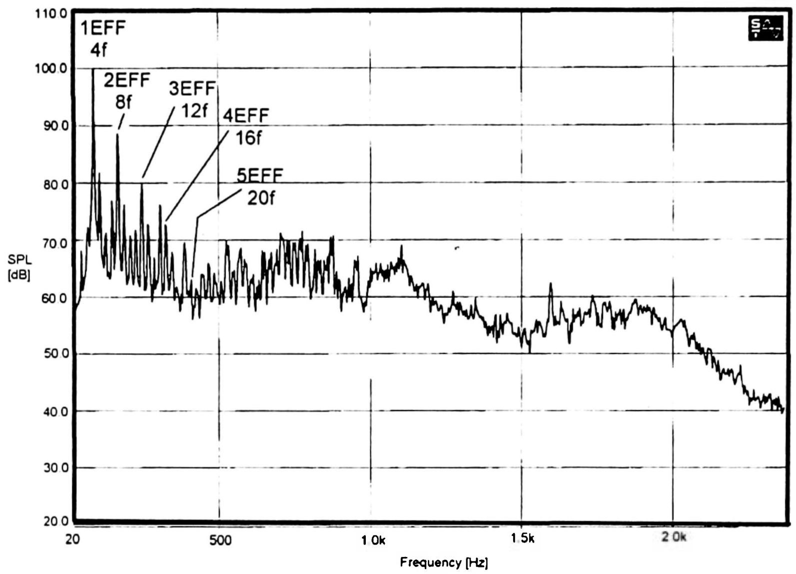
(b)

Figure 25 Noise Spectrum 9 (Lycoming O-320 D1D Aircraft Engine Noise with Cesna 172 Standard Muffler, 2590 rpm)
(a) Frequency Range 20 – 2375 Hz
(b) Frequency Range 20 – 1000 Hz

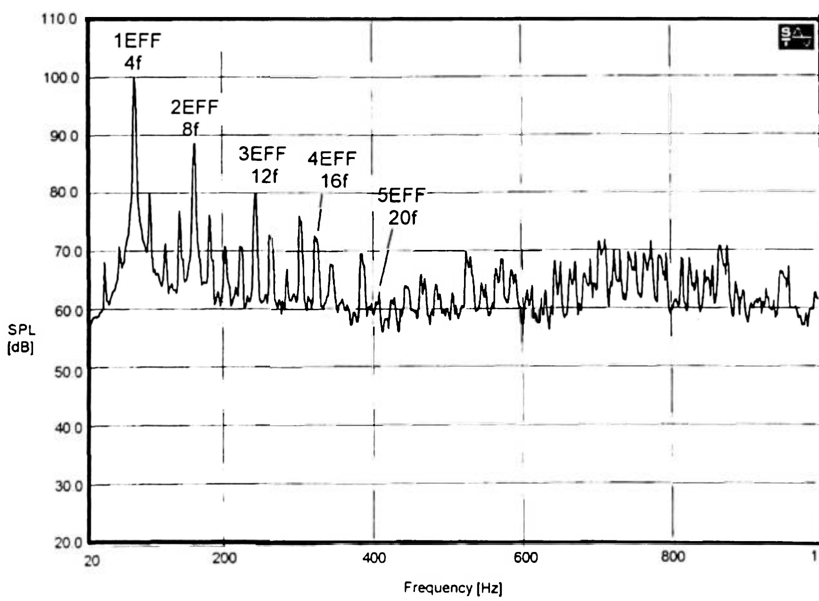
6.8 Engine Exhaust Tonal Noise Normalization

Numerous engine noise exhaust noise measurements at different engine power and rotational speed are made with the Lycoming O-320 D1D aircraft engine with the Cessna 172 standard muffler installed. Comparing the engine firing frequency tones 1EFF through 5EFF reveals that some of these tones do not scale as predicted by Eq. (41). As noted earlier, a literature search indicates that there is significant acoustic sound absorption in exhaust conduits because of the fully developed turbulent pipe flow that exists in intermittent-combustion (IC) aircraft engine exhaust systems [15]. Because of the large acoustic impedance differences between the hot exhaust gases exiting into the cold quiescent air at exhaust exit, acoustic energy is reflected back into the exhaust conduit [18]. A similar phenomenon at the exhaust exit occurs because of the turbulent mixing region between the exhaust gases and surrounding cold air [19]. All three of these nonlinear flow phenomena result in attenuation of sound that is very frequency dependent; i.e. attenuation increases with increasing frequency.

An engine tonal noise normalization procedure is developed, which is based upon empirical data collected using the Lycoming O-320 D1D aircraft engine with the Cessna standard muffler installed. The purpose of this normalization is to create one equation, which calculates the SPL of the EFF tones for any delivered engine power and rotational speed combination for the stated conditions.

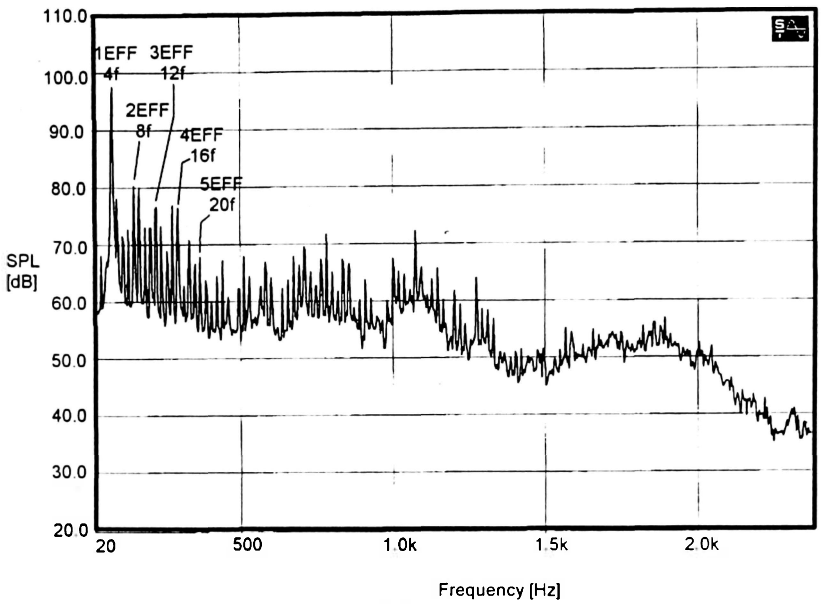


(a)

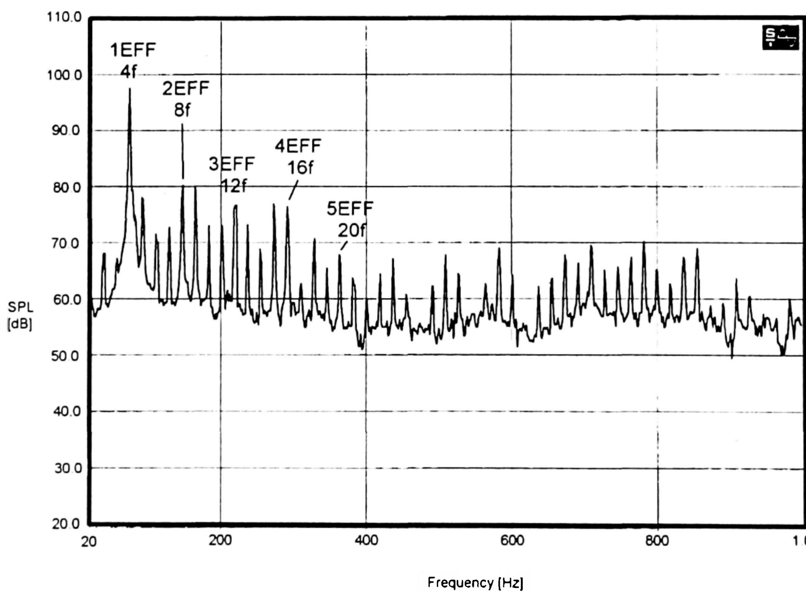


(b)

Figure 26 Noise Spectrum 10 (Lycoming O-320 D1D Aircraft Engine Noise with Cessna 172 Standard Muffler, 2420 rpm)
(a) Frequency Range 20 – 2375 Hz
(b) Frequency Range 20 – 1000 Hz



(a)



(b)

Figure 27 Noise Spectrum 11 (Lycoming O-320 D1D Aircraft Engine Noise with Cessna 172 Standard Muffler, 2160 rpm)
(a) Frequency Range 20 – 2375 Hz
(b) Frequency Range 20 – 1000 Hz

The Cessna 172 standard muffler is mounted on the ERAU aircraft engine noise test facility (ENTF) with the Lycoming O-320 D1D aircraft engine. Far-field acoustic measurements at 50 ft with the laid-down microphone setting are performed at engine rotational speeds of 2750, 2590, 2420 and 2160 rpm at different delivered powers. Spectra for the different engine power and rotational speed conditions are presented in Figures 19 and 25 through 27. Spectrum at 162.3 hp at 2750 rpm is shown in Figure 19, 124 hp at 2590 rpm is presented in Figure 25, 102 hp and 2420 rpm is given in Figure 26, and 75.5 hp and 2160 rpm

in Figure 27. All of these spectra are for the Lycoming O-320 D1D aircraft engine with a Cessna 172 standard muffler installed. Engine firing frequencies from EFF through 5EFF are studied and the results presented in Table 4.

Table 4-(a) gives the environmental data and engine operating conditions using the ERAU aircraft engine noise test facility with a Cessna 172 standard muffler. The ambient temperature is $81\ ^{\circ}\mathrm{F}\ \left(27\ ^{\circ}\mathrm{C}\right)$ and a day when there is no wind is chosen. The speed of sound, c, is calculated using the following equation:

$$\begin{aligned} c &= 20\sqrt{273.2+\left(\text{ambient temperature}\right)} \\ &= 20\sqrt{273.2+27} \\ &= 346.5\ \mathrm{m/s} \end{aligned}$$

The exhaust pipe diameter is represented as d, which is 0.09 m, and the exhaust pipe cross-section area, A, is $6.36\times10^{-3}\,\mathrm{m}^2$. The engine displacement volume, V, for the Lycoming O-329 D1D aircraft engine is $7.58\times10^{-3}\,\mathrm{m}^3$.Table 4-(b) gives the details of the engine run at engine power 147 hp (110 kW) and engine rotational speed 2750 rpm. SPL and frequencies at 1EFF though 5EFF are shown. The actual sound pressure, p_{act}, is calculated from SPL using Eq. (33) and the Strouhal number, S, and the wave number, k,

Table 4 Cessna 172 Standard Muffler Tonal Noise Sound Pressure Level

(a) Engine Environment

Ambient temperature	81 [F] 27 [C]
Speed of sound : c	346.5 [m/s]
diameter : d	0.09 [m]
pipe cross section area : A_d	$6.36 \cdot 10^{-3}$ [m^2]
Engine displacement : V	$7.58 \cdot 10^{-3}$ [m^3]

(b) Engine rotational speed : 2750 rpm

engine power : P	147 [hp] $11.0 \cdot 10^4$ [w]
flow rate : $\tilde{Q}$	0.347 [m^3/s]
$\tilde{Q}/A_d$	54.589 [m/s]

	SPL [dB]	p_{act} [Pa]	f [Hz]	k [m^{-1}]	S [-]	$\overline{P}$ [-]	SPL_{non} [dB]	SPL_{non}* [dB]
1EFF	101.0	2.244	91.7	1.662	0.151	$1.48 \cdot 10^{-7}$	-68.3	-68.3
2EFF	95.4	1.178	183.3	3.324	0.302	$1.02 \cdot 10^{-8}$	-79.9	-79.9
3EFF	83.5	$2.992 \cdot 10^{-1}$	275.0	4.987	0.453	$2.91 \cdot 10^{-10}$	-95.4	-95.4
4EFF	81.6	$2.405 \cdot 10^{-1}$	366.7	6.649	0.605	$1.06 \cdot 10^{-10}$	-99.8	-99.8
5EFF	68.3	$5.200 \cdot 10^{-2}$	458.3	8.311	0.756	$3.17 \cdot 10^{-12}$	-115.0	-115.0

(c) Engine rotational speed : 2590 rpm

engine power : P	124 [hp] $92.5 \cdot 10^3$ [w]
flow rate : $\tilde{Q}$	0.327 [m^3/s]
$\tilde{Q}/A_d$	51.413 [m/s]

	SPL [dB]	p_{act} [Pa]	f [Hz]	k [m^{-1}]	S [-]	$\overline{P}$ [-]	SPL_{non} [dB]	SPL_{non}* [dB]
1EFF	100.5	2.119	86.3	1.566	0.151	$2.08 \cdot 10^{-7}$	-66.8	-65.8
2EFF	91.9	$7.871 \cdot 10^{-1}$	172.7	3.131	0.302	$7.19 \cdot 10^{-9}$	-81.4	-78.3
3EFF	83.5	$2.992 \cdot 10^{-1}$	259.0	4.697	0.453	$4.62 \cdot 10^{-10}$	-93.4	-89.2
4EFF	78.9	$1.762 \cdot 10^{-1}$	345.3	6.262	0.605	$9.01 \cdot 10^{-11}$	-100.5	-95.2
5EFF	70.0	$6.325 \cdot 10^{-2}$	431.7	7.828	0.756	$7.43 \cdot 10^{-12}$	-111.3	-105.0

(d) Engine rotational speed : 2420 rpm

engine power : P	102 [hp] $76.1 \cdot 10^3$ [w]
flow rate : $\tilde{Q}$	0.306 [m^3/s]
$\tilde{Q}/A_d$	48.039 [m/s]

	SPL [dB]	p_{act} [Pa]	f [Hz]	k [m^{-1}]	S [-]	$\overline{P}$ [-]	SPL_{non} [dB]	SPL_{non}* [dB]
1EFF	100.0	2.000	80.7	1.463	0.151	$3.14 \cdot 10^{-7}$	-65.0	-62.8
2EFF	88.7	$5.445 \cdot 10^{-1}$	161.3	2.926	0.302	$5.82 \cdot 10^{-9}$	-82.3	-75.7
3EFF	80.0	$2.000 \cdot 10^{-1}$	242.0	4.388	0.453	$3.49 \cdot 10^{-10}$	-94.6	-85.7
4EFF	72.0	$7.962 \cdot 10^{-2}$	322.7	5.851	0.605	$3.11 \cdot 10^{-11}$	-105.1	-94.0
5EFF	62.7	$2.729 \cdot 10^{-2}$	403.3	7.314	0.756	$2.34 \cdot 10^{-12}$	-116.3	-103.0

(e) Engine rotational speed : 2160 rpm

engine power : P	75.5 [hp] $56.3 \cdot 10^3$ [w]
flow rate : $\tilde{Q}$	0.273 [m^3/s]
$\tilde{Q}/A_d$	42.877 [m/s]

	SPL [dB]	p_{act} [Pa]	f [Hz]	k [m^{-1}]	S [-]	$\overline{P}$ [-]	SPL_{non} [dB]	SPL_{non}* [dB]
1EFF	97.5	1.500	72.0	1.306	0.151	$4.05 \cdot 10^{-7}$	-63.9	-59.7
2EFF	80.2	$2.047 \cdot 10^{-1}$	144.0	2.611	0.302	$1.88 \cdot 10^{-9}$	-87.2	-74.7
3EFF	76.5	$1.337 \cdot 10^{-1}$	216.0	3.917	0.453	$3.57 \cdot 10^{-10}$	-94.5	-77.7
4EFF	76.2	$1.291 \cdot 10^{-1}$	288.0	5.222	0.605	$1.88 \cdot 10^{-10}$	-97.3	-76.3
5EFF	67.7	$4.853 \cdot 10^{-2}$	360.0	6.528	0.756	$1.70 \cdot 10^{-11}$	-107.7	-82.5

are calculated from the frequency using Eqs. (39) and (43) individually. Non-dimensionalized sound pressure, $\overline{P}$, is calculated by Eq. (42) using the actual sound pressure and the wave number. Finally, non-dimensional sound pressure level, SPL_{non}, and this SPL with engine rotational speed correction, SPL_{non}*, are derived using Eqs. (44) and (45) that are discussed later. The same numbers for thedifferent engine power and rotational speed conditions are presented in Table 4-(c) through (e). The data for 124 hp and 2590 rpm is shown in Table 4-(c), 102 hp and 2420 rpm is given in Table 4-(d), and 75.5 hp and 2160 rpm in Table 4-(e).

Considering the SPL difference between each tones, and according to the Dobrynski's normalization, the SPL difference between two engines rpm: N_1 and N_2, is given by $10\log\left(\frac{N_2}{N_1}\right)^4$. However, it is clear that the difference between each tone is not the same. An estimate multiplier, n, must be used instead of 4 as shown in the following equation:

$$\Delta SPL = 10\log\left(\frac{N_2}{N_1}\right)^n \tag{38}$$

Based upon comparing EFF through 5EFF tones in Figures 19, and 25 – 27, it is estimated that n=4 for EFF, n=12 for 2EFF, n=16 for 3EFF, n=20 for 4EFF, and n=24 for 5EFF. In other words, the tones SPL decreases at a rate much greater than predicted and increases as frequency increases.

The reason for the reduction in the SPL with increasing frequency is that the following phenomena tend to occur at higher frequencies:

1) When the incident sound wave from the engine cylinder arrives at the exhaust outlet, partial transmission and partial reflection occur with the reflected wave shifted in phase and reduced in amplitude relative to the incident one [18].
2) When sound propagates through turbulence around the tip of the exhaust pipe, there is a possibility of acoustic absorption by a direct transfer of energy to the turbulent motions [15].

3) Since the air movement is reflected into the exhaust pipe by the turbulence around the exhaust end, the radiation of sound is reduced [19].

To develop the sound pressure level normalization, two non-dimensional parameters are used. These two parameters, non-dimensional frequency and sound pressure (sound pressure level) are very important for the interpretation of IC engine exhaust noise. For the normalizing process, [M] denotes the mass unit in kg, [L] is the characteristic length in m, and [T] is the characteristic time unit in seconds. The dimension of frequency is $[T^{-1}]$, and generally, the Strouhal number is used as the non-dimensional frequency. The Strouhal number is a dimensionless number used in studying the vibration of a body past which a fluid is flowing. It is equal to a characteristic dimension of the body times the frequency of vibrations divided by the fluid velocity relatives to the body, therefore this number is given by:

$$S = \frac{f_{rpm} d}{\tilde{v}} \tag{39}$$

where f_{rpm} is sound frequency, d is the characteristic length which is the exhaust pipe diameter, and $\tilde{v}$ is the mean fluid speed. The mean fluid speed with dimensions of [L/T], is calculated using the volume flow rate, $\tilde{Q}$ with basic units of $[L^3/T]$. according to the following equation:

$$\tilde{v} = \tilde{Q} / A_d \tag{40}$$

where A_d is the cross-section area with diameter d.

Therefore, the Strouhol number is modified as:

$$S = \frac{f\,d}{\tilde{Q}/A_d} \tag{41}$$

Insertion of the basic units L and T into Eqs. (39) and (41) reveals that S is dimensionless, and is the dimensionless frequency used in this investigation.

The unit for sound pressure is Pa, with a dimension $[\mathrm{ML^{-1}T^{-2}}]$. A non-dimensional sound pressure, $\overline{\mathrm{P}}$, is shown as:

$$\overline{P} = \frac{p_{act}\,dc}{Pk} = \frac{[\mathrm{ML^{-1}T^{-2}}][\mathrm{L}][\mathrm{LT^{-1}}]}{[\mathrm{ML^{2}T^{-3}}][\mathrm{L^{-1}}]} = [-] \quad \text{(non-dimensional)} \tag{42}$$

where p_{act} is the actual sound pressure, c is the speed of sound of the hot gas in the exhaust system, P is engine power in watts and k is wave number. The wave number is related to the frequency of the sound wave by:

$$k = \frac{2\pi f}{c} \tag{43}$$

The non-dimensional sound pressure level, SPL_{non}, is given by:

$$SPL_{non} = 10\log \overline{P}^{2} \tag{44}$$

As a result, the frequency domain spectrum can be modified using the Strouhal number as the dimensionless frequency and $\mathrm{SPL_{non}}$ as the dimensionless acoustic power, i.e. dimensionless mean-square value of acoustic pressure. Inspection of Eq. (44) reveals that SPL_{non} is in units of decibels where the dimensionless reference pressure is unity, and therefore not shown. Shown in Figure 28 is SPL_{non} plotted as a function of S, a dimensionless power spectrum based on far-field acoustic measurements of the Lycoming O-320 D1D aircraft engine with standard Cessna exhaust system at various power and engine rotational speed settings. Table 4 lists the various engine power and rotational speed settings used in developing the data presented in Figure 28.

Inspection of Figure 28 indicates that in the S range of approximately 0.15 to 0.52 the curves are impressively similar except for the curve at 2160 rpm. It appears that the normalization procedure implemented works surprising well except at S>0.52.

In an attempt to bring the curves in Figure 28 closer together, $\overline{P}^2$ is divided by $\left(\frac{N_2}{N_1}\right)^n$ in the following manner to modify the SPL_{non} and non-dimensional SPL with engine rotational speed correction, SPL_{non}^*, is calculated.

$$SPL_{non}^* = 10\log\left(\overline{P}^2 \Big/ \left(\frac{N_2}{N_1}\right)^n\right) \qquad (45)$$

Presented in Figure 29 is the SPL_{non}^* plotted as a function of Strouhal, i.e. a modified dimensionless power spectrum. In this graph, the curve representing 2160 rpm is moved

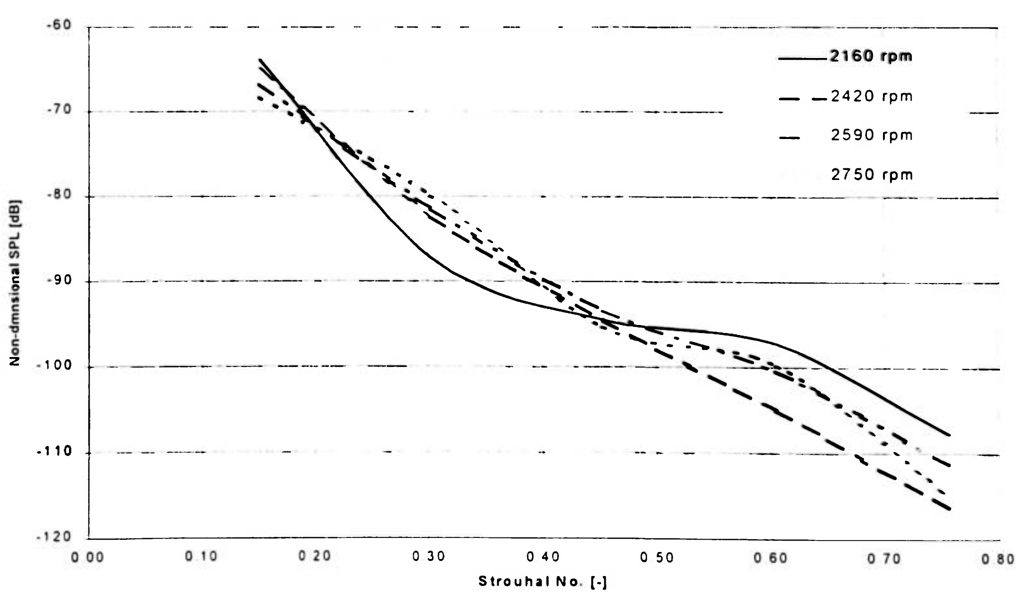


Figure 28 Non-Dimensional Sound Pressure Level
Depends upon Strouhal Number

further from the other curves than when using the normalization technique implemented in Figure 28. The curve representing 2160 rpm at 75 hp is hypothesized to be sufficiently low in power to not truly represent the acoustic data being studied and is, therefore, an anomaly, and should be ignored.

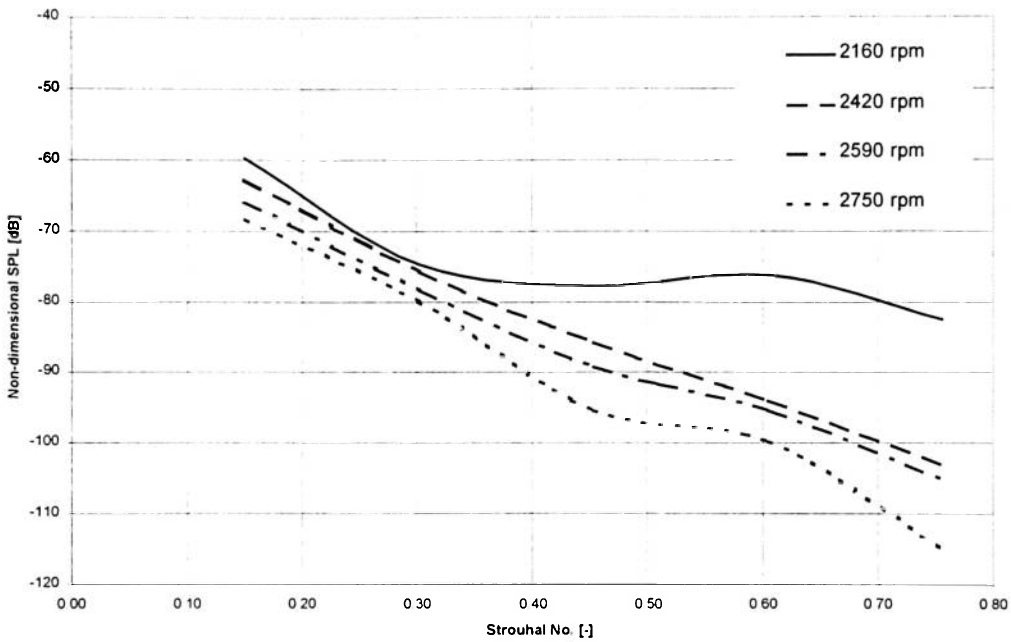


Figure 29 Non-Dimensional Sound Pressure Level with Engine Rotational Speed Correction Depends upon Strouhal Number

To complete this normalization a couple more steps are needed:

1) Additional engine noise recordings must be made incorporating different engine types, exhaust systems and mufflers.

2) The power spectrum normalization technique is very successful, but this approach which ideally reduces all curves at different engine power and rotational speeds to a

single curve must be further developed. Based on this one curve, the sound pressure level of any type of engine with any type of muffler might be predicted.

CHAPTER 7

CONCLUSION

7.1 Aircraft Engine Noise Test Facility Exhaust Pipe Configuration

To measure the engine noise with the Cessna 172 standard muffler, the 4-ft pipe extension and the concrete block wall are not necessary because the engine noise is dominated by exhaust noise and the mechanical noise is negligible. The pipe extension acts as an additional muffler, and reduces the overall sound pressure level (OASPL) engine exhaust noise by 13 dB. Moreover, the concrete block wall helps to make the engine noise OASPL noisier because of sound reflection from the exhaust pipe termination off the hard surface.

Next, the smooth Y-shaped exhaust pipe is better than the corrugated one because excess turbulence is generated in the rough interior surface of the corrugations. The 13 ½-in straight pipe at the pipe exit assures that fully established pipe flow exists at the exit termination. This conduit extension further reduces the engine exhaust noise because of sound dissipated in the extension caused by the fully established turbulent pipe flow.

7.2 Engine Exhaust Noise Directionality Characteristics

To ensure the aircraft engine, which is mounted on the Embry-Riddle Aeronautical University aircraft engine noise test facility, is a monopole noise source, the directionality of engine exhaust noise measurements are made. The laid-down microphone is set at 50-ft and angles of 30^0, 45^0, 60^0, 90^0, 120^0, 135^0, and 150^0. The OASPL difference among the various horizontal azimuthal angles is about 2 dB. This difference indicates that there is only minor directionality characteristics and within experimental error, therefore it is reasonable to state that the engine exhaust far-field radiated noise directionality is spherical, i.e. a monopole source. This conclusion is consistent with the monopole sound source conclusion assumed by Dobrzynski (Reference [3]). Because the acoustic pressure is doubled using a laid-down microphone, the OASPL measurements reported are 6 dB greater than in a free acoustic field.

7.3 IC GA Airplane Engine Exhaust Noise Prediction Algorithm

The internal-combustion (IC) general aviation (GA) aircraft engine exhaust noise prediction algorithm, which is based upon the empirical data (Lycoming O-320 D1D aircraft engine at 2740 rpm), works well. There is no non-weighted difference in the predicted and actual OASPL at 2740 rpm but there is a 0.8 dBA difference, and 1.3 dB (1.3 dBA) at 2450 rpm.

In Dobrzynski's normalization, 57.0 dBA is used as the normalized engine sound pressure level instead of 51.9 dBA. Consequently, it makes the OASPL by his normalization 5 – 6 dBA lower than the OASPL by the prediction algorithm. This difference is reasonable since the noise reduction by the engine exhaust muffler is neglected in Dobrzynski's report.

The predicted OASPL of the Lycoming O-360 A-series aircraft engine at maximum power is reasonable since the difference between this and the Lycoming O-320 D1D aircraft engine is approximately 3.5 dB. The engine power of the Lycoming O-360 is greater by 20 hp than the Lycoming O-320, and correlates well with the predicted noise increase due to the additional engine power.

The engine noise prediction algorithm successfully predicts the engine exhaust noise of the Lycoming O-320 D1D and O-360 A-series aircraft engines without mufflers, and the Lycoming O-320 with a Cessna 172 standard muffler installed. These algorithms predict the exhaust noise of the engine configurations noted at maximum power and standard sea-level conditions, for any engine rotational speed. The predicted tones are given on a per Hz basis while the broadband noise is given in 1/3-octave bands over the frequency range of 20 Hz to 20 kHz.

7.4 Engine Exhaust Tonal Noise Normalization

The actual sound pressure, p_{act}, is made non-dimensional using a reference length, speed of sound, engine power, and wave number. The non-dimensional sound pressure level is calculated using Eq. (45), and the Strouhal number is used as the non-dimensional frequency. The resulting non-dimensional power spectrum is presented in Figure 29, and this non-dimensional SPL is nearly a linear function of the Strouhal number, and this normalization technique almost reduced the power spectrum to a single curve. It is concluded that IC engine exhaust noise tones can be successfully normalized using a dimensionless SPL based on engine power, hot exhaust gas speed of sound, wave number, and exhaust pipe diameter. A dimensionless Strouhal frequency based on pipe diameter and mean exhaust flow speed is also used.

CHAPTER 8

RECOMMENDATIONS

To make the IC GA airplane engine exhaust noise prediction algorithm and engine noise normalization more accurate, more engine exhaust noise measurements should be performed, recorded, and analyzed. The engine configurations, which are recommended, are the following:

1) The Lycoming O-360 A-series airplane engine noise
2) The Lycoming O-320 D1D with the smooth Y-shaped pipe and 13 ½-in straight pipe extension at different engine rotational speed
3) The Lycoming O-320 D1D with the smooth Y-shaped pipe and 27-in, 54-in or 51-in straight extension pipe at 2750 rpm or others.
4) The Lycoming O-320 D1D with the smooth Y-shaped pipe, one of the straight extension pipes and the Cessna 172 standard muffler at 2750 rpm or others.

CHAPTER 9

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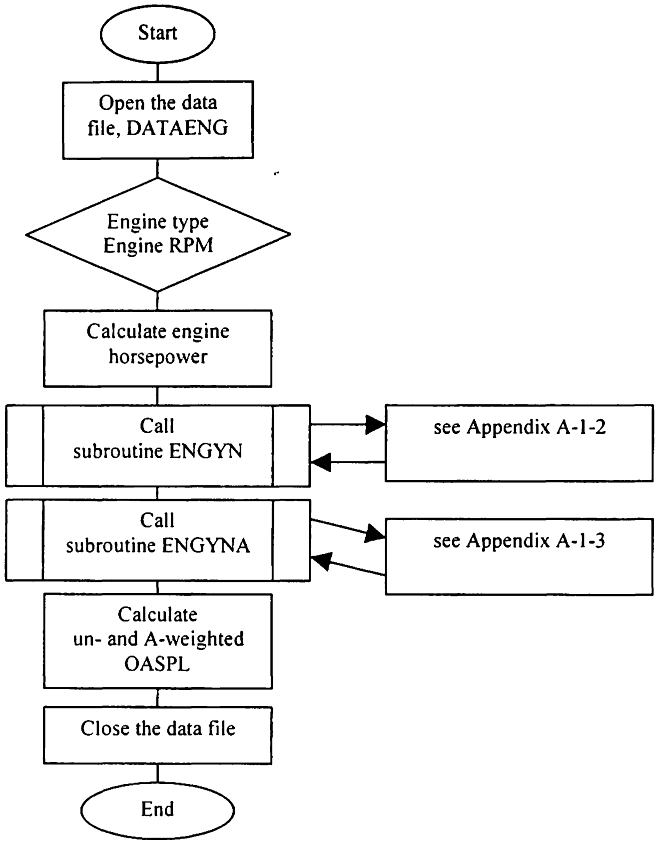
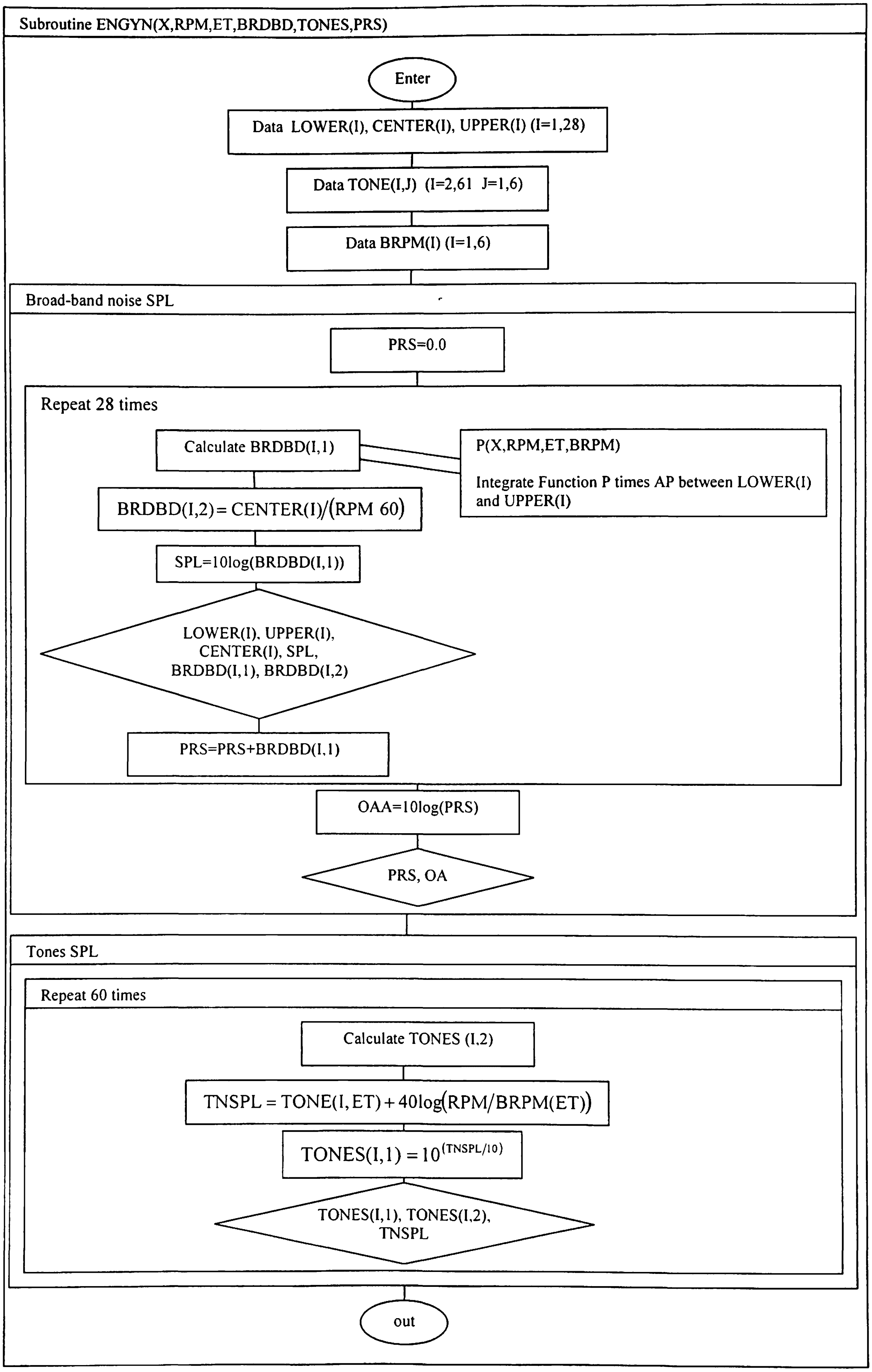
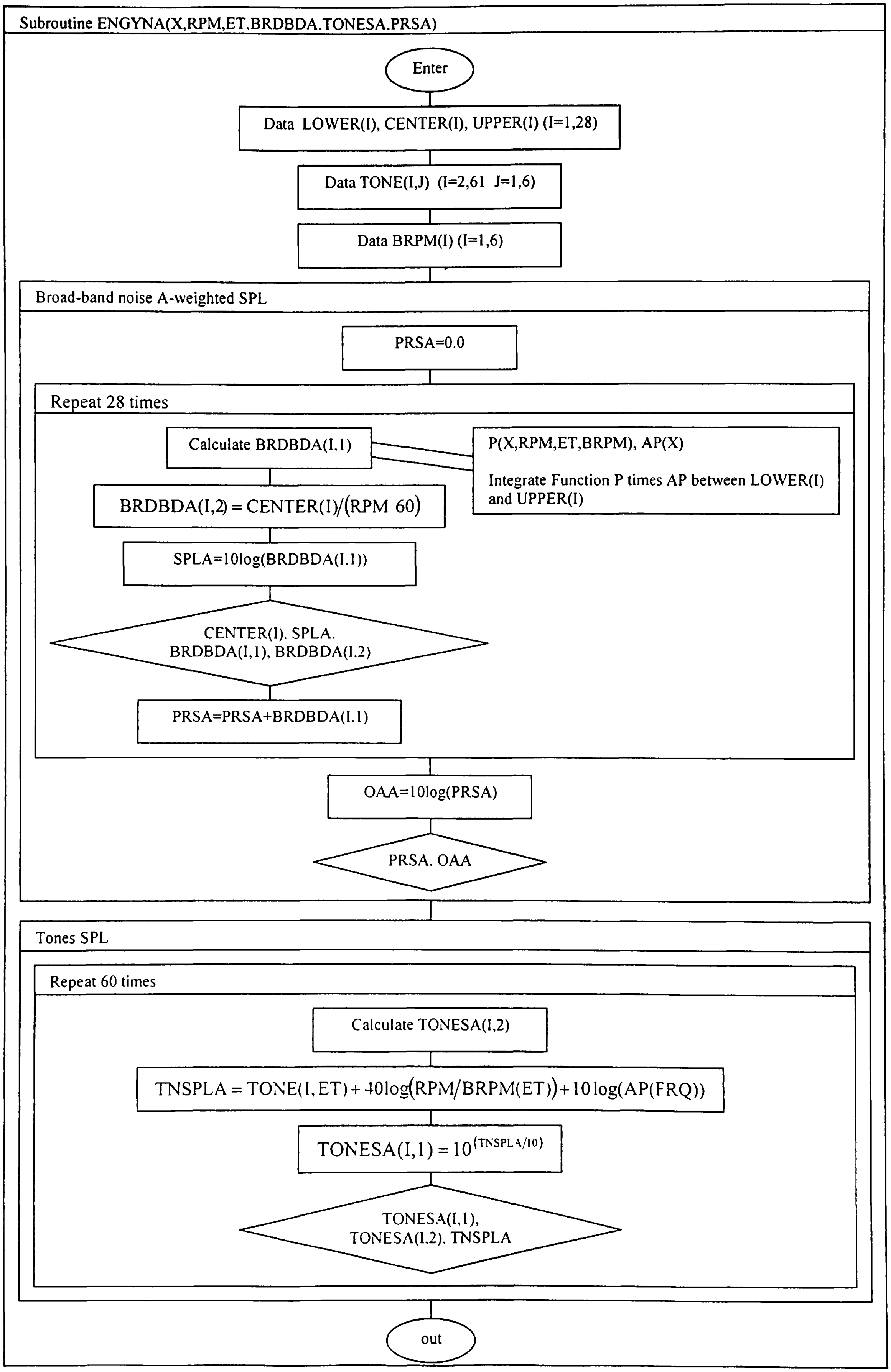
Appendix A-1 IC GA Aircraft Engine Exhaust Engine Noise Prediction Algorithm Flowchart



Note: DATAENG is the predicted noise data output file



Subroutine ENGYN(X,RPM,ET,BRDBD,TONES,PRS)
Enter
Data LOWER(I), CENTER(I), UPPER(I) (I=1,28)
Data TONE(I,J) (I=2,61 J=1,6)
Data BRPM(I) (I=1,6)
Broad-band noise SPL
PRS=0.0
Repeat 28 times
Calculate BRDBD(I,1)
P(X,RPM,ET,BRPM)
Integrate Function P times AP between LOWER(I) and UPPER(I)
BRDBD(I,2)= CENTER(I)/(RPM 60)
SPL=10log(BRDBD(I,1))
LOWER(I), UPPER(I), CENTER(I), SPL, BRDBD(I,1), BRDBD(I,2)
PRS=PRS+BRDBD(I,1)
OAA=10log(PRS)
PRS, OA
Tones SPL
Repeat 60 times
Calculate TONES (I,2)
TNSPL = TONE(I,ET) + 40log(RPM/BRPM(ET))
TONES(I,1) = 10^(TNSPL/10)
TONES(I,1), TONES(I,2), TNSPL
out



Subroutine ENGYNA(X,RPM,ET,BRDBDA,TONESA,PRSA)
Enter
Data LOWER(I), CENTER(I), UPPER(I) (I=1,28)
Data TONE(I,J) (I=2,61 J=1,6)
Data BRPM(I) (I=1,6)
Broad-band noise A-weighted SPL
PRSA=0.0
Repeat 28 times
Calculate BRDBDA(I,1)
P(X,RPM,ET,BRPM), AP(X)
Integrate Function P times AP between LOWER(I) and UPPER(I)
BRDBDA(I,2) = CENTER(I)/(RPM 60)
SPLA=10log(BRDBDA(I,1))
CENTER(I), SPLA, BRDBDA(I,1), BRDBDA(I,2)
PRSA=PRSA+BRDBDA(I,1)
OAA=10log(PRSA)
PRSA, OAA
Tones SPL
Repeat 60 times
Calculate TONESA(I,2)
TNSPLA = TONE(I,ET) + 40log(RPM/BRPM(ET)) + 10 log(AP(FRQ))
TONESA(I,1) = 10^(TNSPLA/10)
TONESA(I,1), TONESA(I,2), TNSPLA
out

Appendix A-2 IC GA Airplane Engine Exhaust Prediction Algorithm FORTRAN Code

```
C     NOISE PREDICTION ALGORITHM

C     PROGRAMER : Hiroko Tada

C     X : frequency
C     RPM : engine rpm
C     ET : engine type
C     BRDBD(I,1) : 1/3 octave broad band-noise sound pressure level
C     BRDBD(I,2) : standard 1/3 octave band non-dimensional center frequency
C     TONES(I,1) : engine tone sound pressure level
C     TONES(I,2) : non-dimensional engine tone frequency
C     BRDBDA(I,1) : 1/3 octave broad-band noise A-weighted sound pressure level
C     BRDBDA(I,2) : standard 1/3 octave band non-dimensional center frequency
C     TONESA(I,1) : engine tone A-weighted sound pressure level
C     TONESA(I,2) : non-dimensional engine tone frequency
C     PRS : un-weighted sound pressure of each tone
C     PRSA : A-weighted sound pressure of each tone
C     LOWER(I) : standard 1/3 octave band lower frequency
C     CENTER(I) : standard 1/3 octave band center frequency
C     UPPER(I) : standard 1/3 octave band upper frequency
C     TONE(I,ET) : engine tone sound pressure level of each maximum engine
C                  RPM up to 1500 Hz
C     BRPM(ET) : maximum engine RPM of each engyne type
C     HH(I,ET) : coefficients of Engine RPM and Power function, HP(RPM,ET)
C     PP(I,J,ET) : coefficients of broad-band noise SPL function, P(X,RPM,ET)
C     AA(I) : coefficients of A-weigted SPL function, AP(X)

      INTEGER ET
      REAL LOWER
      DIMENSION LOWER(28),CENTER(28),UPPER(28)
      DIMENSION TONE(70,6)
      DIMENSION BRDBD(28,2),TONES(60,2)
      DIMENSION BRDBDA(28,2),TONESA(60,2)
      DIMENSION BRPM(6)

C     Open the file, DATAENG, into which the result data is placed
      OPEN(1,FILE='DATAENG',STATUS='OLD')

      WRITE(6,*)'WHICH ENGINE TYPE DO YOU HAVE?'
C     ET=1 : Lycoming O-320 D1D
C     ET=2 : Lycoming O-360 A-series
C     ET=3 : Lycmoing O-320 D1D with Cessna 172 Standard Muffler
C     ET=4 :
C     ET=5 :
C     ET=6 :

C     Pick up the engine type and engine RPM, and compute engine horsepower
      READ(5,*)ET
      WRITE(6,*)'ENGINE RPM?'
      READ(5,*)RPM
      WRITE(1,*)'ENGINE TYPE : ',ET
      WRITE(1,*)' ENGINE ROTATIONAL SPEED, N =',RPM,' rpm'
      WRITE(1,610)HP(RPM,ET)
 610  FORMAT('              ENGINE POWER, P=',F7.1,' HP')
```

```
      CALL ENGYN(X,RPM,ET,BRDBD,TONES,PRS)
      CALL ENGYNA(X,RPM,ET,BRDBDA,TONESA,PRSA)

C     Compute over all sound pressure for un- and A-weighted
      OAMSP=PRS
      OAMSPA=PRSA
      DO 11 I=2,61
       OAMSP=OAMSP+TONES(I,1)
       OAMSPA=OAMSPA+TONESA(I,1)
11    CONTINUE

C     Compute over all sound pressure level for un- and A-weighted
      OASPL=10*LOG10(OAMSP)
      OASPLA=10*LOG10(OAMSPA)
      WRITE(1,611)OAMSP
 611  FORMAT(/,'OVER ALL MEAN SQUARE PRESSURE=',E15.6)
      WRITE(1,612)OASPL
 612  FORMAT('OVER ALL SOUND PRESSURE LEVEL=',F6.1,' dB')
      WRITE(1,613)OAMSPA
 613  FORMAT('A-WGT OVER ALL MEAN SQUARE PRESSURE=',E15.6)
      WRITE(1,614)OASPLA
 614  FORMAT('A-WGT OVER ALL SOUND PRESSURE LEVEL=',F6.1,' dBA')

      CLOSE(1,STATUS='KEEP')

      STOP
      END

*******************************************************************************
      SUBROUTINE ENGYN(X,RPM,ET,BRDBD,TONES,PRS)
C     Lower, center, upper frequencies of standard 1/3 octave bands
C     Un-weighted broad-band noise sound pressure
C     and engine tone sound pressure levels of maxmum engine RPM input arrays
C     Un-weighted 1/3 octave broad-band noise and discrete tones output arrays
C     X : frequency
C     RPM : engine rpm
C     ET : engine type
C     BRDBD(I,1) : 1/3 octave broad band-noise sound pressure level
C     BRDBD(I,2) : standard 1/3 octave band non-dimensional center frequency
C     TONES(I,1) : engine tone sound pressure level
C     TONES(I,2) : non-dimensional engine tone frequency
C     PRS : un-weighted sound pressure of each tone
C     LOWER . standard 1/3 octave band lower frequency
C     CENTER : standard 1/3 octave band center frequency
C     UPPER : standard 1/3 octave band upper frequency
C     TONE : engine tone sound pressure level for 2740rpm up to 1500 Hz
C     BRPM : maximum engine RPM of each engine type

      INTEGER ET
      REAL LOWER
      DIMENSION BRDBD(28,2),TONES(61,2)
      DIMENSION LOWER(28),CENTER(28),UPPER(28)
      DIMENSION TONE(70,6)
      DIMENSION BRPM(6)

C     1/3 octave band lower, center and upper frequencies
      DATA (LOWER(I),I=1,28)/18.0,22.4,28.0,35.5,45.0,56.0,71.0,90.0,
     +  112.0,140.0,180.0,224.0,280.0,355.0,450.0,560.0,710.0,900.0,
     +  1120.0,1400.0,1800.0,2240.0,2800.0,3550.0,4500.0,5600.0,
     +  7100.0,9000.0/,
     +  (CENTER(I),I=1,28)/20.0,25.0,31.5,40.0,50.0,63.0,80.0,100.0,
     +  125.0,160.0,200.0,250.0,315.0,400.0,500.0,630.0,800.0,1000.0,
     +  1250.0,1600.0,2000.0,2500.0,3150.0,4000.0,5000.0,6300 0,8000.0,
```

```
     + 10000.0/,
     + (UPPER(I),I=1,28)/22.4,28.0,35.5,45.0,56.0,71.0,90.0,112.0,
     + 140.0,180.0,224.0,280.0,355.0,450.0,560.0,710.0,900.0,1120.0,
     + 1400.0,1800.0,2240.0,2800.0,3550.0,4500.0,5600.0,7100.0,9000.0,
     + 11200.0/

C     Tone sound pressure levels[dB]
      DATA ((TONE(I,J),I=2,61),J=1,6)/96.2,80.1,86.8,81.6,99.8,76.9,
     + 87.0,72.0,93.1,80.2,93.8,82.0,93.7,74.6,81.0,66.1,80.8,77.8,
     + 86.9,78.3,93.4,81.4,82.0,63.5,73.0,69.7,71.7,74.5,85.0,76.8,
     + 80.1,71.0,71.2,67.6,71.8,70.3,70.7,72.2,72.7,72.7,75.0,78.2,
     + 68.0,65.6,71.3,70.1,82.0,72.1,74.5,70.2,75.7,64.0,66.0,64.2,
     + 70.0,66.0,68.2,68.5,74.0,65.2,
     + 99.8,83.7,90.4,85.2,103.4,80.5,90.6,75.6,96.7,83.8,97.4,85.6,
     + 97.3,78.2,84.6,69.7,84.4,81.4,90.5,81.9,97.0,85.0,85.6,67.1,
     + 76.6,73.3,75.3,78.1,88.6,80.4,83.7,74.6,74.8,71.2,75.4,73.9,
     + 74.3,75.8,76.3,76.3,78.6,81.8,71.6,69.2,74.9,73.7,85.6,75.7,
     + 78.1,73.8,79.3,67.6,69.6,67.8,73.6,69.6,71.8,72.1,77.6,68.8,
     + 102.7,88.0,76.0,79.7,94.5,85.2,76.0,67.0,85.5,77.5,77.5,77.5,
     + 83.5,69.6,75.0,72.3,69.1,70.0,70.5,66.8,71.5,72.5,67.0,67.2,
     + 75.7,75.1,71.0,72.0,77.5,79.0,78.8,76.3,71.5,72.3,71.5,74.1,
     + 65.5,70.0,66.2,71.0,82.1,71.0,69.0,75.6,78.5,68.0,70.0,73.1,
     + 73.3,71.1,65.2,69.0,65.5,66.5,64.0,65.8,62.4,60.0,61.7,60.0,
     + 180*0.0/

C     Baseline RPM for each engine type
      DATA BRPM/2740.0,2700.0,2750.0,3*0.0/

      WRITE(1,*)'ONE-THIRD OCTAVE BAND BROAD BAND NOISE'
      WRITE(1,*)'  LOWER  CENTER   UPPER   SPL   BRDBD(I,1)  BRDRD(I,2)'

C     Compute 1/3 octave spectrum of broad-band noise by integrating
C     broad-band noise spectrum model over each of the 1/3 octave bands
C     and non-dimensional center frequency for output array
      PRS=0.0
      DO 21 I=1,28
       BRDBD(I,2)=CENTER(I)/(RPM/60.0)
       D=AINT(CENTER(I)/5.0)
       H=(UPPER(I)-LOWER(I))/D
       BRDBD(I,1)=(P(LOWER(I),RPM,ET,BRPM)
     +   +P(UPPER(I),RPM,ET,BRPM))*H/2.0
       X=LOWER(I)

       DO 22 J=1.0,D-1.0
        X=X+H
        BRDBD(I,1)=BRDBD(I,1)+H*P(X,RPM,ET,BRPM)
 22    CONTINUE

       PRS=PRS+BRDBD(I,1)
       SPL=10*LOG10(BRDBD(I,1))
       WRITE(1,621)LOWER(I),CENTER(I),UPPER(I),SPL,BRDBD(I,1),BRDBD(I,2)
 621   FORMAT(3F8.1,F6.1,E15.6,F6.1,' rps')
 21   CONTINUE

C     Compute over all broad-band sound pressure level
      OA=10*LOG10(PRS)
      WRITE(1,622)PRS
 622  FORMAT('BROADBAND NOISE MEAN SQUARE PRESSURE=',E15.6)
      WRITE(1,623)OA
 623  FORMAT('          BROADBAND NOISE OASPL=',F6.1,' dB',//)

      WRITE(1,*)'ENGINE TONES NOISE'
      WRITE(1,*)'  TONES(I,1)   TONES(I,2)  SPL'
```

```
C     Compute tone sound pressure level and non-dimensional frequency for
C     output array
      F=RPM/120.0
      FRQ=3.0*F
      DO 23 I=2,61
       FRQ=FRQ+F
       TONES(I,2)=FRQ/(RPM/60.0)
       TNSPL=TONE(I,ET)+40.0*LOG10(RPM/BRPM(ET))
       TONES(I,1)=10**(TNSPL/10.0)
       WRITE(1,624)TONES(I,1),TONES(I,2),TNSPL
 624   FORMAT(E15.6,F6.1,' rps',1X,F6.1)
 23   CONTINUE

      RETURN
      END

******************************************************************************
      SUBROUTINE ENGYNA(X,RPM,ET,BRDBDA,TONESA,PRSA)
C     Lower, center, upper frequencies of standard 1/3 octave bands
C     A-weighted broad-band noise sound pressure
C     and engine tone sound pressure levels of maxmum engine RPM input arrays
C     A-weighted 1/3 octave broad-band noise and discrete tones output arrays

C     X : frequency
C     RPM : engine rpm
C     ET : engine type
C     BRDBDA(I,1) : 1/3 octave broad-band noise A-weighted sound pressure level
C     BRDBDA(I,2) · standard 1/3 octave band non-dimensional center frequency
C     TONESA(I,1) : engine tone A-weighted sound pressure level
C     TONESA(I,2) : non-dimensional engine tone frequency
C     PRSA : A-weighted sound pressure of each tone
C     LOWER : standard 1/3 octave band lower frequency
C     CENTER : standard 1/3 octave band center frequency
C     UPPER : standard 1/3 octave band upper frequency
C     TONE : engine tone sound pressure level for 2740rpm up to 1500 Hz
C     BRPM : maximum engine RPM of each engine type

      INTEGER ET
      REAL LOWER
      DIMENSION BRDBDA(28,2),TONESA(61,2)
      DIMENSION LOWER(28),CENTER(28),UPPER(28)
      DIMENSION TONE(70,6)
      DIMENSION BRPM(6)

C     1/3 octave band lower, center ,and upper frequencies
      DATA (LOWER(I),I=1,28)/18.0,22.4,28.0,35.5,45.0,56.0,71.0,90.0,
     +  112.0,140.0,180.0,224.0,280.0,355.0,450.0,560.0,710.0,900.0,
     +  1120.0,1400.0,1800.0,2240.0,2800.0,3550.0,4500.0,5600.0,
     +  7100.0,9000.0/,
     +  (CENTER(I),I=1,28)/20.0,25.0,31.5,40.0,50.0,63.0,80.0,100.0,
     +  125.0,160.0,200.0,250.0,315.0,400.0,500.0,630.0,800.0,1000.0,
     +  1250.0,1600.0,2000.0,2500.0,3150.0,4000.0,5000.0,6300.0,8000.0,
     +  10000.0/,
     +  (UPPER(I),I=1,28)/22.4,28.0,35.5,45.0,56.0,71.0,90.0,112.0,
     +  140.0,180.0,224.0,280.0,355.0,450.0,560.0,710.0,900.0,1120.0,
     +  1400.0,1800.0,2240.0,2800.0,3550.0,4500.0,5600.0,7100.0,9000.0,
     +  11200.0/

C     Tone sound pressure levels[dB]
      DATA ((TONE(I,J),I=2,61),J=1,6)/96.2,80.1,86.8,81.6,99.8,76.9,
     +  87.0,72.0,93.1,80.2,93.8,82.0,93.7,74.6,81.0,66.1,80.8,77.8,
     +  86.9,78.3,93.4,81.4,82.0,63.5,73.0,69.7,71.7,74.5,85.0,76.8,
```

```
      +  80.1,71.0,71.2,67.6,71.8,70.3,70.7,72.2,72.7,72.7,75.0,78.2,
      +  68.0,65.6,71.3,70.1,82.0,72.1,74.5,70.2,75.7,64.0,66.0,64.2,
      +  70.0,66.0,68.2,68.5,74.0,65.2,
      +  99.8,83.7,90.4,85.2,103.4,80.5,90.6,75.6,96.7,83.8,97.4,85.6,
      +  97.3,78.2,84.6,69.7,84.4,81.4,90.5,81.9,97.0,85.0,85.6,67.1,
      +  76.6,73.3,75.3,78.1,88.6,80.4,83.7,74.6,74.8,71.2,75.4,73.9,
      +  74.3,75.8,76.3,76.3,78.6,81.8,71.6,69.2,74.9,73.7,85.6,75.7,
      +  78.1,73.8,79.3,67.6,69.6,67.8,73.6,69.6,71.8,72.1,77.6,68.8,
      +  101.2,87.0,75.0,78.7,93.0,84.2,75.0,66.0,84.0,76.5,76.5,76.5,
      +  82.0,68.6,74.0,71.3,67.6,69.0,69.5,65.8,69.5,71.5,66.0,66.2,
      +  74.2,74.1,70.0,71.0,76.0,78.0,77.8,75.3,70.0,71.3,70.5,73.1,
      +  64.0,69.0,65.2,70.0,80.6,70.0,68.0,74.6,77.0,67.0,69.0,72.1,
      +  71.8,70.1,64.2,68.0,64.0,65.5,63.0,64.8,60.9,59.0,60.7,59.0,
      +  180*0.0/

C     Baselıne RPM for each engıne type
      DATA BRPM/2740.0,2700.0,2750.0,3*0.0/

      WRITE(1,630)
 630  FORMAT(//,'A-WEIGHTED ONE-THIRD OCTAVE BAND BROAD BAND NOISE')
      WRITE(1,*)' CENTER  SPLA   BRDBDA(I,1)  BRDBDA(I,2)'

C     Compute 1/3 octave spectrum of broad-band noıse by ıntegratıng
C     broad-band noıse spectrum model and A-weıghted spectrum model
C     over each of the 1/3 octave bands and non-dımensıonal center
C     frequency for output array
      PRSA=0.0
      DO 31 I=1,28
       BRDBDA(I,2)=CENTER(I)/(RPM/60.0)
       D=AINT(CENTER(I)/5.0)
       H=(UPPER(I)-LOWER(I))/D
       BRDBDA(I,1)=(P(LOWER(I),RPM,ET,BRPM)*AP(LOWER(I))
     +   +P(UPPER(I),RPM,ET,BRPM)*AP(UPPER(I)))*H/2.0
       X=LOWER(I)

       DO 32 J=1.0,D-1.0
        X=X+H
        BRDBDA(I,1)=BRDBDA(I,1)+H*P(X,RPM,ET,BRPM)*AP(X)
 32    CONTINUE

       PRSA=PRSA+BRDBDA(I,1)
       SPLA=10*LOG10(BRDBDA(I,1))
       WRITE(1,631)CENTER(I),SPLA,BRDBDA(I,1),BRDBDA(I,2)
 631   FORMAT(F8.1,F6.1,E15.6,F6.1,' rps')
 31   CONTINUE

C     Compute over all broad-band sound pressure level
      OAA=10*LOG10(PRSA)
      WRITE(1,632)PRSA
 632  FORMAT('A-WGT BROADBAND NOISE MEAN SQUARE PRESSURE=',E15 6)
      WRITE(1,633)OAA
 633  FOPMAT('          A-WGT BPOADBAND NOISE OASPL=',F6.1,' dBA',//)

      WRITE(1,*)'ENGINE TONES NOISE'
      WRITE(1,*)'  TONESA(I,1)  TONESA(I,2) SPLA'

C     Compute tone A-weıghted sound pressure level and non-dırensıonal
C     frequency for output array
      F=P PM/120.0
      FRQ=3.0*F
       DO 33 I=2,61
       FRQ=FRQ+F
       TONESA(I,2)=FRQ/(RPM/60.0)
```

```
       TNSPLA=TONE(I,ET)+40.0*LOG10(RPM/BRPM(ET))+10*LOG10(AP(FRQ))
       TONESA(I,1)=10**(TNSPLA/10.0)
       WRITE(1,634)TONESA(I,1),TONESA(I,2),TNSPLA
 634   FORMAT(E15.6,F6.1,' rps',1X,F6.1)
 33   CONTINUE

      RETURN
      END

******************************************************************************
      FUNCTION HP(RPM,ET)
C     Computes engine horse power from engine rpm
C     Coefficients are given by data statements

C     HH(I,ET) : coefficients of Engine RPM and Power function, HP(RPM,ET)
      INTEGER ET
      REAL HH(2,6)
      DATA HH/0.04625,35.125,
     +  0.04,72.0,
     +  0.04625,35.125,
     +  6*0.0/

      HP=HH(1,ET)*RPM+HH(2,ET)
      RETURN
      END

******************************************************************************
      FUNCTION P(X,RPM,ET,BRPM)
C     Computes un-weighted broad-band noise sound pressure
C     Coefficients are given by data statements

C     PP(I,J,ET)   coefficients of broad-band noise SPL function,
C                  P(X,RPM,ET,BRPM(ET))

      INTEGER ET
      REAL PP(4,3,6),BRPM(6)

      DATA PP/0.0,1500.0,4000.0,9000.0,
     +  0.0,-1.178,-0.3891,-1.92,-22.09,-21.44,-22.60,-17.58,
     +  0.0,1500.0,4000.0,9000.0,
     +  0.0,-1.161,-0.3834,-1.89,-21.33,-20.68,-21.83,-16.82,
     +  0.0,1500.0,4000.0,9000.0,
     +  0.0,-1.178,-0.3891,-1.92,-22.09,-21.44,-22.60,-17.58,
     +  36*0.0/

      IF(X.GE.RPM*PP(1,1,ET)/BRPM(ET))
     +  P=10**(PP(1,2,ET)*X/RPM+PP(1,3,ET))*RPM**8
      IF(X.GE.RPM*PP(2,1,ET)/BRPM(ET))
     +  P=10**(PP(2,2,ET)*X/RPM+PP(2,3,ET))*RPM**8
      IF(X.GE.RPM*PP(3,1,ET)/BRPM(ET))
     +  P=10**(PP(3,2,ET)*X/RPM+PP(3,3,ET))*RPM**8
      IF(X.GE.RPM*PP(4,1,ET)/BRPM(ET))
     +  P=10**(PP(4,2,ET)*X/RPM+PP(4,3,ET))*RPM**8
      RETURN
      END

******************************************************************************

      FUNCTION AP(X)
C     Computes A-weighted sound pressure level using 10th degree
C     polynomial function
C     Coefficients are given by data statements
```

```
C     AA(I) : coefficients of A-weigted SPL function, AP(X)
      REAL AA(12)

C     Coefficients
      DATA AA/0.0,-.03804604824,1.039846563,-12.54816693,87.8805487,
     + -394.8209468,1186.705893,-2412.103352,3268.347409,
     + -2823.362609,1410.684049,-318.8247035/

      Z=AA(1)
      DO 10 I=2,12
       Z=Z*LOG10(X)+AA(I)
       AP=10**Z
 10   CONTINUE
      RETURN
      END

*******************************************************************************

C     NOISE PREDICTION ALGORITHM

C     PROGRAMER : Hiroko Tada

C     X : frequency
C     RPM : engine rpm
C     ET : engine type
C     BRDBD(I,1) : 1/3 octave broad band-noise sound pressure level
C     BRDBD(I,2) : standard 1/3 octave band non-dimensional center frequency
C     TONES(I,1) : engine tone sound pressure level
C     TONES(I,2) : non-dimensional engine tone frequency
C     BRDBDA(I,1) : 1/3 octave broad-band noise A-weighted sound pressure level
C     BRDBDA(I,2) : standard 1/3 octave band non-dimensional center frequency
C     TONESA(I,1) : engine tone A-weighted sound pressure level
C     TONESA(I,2) : non-dimensional engine tone frequency
C     PRS : un-weighted sound pressure of each tone
C     PRSA : A-weighted sound pressure of each tone
C     LOWER(I) : standard 1/3 octave band lower frequency
C     CENTER(I) : standard 1/3 octave band center frequency
C     UPPER(I) · standard 1/3 octave band upper frequency
C     TONE(I,ET) : engine tone sound pressure level of each maximum engine
C                  RPM up to 1500 Hz
C     BRPM(ET) : maximum engine RPM of each engyne type
C     HH(I,ET) : coefficients of Engine RPM and Power function, HP(RPM,ET)
C     PP(I,J,ET) : coefficients of broad-band noise SPL function, P(X,RPM,ET)
C     AA(I) : coefficients of A-weigted SPL function, AP(X)

      INTEGER ET
      REAL LOWER
      DIMENSION LOWER(28),CENTER(28),UPPER(28)
      DIMENSION TONE(70,6)
      DIMENSION BRDBD(28,2),TONES(60,2)
      DIMENSION BRDBDA(28,2),TONESA(60,2)
      DIMENSION BRPM(6)

C     Open the file, DATAENG, into which the result data is placed
      OPEN(1,FILE='DATAENG',STATUS='OLD')

      WRITE(6,*)'WHICH ENGINE TYPE DO YOU HAVE?'
C     ET=1 : Lycoming O-320 D1D
C     ET=2 : Lycoming O-360 A-series
C     ET=3 : Lycmoing O-320 D1D with Cessna 172 Standard Muffler
C     ET=4 :
C     ET=5 :
C     ET=6 :
```

```
C     Pick up the engine type and engine RPM, and compute engine horsepower
      READ(5,*)ET
      WRITE(6,*)'ENGINE RPM?'
      READ(5,*)RPM
      WRITE(1,*)'ENGINE TYPE : ',ET
      WRITE(1,*)' ENGINE RPM=',RPM,' RPM'
      WRITE(1,610)HP(RPM,ET)
 610  FORMAT('ENGINE POWER=',F7.1,' HP')

      CALL ENGYN(X,RPM,ET,BRDBD,TONES,PRS)
      CALL ENGYNA(X,RPM,ET,BRDBDA,TONESA,PRSA)

C     Compute over all sound pressure for un- and A-weighted
      OAMSP=PRS
      OAMSPA=PRSA
      DO 11 I=2,61
       OAMSP=OAMSP+TONES(I,1)
       OAMSPA=OAMSPA+TONESA(I,1)
11    CONTINUE

C     Compute over all sound pressure level for un- and A-weighted
      OASPL=10*LOG10(OAMSP)
      OASPLA=10*LOG10(OAMSPA)
      WRITE(1,611)OAMSP
 611  FORMAT(/,'OVER ALL MEAN SQUARE PRESSURE=',E15.6)
      WRITE(1,612)OASPL
 612  FORMAT('OVER ALL SOUND PRESSURE LEVEL=',F6.1,' dB')
      WRITE(1,613)OAMSPA
 613  FORMAT('A-WGT OVER ALL MEAN SQUARE PRESSURE=',E15.6)
      WRITE(1,614)OASPLA
 614  FORMAT('A-WGT OVER ALL SOUND PRESSURE LEVEL=',F6.1,' dBA')

      CLOSE(1,STATUS='KEEP')

      STOP
      END

*****************************************************************************
      SUBROUTINE ENGYN(X,RPM,ET,BRDBD,TONES,PRS)
C     Lower, center, upper frequencies of standard 1/3 octave bands
C     Un-weighted broad-band noise sound pressure
C     and engine tone sound pressure levels of maxmum engine RPM input arrays
C     Un-weighted 1/3 octave broad-band noise and discrete tones output arrays

C     X · frequency
C     RPM : engine rpm
C     ET · engine type
C     BRDBD(I,1) : 1/3 octave broad band-noise sound pressure level
C     BRDBD(I,2) : standard 1/3 octave band non-dimensional center frequency
C     TONES(I,1) : engine tone sound pressure level
C     TONES(I,2) : non-dimensional engine tone frequency
C     PRS . un-weighted sound pressure of each tone
C     LOWER : standard 1/3 octave band lower frequency
C     CENTER : standard 1/3 octave band center frequency
C     UPPER : standard 1/3 octave band upper frequency
C     TONE : engine tone sound pressure level for 2740rpm up to 1500 Hz
C     BRPM : maximum engine RPM of each engine type

      INTEGER ET
      REAL LOWER
      DIMENSION BRDBD(28,2),TONES(61,2)
      DIMENSION LOWER(28),CENTER(28),UPPER(28)
```

```
      DIMENSION TONE(70,6)
      DIMENSION BRPM(6)

C     1/3 octave band lower, center and upper frequencies
      DATA (LOWER(I),I=1,28)/18.0,22.4,28.0,35.5,45.0,56.0,71.0,90.0,
     +  112.0,140.0,180.0,224.0,280.0,355.0,450.0,560.0,710.0,900.0,
     +  1120.0,1400.0,1800.0,2240.0,2800.0,3550.0,4500.0,5600.0,
     +  7100.0,9000.0/,
     +  (CENTER(I),I=1,28)/20.0,25.0,31.5,40.0,50.0,63.0,80.0,100.0,
     +  125.0,160.0,200.0,250.0,315.0,400.0,500.0,630.0,800.0,1000.0,
     +  1250.0,1600.0,2000.0,2500.0,3150.0,4000.0,5000.0,6300.0,8000.0,
     +  10000.0/,
     +  (UPPER(I),I=1,28)/22.4,28.0,35.5,45.0,56.0,71.0,90.0,112.0,
     +  140.0,180.0,224.0,280.0,355.0,450.0,560.0,710.0,900.0,1120.0,
     +  1400.0,1800.0,2240.0,2800.0,3550.0,4500.0,5600.0,7100.0,9000.0,
     +  11200.0/

C     Tone sound pressure levels[dB]
      DATA ((TONE(I,J),I=2,61),J=1,6)/96.2,80.1,86.8,81.6,99.8,76.9,
     +  87.0,72.0,93.1,80.2,93.8,82.0,93.7,74.6,81.0,66.1,80.8,77.8,
     +  86.9,78.3,93.4,81.4,82.0,63.5,73.0,69.7,71.7,74.5,85.0,76.8,
     +  80.1,71.0,71.2,67.6,71.8,70.3,70.7,72.2,72.7,72.7,75.0,78.2,
     +  68.0,65.6,71.3,70.1,82.0,72.1,74.5,70.2,75.7,64.0,66.0,64.2,
     +  70.0,66.0,68.2,68.5,74.0,65.2,
     +  99.8,83.7,90.4,85.2,103.4,80.5,90.6,75.6,96.7,83.8,97.4,85.6,
     +  97.3,78.2,84.6,69.7,84.4,81.4,90.5,81.9,97.0,85.0,85.6,67.1,
     +  76.6,73.3,75.3,78.1,88.6,80.4,83.7,74.6,74.8,71.2,75.4,73.9,
     +  74.3,75.8,76.3,76.3,78.6,81.8,71.6,69.2,74.9,73.7,85.6,75.7,
     +  78.1,73.8,79.3,67.6,69.6,67.8,73.6,69.6,71.8,72.1,77.6,68.8,
     +  102.7,88.0,76.0,79.7,94.5,85.2,76.0,67.0,85.5,77.5,77.5,77.5,
     +  83.5,69.6,75.0,72.3,69.1,70.0,70.5,66.8,71.5,72.5,67.0,67.2,
     +  75.7,75.1,71.0,72.0,77.5,79.0,78.8,76.3,71.5,72.3,71.5,74.1,
     +  65.5,70.0,66.2,71.0,82.1,71.0,69.0,75.6,78.5,68.0,70.0,73.1,
     +  73.3,71.1,65.2,69.0,65.5,66.5,64.0,65.8,62.4,60.0,61.7,60.0,
     +  180*0.0/

C     Baseline RPM for each engine type
      DATA BRPM/2740.0,2700.0,2750.0,3*0.0/

      WRITE(1,*)'ONE-THIRD OCTAVE BAND BROAD BAND NOISE'
      WRITE(1,*)'  LOWER  CENTER   UPPER    SPL   BRDBD(I,1)  BRDRD(I,2)'

C     Compute 1/3 octave spectrum of broad-band noise by integrating
C     broad-band noise spectrum model over each of the 1/3 octave bands
C     and non-dimensional center frequency for output array
      PRS=0.0
      DO 21 I=1,28
       BRDBD(I,2)=CENTER(I)/(RPM/60.0)
       D=AINT(CENTER(I)/5.0)
       H=(UPPER(I)-LOWER(I))/D
       BRDBD(I,1)=(P(LOWER(I),RPM,ET,BRPM)
     +   +P(UPPER(I),RPM,ET,BRPM))*H/2.0
       X=LOWER(I)

       DO 22 J=1.0,D-1.0
        X=X+H
        BRDBD(I,1)=BRDBD(I,1)+H*P(X,RPM,ET,BRPM)
 22    CONTINUE

       PRS=PRS+BRDBD(I,1)
       SPL=10*LOG10(BRDBD(I,1))
       WRITE(1,621)LOWER(I),CENTER(I),UPPER(I),SPL,BRDBD(I,1),BRDBD(I,2)
 621   FORMAT(3F8.1,F6.1,E15.6,F6.1,' RPM')
```

```
 21   CONTINUE

C     Compute over all broad-band sound pressure level
      OA=10*LOG10(PRS)
      WRITE(1,622)PRS
 622  FORMAT('BROADBAND NOISE MEAN SQUARE PRESSURE=',E15.6)
      WRITE(1,623)OA
 623  FORMAT('         BROADBAND NOISE OASPL=',F6.1,' dB',//)

      WRITE(1,*)'ENGINE TONES NOISE'
      WRITE(1,*)'  TONES(I,1)   TONES(I,2)  SPL'

C     Compute tone sound pressure level and non-dimensional frequency for
C     output array
      F=RPM/120.0
      FRQ=3.0*F
      DO 23 I=2,61
       FRQ=FRQ+F
       TONES(I,2)=FRQ/(RPM/60.0)
       TNSPL=TONE(I,ET)+40.0*LOG10(RPM/BRPM(ET))
       TONES(I,1)=10**(TNSPL/10.0)
       WRITE(1,624)TONES(I,1),TONES(I,2),TNSPL
 624   FORMAT(E15.6,F6.1,' RPM',1X,F6.1)
 23   CONTINUE

      RETURN
      END

****************************************************************************
      SUBROUTINE ENGYNA(X,RPM,ET,BRDBDA,TONESA,PRSA)
C     Lower, center, upper frequencies of standard 1/3 octave bands
C     A-weighted broad-band noise sound pressure
C     and engine tone sound pressure levels of maxmum engine RPM input arrays
C     A-weighted 1/3 octave broad-band noise and discrete tones output arrays

C     X : frequency
C     RPM : engine rpm
C     ET : engine type
C     BRDBDA(I,1) · 1/3 octave broad-band noise A-weighted sound pressure level
C     BRDBDA(I,2) : standard 1/3 octave band non-dimensional center frequency
C     TONESA(I,1) : engine tone A-weighted sound pressure level
C     TONESA(I,2) . non-dimensional engine tone frequency
C     PRSA : A-weighted sound pressure of each tone
C     LOWER . standard 1/3 octave band lower frequency
C     CENTER : standard 1/3 octave band center frequency
C     UPPER . standard 1/3 octave band upper frequency
C     TONE : engine tone sound pressure level for 2740rpm up to 1500 Hz
C     BRPM : maximum engine RPM of each engine type

      INTEGER ET
      REAL LOWER
      DIMENSION BRDBDA(28,2),TONESA(61,2)
      DIMENSION LOWER(28),CENTER(28),UPPER(28)
      DIMENSION TONE(70,6)
      DIMENSION BRPM(6)

C     1/3 octave band lower, center ,and upper frequencies
      DATA (LOWER(I),I=1,28)/18.0,22.4,28.0,35.5,45.0,56.0,71.0,90.0,
     +  112.0,140.0,180.0,224.0,280.0,355.0,450.0,560.0,710.0,900.0,
     +  1120.0,1400.0,1800.0,2240.0,2800.0,3550.0,4500.0,5600.0,
     +  7100.0,9000.0/,
     +  (CENTER(I),I=1,28)/20.0,25.0,31.5,40.0,50.0,63.0,80.0,100.0,
     +  125.0,160.0,200.0,250.0,315.0,400.0,500.0,630.0,800.0,1000.0,
```

```
     +  1250.0,1600.0,2000.0,2500.0,3150.0,4000.0,5000.0,6300.0,8000.0,
     +  10000.0/,
     +  (UPPER(I),I=1,28)/22.4,28.0,35.5,45.0,56.0,71.0,90.0,112.0,
     +  140.0,180.0,224.0,280.0,355.0,450.0,560.0,710.0,900.0,1120.0,
     +  1400.0,1800.0,2240.0,2800.0,3550.0,4500.0,5600.0,7100.0,9000.0,
     +  11200.0/

C     Tone sound pressure levels[dB]
      DATA ((TONE(I,J),I=2,61),J=1,6)/96.2,80.1,86.8,81.6,99.8,76.9,
     +  87.0,72.0,93.1,80.2,93.8,82.0,93.7,74.6,81.0,66.1,80.8,77.8,
     +  86.9,78.3,93.4,81.4,82.0,63.5,73.0,69.7,71.7,74.5,85.0,76.8,
     +  80.1,71.0,71.2,67.6,71.8,70.3,70.7,72.2,72.7,72.7,75.0,78.2,
     +  68.0,65.6,71.3,70.1,82.0,72.1,74.5,70.2,75.7,64.0,66.0,64.2,
     +  70.0,66.0,68.2,68.5,74.0,65.2,
     +  99.8,83.7,90.4,85.2,103.4,80.5,90.6,75.6,96.7,83.8,97.4,85.6,
     +  97.3,78.2,84.6,69.7,84.4,81.4,90.5,81.9,97.0,85.0,85.6,67.1,
     +  76.6,73.3,75.3,78.1,88.6,80.4,83.7,74.6,74.8,71.2,75.4,73.9,
     +  74.3,75.8,76.3,76.3,78.6,81.8,71.6,69.2,74.9,73.7,85.6,75.7,
     +  78.1,73.8,79.3,67.6,69.6,67.8,73.6,69.6,71.8,72.1,77.6,68.8,
     +  101.2,87.0,75.0,78.7,93.0,84.2,75.0,66.0,84.0,76.5,76.5,76.5,
     +  82.0,68.6,74.0,71.3,67.6,69.0,69.5,65.8,69.5,71.5,66.0,66.2,
     +  74.2,74.1,70.0,71.0,76.0,78.0,77.8,75.3,70.0,71.3,70.5,73.1,
     +  64.0,69.0,65.2,70.0,80.6,70.0,68.0,74.6,77.0,67.0,69.0,72.1,
     +  71.8,70.1,64.2,68.0,64.0,65.5,63.0,64.8,60.9,59.0,60.7,59.0,
     +  180*0.0/

C     Baseline RPM for each engine type
      DATA BRPM/2740.0,2700.0,2750.0,3*0.0/

      WRITE(1,630)
 630  FORMAT(//,'A-WEIGHTED ONE-THIRD OCTAVE BAND BROAD BAND NOISE')
      WRITE(1,*)' CENTER  SPLA   BRDBDA(I,1)  BRDBDA(I,2)'

C     Compute 1/3 octave spectrum of broad-band noise by integrating
C     broad-band noise spectrum model and A-weighted spectrum model
C     over each of the 1/3 octave bands and non-dimensional center
C     frequency for output array
      PRSA=0.0
      DO 31 I=1,28
       BRDBDA(I,2)=CENTER(I)/(RPM/60.0)
       D=AINT(CENTER(I)/5.0)
       H=(UPPER(I)-LOWER(I))/D
       BRDBDA(I,1)=(P(LOWER(I),RPM,ET,BRPM)*AP(LOWER(I))
     +   +P(UPPER(I),RPM,ET,BRPM)*AP(UPPER(I)))*H/2.0
       X=LOWER(I)

       DO 32 J=1.0,D-1.0
        X=X+H
        BRDBDA(I,1)=BRDBDA(I,1)+H*P(X,RPM,ET,BRPM)*AP(X)
 32    CONTINUE

       PRSA=PRSA+BRDBDA(I,1)
       SPLA=10*LOG10(BRDBDA(I,1))
       WRITE(1,631)CENTER(I),SPLA,BRDBDA(I,1),BRDBDA(I,2)
 631   FORMAT(F8.1,F6.1,E15.6,F6.1,' RPM')
 31   CONTINUE

C     Compute over all broad-band sound pressure level
      OAA=10*LOG10(PRSA)
      WRITE(1,632)PRSA
 632  FORMAT('A-WGT BROADBAND NOISE MEAN SQUARE PRESSURE=',E15.6)
      WRITE(1,633)OAA
 633  FORMAT('        A-WGT BROADBAND NOISE OASPL=',F6.1,' dBA',//)
```

```
      WRITE(1,*)'ENGINE TONES NOISE'
      WRITE(1,*)'  TONESA(I,1)  TONESA(I,2) SPLA'

C     Compute tone A-weighted sound pressure level and non-dimensional
C     frequency for output array
      F=RPM/120.0
      FRQ=3.0*F
       DO 33 I=2,61
       FRQ=FRQ+F
       TONESA(I,2)=FRQ/(RPM/60.0)
       TNSPLA=TONE(I,ET)+40.0*LOG10(RPM/BRPM(ET))+10*LOG10(AP(FRQ))
       TONESA(I,1)=10**(TNSPLA/10.0)
       WRITE(1,634)TONESA(I,1),TONESA(I,2),TNSPLA
 634   FORMAT(E15.6,F6.1,' RPM',1X,F6.1)
 33   CONTINUE

      RETURN
      END

*****************************************************************************
      FUNCTION HP(RPM,ET)
C     Computes engine horse power from engine rpm
C     Coefficients are given by data statements

C     HH(I,ET) : coefficients of Engine RPM and Power function, HP(RPM,ET)
      INTEGER ET
      REAL HH(2,6)
      DATA HH/0.04625,35.125,
     +  0.04,72.0,
     +  0.04625,35.125,
     +  6*0.0/

      HP=HH(1,ET)*RPM+HH(2,ET)
      RETURN
      END

*****************************************************************************
      FUNCTION P(X,RPM,ET,BRPM)
C     Computes un-weighted broad-band noise sound pressure
C     Coefficients are given by data statements

C     PP(I,J,ET) : coefficients of broad-band noise SPL function,
C                  P(X,RPM,ET,BRPM(ET))

      INTEGER ET
      REAL PP(4,3,6),BRPM(6)

      DATA PP/0.0,1500.0,4000.0,9000.0,
     +  0.0,-1.178,-0.3891,-1.92,-22.09,-21.44,-22.60,-17.58,
     +  0.0,1500.0,4000.0,9000.0,
     +  0.0,-1.161,-0.3834,-1.89,-21.33,-20.68,-21.83,-16.82,
     +  0.0,1500.0,4000.0,9000.0,
     +  0.0,-1.178,-0.3891,-1.92,-22.09,-21.44,-22.60,-17.58,
     +  36*0.0/

      IF(X.GE.RPM*PP(1,1,ET)/BRPM(ET))
     +  P=10**(PP(1,2,ET)*X/RPM+PP(1,3,ET))*RPM**8
      IF(X.GE.RPM*PP(2,1,ET)/BRPM(ET))
     +  P=10**(PP(2,2,ET)*X/RPM+PP(2,3,ET))*RPM**8
      IF(X.GE.RPM*PP(3,1,ET)/BRPM(ET))
     +  P=10**(PP(3,2,ET)*X/RPM+PP(3,3,ET))*RPM**8
      IF(X.GE.RPM*PP(4,1,ET)/BRPM(ET))
```

```
     +  P=10**(PP(4,2,ET)*X/RPM+PP(4,3,ET))*RPM**8
      RETURN
      END

********************************************************************************

      FUNCTION AP(X)
C     Computes A-weighted sound pressure level using 10th degree
C     polynomial function
C     Coefficients are given by data statements

C     AA(I) : coefficients of A-weigted SPL function, AP(X)
      REAL AA(12)

C     Coefficients
      DATA AA/0.0,-.03804604824,1.039846563,-12.54816693,87.8805487,
     +  -394.8209468,1186.705893,-2412.103352,3268.347409,
     +  -2823.362609,1410.684049,-318.8247035/

      Z=AA(1)
      DO 10 I=2,12
       Z=Z*LOG10(X)+AA(I)
       AP=10**Z
 10   CONTINUE
      RETURN
      END

********************************************************************************
```

Appendix B-1 Data Sheet 1 (Lycoming O-320 D1D, 2740 rpm)

ENGINE TYPE : 1
ENGINE ROTATIONAL SPEED, N = 2740. rpm
ENGINE POWER, P= 161.9 HP

ONE-THIRD OCTAVE BAND BROAD BAND NOISE

LOWER	CENTER	UPPER	SPL	BRDBD(I,1)	BRDRD(I,2)
18.0	20.0	22.4	60.6	0.113621E+07	0.4 rps
22.4	25.0	28.0	61.6	0.144608E+07	0.5 rps
28.0	31.5	35.5	62.9	0.193671E+07	0.7 rps
35.5	40.0	45.0	63.9	0.245317E+07	0.9 rps
45.0	50.0	56.0	64.5	0.284051E+07	1.1 rps
56.0	63.0	71.0	65.9	0.387343E+07	1.4 rps
71.0	80.0	90.0	66.9	0.490634E+07	1.8 rps
90.0	100.0	112.0	67.5	0.568103E+07	2.2 rps
112.0	125.0	140.0	68.6	0.723040E+07	2.7 rps
140.0	160.0	180.0	70.1	0.103291E+08	3.5 rps
180.0	200.0	224.0	70.6	0.113621E+08	4.4 rps
224.0	250.0	280.0	71.6	0.144608E+08	5.5 rps
280.0	315.0	355.0	72.9	0.193672E+08	6.9 rps
355.0	400.0	450.0	73.9	0.245317E+08	8.8 rps
450.0	500.0	560.0	74.5	0.284052E+08	10.9 rps
560.0	630.0	710.0	75.9	0.387344E+08	13.8 rps
710.0	800.0	900.0	76.9	0.490635E+08	17.5 rps
900.0	1000.0	1120.0	77.5	0.568104E+08	21.9 rps
1120.0	1250.0	1400.0	78.6	0.723040E+08	27.4 rps
1400.0	1600.0	1800.0	79.7	0.936421E+08	35.0 rps
1800.0	2000.0	2240.0	78.4	0.692520E+08	43.8 rps
2240.0	2500.0	2800.0	77.3	0.539898E+08	54.7 rps
2800.0	3150.0	3550.0	75.8	0.381929E+08	69.0 rps
3550.0	4000.0	4500.0	73.5	0.224210E+08	87.6 rps
4500.0	5000.0	5600.0	72.3	0.169275E+08	109.5 rps
5600.0	6300.0	7100.0	71.8	0.151599E+08	138.0 rps
7100.0	8000.0	9000.0	70.4	0.110805E+08	175.2 rps
9000.0	10000.0	11200.0	64.0	0.248397E+07	219.0 rps

BROADBAND NOISE MEAN SQUARE PRESSURE= 0.680022E+09
BROADBAND NOISE OASPL= 88.3 dB

ENGINE TONES NOISE

TONES(I,1)	TONES(I,2)	SPL
0.416869E+10	2.0 rps	96.2
0.102329E+09	2.5 rps	80.1
0.478630E+09	3.0 rps	86.8
0.144544E+09	3.5 rps	81.6
0.954994E+10	4.0 rps	99.8
0.489779E+08	4.5 rps	76.9
0.501187E+09	5.0 rps	87.0
0.158489E+08	5.5 rps	72.0
0.204174E+10	6.0 rps	93.1
0.104713E+09	6.5 rps	80.2
0.239883E+10	7.0 rps	93.8
0.158489E+09	7.5 rps	82.0

0.234423E+10	8.0	rps	93.7
0.288403E+08	8.5	rps	74.6
0.125893E+09	9.0	rps	81.0
0.407380E+07	9.5	rps	66.1
0.120226E+09	10.0	rps	80.8
0.602560E+08	10.5	rps	77.8
0.489779E+09	11.0	rps	86.9
0.676084E+08	11.5	rps	78.3
0.218776E+10	12.0	rps	93.4
0.138039E+09	12.5	rps	81.4
0.158489E+09	13.0	rps	82.0
0.223872E+07	13.5	rps	63.5
0.199526E+08	14.0	rps	73.0
0.933254E+07	14.5	rps	69.7
0.147911E+08	15.0	rps	71.7
0.281838E+08	15.5	rps	74.5
0.316228E+09	16.0	rps	85.0
0.478630E+08	16.5	rps	76.8
0.102329E+09	17.0	rps	80.1
0.125893E+08	17.5	rps	71.0
0.131826E+08	18.0	rps	71.2
0.575440E+07	18.5	rps	67.6
0.151356E+08	19.0	rps	71.8
0.107152E+08	19.5	rps	70.3
0.117490E+08	20.0	rps	70.7
0.165959E+08	20.5	rps	72.2
0.186208E+08	21.0	rps	72.7
0.186208E+08	21.5	rps	72.7
0.316228E+08	22.0	rps	75.0
0.660693E+08	22.5	rps	78.2
0.630958E+07	23.0	rps	68.0
0.363078E+07	23.5	rps	65.6
0.134896E+08	24.0	rps	71.3
0.102329E+08	24.5	rps	70.1
0.158489E+09	25.0	rps	82.0
0.162181E+08	25.5	rps	72.1
0.281838E+08	26.0	rps	74.5
0.104713E+08	26.5	rps	70.2
0.371535E+08	27.0	rps	75.7
0.251189E+07	27.5	rps	64.0
0.398107E+07	28.0	rps	66.0
0.263027E+07	28.5	rps	64.2
0.100000E+08	29.0	rps	70.0
0.398107E+07	29.5	rps	66.0
0.660693E+07	30.0	rps	68.2
0.707946E+07	30.5	rps	68.5
0.251189E+08	31.0	rps	74.0
0.331131E+07	31.5	rps	65.2

A-WEIGHTED ONE-THIRD OCTAVE BAND BROAD BAND NOISE

CENTER	SPLA	BRDBDA(I,1)	BRDBDA(I,2)
20.0	10.5	0.113325E+02	0.4 rps
25.0	16.9	0.491252E+02	0.5 rps
31.5	23.5	0.223854E+03	0.7 rps
40.0	29.6	0.909706E+03	0.9 rps
50.0	34.6	0.290497E+04	1.1 rps

63.0	40.0	0.100512E+05	1.4 rps
80.0	44.8	0.301171E+05	1.8 rps
100.0	48.6	0.728947E+05	2.2 rps
125.0	52.5	0.178449E+06	2.7 rps
160.0	56.9	0.486233E+06	3.5 rps
200.0	59.8	0.949052E+06	4.4 rps
250.0	63.0	0.199224E+07	5.5 rps
315.0	66.3	0.427903E+07	6.9 rps
400.0	69.2	0.833279E+07	8.8 rps
500.0	71.4	0.136932E+08	10.9 rps
630.0	74.0	0.252275E+08	13.8 rps
800.0	76.1	0.407634E+08	17.5 rps
1000.0	77.5	0.562614E+08	21.9 rps
1250.0	79.1	0.815412E+08	27.4 rps
1600.0	80.6	0.114816E+09	35.0 rps
2000.0	79.5	0.891178E+08	43.8 rps
2500.0	78.4	0.699540E+08	54.7 rps
3150.0	76.8	0.481809E+08	69.0 rps
4000.0	74.2	0.265294E+08	87.6 rps
5000.0	72.5	0.178438E+08	109.5 rps
6300.0	71.3	0.136056E+08	138.0 rps
8000.0	68.9	0.782281E+07	175.2 rps
10000.0	61.3	0.136252E+07	219.0 rps

A-WGT BROADBAND NOISE MEAN SQUARE PRESSURE= 0.623055E+09

A-WGT BROADBAND NOISE OASPL= 87.9 dBA

ENGINE TONES NOISE

TONESA(I,1)	TONESA(I,2)	SPLA
0.384670E+08	2.0 rps	75.9
0.187671E+07	2.5 rps	62.7
0.148376E+08	3.0 rps	71.7
0.672597E+07	3.5 rps	68.3
0.623783E+09	4.0 rps	88.0
0.422317E+07	4.5 rps	66.3
0.557995E+08	5.0 rps	77.5
0.216170E+07	5.5 rps	63.3
0.335080E+09	6.0 rps	85.3
0.202506E+08	6.5 rps	73.1
0.544028E+09	7.0 rps	87.4
0.402574E+08	7.5 rps	76.0
0.666775E+09	8.0 rps	88.2
0.913422E+07	8.5 rps	69.6
0.445323E+08	9.0 rps	76.5
0.156342E+07	9.5 rps	61.9
0.503937E+08	10.0 rps	77.0
0.271715E+08	10.5 rps	74.3
0.232141E+09	11.0 rps	83.7
0.347072E+08	11.5 rps	75.4
0.119600E+10	12.0 rps	90.8
0.801862E+08	12.5 rps	79.0
0.934937E+08	13.0 rps	79.7
0.141190E+07	13.5 rps	61.5
0.131995E+08	14.0 rps	71.2
0.636370E+07	14.5 rps	68.0
0.105854E+08	15.0 rps	70.2
0.208634E+08	15.5 rps	73.2

0.234223E+09	16.0	rps	83.7
0.376568E+08	16.5	rps	75.8
0.817688E+08	17.0	rps	79.1
0.103291E+08	17.5	rps	70.1
0.112287E+08	18.0	rps	70.5
0.496283E+07	18.5	rps	67.0
0.136014E+08	19.0	rps	71.3
0.980658E+07	19.5	rps	69.9
0.110437E+08	20.0	rps	70.4
0.156468E+08	20.5	rps	71.9
0.179389E+08	21.0	rps	72.5
0.180374E+08	21.5	rps	72.6
0.313925E+08	22.0	rps	75.0
0.660507E+08	22.5	rps	78.2
0.660259E+07	23.0	rps	68.2
0.381330E+07	23.5	rps	65.8
0.138956E+08	24.0	rps	71.4
0.106391E+08	24.5	rps	70.3
0.169872E+09	25.0	rps	82.3
0.182144E+08	25.5	rps	72.6
0.316752E+08	26.0	rps	75.0
0.119838E+08	26.5	rps	70.8
0.430945E+08	27.0	rps	76.3
0.286906E+07	27.5	rps	64.6
0.449315E+07	28.0	rps	66.5
0.288469E+07	28.5	rps	64.6
0.112807E+08	29.0	rps	70.5
0.465186E+07	29.5	rps	66.7
0.760868E+07	30.0	rps	68.8
0.812826E+07	30.5	rps	69.1
0.307727E+08	31.0	rps	74.9
0.386137E+07	31.5	rps	65.9

OVER ALL MEAN SQUARE PRESSURE= 0.272301E+11
OVER ALL SOUND PRESSURE LEVEL= 104.4 dB
A-WGT OVER ALL MEAN SQUARE PRESSURE= 0.574910E+10
A-WGT OVER ALL SOUND PRESSURE LEVEL= 97.6 dBA

Appendix B-2 Data Sheet 2 (Lycoming O-320 D1D, 2450 rpm)

ENGINE TYPE : 1
ENGINE ROTATIONAL SPEED, N = 2450. rpm
ENGINE POWER, P= 148.4 HP
ONE-THIRD OCTAVE BAND BROAD BAND NOISE

LOWER	CENTER	UPPER	SPL	BRDBD(I,1)	BRDRD(I,2)
18.0	20.0	22.4	56.7	0.464281E+06	0.5 rps
22.4	25.0	28.0	57.7	0.590904E+06	0.6 rps
28.0	31.5	35.5	59.0	0.791389E+06	0.8 rps
35.5	40.0	45.0	60.0	0.100243E+07	1.0 rps
45.0	50.0	56.0	60.6	0.116070E+07	1.2 rps
56.0	63.0	71.0	62.0	0.158278E+07	1.5 rps
71.0	80.0	90.0	63.0	0.200485E+07	2.0 rps
90.0	100.0	112.0	63.7	0.232141E+07	2.4 rps
112.0	125.0	140.0	64.7	0.295452E+07	3.1 rps
140.0	160.0	180.0	66.3	0.422074E+07	3.9 rps
180.0	200.0	224.0	66.7	0.464281E+07	4.9 rps
224.0	250.0	280.0	67.7	0.590903E+07	6.1 rps
280.0	315.0	355.0	69.0	0.791388E+07	7.7 rps
355.0	400.0	450.0	70.0	0.100242E+08	9.8 rps
450.0	500.0	560.0	70.6	0.116070E+08	12.2 rps
560.0	630.0	710.0	72.0	0.158278E+08	15.4 rps
710.0	800.0	900.0	73.0	0.200485E+08	19.6 rps
900.0	1000.0	1120.0	73.7	0.232140E+08	24.5 rps
1120.0	1250.0	1400.0	74.7	0.294189E+08	30.6 rps
1400.0	1600.0	1800.0	75.1	0.323314E+08	39.2 rps
1800.0	2000.0	2240.0	73.5	0.223778E+08	49.0 rps
2240.0	2500.0	2800.0	72.2	0.164733E+08	61.2 rps
2800.0	3150.0	3550.0	70.3	0.108195E+08	77.1 rps
3550.0	4000.0	4500.0	68.5	0.715190E+07	98.0 rps
4500.0	5000.0	5600.0	67.6	0.569660E+07	122.4 rps
5600.0	6300.0	7100.0	66.9	0.485704E+07	154.3 rps
7100.0	8000.0	9000.0	64.3	0.271301E+07	195.9 rps
9000.0	10000.0	11200.0	52.2	0.164355E+06	244.9 rps

BROADBAND NOISE MEAN SQUARE PRESSURE= 0.248285E+09
BROADBAND NOISE OASPL= 83.9 dB

ENGINE TONES NOISE

TONES(I,1)	TONES(I,2)	SPL
0.266478E+10	2.0 rps	94.3
0.654126E+08	2.5 rps	78.2
0.305958E+09	3.0 rps	84.9
0.923978E+08	3.5 rps	79.7
0.610466E+10	4.0 rps	97.9
0.313085E+08	4.5 rps	75.0
0.320377E+09	5.0 rps	85.1
0.101312E+08	5.5 rps	70.1
0.130515E+10	6.0 rps	91.2
0.669363E+08	6.5 rps	78.3
0.153342E+10	7.0 rps	91.9
0.101312E+09	7.5 rps	80.1

0.149851E+10	8.0	rps	91.8
0.184358E+08	8.5	rps	72.7
0.804751E+08	9.0	rps	79.1
0.260412E+07	9.5	rps	64.2
0.768532E+08	10.0	rps	78.9
0.385178E+08	10.5	rps	75.9
0.313085E+09	11.0	rps	85.0
0.432177E+08	11.5	rps	76.4
0.139850E+10	12.0	rps	91.5
0.882393E+08	12.5	rps	79.5
0.101312E+09	13.0	rps	80.1
0.143107E+07	13.5	rps	61.6
0.127545E+08	14.0	rps	71.1
0.596570E+07	14.5	rps	67.8
0.945499E+07	15.0	rps	69.8
0.180161E+08	15.5	rps	72.6
0.202145E+09	16.0	rps	83.1
0.305958E+08	16.5	rps	74.9
0.654126E+08	17.0	rps	78.2
0.804751E+07	17.5	rps	69.1
0.842678E+07	18.0	rps	69.3
0.367842E+07	18.5	rps	65.7
0.967524E+07	19.0	rps	69.9
0.684955E+07	19.5	rps	68.4
0.751037E+07	20.0	rps	68.8
0.106087E+08	20.5	rps	70.3
0.119031E+08	21.0	rps	70.8
0.119031E+08	21.5	rps	70.8
0.202144E+08	22.0	rps	73.1
0.422339E+08	22.5	rps	76.3
0.403331E+07	23.0	rps	66.1
0.232093E+07	23.5	rps	63.7
0.862308E+07	24.0	rps	69.4
0.654126E+07	24.5	rps	68.2
0.101312E+09	25.0	rps	80.1
0.103672E+08	25.5	rps	70.2
0.180161E+08	26.0	rps	72.6
0.669363E+07	26.5	rps	68.3
0.237499E+08	27.0	rps	73.8
0.160569E+07	27.5	rps	62.1
0.254485E+07	28.0	rps	64.1
0.168136E+07	28.5	rps	62.3
0.639237E+07	29.0	rps	68.1
0.254485E+07	29.5	rps	64.1
0.422339E+07	30.0	rps	66.3
0.452545E+07	30.5	rps	66.6
0.160569E+08	31.0	rps	72.1
0.211671E+07	31.5	rps	63.3

A-WEIGHTED ONE-THIRD OCTAVE BAND BROAD BAND NOISE

CENTER	SPLA	BRDBDA(I,1)	BRDBDA(I,2)
20.0	6.7	0.463075E+01	0.5 rps
25.0	13.0	0.200737E+02	0.6 rps
31.5	19.6	0.914721E+02	0.8 rps
40.0	25.7	0.371728E+03	1.0 rps
50.0	30.7	0.118704E+04	1.2 rps

63.0	36.1	0.410717E+04	1.5 rps
80.0	40.9	0.123066E+05	2.0 rps
100.0	44.7	0.297866E+05	2.4 rps
125.0	48.6	0.729185E+05	3.1 rps
160.0	53.0	0.198687E+06	3.9 rps
200.0	55.9	0.387806E+06	4.9 rps
250.0	59.1	0.814076E+06	6.1 rps
315.0	62.4	0.174852E+07	7.7 rps
400.0	65.3	0.340498E+07	9.8 rps
500.0	67.5	0.559539E+07	12.2 rps
630.0	70.1	0.103086E+08	15.4 rps
800.0	72.2	0.166569E+08	19.6 rps
1000.0	73.6	0.229898E+08	24.5 rps
1250.0	75.2	0.331700E+08	30.6 rps
1600.0	76.0	0.396122E+08	39.2 rps
2000.0	74.6	0.287935E+08	49.0 rps
2500.0	73.3	0.213441E+08	61.2 rps
3150.0	71.4	0.136536E+08	77.1 rps
4000.0	69.3	0.844239E+07	98.0 rps
5000.0	67.8	0.600789E+07	122.4 rps
6300.0	66.4	0.436325E+07	154.3 rps
8000.0	62.9	0.196265E+07	195.9 rps
10000.0	49.6	0.907705E+05	244.9 rps

A-WGT BROADBAND NOISE MEAN SQUARE PRESSURE= 0.219666E+09

A-WGT BROADBAND NOISE OASPL= 83.4 dBA

ENGINE TONES NOISE

TONESA(I,1)	TONESA(I,2)	SPLA
0.169424E+08	2.0 rps	72.3
0.859453E+06	2.5 rps	59.3
0.690910E+07	3.0 rps	68.4
0.321488E+07	3.5 rps	65.1
0.301569E+09	4.0 rps	84.8
0.206319E+07	4.5 rps	63.1
0.271744E+08	5.0 rps	74.3
0.107707E+07	5.5 rps	60.3
0.170283E+09	6.0 rps	82.3
0.102226E+08	6.5 rps	70.1
0.278397E+09	7.0 rps	84.4
0.209706E+08	7.5 rps	73.2
0.346404E+09	8.0 rps	85.4
0.479538E+07	8.5 rps	66.8
0.234169E+08	9.0 rps	73.7
0.841159E+06	9.5 rps	59.2
0.265680E+08	10.0 rps	74.2
0.145390E+08	10.5 rps	71.6
0.124880E+09	11.0 rps	81.0
0.186418E+08	11.5 rps	72.7
0.654515E+09	12.0 rps	88.2
0.429546E+08	12.5 rps	76.3
0.527602E+08	13.0 rps	77.2
0.786913E+06	13.5 rps	59.0
0.735508E+07	14.0 rps	68.7
0.357528E+07	14.5 rps	65.5
0.584314E+07	15.0 rps	67.7
0.116780E+08	15.5 rps	70.7

0.132046E+09	16.0 rps	81.2
0.212489E+08	16.5 rps	73.3
0.476260E+08	17.0 rps	76.8
0.595265E+07	17.5 rps	67.7
0.645065E+07	18.0 rps	68.1
0.296256E+07	18.5 rps	64.7
0.774158E+07	19.0 rps	68.9
0.558638E+07	19.5 rps	67.5
0.632656E+07	20.0 rps	68.0
0.912947E+07	20.5 rps	69.6
0.103505E+08	21.0 rps	70.1
0.109114E+08	21.5 rps	70.4
0.188136E+08	22.0 rps	72.7
0.384467E+08	22.5 rps	75.8
0.378640E+07	23.0 rps	65.8
0.219452E+07	23.5 rps	63.4
0.838290E+07	24.0 rps	69.2
0.666140E+07	24.5 rps	68.2
0.101569E+09	25.0 rps	80.1
0.105524E+08	25.5 rps	70.2
0.186093E+08	26.0 rps	72.7
0.697501E+07	26.5 rps	68.4
0.258939E+08	27.0 rps	74.1
0.173863E+07	27.5 rps	62.4
0.264680E+07	28.0 rps	64.2
0.188395E+07	28.5 rps	62.8
0.710044E+07	29.0 rps	68.5
0.287643E+07	29.5 rps	64.6
0.468825E+07	30.0 rps	66.7
0.525020E+07	30.5 rps	67.2
0.180055E+08	31.0 rps	72.6
0.241922E+07	31.5 rps	63.8

OVER ALL MEAN SQUARE PRESSURE= 0.172201E+11
OVER ALL SOUND PRESSURE LEVEL= 102.4 dB
A-WGT OVER ALL MEAN SQUARE PRESSURE= 0.295373E+10
A-WGT OVER ALL SOUND PRESSURE LEVEL= 94.7 dBA

Appendix B-3 Data Sheet 3 (Lycoming O-360 A-series, 2700 rpm)

ENGINE TYPE : 2

ENGINE ROTATIONAL SPEED, N = 2700. rpm

ENGINE POWER, P= 180.0 HP

ONE-THIRD OCTAVE BAND BROAD BAND NOISE

LOWER	CENTER	UPPER	SPL	BRDBD(I,1)	BRDRD(I,2)
18.0	20.0	22.4	67.6	0.581250E+07	0.4 rps
22.4	25.0	28.0	68.7	0.739773E+07	0.6 rps
28.0	31.5	35.5	70.0	0.990767E+07	0.7 rps
35.5	40.0	45.0	71.0	0.125497E+08	0.9 rps
45.0	50.0	56.0	71.6	0.145312E+08	1.1 rps
56.0	63.0	71.0	73.0	0.198153E+08	1.4 rps
71.0	80.0	90.0	74.0	0.250994E+08	1.8 rps
90.0	100.0	112.0	74.6	0.290625E+08	2.2 rps
112.0	125.0	140.0	75.7	0.369886E+08	2.8 rps
140.0	160.0	180.0	77.2	0.528409E+08	3.6 rps
180.0	200.0	224.0	77.6	0.581250E+08	4.4 rps
224.0	250.0	280.0	78.7	0.739772E+08	5.6 rps
280.0	315.0	355.0	80.0	0.990767E+08	7.0 rps
355.0	400.0	450.0	81.0	0.125497E+09	8.9 rps
450.0	500.0	560.0	81.6	0.145313E+09	11.1 rps
560.0	630.0	710.0	83.0	0.198153E+09	14.0 rps
710.0	800.0	900.0	84.0	0.250995E+09	17.8 rps
900.0	1000.0	1120.0	84.6	0.290625E+09	22.2 rps
1120.0	1250.0	1400.0	85.7	0.369887E+09	27.8 rps
1400.0	1600.0	1800.0	86.8	0.478950E+09	35.6 rps
1800.0	2000.0	2240.0	85.5	0.354154E+09	44.4 rps
2240.0	2500.0	2800.0	84.4	0.276080E+09	55.6 rps
2800.0	3150.0	3550.0	82.9	0.195281E+09	70.0 rps
3550.0	4000.0	4500.0	80.6	0.115850E+09	88.9 rps
4500.0	5000.0	5600.0	79.5	0.886206E+08	111.1 rps
5600.0	6300.0	7100.0	79.0	0.793686E+08	140.0 rps
7100.0	8000.0	9000.0	77.6	0.580127E+08	177.8 rps
9000.0	10000.0	11200.0	71.1	0.129129E+08	222.2 rps

BROADBAND NOISE MEAN SQUARE PRESSURE= 0.348488E+10

BROADBAND NOISE OASPL= 95.4 dB

ENGINE TONES NOISE

TONES(I,1)	TONES(I,2)	SPL
0.954994E+10	2.0 rps	99.8
0.234423E+09	2.5 rps	83.7
0.109648E+10	3.0 rps	90.4
0.331131E+09	3.5 rps	85.2
0.218776E+11	4.0 rps	103.4
0.112202E+09	4.5 rps	80.5
0.114815E+10	5.0 rps	90.6
0.363078E+08	5.5 rps	75.6
0.467735E+10	6.0 rps	96.7
0.239883E+09	6.5 rps	83.8
0.549541E+10	7.0 rps	97.4
0.363078E+09	7.5 rps	85.6

0.537032E+10	8.0	rps	97.3
0.660693E+08	8.5	rps	78.2
0.288403E+09	9.0	rps	84.6
0.933254E+07	9.5	rps	69.7
0.275423E+09	10.0	rps	84.4
0.138039E+09	10.5	rps	81.4
0.112202E+10	11.0	rps	90.5
0.154882E+09	11.5	rps	81.9
0.501187E+10	12.0	rps	97.0
0.316228E+09	12.5	rps	85.0
0.363078E+09	13.0	rps	85.6
0.512861E+07	13.5	rps	67.1
0.457088E+08	14.0	rps	76.6
0.213796E+08	14.5	rps	73.3
0.338844E+08	15.0	rps	75.3
0.645654E+08	15.5	rps	78.1
0.724435E+09	16.0	rps	88.6
0.109648E+09	16.5	rps	80.4
0.234423E+09	17.0	rps	83.7
0.288403E+08	17.5	rps	74.6
0.301996E+08	18.0	rps	74.8
0.131826E+08	18.5	rps	71.2
0.346737E+08	19.0	rps	75.4
0.245471E+08	19.5	rps	73.9
0.269154E+08	20.0	rps	74.3
0.380190E+08	20.5	rps	75.8
0.426580E+08	21.0	rps	76.3
0.426580E+08	21.5	rps	76.3
0.724435E+08	22.0	rps	78.6
0.151356E+09	22.5	rps	81.8
0.144544E+08	23.0	rps	71.6
0.831763E+07	23.5	rps	69.2
0.309030E+08	24.0	rps	74.9
0.234423E+08	24.5	rps	73.7
0.363078E+09	25.0	rps	85.6
0.371535E+08	25.5	rps	75.7
0.645654E+08	26.0	rps	78.1
0.239883E+08	26.5	rps	73.8
0.851139E+08	27.0	rps	79.3
0.575440E+07	27.5	rps	67.6
0.912011E+07	28.0	rps	69.6
0.602560E+07	28.5	rps	67.8
0.229087E+08	29.0	rps	73.6
0.912011E+07	29.5	rps	69.6
0.151356E+08	30.0	rps	71.8
0.162181E+08	30.5	rps	72.1
0.575440E+08	31.0	rps	77.6
0.758578E+07	31.5	rps	68.8

A-WEIGHTED ONE-THIRD OCTAVE BAND BROAD BAND NOISE

CENTER	SPLA	BRDBDA(I,1)	BRDBDA(I,2)
20.0	17.6	0.579740E+02	0.4 rps
25.0	24.0	0.251310E+03	0.6 rps
31.5	30.6	0.114517E+04	0.7 rps
40.0	36.7	0.465379E+04	0.9 rps
50.0	41.7	0.148610E+05	1.1 rps

63.0	47.1	0.514191E+05	1.4 rps
80.0	51.9	0.154070E+06	1.8 rps
100.0	55.7	0.372908E+06	2.2 rps
125.0	59.6	0.912893E+06	2.8 rps
160.0	64.0	0.248743E+07	3.6 rps
200.0	66.9	0.485507E+07	4.4 rps
250.0	70.1	0.101917E+08	5.6 rps
315.0	73.4	0.218903E+08	7.0 rps
400.0	76.3	0.426281E+08	8.9 rps
500.0	78.5	0.700507E+08	11.1 rps
630.0	81.1	0.129057E+09	14.0 rps
800.0	83.2	0.208534E+09	17.8 rps
1000.0	84.6	0.287817E+09	22.2 rps
1250.0	86.2	0.417141E+09	27.8 rps
1600.0	87.7	0.587248E+09	35.6 rps
2000.0	86.6	0.455747E+09	44.4 rps
2500.0	85.5	0.357714E+09	55.6 rps
3150.0	83.9	0.246350E+09	70.0 rps
4000.0	81.4	0.137039E+09	88.9 rps
5000.0	79.7	0.934176E+08	111.1 rps
6300.0	78.5	0.712310E+08	140.0 rps
8000.0	76.1	0.409568E+08	177.8 rps
10000.0	68.5	0.708263E+07	222.2 rps

A-WGT BROADBAND NOISE MEAN SQUARE PRESSURE= 0.319295E+10
A-WGT BROADBAND NOISE OASPL= 95.0 dBA

ENGINE TONES NOISE

TONESA(I,1)	TONESA(I,2)	SPLA
0.840170E+08	2.0 rps	79.2
0.415524E+07	2.5 rps	66.2
0.326266E+08	3.0 rps	75.1
0.148513E+08	3.5 rps	71.7
0.138326E+10	4.0 rps	91.4
0.938083E+07	4.5 rps	69.7
0.122793E+09	5.0 rps	80.9
0.476276E+07	5.5 rps	66.8
0.738057E+09	6.0 rps	88.7
0.449822E+08	6.5 rps	76.5
0.119459E+10	7.0 rps	90.8
0.913666E+08	7.5 rps	79.6
0.148965E+10	8.0 rps	91.7
0.206101E+08	8.5 rps	73.1
0.991414E+08	9.0 rps	80.0
0.350048E+07	9.5 rps	65.4
0.111373E+09	10.0 rps	80.5
0.599413E+08	10.5 rps	77.8
0.540430E+09	11.0 rps	87.3
0.785156E+08	11.5 rps	78.9
0.268518E+10	12.0 rps	94.3
0.175667E+09	12.5 rps	82.4
0.214528E+09	13.0 rps	83.3
0.320259E+07	13.5 rps	65.1
0.306533E+08	14.0 rps	74.9
0.142382E+08	14.5 rps	71.5
0.240342E+08	15.0 rps	73.8
0.473939E+08	15.5 rps	76.8

0.545814E+09	16.0	rps	87.4
0.853682E+08	16.5	rps	79.3
0.180474E+09	17.0	rps	82.6
0.233997E+08	17.5	rps	73.7
0.246684E+08	18.0	rps	73.9
0.112192E+08	18.5	rps	70.5
0.296800E+08	19.0	rps	74.7
0.220016E+08	19.5	rps	73.4
0.247388E+08	20.0	rps	73.9
0.351564E+08	20.5	rps	75.5
0.395126E+08	21.0	rps	76.0
0.426190E+08	21.5	rps	76.3
0.715632E+08	22.0	rps	78.5
0.151590E+09	22.5	rps	81.8
0.144077E+08	23.0	rps	71.6
0.851515E+07	23.5	rps	69.3
0.310794E+08	24.0	rps	74.9
0.255586E+08	24.5	rps	74.1
0.391759E+09	25.0	rps	85.9
0.399956E+08	25.5	rps	76.0
0.696463E+08	26.0	rps	78.4
0.261521E+08	26.5	rps	74.2
0.940515E+08	27.0	rps	79.7
0.640980E+07	27.5	rps	68.1
0.103012E+08	28.0	rps	70.1
0.688191E+07	28.5	rps	68.4
0.262711E+08	29.0	rps	74.2
0.106546E+08	29.5	rps	70.3
0.177519E+08	30.0	rps	72.5
0.194363E+08	30.5	rps	72.9
0.691372E+08	31.0	rps	78.4
0.897677E+07	31.5	rps	69.5

OVER ALL MEAN SQUARE PRESSURE= 0.643076E+11
OVER ALL SOUND PRESSURE LEVEL= 108.1 dB
A-WGT OVER ALL MEAN SQUARE PRESSURE= 0.146806E+11
A-WGT OVER ALL SOUND PRESSURE LEVEL= 101.7 dBA

Appendix B-4 Data Sheet 4 (Lycoming O-320 D1D with Cessna 172 Standard Muffler, 2750 rpm)

ENGINE TYPE : 3
ENGINE ROTATIONAL SPEED, N = 2750. rpm
ENGINE POWER, P= 162.3 HP
ONE-THIRD OCTAVE BAND BROAD BAND NOISE

LOWER	CENTER	UPPER	SPL	BRDBD(I,1)	BRDRD(I,2)
18.0	20.0	22.4	60.7	0.116981E+07	0.4 rps
22.4	25.0	28.0	61.7	0.148884E+07	0.5 rps
28.0	31.5	35.5	63.0	0.199399E+07	0.7 rps
35.5	40.0	45.0	64.0	0.252572E+07	0.9 rps
45.0	50.0	56.0	64.7	0.292452E+07	1.1 rps
56.0	63.0	71.0	66.0	0.398798E+07	1.4 rps
71.0	80.0	90.0	67.0	0.505144E+07	1.7 rps
90.0	100.0	112.0	67.7	0.584903E+07	2.2 rps
112.0	125.0	140.0	68.7	0.744422E+07	2.7 rps
140.0	160.0	180.0	70.3	0.106346E+08	3.5 rps
180.0	200.0	224.0	70.7	0.116981E+08	4.4 rps
224.0	250.0	280.0	71.7	0.148884E+08	5.5 rps
280.0	315.0	355.0	73.0	0.199399E+08	6.9 rps
355.0	400.0	450.0	74.0	0.252572E+08	8.7 rps
450.0	500.0	560.0	74.7	0.292452E+08	10.9 rps
560.0	630.0	710.0	76.0	0.398798E+08	13.7 rps
710.0	800.0	900.0	77.0	0.505144E+08	17.5 rps
900.0	1000.0	1120.0	77.7	0.584904E+08	21.8 rps
1120.0	1250.0	1400.0	78.7	0.744421E+08	27.3 rps
1400.0	1600.0	1800.0	79.9	0.968263E+08	34.9 rps
1800.0	2000.0	2240.0	78.6	0.718162E+08	43.6 rps
2240.0	2500.0	2800.0	77.5	0.560878E+08	54.5 rps
2800.0	3150.0	3550.0	76.0	0.397678E+08	68.7 rps
3550.0	4000.0	4500.0	73.7	0.233107E+08	87.3 rps
4500.0	5000.0	5600.0	72.4	0.175323E+08	109.1 rps
5600.0	6300.0	7100.0	72.0	0.157254E+08	137.5 rps
7100.0	8000.0	9000.0	70.6	0.115167E+08	174.5 rps
9000.0	10000.0	11200.0	64.3	0.270490E+07	218.2 rps

BROADBAND NOISE MEAN SQUARE PRESSURE= 0.702714E+09
BROADBAND NOISE OASPL= 88.5 dB

ENGINE TONES NOISE

TONES(I,1)	TONES(I,2)	SPL
0.186209E+11	2.0 rps	102.7
0.630958E+09	2.5 rps	88.0
0.398107E+08	3.0 rps	76.0
0.933254E+08	3.5 rps	79.7
0.281838E+10	4.0 rps	94.5
0.331131E+09	4.5 rps	85.2
0.398107E+08	5.0 rps	76.0
0.501187E+07	5.5 rps	67.0
0.354814E+09	6.0 rps	85.5
0.562341E+08	6.5 rps	77.5
0.562341E+08	7.0 rps	77.5
0.562341E+08	7.5 rps	77.5

0.223872E+09	8.0	rps	83.5
0.912011E+07	8.5	rps	69.6
0.316228E+08	9.0	rps	75.0
0.169825E+08	9.5	rps	72.3
0.812830E+07	10.0	rps	69.1
0.100000E+08	10.5	rps	70.0
0.112202E+08	11.0	rps	70.5
0.478630E+07	11.5	rps	66.8
0.141254E+08	12.0	rps	71.5
0.177828E+08	12.5	rps	72.5
0.501187E+07	13.0	rps	67.0
0.524807E+07	13.5	rps	67.2
0.371535E+08	14.0	rps	75.7
0.323593E+08	14.5	rps	75.1
0.125893E+08	15.0	rps	71.0
0.158489E+08	15.5	rps	72.0
0.562341E+08	16.0	rps	77.5
0.794328E+08	16.5	rps	79.0
0.758578E+08	17.0	rps	78.8
0.426580E+08	17.5	rps	76.3
0.141254E+08	18.0	rps	71.5
0.169825E+08	18.5	rps	72.3
0.141254E+08	19.0	rps	71.5
0.257039E+08	19.5	rps	74.1
0.354814E+07	20.0	rps	65.5
0.100000E+08	20.5	rps	70.0
0.416869E+07	21.0	rps	66.2
0.125893E+08	21.5	rps	71.0
0.162181E+09	22.0	rps	82.1
0.125893E+08	22.5	rps	71.0
0.794328E+07	23.0	rps	69.0
0.363078E+08	23.5	rps	75.6
0.707946E+08	24.0	rps	78.5
0.630958E+07	24.5	rps	68.0
0.100000E+08	25.0	rps	70.0
0.204174E+08	25.5	rps	73.1
0.213796E+08	26.0	rps	73.3
0.128825E+08	26.5	rps	71.1
0.331131E+07	27.0	rps	65.2
0.794328E+07	27.5	rps	69.0
0.354814E+07	28.0	rps	65.5
0.446684E+07	28.5	rps	66.5
0.251189E+07	29.0	rps	64.0
0.380190E+07	29.5	rps	65.8
0.173780E+07	30.0	rps	62.4
0.100000E+07	30.5	rps	60.0
0.147911E+07	31.0	rps	61.7
0.100000E+07	31.5	rps	60.0

A-WEIGHTED ONE-THIRD OCTAVE BAND BROAD BAND NOISE

CENTER	SPLA	BRDBDA(I,1)	BRDBDA(I,2)
20.0	10.7	0.116677E+02	0.4 rps
25.0	17.0	0.505780E+02	0.5 rps
31.5	23.6	0.230474E+03	0.7 rps
40.0	29.7	0.936609E+03	0.9 rps
50.0	34.8	0.299088E+04	1.1 rps

63.0	40.1	0.103485E+05	1.4 rps
80.0	44.9	0.310077E+05	1.7 rps
100.0	48.8	0.750505E+05	2.2 rps
125.0	52.6	0.183726E+06	2.7 rps
160.0	57.0	0.500612E+06	3.5 rps
200.0	59.9	0.977118E+06	4.4 rps
250.0	63.1	0.205115E+07	5.5 rps
315.0	66.4	0.440558E+07	6.9 rps
400.0	69.3	0.857921E+07	8.7 rps
500.0	71.5	0.140982E+08	10.9 rps
630.0	74.1	0.259735E+08	13.7 rps
800.0	76.2	0.419689E+08	17.5 rps
1000.0	77.6	0.579252E+08	21.8 rps
1250.0	79.2	0.839526E+08	27.3 rps
1600.0	80.7	0.118726E+09	34.9 rps
2000.0	79.7	0.924180E+08	43.6 rps
2500.0	78.6	0.726724E+08	54.5 rps
3150.0	77.0	0.501671E+08	68.7 rps
4000.0	74.4	0.275847E+08	87.3 rps
5000.0	72.7	0.184811E+08	109.1 rps
6300.0	71.5	0.141126E+08	137.5 rps
8000.0	69.1	0.813031E+07	174.5 rps
10000.0	61.7	0.148337E+07	218.2 rps

A-WGT BROADBAND NOISE MEAN SQUARE PRESSURE= 0.644512E+09

A-WGT BROADBAND NOISE OASPL= 88.1 dBA

ENGINE TONES NOISE

TONESA(I,1)	TONESA(I,2)	SPLA
0.123209E+09	2.0 rps	80.9
0.930938E+07	2.5 rps	69.7
0.991046E+06	3.0 rps	60.0
0.348776E+07	3.5 rps	65.4
0.131264E+09	4.0 rps	81.2
0.230736E+08	4.5 rps	73.6
0.350246E+07	5.0 rps	65.4
0.553007E+06	5.5 rps	57.4
0.412007E+08	6.0 rps	76.1
0.869880E+07	6.5 rps	69.4
0.101232E+08	7.0 rps	70.1
0.114647E+08	7.5 rps	70.6
0.465572E+08	8.0 rps	76.7
0.232639E+07	8.5 rps	63.7
0.880519E+07	9.0 rps	69.4
0.518061E+07	9.5 rps	67.1
0.242678E+07	10.0 rps	63.9
0.356834E+07	10.5 rps	65.5
0.429339E+07	11.0 rps	66.3
0.195543E+07	11.5 rps	62.9
0.497118E+07	12.0 rps	67.0
0.815538E+07	12.5 rps	69.1
0.236585E+07	13.0 rps	63.7
0.263167E+07	13.5 rps	64.2
0.171057E+08	14.0 rps	72.3
0.175653E+08	14.5 rps	72.4
0.721617E+07	15.0 rps	68.6
0.920996E+07	15.5 rps	69.6

0.302657E+08	16.0	rps	74.8
0.497531E+08	16.5	rps	77.0
0.490713E+08	17.0	rps	76.9
0.280997E+08	17.5	rps	74.5
0.835891E+07	18.0	rps	69.2
0.117408E+08	18.5	rps	70.7
0.100942E+08	19.0	rps	70.0
0.186506E+08	19.5	rps	72.7
0.239115E+07	20.0	rps	63.8
0.757585E+07	20.5	rps	68.8
0.320508E+07	21.0	rps	65.1
0.989654E+07	21.5	rps	70.0
0.116048E+09	22.0	rps	80.6
0.997544E+07	22.5	rps	70.0
0.622940E+07	23.0	rps	67.9
0.289703E+08	23.5	rps	74.6
0.519401E+08	24.0	rps	77.2
0.542682E+07	24.5	rps	67.3
0.864578E+07	25.0	rps	69.4
0.174968E+08	25.5	rps	72.4
0.170549E+08	26.0	rps	72.3
0.111332E+08	26.5	rps	70.5
0.292984E+07	27.0	rps	64.7
0.702179E+07	27.5	rps	68.5
0.292792E+07	28.0	rps	64.7
0.397314E+07	28.5	rps	66.0
0.233080E+07	29.0	rps	63.7
0.337315E+07	29.5	rps	65.3
0.143413E+07	30.0	rps	61.6
0.904729E+06	30.5	rps	59.6
0.135171E+07	31.0	rps	61.3
0.974555E+06	31.5	rps	59.9

OVER ALL MEAN SQUARE PRESSURE= 0.250084E+11
OVER ALL SOUND PRESSURE LEVEL= 104.0 dB
A-WGT OVER ALL MEAN SQUARE PRESSURE= 0.168497E+10
A-WGT OVER ALL SOUND PRESSURE LEVEL= 92.3 dBA

Appendix B-5 Data Sheet 5 (Lycoming O-320 D1D with Cessna 172 Standard Muffler, 2590 rpm)

ENGINE TYPE : 3
ENGINE ROTATIONAL SPEED, N = 2590. rpm
ENGINE POWER, P= 154.9 HP

ONE-THIRD OCTAVE BAND BROAD BAND NOISE

LOWER	CENTER	UPPER	SPL	BRDBD(I,1)	BRDRD(I,2)
18.0	20.0	22.4	58.6	0.724187E+06	0.5 rps
22.4	25.0	28.0	59.6	0.921692E+06	0.6 rps
28.0	31.5	35.5	60.9	0.123441E+07	0.7 rps
35.5	40.0	45.0	61.9	0.156359E+07	0.9 rps
45.0	50.0	56.0	62.6	0.181047E+07	1.2 rps
56.0	63.0	71.0	63.9	0.246882E+07	1.5 rps
71.0	80.0	90.0	65.0	0.312717E+07	1.9 rps
90.0	100.0	112.0	65.6	0.362093E+07	2.3 rps
112.0	125.0	140.0	66.6	0.460846E+07	2.9 rps
140.0	160.0	180.0	68.2	0.658352E+07	3.7 rps
180.0	200.0	224.0	68.6	0.724187E+07	4.6 rps
224.0	250.0	280.0	69.6	0.921692E+07	5.8 rps
280.0	315.0	355.0	70.9	0.123441E+08	7.3 rps
355.0	400.0	450.0	71.9	0.156358E+08	9.3 rps
450.0	500.0	560.0	72.6	0.181047E+08	11.6 rps
560.0	630.0	710.0	73.9	0.246882E+08	14.6 rps
710.0	800.0	900.0	75.0	0.312717E+08	18.5 rps
900.0	1000.0	1120.0	75.6	0.362093E+08	23.2 rps
1120.0	1250.0	1400.0	76.6	0.460847E+08	29.0 rps
1400.0	1600.0	1800.0	77.4	0.553990E+08	37.1 rps
1800.0	2000.0	2240.0	75.9	0.393493E+08	46.3 rps
2240.0	2500.0	2800.0	74.7	0.298276E+08	57.9 rps
2800.0	3150.0	3550.0	73.1	0.203469E+08	73.0 rps
3550.0	4000.0	4500.0	70.9	0.124128E+08	92.7 rps
4500.0	5000.0	5600.0	69.9	0.981140E+07	115.8 rps
5600.0	6300.0	7100.0	69.3	0.857793E+07	145.9 rps
7100.0	8000.0	9000.0	67.6	0.573693E+07	185.3 rps
9000.0	10000.0	11200.0	58.1	0.648972E+06	231.7 rps

BROADBAND NOISE MEAN SQUARE PRESSURE= 0.409571E+09
BROADBAND NOISE OASPL= 86.1 dB

ENGINE TONES NOISE

TONES(I,1)	TONES(I,2)	SPL
0.146510E+11	2.0 rps	101.7
0.496441E+09	2.5 rps	87.0
0.313233E+08	3.0 rps	75.0
0.734290E+08	3.5 rps	78.7
0.221752E+10	4.0 rps	93.5
0.260536E+09	4.5 rps	84.2
0.313233E+08	5.0 rps	75.0
0.394338E+07	5.5 rps	66.0
0.279169E+09	6.0 rps	84.5
0.442454E+08	6.5 rps	76.5
0.442454E+08	7.0 rps	76.5
0.442454E+08	7.5 rps	76.5

0.176144E+09	8.0	rps	82.5
0.717576E+07	8.5	rps	68.6
0.248810E+08	9.0	rps	74.0
0.133619E+08	9.5	rps	71.3
0.639540E+07	10.0	rps	68.1
0.786806E+07	10.5	rps	69.0
0.882812E+07	11.0	rps	69.5
0.376589E+07	11.5	rps	65.8
0.111139E+08	12.0	rps	70.5
0.139916E+08	12.5	rps	71.5
0.394338E+07	13.0	rps	66.0
0.412922E+07	13.5	rps	66.2
0.292326E+08	14.0	rps	74.7
0.254605E+08	14.5	rps	74.1
0.990530E+07	15.0	rps	70.0
0.124700E+08	15.5	rps	71.0
0.442454E+08	16.0	rps	76.5
0.624983E+08	16.5	rps	78.0
0.596854E+08	17.0	rps	77.8
0.335636E+08	17.5	rps	75.3
0.111139E+08	18.0	rps	70.5
0.133619E+08	18.5	rps	71.3
0.111139E+08	19.0	rps	70.5
0.202240E+08	19.5	rps	73.1
0.279170E+07	20.0	rps	64.5
0.786806E+07	20.5	rps	69.0
0.327995E+07	21.0	rps	65.2
0.990530E+07	21.5	rps	70.0
0.127605E+09	22.0	rps	81.1
0.990530E+07	22.5	rps	70.0
0.624983E+07	23.0	rps	68.0
0.285672E+08	23.5	rps	74.6
0.557016E+08	24.0	rps	77.5
0.496441E+07	24.5	rps	67.0
0.786806E+07	25.0	rps	69.0
0.160645E+08	25.5	rps	72.1
0.168216E+08	26.0	rps	72.3
0.101360E+08	26.5	rps	70.1
0.260536E+07	27.0	rps	64.2
0.624983E+07	27.5	rps	68.0
0.279170E+07	28.0	rps	64.5
0.351454E+07	28.5	rps	65.5
0.197637E+07	29.0	rps	63.0
0.299136E+07	29.5	rps	64.8
0.136731E+07	30.0	rps	61.4
0.786807E+06	30.5	rps	59.0
0.116377E+07	31.0	rps	60.7
0.786807E+06	31.5	rps	59.0

A-WEIGHTED ONE-THIRD OCTAVE BAND BROAD BAND NOISE

CENTER	SPLA	BRDBDA(I,1)	BRDBDA(I,2)
20.0	8.6	0.722305E+01	0.5 rps
25.0	15.0	0.313111E+02	0.6 rps
31.5	21.5	0.142678E+03	0.7 rps
40.0	27.6	0.579822E+03	0.9 rps
50.0	32.7	0.185155E+04	1.2 rps

63.0	38.1	0.640637E+04	1.5 rps
80.0	42.8	0.191958E+05	1.9 rps
100.0	46.7	0.464611E+05	2.3 rps
125.0	50.6	0.113738E+06	2.9 rps
160.0	54.9	0.309912E+06	3.7 rps
200.0	57.8	0.604900E+06	4.6 rps
250.0	61.0	0.126980E+07	5.8 rps
315.0	64.4	0.272734E+07	7.3 rps
400.0	67.3	0.531109E+07	9.3 rps
500.0	69.4	0.872770E+07	11.6 rps
630.0	72.1	0.160793E+08	14.6 rps
800.0	74.1	0.259815E+08	18.5 rps
1000.0	75.5	0.358595E+08	23.2 rps
1250.0	77.2	0.519722E+08	29.0 rps
1600.0	78.3	0.678852E+08	37.1 rps
2000.0	77.0	0.506340E+08	46.3 rps
2500.0	75.9	0.386471E+08	57.9 rps
3150.0	74.1	0.256722E+08	73.0 rps
4000.0	71.7	0.146653E+08	92.7 rps
5000.0	70.1	0.103449E+08	115.8 rps
6300.0	68.9	0.770208E+07	145.9 rps
8000.0	66.1	0.408429E+07	185.3 rps
10000.0	55.5	0.357202E+06	231.7 rps

A-WGT BROADBAND NOISE MEAN SQUARE PRESSURE= 0.369024E+09

A-WGT BROADBAND NOISE OASPL= 85.7 dBA

ENGINE TONES NOISE

TONESA(I,1)	TONESA(I,2)	SPLA
0.801378E+08	2.0 rps	79.0
0.615889E+07	2.5 rps	67.9
0.660417E+06	3.0 rps	58.2
0.235393E+07	3.5 rps	63.7
0.890976E+08	4.0 rps	79.5
0.156715E+08	4.5 rps	72.0
0.240642E+07	5.0 rps	63.8
0.375573E+06	5.5 rps	55.7
0.286801E+08	6.0 rps	74.6
0.602643E+07	6.5 rps	67.8
0.696704E+07	7.0 rps	68.4
0.800649E+07	7.5 rps	69.0
0.321480E+08	8.0 rps	75.1
0.165334E+07	8.5 rps	62.2
0.632316E+07	9.0 rps	68.0
0.370724E+07	9.5 rps	65.7
0.170552E+07	10.0 rps	62.3
0.259182E+07	10.5 rps	64.1
0.307429E+07	11.0 rps	64.9
0.140078E+07	11.5 rps	61.5
0.348121E+07	12.0 rps	65.4
0.582246E+07	12.5 rps	67.7
0.177299E+07	13.0 rps	62.5
0.192469E+07	13.5 rps	62.8
0.125924E+08	14.0 rps	71.0
0.129717E+08	14.5 rps	71.1
0.516533E+07	15.0 rps	67.1
0.680858E+07	15.5 rps	68.3

0.228349E+08	16.0	rps	73.6
0.366465E+08	16.5	rps	75.6
0.358156E+08	17.0	rps	75.5
0.210922E+08	17.5	rps	73.2
0.624403E+07	18.0	rps	68.0
0.894391E+07	18.5	rps	69.5
0.760572E+07	19.0	rps	68.8
0.144088E+08	19.5	rps	71.6
0.175976E+07	20.0	rps	62.5
0.578819E+07	20.5	rps	67.6
0.242090E+07	21.0	rps	63.8
0.732283E+07	21.5	rps	68.6
0.883226E+08	22.0	rps	79.5
0.753105E+07	22.5	rps	68.8
0.494561E+07	23.0	rps	66.9
0.228116E+08	23.5	rps	73.6
0.408525E+08	24.0	rps	76.1
0.420052E+07	24.5	rps	66.2
0.629036E+07	25.0	rps	68.0
0.131964E+08	25.5	rps	71.2
0.123286E+08	26.0	rps	70.9
0.838743E+07	26.5	rps	69.2
0.223519E+07	27.0	rps	63.5
0.553995E+07	27.5	rps	67.4
0.213970E+07	28.0	rps	63.3
0.313247E+07	28.5	rps	65.0
0.180563E+07	29.0	rps	62.6
0.266092E+07	29.5	rps	64.3
0.111491E+07	30.0	rps	60.5
0.717674E+06	30.5	rps	58.6
0.106668E+07	31.0	rps	60.3
0.739742E+06	31.5	rps	58.7

OVER ALL MEAN SQUARE PRESSURE= 0.195335E+11
OVER ALL SOUND PRESSURE LEVEL= 102.9 dB
A-WGT OVER ALL MEAN SQUARE PRESSURE= 0.111961E+10
A-WGT OVER ALL SOUND PRESSURE LEVEL= 90.5 dBA