

Estimation of far-field sound pressure levels due to buzz-saw noise of a supersonic fan or compressor

**Associated software: ESDUpac A7520
ESDUpac B7520**

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THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Aircraft Noise Committee which first met in 1971 and now has the following membership:

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ESTIMATION OF FAR-FIELD SOUND PRESSURE LEVELS DUE TO BUZZ-SAW NOISE OF A SUPERSONIC FAN OR COMPRESSOR

1. INTRODUCTION

Buzz-saw tones (also known as combination tones) are generated by a fan or compressor when the rotor-blade Mach number relative to the incident air stream exceeds unity. In a practical rotor the resulting shock waves propagate from the rotor face with differing intensities, spacing and angles caused by geometric and aeroelastic differences between individual blades (see Figure 1). These variations can give rise to tones at low frequencies that are integral multiples of shaft frequency.

This Item provides a method of estimating the sound pressure levels of buzz-saw tones in the far-field outside the intake duct of a static engine for intake duct lengths greater than twice the duct diameter. It is based on a theory employing statistical analysis of the number, spacing and amplitude of the shocks generated from a fan of conventional design.

To extend the application of this Item to non-stationary engines the predicted levels will require correction for "in-flight effects" such as Doppler frequency shift, etc.

2. NOTATION

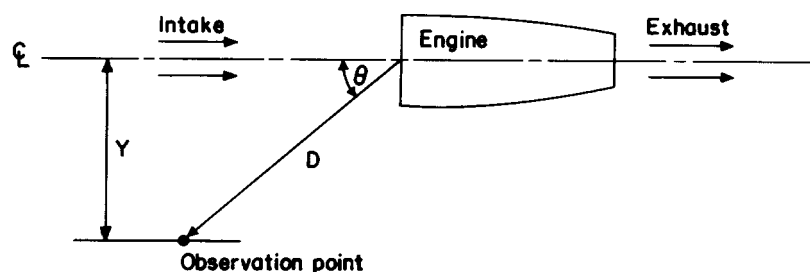
		<i>Units</i>	
		<i>SI</i>	<i>British</i>
B	number of fan or compressor blades		
D	radial distance from centre of duct intake plane = $Y/\sin\theta$ (see Sketch 2.1)	m	ft
E	shaft rotation frequency	Hz	Hz
f	frequency of buzz-saw tone	Hz	Hz
K	shaft-order number, f/E		
K_{co}	shaft-order number at cut-off		
L	axial length of intake duct	m	ft
L_B	component of L_K dependent upon number of blades and surviving shocks	dB*	dB*
L_D	component of L_K dependent upon D/R	dB*	dB*
L_K	average sound pressure level of tone of shaft-order K in intake duct at distance D from duct intake plane, given by $L_L + L_M + L_B + L_\theta + L_D + L_{K\sigma}$	dB*	dB*

For Footnote refer to end of Notation Section

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$L_{K\sigma}$	component of L_K dependent upon shaft-order number and standard deviations of shock spacing and amplitude	dB*	dB*
L_L	component of L_K dependent upon L/R	dB*	dB*
L_M	component of L_K dependent upon Mach number of incident flow on blades	dB*	dB*
L_θ	component of L_K dependent upon θ	dB*	dB*
M_A	intake axial-flow Mach number		
M_T	tangential Mach number at blade tip		
N	number of shock waves per shaft revolution surviving at position under consideration		
p_0	static pressure in intake duct	N/m ²	lbf/ft ²
p_{ref}	reference pressure for decibel scale, taken as $20 \mu \text{ N/m}^2$ (0.0002 dyn/cm ² or 0.42×10^{-6} lbf/ft ²)	N/m ²	lbf/ft ²
R	tip radius of fan or compressor	m	ft
Y	linear distance from duct axis (see Sketch 2.1)	m	ft
γ	ratio of specific heat capacities for air (taken as 1.4)		
θ	angle of duct axis at duct intake plane (see Sketch 2.1)	degrees	degrees
σ_A	standard deviation of normalized shock-wave amplitude		
σ_E	standard deviation of normalized shock-wave spacing		

* The reference pressure for all decibels is $20 \mu \text{ N/m}^2$ (0.0002 dyn/cm² or 0.42×10^{-6} lbf/ft²).



Sketch 2.1

3. NOTES

3.1 Summary of Method

The sound pressure level at a distance D from the inlet duct face, for any buzz-saw tone, is estimated from the sum $L_K = L_L + L_M + L_B + L_\theta + L_D + L_{K\sigma}$.

The factors L_L , L_M and L_B are plotted in Figures 2, 3 and 4 against the appropriate engine parameters. The factors L_θ and L_D are plotted in Figures 5 and 6 against the appropriate co-ordinates of the observation point.

The factor $L_{K\sigma}$ is plotted in Figures 7 and 8. This factor defines the shape of the envelope of the peaks of the buzz-saw tone spectrum and must be evaluated for each tone required. Figure 7 relates to tones at integer multiples, K , of shaft frequency and Figure 8 to tones at integer multiples, K/B , of blade passage frequency. In Figure 8 a value $\sigma_A = 0.2$ has been assumed. Departures from this value have a negligible effect on the value of $L_{K\sigma}$ for integral values of K/B .

Tones below a critical cut-off frequency do not propagate efficiently along the duct. Figure 9 gives the value of the shaft-order at this cut-off, K_{co} . Estimates at frequencies less than K_{co} may not be accurate.

It is assumed that values of L , B , M_T , M_A , p_0 and R are known and the co-ordinates D and θ of the observation point have been chosen. The remaining parameters required to estimate L_K are the standard deviations of shock-wave amplitude and spacing, σ_A and σ_E , and the number of surviving shock waves N . The values of these parameters for a given fan are not always available. Guidance on their estimation is given in Appendix A.

A computer program, known as ESDUpac A7520, is provided. It permits the user to estimate both pure-tone and 1/3-octave band sound pressure levels of buzz-saw tones generated in the far-field outside the intake duct of a static engine (including the estimation of σ_E). The use of the program is described in Appendix B. Program B7520, also provided, can be used to create input files.

3.2 Assumptions and Limitations

No allowance is made for the effect of any acoustic lining of the duct. It is assumed that the inlet flow is axial and uniform across the intake guide vanes.

No allowance is made for such modifying effects as ground reflection or atmospheric absorption. Reflections of the sound off the ground generally produce an interference modulation over the whole spectrum. Absorption of the sound depends upon the distance from the source, the relative humidity and temperature of the air, and the frequency of the tone, higher frequencies being attenuated more rapidly.

Because the noise at shaft-order frequencies is caused by small differences between individual rotor blades each rotor has its own unique spectrum of buzz-saw levels. Also the levels at multiples of blade-passage frequency may be affected by noise mechanisms in the compressor not accounted for in this Item. This method can therefore only give typical buzz-saw spectra and should not be expected to produce precise agreement with any one set of measured results. However, agreement to within 2 dB of experimental results measured outside the intake duct of convex bladed fans has been obtained.

Because of Doppler frequency shifting and other effects, estimates made by this method are directly applicable only to a static engine.

4. DERIVATION

The figures are based on the following expressions.

Figure 2.

$$L_L = 20 \log_{10} \left[\frac{\gamma}{\gamma + 1} \cdot \frac{P_0}{p_{ref}} \cdot \frac{\pi R}{L} \right] + 10 \log \left[\frac{4\pi}{3} \right] \text{dB},$$

Figure 3.

$$L_M = 20 \log_{10} \left\{ \left[\frac{2(M_R^2 - 1)^{3/2}}{M_T + (M_R^2 - 1)^{1/2}} \right] \left[\frac{(1 - M_a^2)}{M_2 + M_A(M_R^2 - 1)^{1/2}} \right] \left[\frac{M_A(M_R^2 - 1)^{1/2} - M_T}{M_R^2} \right]^2 \right\} \text{dB},$$

where $M_R^2 = M_A^2 + M_T^2.$

Figure 4.

$$L_B = 30 \log_{10} \left[\frac{1}{B} \cdot \frac{B}{N} \right] \text{dB}.$$

Figure 6.

$$L_D = 20 \log_{10} \left[\frac{R}{D} \right] \text{dB}.$$

Figure 7.

$$L_{K\sigma} = 10 \log_{10} \left\{ \frac{4}{\eta_1^2} + [2(1 - \cos \eta_1) - 2\eta_1 \sin \eta_1](1 + 6\sigma_E^2)[1 + \sigma_A^2 - \exp(-\sigma_E^2 \eta_1^2)] \right\} \text{dB},$$

where $\eta_1 = 2\pi K/N.$

Figure 8.

$$L_{K\sigma} = 10 \log_{10} \left\{ \frac{4}{\eta_2^2} (1 + 6\sigma_E^2)[1 + \sigma_A^2 + (B - 1) \exp(-\sigma_E^2 \eta_2^2)] \right\} \text{dB},$$

where $\eta_2 = 2\pi K/B.$

Figure 9.

$$K_{co} = 0.77 \left[\frac{M_T}{(1 - M_A^2)^{1/2} \left[1 - 0.1 \exp 23.03 \left\{ 1 - (M_A^2 + M_T^2)^{1/2} \right\} \right]} - 1.0 \right]^{-3/2}.$$

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FISHER, M.J. Shock-wave radiation from a supersonic ducted rotor. *Aeronaut, J.*, Vol. 74, No. 715, pp. 579-585, July 1970.
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4. PICKETT, G.F. The prediction of the spectral content of combination tone noise. AIAA/SAE 7th Propulsion Joint Specialist Conference, AIAA paper 71-730, June 1971.
5. – Standard values of atmospheric absorption as a function of temperature and humidity for use in evaluating aircraft flyover noise. Society of Automotive Engineers ARP866, August 1964. (Amendment A, 1975.)
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5. EXAMPLE

Determine the maximum spectrum levels of buzz-saw tones up to 10 kHz for a fan with blades which have a convex suction surface near the leading edge (see Appendix A) and the following dimensions and running conditions

$$\begin{aligned} B &= 33, & R &= 1.085 \text{ m}, & E &= 57 \text{ Hz}, \\ M_A &= 0.47, & L &= 1.167 \text{ m}, & Y &= 30.43 \text{ m} \\ M_T &= 1.18, & \sigma_A &= 0.2, \\ p_0 &= 8.667 \times 10^4 \text{ N/m}^2, & \sigma_E &= 0.13, \end{aligned}$$

From Figure 2, for $L/R = 1.08$ and $p_0 = 8.667 \times 10^4 \text{ N/m}^2$,

$$L_L = 204 \text{ dB}.$$

From Figure 3, for $M_A = 0.47$ and $M_T = 1.18$,

$$L_M = -24 \text{ dB}.$$

From Figure 4, $B/N = 1$ (appropriate to blades with a convex suction surface near the leading edge (see

Appendix A)) and $B = 33$,

$$L_B = -46 \text{ dB.}$$

From Figure 5, the maximum spectrum level occurs at $\theta \approx 53^\circ$ when

$$L_\theta = +6 \text{ dB.}$$

Hence
$$D = \frac{Y}{\sin 53^\circ}$$

$$= 38.1 \text{ m.}$$

From Figure 6, for $R/D = 2.8 \times 10^{-2}$,

$$L_D = -31 \text{ dB.}$$

Then $L_L + L_M + L_B + L_\theta + L_D = 204 - 24 - 46 + 6 - 31 = 109 \text{ dB.}$

Referring to Figure 7, a range of values of K is chosen.

The frequency of a tone is governed by the equation $f = KE$. To obtain buzz-saw frequencies up to $f = 10 \text{ kHz}$ it is necessary to take a range of K up to about $10\,000/E = 10\,000/57 = 176$.

From Figure 7, the following table is constructed, using values of $\sigma_A = 0.2$, $\sigma_E = 0.13$, and $N = B = 33$. The value of L_K is then obtained from $L_K = L_L + L_M + L_B + L_\theta + L_D + L_{K\sigma} = 109 + L_{K\sigma}$.

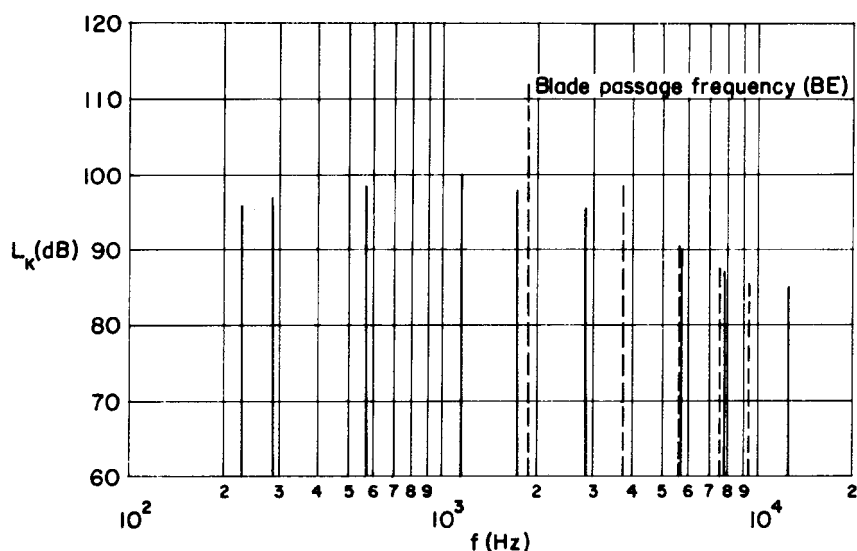
K	f Hz	K/N	$L_{K\sigma}$ dB	L_K dB
1	57	0.0303	-13.5	95.5
2	114	0.0606	-13.5	95.5
3	171	0.0909	-13	96
4	228	0.121	-13	96
5	285	0.152	-12.5	96.5
10	570	0.303	-10.5	98.5
20	1140	0.606	-9	100
30	1710	0.909	-11	98
50	2850	1.52	-13.5	95.5
100	5700	3.03	-19	90
140	7980	4.24	-22	87
180	10 260	5.45	-24	85

From Figure 8, the following values are obtained.

K	f Hz	K/B	$L_{K\sigma}$ dB	L_K dB
33	1881	1	+3	112
66	3762	2	-10.5	98.5
99	5643	3	-18.5	90.5
132	7524	4	-21.5	87.5
165	9405	5	-23.5	85.5

From Figure 9, for $M_A = 0.47$ and $M_T = 1.18$, $K_{co} = 4$.

The following spectrum of buzz-saw tones is estimated ignoring the tones for K less than K_{co} , i.e. K less than 4.



To obtain 1/3-octave band spectra the sound pressure level of each tone contained within the 1/3-octave band under consideration must be summed. Guidance on the summation of sound pressure levels in dBs is given in Item No. 66017.