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Noise
Session 3aNSa: Wind Turbine Noise I

3aNSa5. Can wind turbine sound that is below the threshold of hearing be heard?

Paul Schomer*

***Corresponding author's address: Schomer and Associates, 2117 Robert Drive, Champaign, IL 61821, schomer@SchomerAndAssociates.com**

This paper is geared towards wind turbine sound, but it is really a simple variation on the basic concepts that this author used in the development of loudness-level-weighted sound exposure (Schomer et al., J. Acoust. Soc. Am, 110(5), Pt. 1, 2390-2397, 2001) and of Rating Noise Curves (RNC) (Schomer, Noise Cont. Eng. J., 48(3), 85-96, 2000), which are used in the Standard, ANSI/ASA S12.2 Criteria for evaluating room noise. The fundamental issue is: Can we hear slowly surging or pulsating sounds for which the LEQ spectrum is below the threshold of hearing, where "slowly" means that the pulses come at a rate that is no faster than about 4 pulses per second? The short answer is yes, and the longer answer is that this effect is a function of the spectral content and becomes more-and-more prominent as the spectral content goes lower-and-lower in the audible frequency range. So surging or pulsing sound that is primarily in the 16 or 31 Hz octave bands will show the greatest effect. This paper shows the applicability of these results to wind-turbine sound.

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INTRODUCTION

The threshold of hearing should be understood as the lowest-level pure tone at a given frequency that can be detected by the average person with good hearing. It varies greatly with frequency; the threshold is lowest at about 2.5 kHz and grows higher as one goes to lower frequencies. The threshold of hearing is measured with pure continuous tones, and is applicable to only pure continuous tones. If one introduces a non-pure tone, such as a square wave, the ear will react entirely differently than to a sinusoid, because of the harmonics that are part of the square wave spectrum. If one introduces a temporal pattern such as an "on / off" modulation of a pure tone, then one will get different answers than they would from a continuous tone. This limited applicability of the threshold of hearing is frequently misunderstood. People treat signals that have a temporal pattern as if they were continuous signals, and that is just incorrect.

RESPONSE OF THE EAR

Spectral

Equal-loudness contours measure the change in the ear's response with frequency and amplitude. Figure 1 shows the equal-loudness contours from ISO 226 (1987). They are measured by having test subjects balance the loudness of two tones. The 1000 Hz tone is typically used as the reference tone while the other tone is varied in frequency to establish the contour. These tests utilize pure tones; the subject compares one tone to the other, and adjusts the loudness of the variable tone to be equal to the loudness of the 1000 Hz tone.

If one examines the equal-loudness contours of Figure 1, they will note that they are not constant with amplitude, but tend to flatten out as the amplitude goes up. Above about 300 Hz, they look like parallel curves, each spaced 10 dB from its adjacent curve. Frequently the equal-loudness contours are expressed in phons, which are a measure of the loudness level. Phons are equal to the sound pressure level at 1000 Hz. So at 1000 Hz, a 10 dB change in the sound pressure level corresponds to a 10 phon change. At the lower frequencies—below 300 Hz—the curves tend to compress together so that at 31 Hz, a 5 dB change in sound pressure level is equal to a change of 10 phons.

Loudness is actually expressed in sones, and it is such that a change of 10 phons is a doubling of loudness. Forty phons is typically taken to be one sone, so fifty phons is two sones, and sixty phons is four sones, etc. In general,

$$2^{(\text{Phons - 40}) /10} = \text{Sones} \tag{1}$$

It is emphasized that the equal-loudness contours are developed using pure tones and can only represent the loudness of pure tones. Anything that isn't a pure tone has other frequencies to at least some degree. For example, a square wave has the fundamental and every odd harmonic. And one could never develop equal-loudness contours with the multiple frequencies of the square wave because one wouldn't be comparing one tone to another anymore. So if one has a pure tone of 50 dB at 1000 Hz, this has a loudness of two sones. If one has a tone of 50 dB at 30 Hz, this is just at the minimum audible threshold (MAF). And if one has a tone of 50 dB at 20 Hz, the tone is 12 dB below the threshold of hearing; these three sounds would be heard clearly, barely, and not at all, respectively.

Temporal

There is also a temporal picture of hearing. Short-duration sounds are not perceived with their full loudness until they are present for the time constant of one's ear. The shorter the time that the sound is present, the lower the perception of its loudness. Long-duration sounds, i.e., sounds that are present for more than the time constant of one's ear, are perceived with their full loudness, which does not vary with an increase in time beyond the time constant. That is, to be perceived with full loudness, sound must be present for a duration that is longer than the time constant of the ear. There is some general agreement that the time constant of the ear lies between 25 ms and 250 ms (Boone, 1973; Miller, 1948; Zwicker 1966). Thus, level variations that occur over times that are long compared to 250 ms will be perceived by the auditory system as varying in loudness. But the hearing process will not perceive level variations that occur over times that are short compared to 25 ms.

DISCUSSION

Now that we have introduced the pictorial and temporal representations of hearing, we consider how different frequencies and temporal patterns will be perceived by the ear. First we consider a 1000 Hz sine wave, which is a pure continuous tone at 1000 Hz (Figure 2a). The threshold of hearing for this tone is 0 dB. But what if this sine wave has a repetitive temporal pattern, such that it is on at full amplitude for 1/4 of a second, and on at zero amplitude for 1/4 of a second (Figure 2b)? First of all, since the signal is off half the time, the LEQ must drop by 3 dB. This means that we could increase the amplitude of the sine wave by 3 dB during the two quarters of a second when the wave is non-zero, and still be at the threshold of hearing. Let's assume that the amplitude is increased to a very small amount below the threshold of hearing--an almost 3 dB increase. During the two 250 ms periods when the signal is on, the ear will hear these sounds and they will grow to full loudness during the 250 ms period levels will be 3 dB above the threshold of hearing. So a person with normal hearing would clearly hear two pulses per second for a signal for which the LEQ was just below the threshold of hearing.

The disparity gets even greater if one considers a signal that is only on for one 250 ms period and is off for the remaining 750 ms of each second (Figure 2c). This signal, when crafted from a pure tone just below the threshold of hearing, can rise in amplitude to 6 dB above the threshold of hearing when it is present because it is only present 1/4 of the time, and its LEQ will still be just below the threshold of hearing. So in round numbers, if the time constant of the ear at a given frequency and amplitude is at its maximum (250 ms), then a signal that has an LEQ below the threshold of hearing can be perceived as having a loudness that is 6 dB or 6 phons above the threshold of hearing. At frequencies or amplitudes where the time constant of the ear is shorter than 250 ms (let us assume 100 ms), the loudness sensation can grow to 10 dB or 10 phons (double the loudness) above the threshold of hearing while the LEQ still measures below the threshold of hearing.

We consider the example we have just used but with the sinusoidal frequency changed from 1000 Hz to 31 Hz (Figure 3a). That is, the time constant of the ear is taken at first to be 250 ms, and the pulse that occurs once per second is taken to be 250 ms in duration. So as above, the LEQ will be just below the threshold of hearing, and the sound level of the 31 Hz sinusoid will be about 6 dB above the threshold of hearing, but in this case, the loudness at 31 Hz for a signal that is 6 dB above the threshold of hearing is more than two times as loud as a continuous signal of 31 Hz at the threshold of hearing.

As a final example, we again consider the time constant of the ear to be 100 ms and the 31 Hz signal to be present for the full 100 ms period. In this case, the number of cycles is becoming so few that the spectrum will be able to form sin(x) / x, and this will limit the analysis as if it were approximately a higher frequency of about 40 to 50 Hz. At this higher frequency of about 40 to 50 Hz, it takes a 6 dB change in sound level to equal a 10 phon change in loudness. So in this case, the loudness change will be a little over a factor of three, and not the factor of four one would get from changing the sound pressure level of a continuous 31 Hz tone. Nevertheless, this shows the LEQ can be almost 10 dB below the threshold of hearing and still be audible.

CONCLUSIONS FOR WIND TURBINES

If we now turn our attention to a wind turbine, the blade passage frequency is on the order of 1 second or less, and one of the newest machines, the Nordex N-100, a 2.5 MW wind turbine, has a blade passage frequency in the 0.5 to 0.7 Hz range. These pulses are not dissimilar to the 1 pulse per second scenario (above), so clearly pulses are and will be heard even if the LEQ is well below the threshold of hearing.

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FIGURES

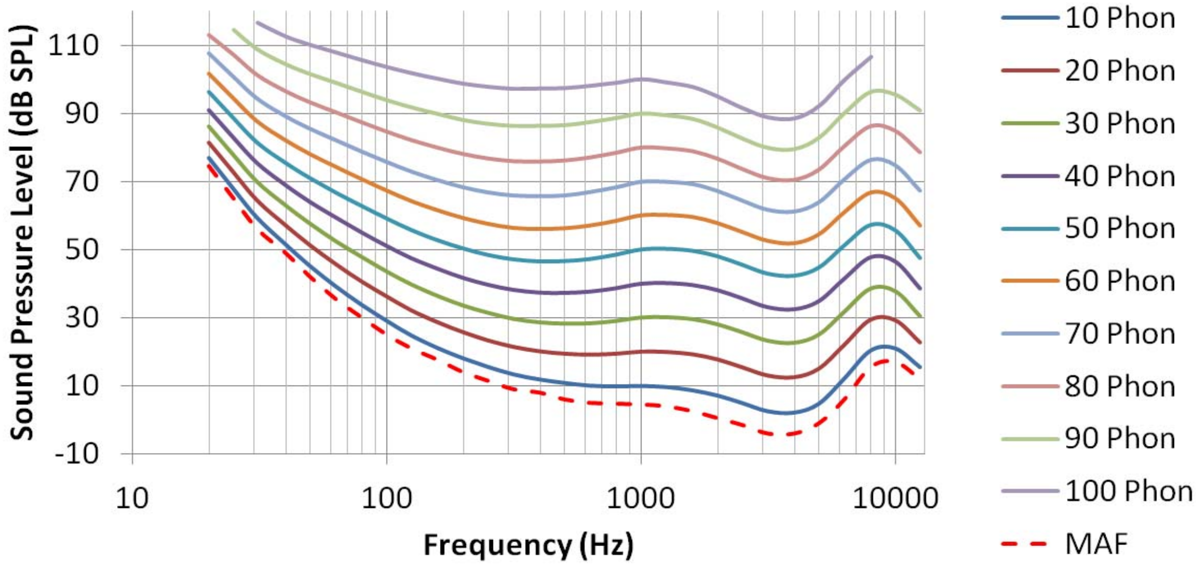

FIGURE 1. This figure shows the equal-loudness contours in accordance with ISO 226:1987. Note that at low frequencies the contours come together, and for most of the 20 to 30 Hz range, a 10 dB change in sound pressure level corresponds to a 20 phon change. NOTE: the 1987 contours are used because the 2003 contours are only defined from 20 phon to 90 phon, and they do not include the minimum audible field (MAF).

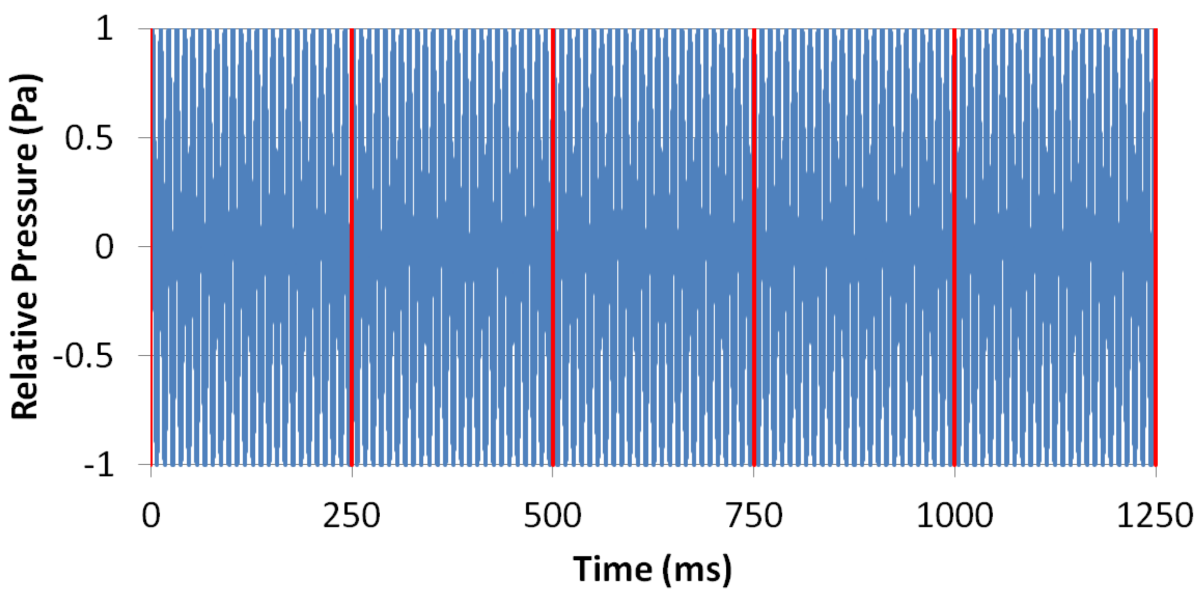

FIGURE 2a. This figure notionally shows a 1000 Hz sine wave with a continuous waveform. Since this figure cannot be meaningfully analyzed in this form, the following 1000 Hz figures are notional 1000 Hz figures, because the actual frequency rate portrayed is about 100 Hz rather than 1000 Hz, which would just appear as a solid block. Red lines mark each 250 ms interval.

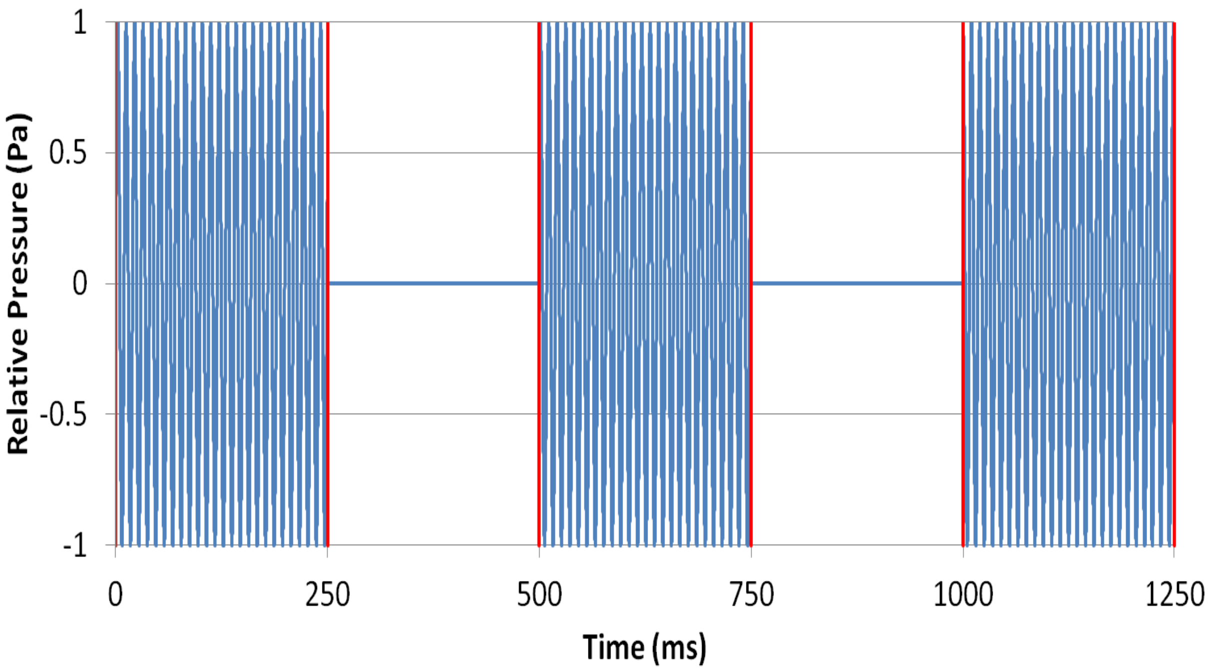

FIGURE 2b. This figure shows a notional 1000 Hz wave form turning on and off every 250 ms (we term this notional because the actual frequency rate portrayed is about 100 Hz rather than 1000 Hz, which would just show as a solid block, and not as a sine wave). Red lines mark each 250 ms interval.

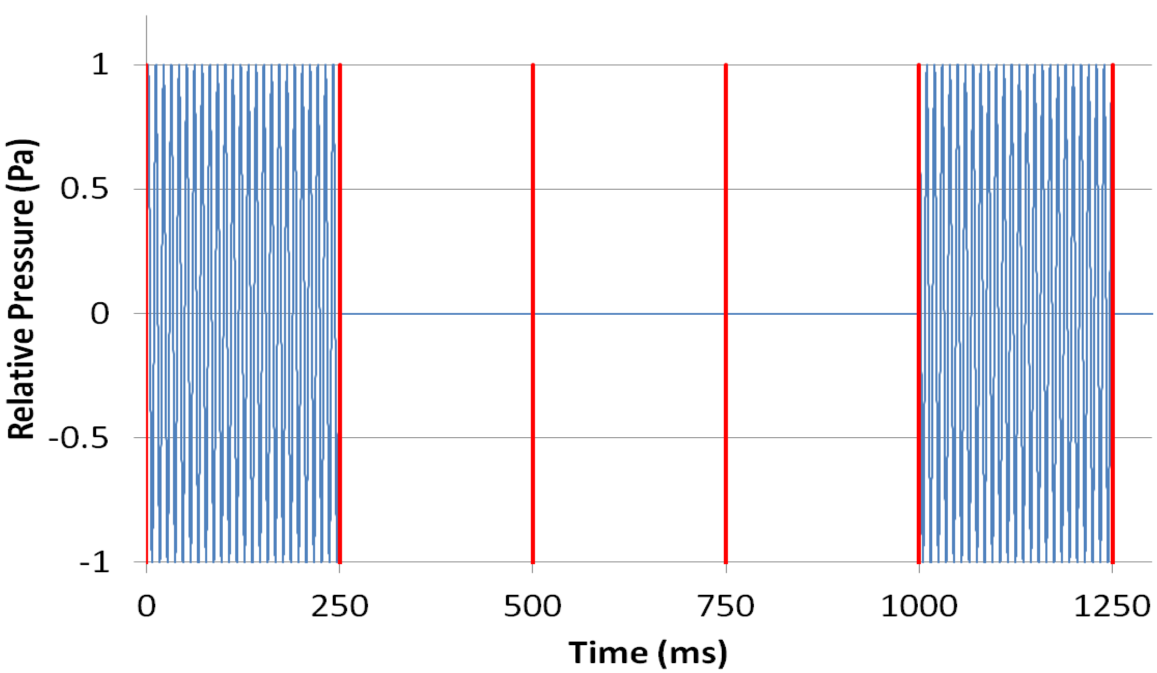

FIGURE 2c. This figure shows a notional 1000 Hz wave form present for the first 250 ms of each second. We term this notional because the actual frequency rate portrayed is about 100 Hz rather than 1000 Hz, which would just show as a solid block, and not as a sine wave. Red lines mark each 250 ms interval.

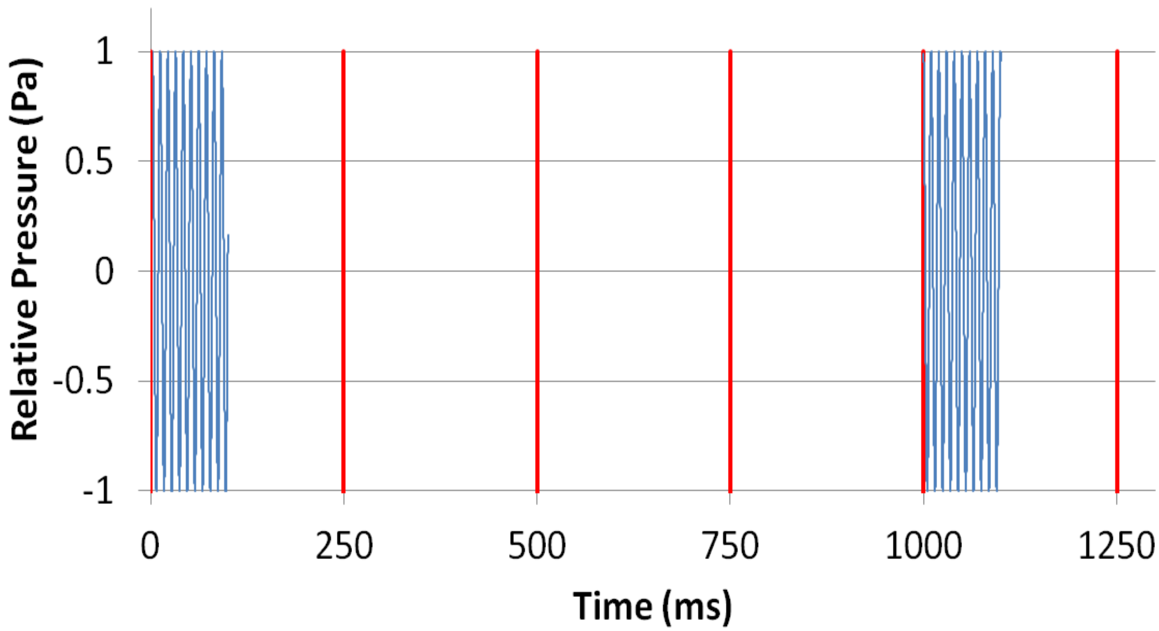

FIGURE 2d. This figure shows a notional 1000 Hz wave form present for the first 100 ms of each second. We term this notional because the actual frequency rate portrayed is about 100 Hz rather than 1000 Hz, which would just show as a solid block, and not as a sine wave. Red lines mark each 250 ms interval.

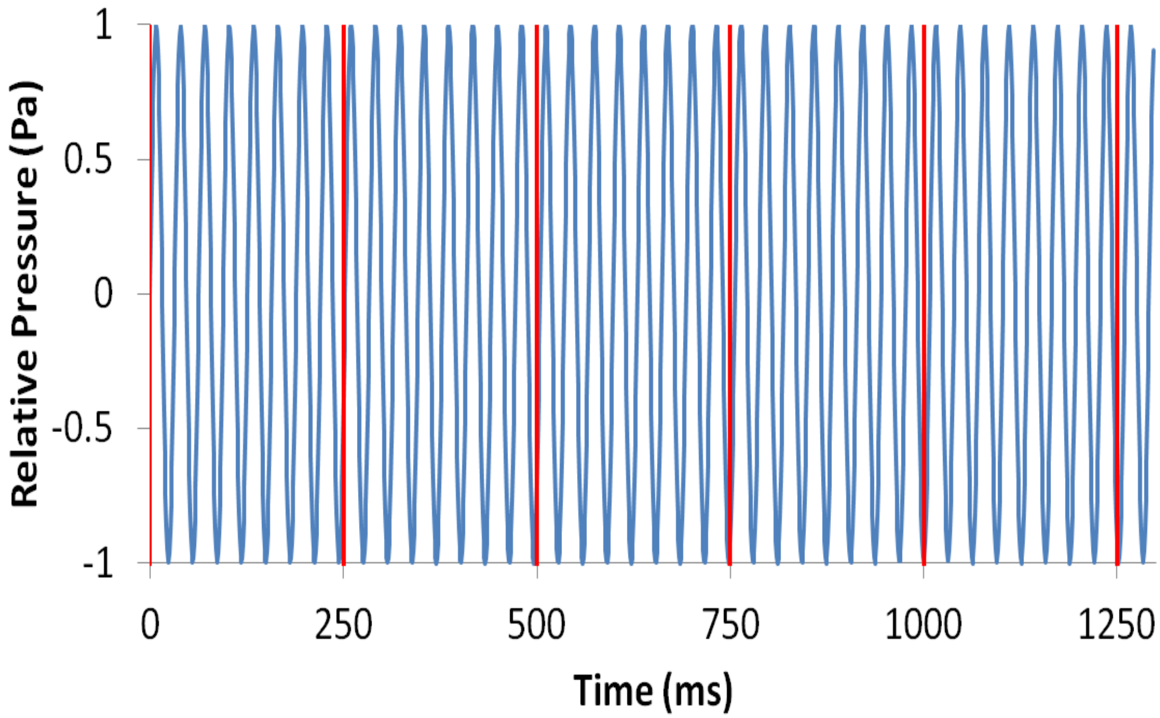

FIGURE 3a. This figure shows a 31.5 Hz continuous waveform. Red lines mark each 250 ms interval.

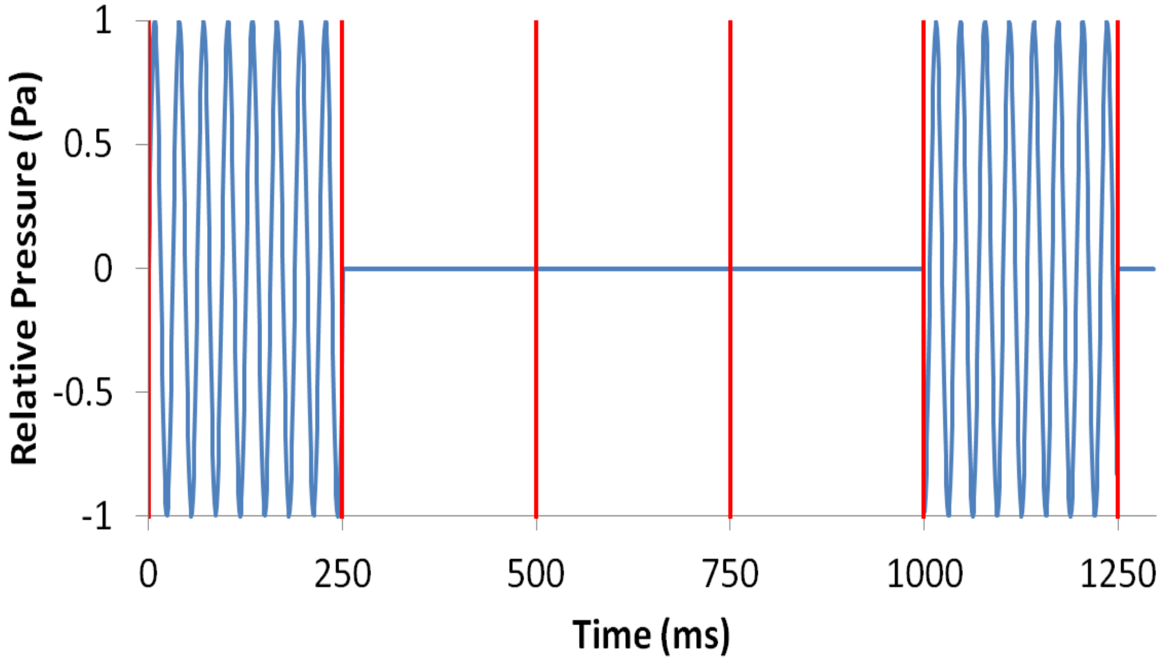

FIGURE 3b. This figure shows a 31.5 Hz wave form present for the first 250 ms of each second. Red lines mark each 250 ms interval.

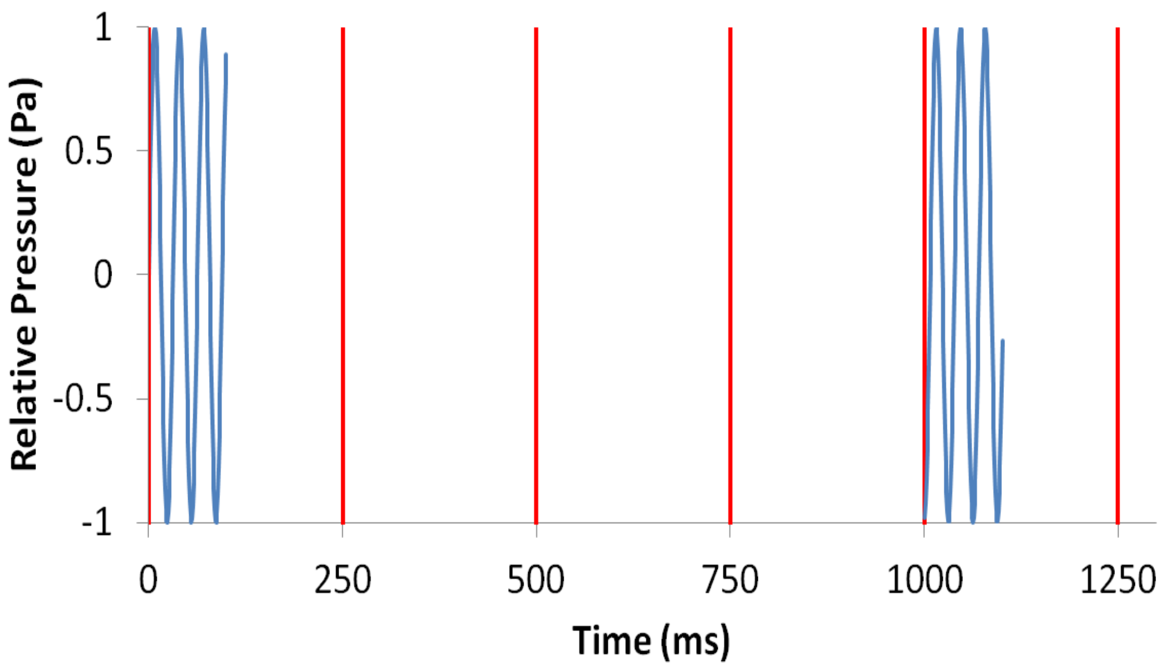

FIGURE 3c. This figure shows a 31.5 Hz wave form present for the first 100 ms of each second. Red lines mark each 250 ms interval.