Pickleball Noise Assessment

Sampson Creek

Prepared for

Saint Johns Golf and Country Club
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1. Summary

The noise impact of three proposed pickleball courts at the Saint Johns Golf and Country Club has been analyzed in regard to neighboring residential land uses. Acoustical modeling has been constructed accounting for pickleball court directivity, the topology of the area, and adjusting for the impulsive nature of the paddle impacts according to ANSI S12.9 Part 4. A set of sound pressure level contours has been shown indicating the spread of the sound from the pickleball courts into the adjacent neighborhood. Results have been compared to the Saint Johns County Noise Ordinances.

The ANSI S12.9 Part 4 assessment of the adjusted sound pressure levels at the nearest residential land uses found that the levels were below 55 dBA at the property lines for the homes. This is considered to comply with the annoyance criterion of Saint Johns County Ordinance 2015-19. No prescribed noise abatement treatments are needed for the proposed pickleball courts.

2. Characteristics of Pickleball Sound

Spendiarian & Willis has prepared many noise abatement plans for pickleball courts. This chapter summarizes some of the knowledge gained over the years of working with this sound source.

The main concern in regard to noise from the pickleball courts is the sound produced by the impact of the hard plastic ball on the paddles. This sound is characterized by a sudden onset and brief duration, thus classifying it as impulsive sound. The spectral content of the paddle impact is narrowband with a center frequency typically between 1,000 and 2,000 Hertz. This is near the most sensitive frequency range of human hearing.

2.1 Acoustical Characteristics

The sound produced by the impact between a pickleball and paddle is characterized by a rapid onset and brief duration, typically on the order of two milliseconds (0.002 seconds) for the direct path sound. This classifies it as impulsive sound. Figure 2.1 shows a time trace of a pickleball paddle impact measured near Phoenix, Arizona. The main part of the direct sound impulse can be seen to be less than two milliseconds followed by a rapid decay and some later reverberant arrivals.

The spectral content of the paddle impact is narrowband with a center frequency typically between 1,000 and 2,000 Hertz (see Figure 2.2). Although it does not meet most guidelines for tonal prominence such as Annex C of ANSI S12.9 Part 4 or ANSI S1.13, it does impart a vague sensation of pitch similar to a wood block percussion musical instrument. The radiation pattern of the paddle is more or less a dipole, i.e. the sound from the front and back of the paddle is of opposite polarity and cancels itself in the plane of the paddle. Therefore, orienting the courts so that the direction of play faces away from noise sensitive areas can provide some attenuation.

The sound power spectrum of the pickleball and paddle impact has two basic shapes depending on how the ball is hit. Figure 2.2 and Figure 2.3 show the power spectra of a 'sharp' hit and a 'dull' hit. The curves are not calibrated for absolute level, but can be compared relatively.

The sharp hit spectrum shows a narrowband signature. The frequency of the peak typically varies between 1,000 and 2,000 Hz. The energy in the dull hit is more spread out, but still peaks between 1,000 and 2,000 Hz.

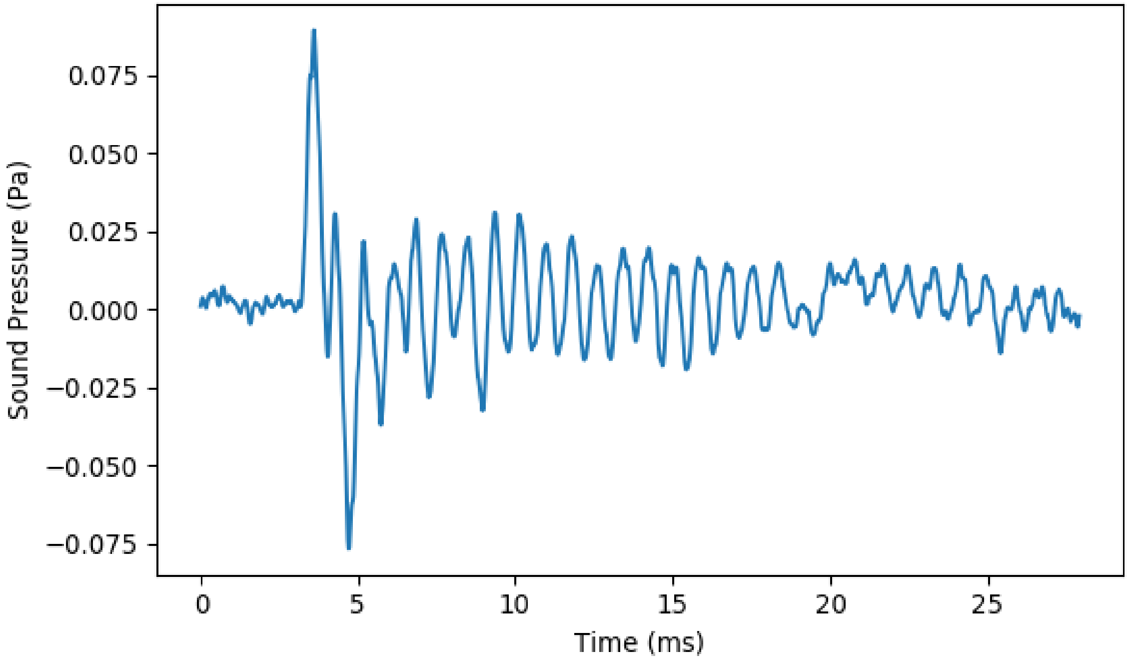

Figure 2.1. Pickleball Paddle and Ball Impact Sound Pressure Trace

1 millisecond (ms) = 0.001 seconds.

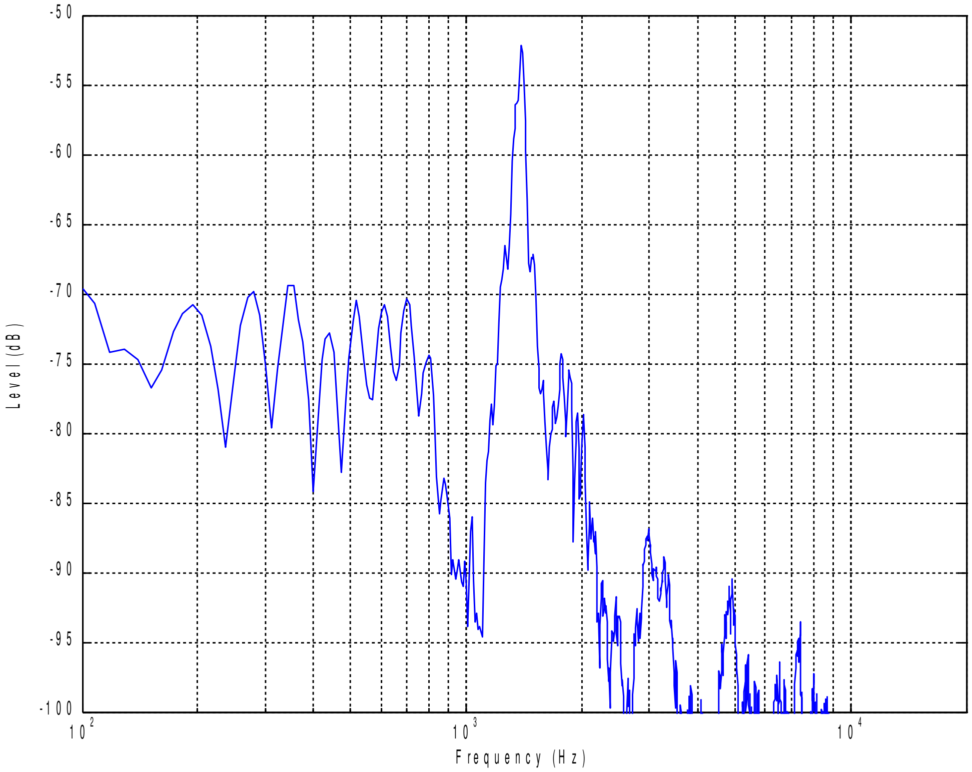

Figure 2.2. Spectral Response of a Sharp Hit

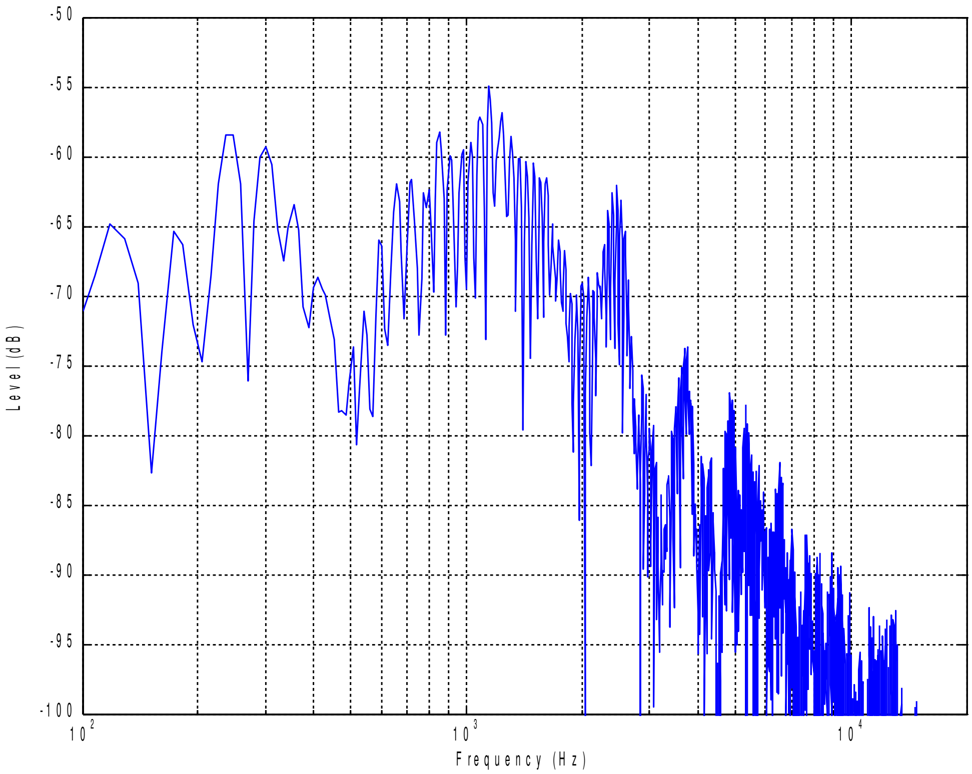

Figure 2.3. Spectral Response of a Dull Hit

A sound wall design will require effective attenuation in the 1,000 Hz octave band and above. In most applications, any material having a sound transmission class meeting STC 20 can be used to construct a sound wall or fence for pickleball provided best practices for sound barrier construction are followed.

2.2 Measuring Pickleball Sound

Due to the short duration of the impact, averaging sound pressure level metrics such as equivalent-continuous level (Leq), maximum fast exponential time weighted level (Lmax), and impulse time weighting (LAI) fail to accurately represent the perceived loudness and annoyance of the paddle impact and impact processes in general. The fast exponential time weighting filter is a first order lowpass filter with a 125 millisecond time constant applied to the square of the acoustic pressure waveform. If a tone burst is applied to the squaring circuit and filter, after two milliseconds the filter output will only rise to a level that is 18 dB lower than the equivalent-continuous sound pressure level of the input signal. Because the short impulse is being significantly attenuated by the averaging in the sound level meter, in practice it is generally not possible to distinguish pickleball paddle impacts from the background noise when measuring Leq or Lmax even though the paddle impacts may be identified by a listener as the primary sound source. To get a better correlation with the actual response of the surrounding community to this type of sound, metrics with a shorter time scale are needed.

The paddle impact sound pressure level is better represented by a combination of peak sound pressure level and sound exposure level (SEL). Using the sound exposure level involves windowing the measured sound pressure in time to include only the paddle impact and reflections from nearby surfaces as seen in Figure 2.1. The equivalent-continuous sound pressure level of the windowed impact is then normalized to the length of the window giving a representation of the energy in the impact alone. Appropriate adjustments for impulsive sounds can then be applied to the impacts as described next.

Most acoustical standards for sound pressure levels with regard to compatible land use provide adjustment factors for different types of sound, e.g. impulsive, tonal, time of day, etc. Each of these categories of sound produces different levels of community impact and annoyance due to their temporal or spectral characteristics in comparison to a broadband sound that does not vary in level or frequency content with time. The purpose of the adjustment factors is to normalize these types of sound to a neutral broadband sound pressure level so that they can be reasonably compared to a defined sound pressure level limit or the background noise level.

ANSI S12.9 Part 4 and ISO 1996 Part 1 give criteria for assigning adjustment factors to a variety of impulsive sounds. Sounds produced by impact processes are typically classified as 'highly impulsive' due to their high onset rates and assigned a 12 dB adjustment. Experience has shown that pickleball paddle impacts should be adjusted as highly impulsive sounds in order to set appropriate performance goals for abatement treatments. Inadequate abatement treatment may lead to ongoing complaints, strained relations with neighbors, legal action, the need for continued involvement on the part of authorities, retrofitting, and possibly demolition costs to improve the abatement later.

2.3 Problems with Exponential Time Weighting

Fast exponential time weighting is often recommended for assessing impulsive sound. For highly impulsive sounds having short durations this metric does not work well. When the averaging time of the time weighting is longer than the duration of the impulse, the impulse is in the stopband of the filter. In other words, the time weighting is filtering out the impulsive sound source being measured.

Figure 2.4 demonstrates the filter response to a burst of sound just long enough to achieve a reasonably accurate reading within 0.5 dB of the true sound pressure level. The red curve represents the envelop of a burst of sound 0.277 seconds in duration. This is the time required for the output of the fast exponential time averaging filter (blue curve) to rise to within 0.5 dB of the actual sound pressure level of the sound burst. When the sound burst ends, the output of the exponential time averaging filter begins to decay. The peak value in the output of the fast exponential time averaging filter, after being converted to sound pressure level, is known as the Lmax level.

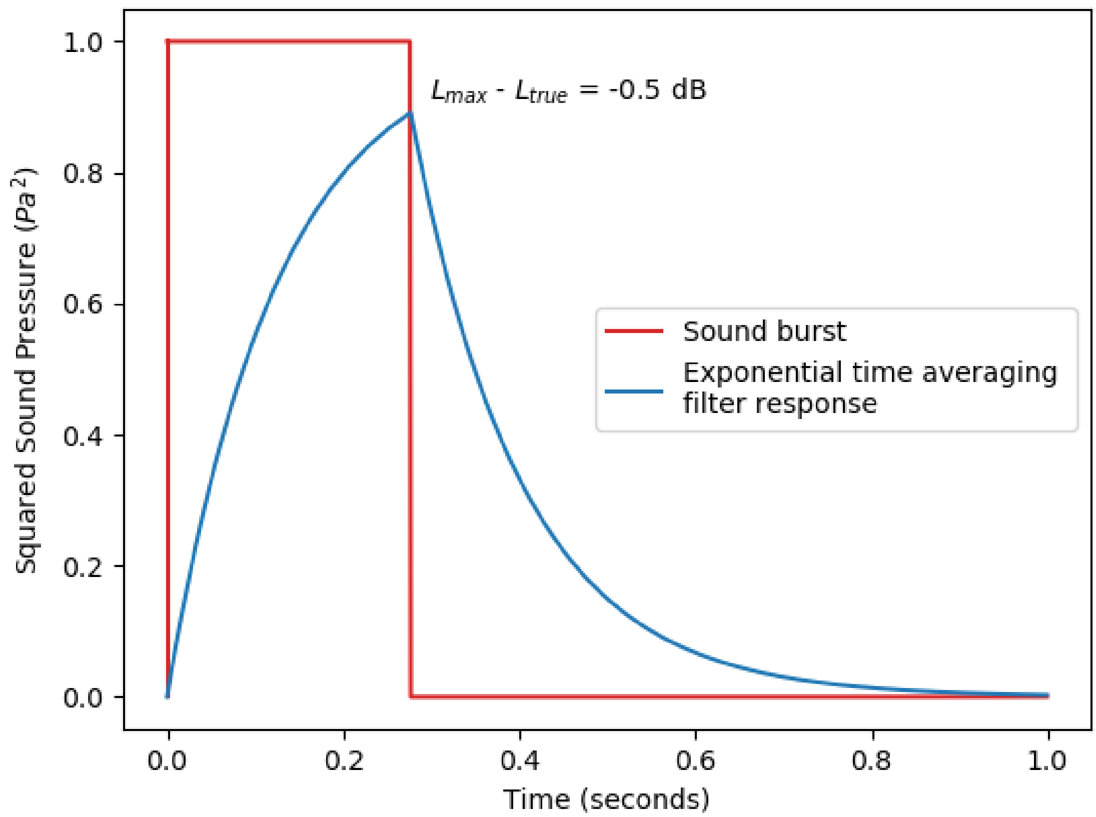

Figure 2.4. Fast Time Averaging Filter Response to a 0.277 Second Sound Burst

Figure 2.4 shows the behavior of the fast exponential time averaging filter and Lmax when used properly. Figure 2.5 illustrates how the fast exponential time averaging filter responds to a typical pickleball paddle impact. Note that the time scale has been reduced for clarity. At the end of the 0.002 second impulse, the fast exponential time averaging filter has only had time to rise to a level that is 18 dB below the true sound pressure level of the impulse. The pickleball paddle impulse is so much shorter than the time constant of the averaging filter that the exponential curvature of the filter response is not even visible. It is clear that fast exponential time weighting, much less slow exponential time weighting, cannot be used to assess the noise impact of pickleball paddle impacts.

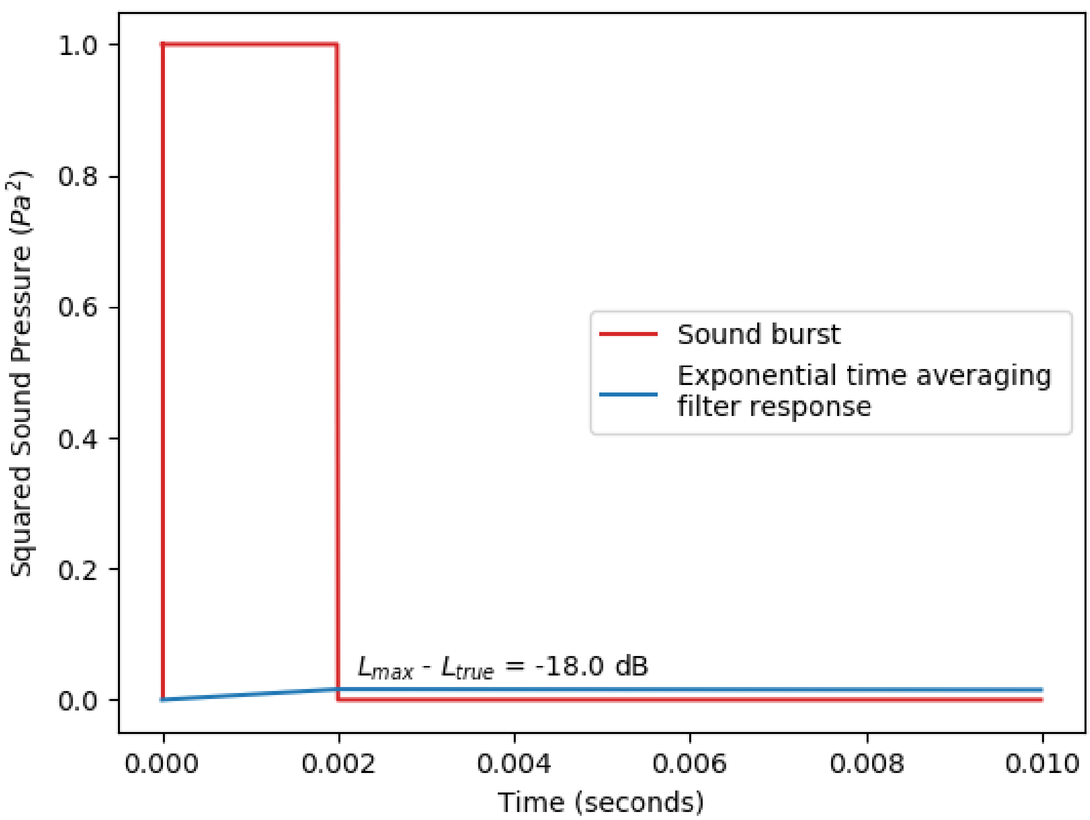

Figure 2.5. Fast Time Averaging Filter Response to a Typical Pickleball Paddle Impact

2.4 Directivity of Pickleball Courts

The impulsive sound of the paddle impacts is radiated mainly by the large, flat paddle surface. Since both faces of the paddle are connected internally by a honeycomb structure and move together in vibration, one side of the paddle will produce a positive sound pressure while the other produces a negative sound pressure similar to a loudspeaker diaphragm that is not mounted in a cabinet. The result is that these two pressure waves having opposite polarity will cancel in the plane of the paddle where the path length from each face is the same to all receiver locations. This is known as a dipole or figure eight radiation pattern.

The positions of the paddles relative to the court change with each hit; however, the object of the game is to hit the ball to the opposite half of the court. Therefore, the dipole axis of each paddle impact will be in the general direction of play and not completely random. Measurements of several pickleball facilities have shown that this results in a null depth of four to five dB. Figure 2.6 compares a typical pickleball court directivity pattern to a mathematical dipole where 0º and 180º are in the direction of play and the null is on the 90º and 270º bearings. Several decibels of attenuation can often be obtained simply by optimizing the orientation of the courts with respect to noise sensitive areas.

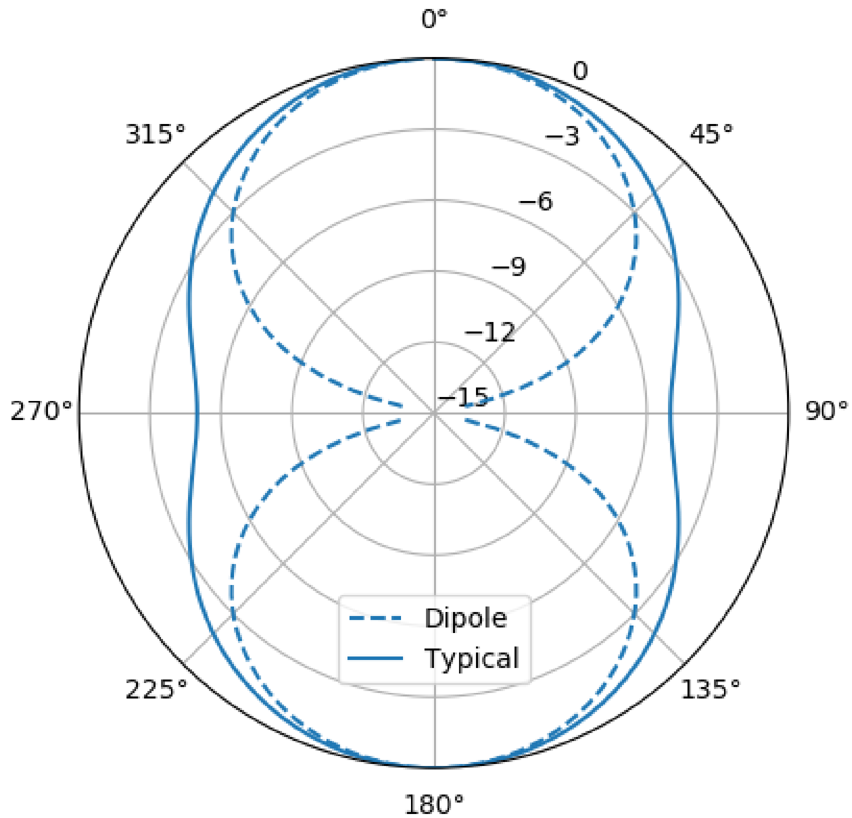

Figure 2.6. Typical Pickleball Court Directivity in Decibels

3. Site Plan Analysis

3.1 Noise Assessment Criteria

Saint Johns County Ordinance 2015-19 gives subjective criteria for assessing noise. In Section 4 noise is defined as,

> a sound or vibration that annoys or disturbs a human or which causes or tends to cause an adverse psychological or physiological effect on humans; loud or offensive disturbing sounds or vibrations. This term shall be used synonymously with "sound."

Section 3 states the measurement method.

> The measurement of sound or noise under this Ordinance shall be "plainly audible" by a human ear without the benefit of a hearing aid by a reasonable person of ordinary sensibilities, or "plainly discernible" by the human senses of a reasonable person of ordinary sensibilities.

These two parts of the Ordinance are in conflict with each other. While plainly audible or plainly discernible can serve as minimum thresholds for finding a noise violation, not all plainly audible or plainly discernible sounds cause annoyance. In fact, one will always be able to hear one's neighbors at certain times or under certain atmospheric conditions when the background noise level is low and conditions are favorable for propagation. The plainly discernible criterion is therefore a moving target and cannot be used as a basis for determination of the amount of noise mitigation required by a project site or what sound pressure level would be considered reasonable.

Annoyance, however, has specific meaning in the context of noise. There are national and international standards for quantifying and assessing this criterion. ANSI S12.9 is a national standard for quantifying annoyance caused by sound and is an appropriate method for assessing the noise impact of highly impulsive sound produced by impact processes such as pickleball paddle impacts. Part 5 of the standard recommends a maximum day-night level of 55 dBA for residential areas. This translates into a 55 dBA adjusted equivalent-continuous sound pressure level limit for daytime activities. While using this sound level as a design goal for abatement does not guarantee that a sound will not be plainly audible, it does reduce the noise impact of a site to a level that would be considered normally acceptable.

The 55 dBA day-night level recommended in ANSI S12.9 Part 5 is based on attitudinal survey studies funded by various federal agencies. Day-night level is a 24 hour equivalent-continuous sound pressure level with a 10 dBA adjustment for nighttime hours. It works well for most transportation noise sources (community response to aircraft flyovers has been found to correlate better with maximum fast exponential time weighted level). It does not work for impulsive or tonal sound sources. Additional research was therefore funded in the 1980s and 1990s to determine adjustments for sounds with special characteristics so that they could be compared to established day-night level limits for more neutral sound sources. In 1996, this noise assessment methodology was standardized in ANSI S12.9.

3.2 Modeling Parameters

3.2.1 Methodology

The acoustical site model has been constructed using the iNoise package version 2023.01 developed by DGMR. The sound propagation model is ISO 9613. This software conforms with the ISO/TR 17534-3 quality standard for implementing the ISO 9613 Part 2 outdoor sound propagation model.

3.2.2 Pickleball Paddle Sources

Spendiarian & Willis has not conducted measurements of pickleball on this site; however, we have test data from numerous other sites that has been used to construct the pickleball paddle sources for this site model.

For the reasons described in the previous chapter, neither the equivalent-continuous nor the fast exponential time weighted sound pressure level is sufficient to provide an assessment of the short duration paddle and ball impact sounds that correlates well with the community response to this type of sound. Therefore, the methodology of ANSI S12.9 Part 4 has been selected to assess the annoyance of the sound of the pickleball paddle impacts.

Pickleball paddle impacts in the model are based on measurements at a location in California using Dura 40 regulation balls with various paddles. The data was measured at 60 to 65 feet from the pickleball courts over a hard surface. The various ground types on and around the existing site have been included in the site models according to ISO 9613. The sound pressure levels of the paddle impacts are calculated from the mean sound exposure levels using 12 paddle impacts per minute for each court. Paddle impacts have been adjusted according to ANSI S12.9 Part 4 for highly impulsive characteristic (12 dB) and time of day (weekend, 5 dB). The resulting sound power is 102.8 dBA per court for an omni-directional sound source. The sound source for each court has been split into two vertical area sources placed at the serve lines with dipole directivity profiles applied having a null depth of 5.5 dB. The vertical area sources extend to the sidelines of the pickleball court (20 feet) and from the playing surface to a height of 8 feet to include overhead paddle impacts.

3.2.3 Sound Pressure Level Contour Maps

Sound pressure level contours in the figures below are displayed in 5 dBA increments. The grid height for the contours is 5 feet above grade. The legend identifying the map symbols is in Figure 3.1 and all sound pressure levels are A-weighted ANSI S12.9 adjusted levels as described above. Sound walls are labeled as barriers in the iNoise software.

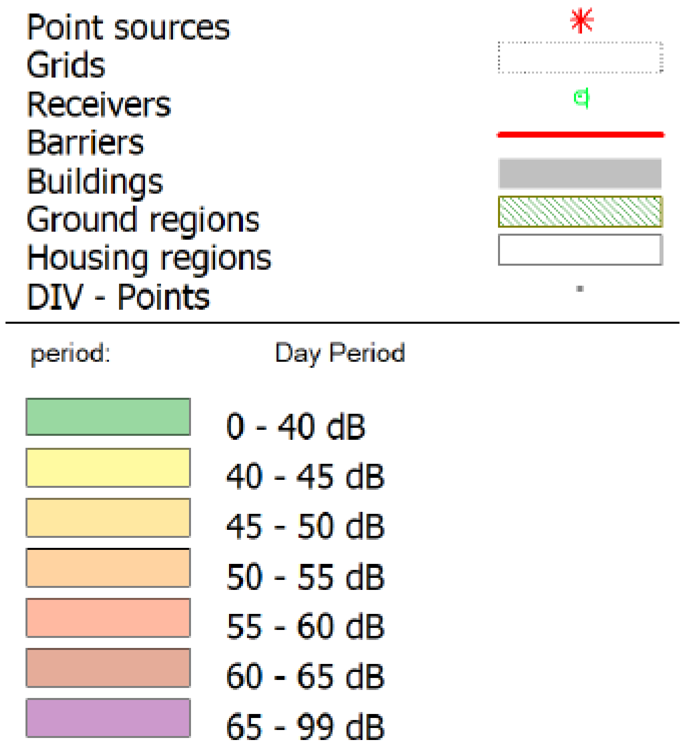

Figure 3.1 Legend for Sound Pressure Level Contour Maps

3.3 Pickleball Courts and Surrounding Area

Three pickleball courts are proposed at Sampson Creek on Cemetery Road. These are outlined in blue in Figure 3.2. The two closest residences have been selected as noise assessment locations. The residences are:

- 509 Stonebridge Path (540 feet east of proposed pickleball courts)
- 933 Brookhaven (570 feet south of proposed pickleball courts)

The noise assessment locations are shown as small green dots in Figure 3.2 and are called out by house number. The house at 933 Brookhaven is to the right of the figure.

Ground types in the ISO 9613 model are friable soil (ground factor = 1.0) everywhere except the pickleball and tennis court surfaces (ground factor, 0.0), water (ground factor, 0.0), and streets (ground factor, 0.1).

Figure 3.2. Proposed Pickleball Courts at Sampson

3.4 Proposed Pickleball Courts without Noise Abatement

Adjusted sound pressure level contours for the proposed pickleball courts are shown in Figure 3.3. The north-south projection of the sound in the direction of play can be seen in the oblong shape of the contours near the courts. The 55 dBA contour extends north to the clubhouses across the lake. Propagation in this direction is aided by the hard surface of the water and reflections from the facades of the clubhouse buildings.

Adjusted sound pressure levels are listed in Table 3.1 with ANSI S12.9 Part 5 recommended limits for single family residential land uses. Due to the distance of these homes, the adjusted levels are well below the target sound pressure level.

Location	Height Above Grade (ft)	Adjusted Sound Pressure Level (dBA)	Recommended Limit (dBA)	Exceeds Limit
509 Stonebridge Path	5	48.0	55	no
933 Brookhaven	5	50.2	55	no

Table 3.1. Adjusted Sound Pressure Levels for Proposed Courts

Figure 3.3. Adjusted Sound Pressure Level Contours for Proposed Pickleball Courts

4. Conclusions and Recommendations

4.1 Summary of Results

The noise impact of three proposed pickleball courts at the Saint Johns Golf and Country Club has been analyzed in regard to neighboring residential land uses. Acoustical modeling has been constructed accounting for pickleball court directivity, the topology of the area, and adjusting for the impulsive nature of the paddle impacts according to ANSI S12.9 Part 4. A set of sound pressure level contours has been shown indicating the spread of the sound from the pickleball courts into the adjacent neighborhood. Results have been compared to the Saint Johns County Noise Ordinances.

4.2 Noise Assessment

In order to avoid impacting the quality of life of neighbors and incurring complaints, Spendiarian & Willis has found that it is necessary to limit adjusted sound pressure levels at residential land uses to 55 dBA as recommended in ANSI S12.9 Part 5. This is not only to reduce impacts inside the home, but to preserve the ability to utilize outdoor spaces as well. Pickleball paddle impacts greater than this level are commonly audible inside homes.

The ANSI S12.9 Part 4 assessment of the adjusted sound pressure levels at the nearest residential land uses found that the levels were below 55 dBA at the property lines for the homes.

4.3 Saint Johns County Code Compliance

The Saint Johns County Ordinance 2015-19 does not provide an objective standard for compliance. Instead, two subjective criteria are given. As discussed in Section 3.1 above, the plainly discernible criterion cannot be used for quantitatively determining the amount of noise abatement needed due to unpredictable variations in background noise levels and meteorological conditions. The annoyance criterion is well researched and can be quantitatively assessed using ANSI S12.9 Part 4. This is the noise assessment methodology used in this report.

The ANSI S12.9 Part 4 analysis of sound produced by pickleball paddle impacts at the proposed site resulted in adjusted sound pressure levels that are within the range of sound pressure levels considered normally acceptable in ANSI S12.9 Part 5. This is considered to comply with the annoyance criterion of Saint Johns County Ordinance 2015-19.

4.4 Recommendations

Due to the long setbacks to the nearest homes, no prescribed noise abatement treatments are needed for the proposed pickleball courts.

References

ANSI S12.9-2021, *Quantities and Procedures for Description and Measurement of Environmental Sound – Part 4: Noise Assessment and Prediction of Long Term Community Response*, American National Standards Institute, 2021.

ISO 1996-1, *Acoustics - Description, measurement and assessment of environmental noise - Part 1: Basic quantities and assessment procedures*, International Organization for Standardization (ISO), 2016.

ISO 9613-2, *Acoustics — Attenuation of sound during propagation outdoors — Part 2: General method of calculation*, International Organization for Standardization (ISO), 1996.

Schultz, T. J., "Synthesis of Social Surveys on Noise Annoyance," Journal of the Acoustical Society of America v. 64, pp. 377-405, 1978.

World Health Organization, Night Noise Guidelines for Europe, http://www.euro.who.int, 2009.

Appendix

A1. Glossary of Acoustical Terms and Abbreviations

A1.1 Abbreviations

AI: articulation index

ASEL: A-weighted sound exposure level

ASTC: apparent sound transmission class

dB: decibel

DNL: day - night level

FSTC: field sound transmission class

Hz: Hertz

IIC: impact insulation class

kHz: kilohertz

L_{eq}, LA_{eq}, LC_{eq}: equivalent sound pressure level

Lmax, LAmax: maximum fast sound pressure level

NC: noise criteria

NIC: noise isolation class

NIPTS: noise induced permanent threshold shift

NR: noise reduction

Pa: Pascal

POE: probable occupant evaluation (see room criteria)

PTS: permanent threshold shift

PWL: sound power level

QAI: quality assessment index (see room criteria)

RC: room criteria

RT_{60}: reverberation time

SEL: sound exposure level

SII: speech interference index

SIL: speech interference level

SLM: sound level meter

SPI: speech privacy index

SPL: sound pressure level

STI: speech transmission index

TTS: temporary threshold shift

A1.2 Terms

A-weighting: see frequency weighting

absorption coefficient: see sound absorption coefficient

acoustical coupler: a cavity of predetermined shape and volume used for the calibration of earphones or microphones in conjunction with a calibrated microphone adapted to measure the sound pressure developed within the cavity

anechoic room: a room whose boundaries absorb practically all of the sound incident thereon, thereby providing essentially freefield conditions

articulation index (AI): a number (ranging from 0 to 1) which is a measure of the intelligibility of speech- the higher the number the greater the intelligibility. This metric has been replaced by the Speech Intelligibility Index (SII) defined in ANSI S3.5.

average sound level: see equivalent-continuous sound level

background noise: the total noise from all sound sources excluding a particular sound source that is of interest

band: a subsection of the frequency spectrum

C-weighting: see frequency weighting

coupler: see acoustical coupler

day-night level (DNL): the 24 hour equivalent (average) A-weighted sound pressure level. A 10 dBA penalty is incurred between the hours of 10:00 PM and 7:00 AM. The DNL system has been adopted by the U.S. Department of Housing and Urban Development, the Department of Defense, and the Federal Aviation Administration.

decibel (dB): a unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the common logarithm (base 10) of this ratio.

diffuse field: a sound field which has statistically uniform energy density and in which the directions of propagation of the sound waves are randomly distributed. In a practical sense, the sound pressure levels at all points in the room are nearly the same except near the room boundaries and a sound wave reaching a given point in the room is equally likely to arrive from all directions.

direct sound: sound which reaches a given location in a direct line from the source without any reflections.

equivalent-continuous sound level (L_{eq}): the level of steady sound which, in a stated time period and at a stated location, has the same sound energy as the time varying sound. If frequency weighting is applied, the equivalent continuous sound level may be designated LA_{eq} to indicate A-weighting or LC_{eq} to indicate C-weighting, etc. See also frequency weighting.

fast exponential time weighting: a lowpass filter for the purpose of averaging a signal having a time constant of 0.125 seconds applied to the square of the sound pressure as specified in ANSI S1.4.

field sound transmission class (FSTC): a single number rating similar to sound transmission class (STC), except that the transmission loss values used to derive this class are measured in the field. FSTC ratings are typically lower than STC ratings which are measured under laboratory conditions.

flanking path: A wall or floor/ceiling construction that permits sound to be transmitted along its surface; or any opening, which permits the direct transmission of sound through the air.

freefield: a sound field in which the boundaries have negligible effect over the frequency range of interest.

frequency: the number of times that a waveform repeats itself in a given period of time, usually one second, i.e. the number of cycles per second). Unit: Hz.

frequency weighting: a prescribed frequency dependent attenuation or amplification applied to measured sound data usually intended to better approximate the sensation of loudness in a human listener. For example, A, B, and C weighting approximate the frequency dependent shape of the equal loudness contours for soft, moderate, and loud sounds.

Hertz (Hz): unit of frequency, cycles per second.

impact insulation class (IIC): a single number metric used to compare the effectiveness of floor-ceiling assemblies in providing reduction of impact-generated sounds such as footsteps. This rating is derived from values of normalized impact sound pressure levels in accordance with ASTM E492.

impulsive sound: sound that is characterized by brief excursions of sound pressure, typically less than one second,whose peak pressure significantly exceeds the background sound pressure.

insertion loss: the reduction in sound level at the location of the receiver when a noise reduction measure such as a barrier, attenuator, muffler, etc. is inserted into the transmission path between the source and receiver. Unit: dB.

level: the logarithm of the ratio of a given quantity to the reference quantity of the same kind. Levels represent physical quantities such as sound pressure on a logarithmic scale and are therefore expressed in decibels. Unit: dB.

loudness: that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud. Unit: sone.

masking: the process by which the threshold of hearing for one sound is raised by the presence of another sound.

maximum fast sound pressure level: the maximum sound pressure level recorded using fast exponential time weighting.

noise criteria (NC): a single number criteria for the HVAC or mechanical noise level in a room derived from measured octave band data. The octave bands are weighted to de-emphasize low frequencies because the human ear is least sensitive to these frequencies. This metric is not valid for outdoor measurements.

noise induced permanent threshold shift (NIPTS): the permanent hearing loss resulting from noise exposure.

noise isolation class (NIC): a single number rating derived from measured values of noise reduction between two enclosed spaces that are connected by one or more paths. This rating is not adjusted or normalized to a standard reverberation time.

noise reduction (NR): the difference in sound pressure level between any two points along the path of sound propagation, e.g. the difference in level between the interior and exterior of a building where the sound level inside is due only to exterior noise.

octave: the frequency interval between two tones whose frequency ratio is 2.

omnidirectional microphone: a microphone whose response is independent of the direction of the incident sound wave.

Pascal (Pa): a unit of pressure. 1 Pascal = 1 Newton per square meter ($1 \ N / m^2$).

permanent threshold shift (PTS): a permanent increase in the threshold of hearing at a given frequency.

point source: a source that radiates sound as if from a single point.

receiver: a person (or persons) or equipment which is affected by sound.

refraction: (1) the phenomenon by which the direction of propagation of a sound wave is changed as a result of a spatial variation is the speed of sound. (2) The angular change in direction of a sound wave as it passes obliquely from one medium to another having different sound speed.

reverberation time (RT_{60}): of an enclosure, for a sound of a given frequency or frequency band, the time that is required for the sound pressure level in the enclosure to decrease by 60 dB after the source has stopped. Unit: second.

room criteria (RC, RC Mark II): an octave band metric for evaluating HVAC noise inside a room. RC is a two dimensional metric consisting of a curve number that is the arithmetic average of the 500, 1000, and 2000 Hz octave band sound pressure levels and a qualitative descriptor identifying the character of the sound spectrum. The descriptor can be (N) for neutral, (LF) for low frequency dominance (rumble), (MF) for midfrequency dominance (roar), and (HF) for high frequency dominance (hiss). In addition, acoustically induced vibration can be designated by (LFV_B) for moderate, but perceptible vibration and (LFV_A) for clearly perceptible vibration. As an example, the maximum RC prerequisite for LEED is designated as RC 37(N) indicating curve number 37 with a neutral spectrum.

Further, two intermediary metrics are used in calculating the room criteria. The quality assessment index (QAI) is a measure of the deviation from the given RC curve. The probable occupant evaluation (POE) is based on the magnitude of the QAI and can be 'Acceptable,' 'Marginal,' or Objectionable.'

Sabin: a unit of measure of sound absorption; a measure of sound absorption of a surface. It is the equivalent of 1 square foot of a perfectly absorbing surface; a metric Sabin is the equivalent of 1 square meter of a perfectly absorbing surface.

sone: the unit of loudness. One sone is the loudness of a pure tone presented frontally at a frequency of 1000 Hz and a sound pressure level of 40 dB referenced to 20 micropascals.

sound absorption coefficient (α): ideally, the fraction of diffusely incident sound power that is absorbed (or otherwise not reflected) by a material or surface.

sound exposure level (SEL): over a stated time period or event, 10 times the logarithm base 10 of the ratio of the time integral of the sound pressure squared to the product of the reference sound pressure, 20 μPa, squared and the reference time, one second.

sound level meter (SLM): an instrument that is used to measure sound level, with a standard frequency weighting and standard exponentially weighted time averaging.

sound power level (PWL): the total acoustical power emitted from a sound source expressed in decibels relative to 10^{-12} Watts.

sound pressure level (SPL): the acoustical pressure amplitude expressed in decibels relative to 20 micropascals.

sound transmission class (STC): a single number rating used to compare sound insulation properties of walls, floors, ceilings, windows, or doors. See also field sound transmission class.

speech intelligibility index (SII): metric defined under ANSI S3.5 to quantifiy the intelligibility of speech under adverse listening conditions such as noise masking, spectral filtering, and reverberation. The SII is defined for a scale of 0 to 1 where values greater than 0.75 indicate good communication and values below 0.45 indicate generally poor communication conditions.

speech intelligibility test: a procedure that measures the portion of test items (such as syllables, monosyllabic words, or sentences) that are heard correctly.

speech interference level (SIL): an index for assessing the interference effects of noise on the intelligibility of speech, derived from measurements of the background noise level of contiguous octave bands; i.e. the arithmetic average of the octave band sound levels for the bands centered at 500, 1000, 2000, and 4000 Hz (four band method) or the corresponding average for the octave bands centered at 500, 1000, and 2000 Hz (three band method). If other octave bands are used they must be specified. Unit: dB.

speech privacy index (SPI): The SPI is essentially the opposite of the speech intelligibility index and is defined as 1 - SII and usually represented as a percentage. An SPI above 80% is considered normal privacy while an SPI above 95% would meet the requirements of confidential privacy.

speech transmission index (STI): an index for rating the intelligibility of speech that takes both noise and reverberation into account.

temporary threshold shift (TTS): a temporary increase in the threshold of hearing at a given frequency.

threshold of hearing: for a given listener, the minimum sound pressure level of a specified sound that is capable of evoking an auditory sensation. The sound reaching the ears from other sources is assumed negligible.

transducer: a device designed to receive an input signal of a given kind and to furnish an output signal of a different kind in such a manner that the desired characteristics of the input signal appear in the output signal. For example, a microphone takes an acoustic pressure as an input and produces an electrical voltage as an output that is direct proportion to the instantaneous acoustic pressure amplitude. Other common examples in noise measurement would be a loudspeaker, accelerometer, or laser Doppler vibrometer (LDV).

transmission loss: the reduction in sound level from one side of a partition to the other.

wavelength: the distance a sound wave travels in the time it takes to complete one cycle.

weighting: see frequency weighting

A2. General Acoustics

Sound Pressure Level (SPL)

Sound is small, rapidly varying perturbations of atmospheric pressure with respect to the slowly changing ambient pressure. The ambient pressure is measured with a barometer while the small acoustic perturbations are measured with a microphone.

The unit of sound pressure is the Pascal (Pa). However, due to the wide range of acoustic amplitudes that can be heard by the human ear, sound pressure is normally expressed on a logarithmic scale having units of decibels (dB). Sound pressure expressed this way is known as the sound pressure level (SPL) and has the following relation to sound pressure.

$$SPL = 20\log_{10}\left(\frac{p}{p_{ref}}\right) \qquad \text{(A2.1)}$$

Here p is the sound pressure in Pascals. p_{ref} is a reference pressure, the threshold of hearing at 1000 Hertz (Hz), 20 x 10^{-6} Pa.

A-Weighting

The above formulation of SPL is a purely physical quantity. Due to the nonlinear and frequency dependent characteristics of the human ear it does not always correlate well with the perception of loudness. To improve the correlation for noise assessment purposes, a frequency weighting is often applied called A-weighting. The A-weighting function is based on listening tests in which human subjects adjusted tones throughout a range of frequencies to have equal loudness compared to a tone having an SPL of 40 dB at 1000 Hz. Figure A2.1 shows equal loudness contours according to ISO 226.

Thus applying A-weighting to measured sound pressures more closely represents the frequency response of the human ear for low to moderate amplitude sound. Sound pressure levels that have been A-weighted are denoted by the symbol, dBA. Figure A2.2 shows the A frequency weighting and several other common weightings.

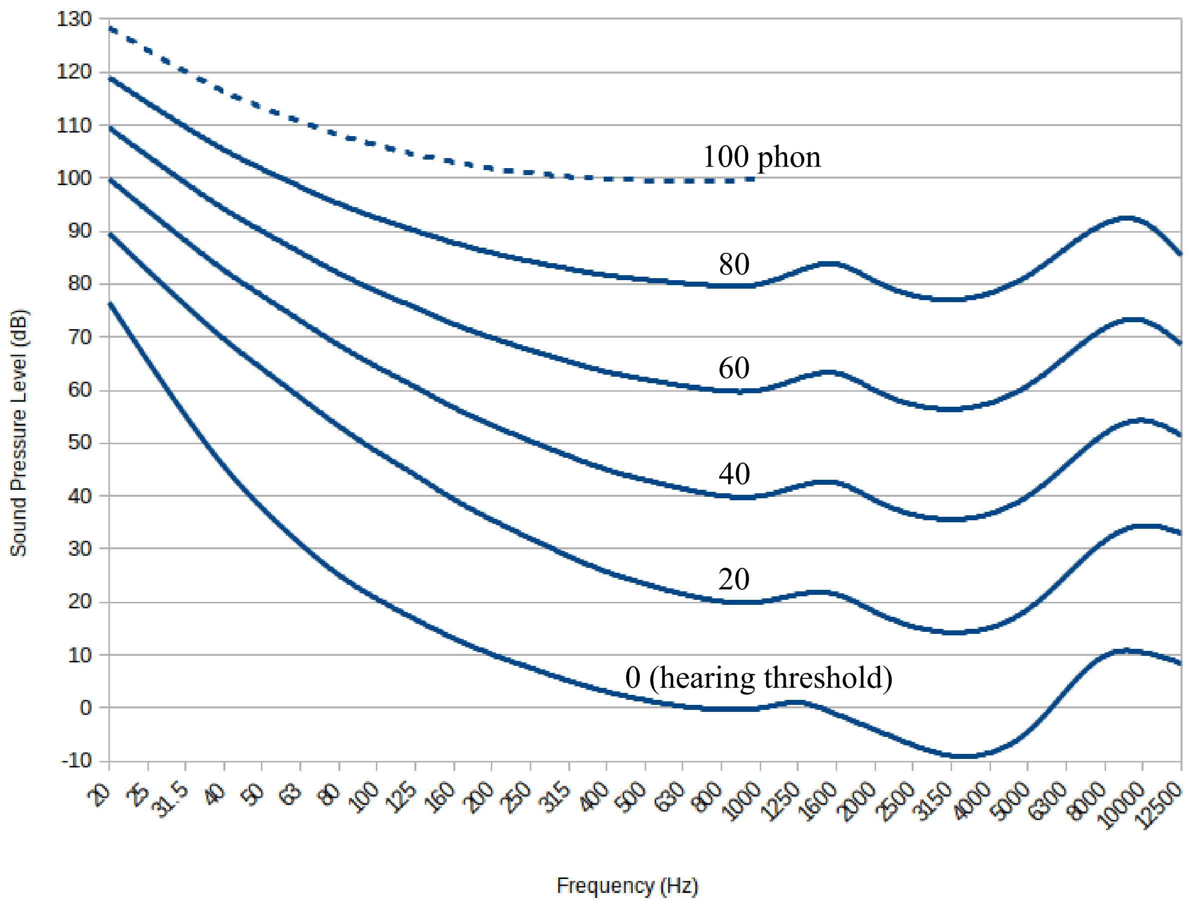

Figure A2.1. ISO 226 Equal Loudness Contours

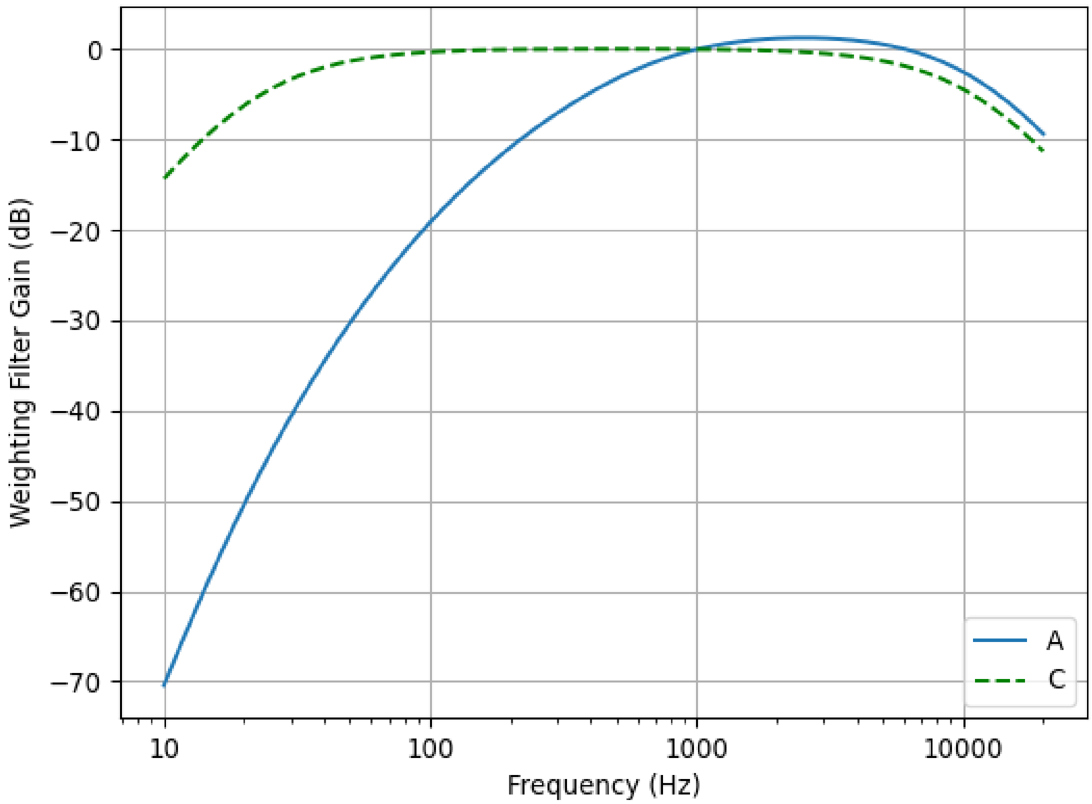

Figure A2.2. Frequency Weighting Filter Curves

The Perception of Sound

The most basic descriptions of sound are loudness (amplitude) and pitch (frequency). The frequency range of human hearing is roughly 20 to 20,000 Hz, although most people can not hear this full range because high frequencies are lost as a natural part of aging and other factors such as illness and exposure to high levels of noise that may cause permanent hearing loss.

Amplitude Attenuation with Distance

Sound originating from a small point source will spread spherically in all directions, absent any nearby surfaces. The conservation of energy requires the sound pressure spreading out from such a source to decrease by half with each doubling of distance. This is known as the inverse square law and is demonstrated in Table A2.1 and Figure A2.3.

Distance from Source (ft)	SPL (dBA)	SPL Loss Relative to 10 ft
10	90	
20	84	6
40	78	12
80	72	18
160	66	24
320	60	30

Table A2.1. Decrease of SPL with Distance Due to Spherical Spreading

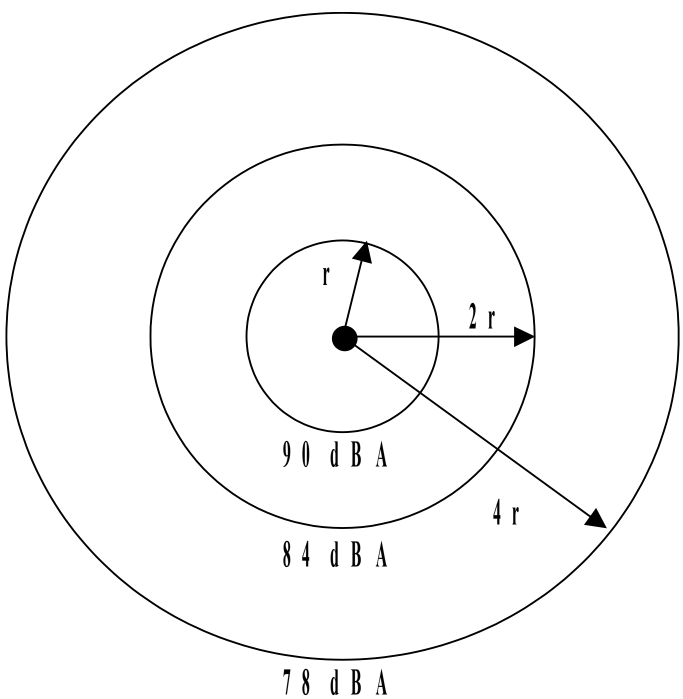

Figure A2.3. Decrease of SPL with Distance Due to Spherical Spreading

Adding Decibels

Summing the contributions from multiple sound sources to obtain the total SPL is *not* done simply by adding the decibel levels because SPL is a logarithmic quantity.

Imagine a fan produces a moderate SPL of 65 dBA at 6 feet. If a second identical fan were turned on the resulting SPL would not be 130 dBA. This would be equivalent to a commercial jetliner taking off at close range.

The correct method of adding the SPL from each source is to sum the acoustic power produced by each source. This implies that each time the number of sources having equal SPL is doubled, the SPL will increase by 3 dBA. Therefore, in the example with two fans, the correct total SPL would be 68 dBA. More examples with multiple sources producing equal SPL are shown in Figure A2.4.

65 dBA + 65 dBA $\neq$ 130 dBA **WRONG** (A2.2)

65 dBA + 65 dBA = 68 dBA **RIGHT** (A2.3)

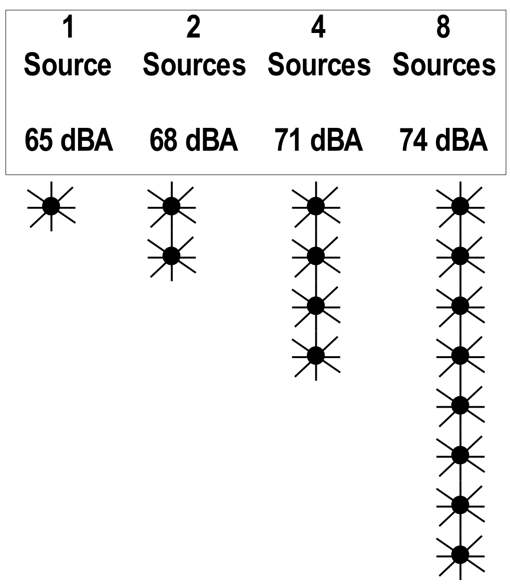

Figure A2.4. Total SPL from Multiple Sources with Equal SPL Output

Further Reading

Bruel and Kjaer, "Measuring Sound." Covers topics in this appendix in more detail. Available on the Bruel and Kjaer website, www.bkhome.com. Find this and other primers under the library section of the site.

Cyril M. Harris, Ed. Handbook of Acoustical Measurements and Noise Control, 3rd Edition. Acoustical Society of America, Melville, NY, 1998.