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CONSIDERATIONS FOR A NOISE ORDINANCE

Introduction

The goal of this memo is to discuss some of the issues that may be relevant for making decisions relating to a noise ordinance that is realistic and consistent. Obviously, some of these issues are somewhat technical, and for this reason, an attempt is made here to keep math and physics to a minimum, and to draw heavily on everyday observations and analogy wherever possible. In addition, it is important to develop a basic knowledge of perceptual psychology as it relates to human hearing, since ultimately the receiver of sound is a human ear, and not an electrical instrument. In addition to the engineering and scientific issues relating to the ear, we must not ignore issues of a more subjective nature. We should always seek to make our objective measurements correlate with the most generally held opinions (regarding reasonable sound levels) while at the same time better understanding how minority points of view that are honestly held come about.

Subjective, Objective, or Both?

A noise ordinance might well involve both subjective and objective descriptions of the nature of sounds that would violate that ordinance. On the one hand, over-reliance on a subjective description (e.g., "unreasonable noise") clearly could lead to an endless expression of varying opinion. On the other hand, an objective description (e.g., not over 60 decibels) would seem clear cut, but leads to two problems. First, there is a bit more to specifying a decibel limit than just one threshold number. But actually, there is not a great deal more - just a few meter settings to select wisely. Secondly, the actual decibel levels chosen need to be carefully chosen so as to reflect a carefully considered range of opinion as to what is reasonable versus unreasonable.

It can perhaps be mentioned here that simple sound level meters are inexpensive (as little as $50) and are far, far simpler to use than most remote controls for entertainment systems (and are about the same size). Further, while these simple meters might not be (legally) adequate from an enforcement point of view, they do tell a more than adequate version of the truth. Accordingly, numerous inexpensive meters, readily available to enforcement officials, and perhaps to lend to the public, could provide a lot of sobering information both for noise producers and noise consumers.

Levels of Loudness (Decibels and the Way the Ear Hears)

When we are speaking of sound levels, the word "decibels" soon comes up. It is useful to understand decibels (i.e., mathematical logarithms), but more importantly, the reason why sound pressure levels (the measurable correlate of perceptual "loudness") are measured on a logarithmic scale. The reason is that the ear can hear sound over an enormously wide range. Generally this is considered to be a range of 120 decibels, where 0 db is a "threshold of hearing" (you can just detect a sound) and 120 db has the more ominous but accurate description as the "threshold of pain." Perceptible sound pressure levels (the actual air pressure, in the same sense that a tire has pressure) on the eardrum ranges over a million to one when expressed as ordinary numbers instead of db. And the ear does this entire range without a "range switch" - something engineers can't build. There is no reason why we absolutely have to use logarithms (decibels). It is a matter of convenience and proves very useful. And we are stuck with it!

The reader who has forgotten how to do logarithms will be here very briefly reminded of the mathematics, which is not essential. If one sound has a pressure (force/area) of P_1 and another sound has a pressure P_2, the arithmetic ratio is P_1/P_2 while the very same ratio expressed in decibels is:

$$db = 20\ \mathrm{Log}_{10}(P_1/P_2)$$

We notice that this is the ratio of two sound pressures. No one sound level can be expressed in decibels, unless a second "reference" level is specifically stated or implied by tradition. For sound levels, the sound pressure level of 20 micro-Newtons per square meter is the usual reference. (The units of Newtons per square meter are also called "Pascals.") This is what is considered to be the "threshold of hearing" - the very smallest sound level we can hear. Thus if P_2 is this threshold reference, and P_1 is also at this threshold, then we have 0 db for the threshold of hearing, since $\mathrm{Log}_{10}(1)=0$, i.e., $10^0=1$. If the sound pressure is a million times larger, we have 120 db, Note that 60 db is only 1000 times larger than the threshold, and, for that matter, 1000 times smaller than pain.

[It should perhaps be appreciated that the sound pressure level changes at the eardrum are absolutely tiny relative to the ambient atmospheric pressure (as reported on the weather report) that normally presses equally on both sides of the eardrum (our ears make the familiar "pop" when equilibrium is restored following some upset of balance such as going up and down a hill). In terms of the standing atmospheric pressure, the threshold of hearing is about two ten-billionths of an atmosphere, and the threshold of pain is accordingly only two ten-thousandths of an atmosphere. This demonstrates that the ear is astoundingly sensitive both in terms of the low levels it can detect and in terms of overall range of levels it can handle. Again we mention that what the ear does easily is tough for engineers to do.]

One inherent consequences of using decibels is that we are dealing with ratios, and in fact with ratios that vary over wide ranges (a factor of a million). The use of logarithms just makes these ratios easier to write down with fewer digits. Any ratio is a single number, and it discards half the information contained if we kept both numbers. For example, if we say that Bill's income is twice that of Jane, we know nothing about their actual incomes until one or the other is specifically mentioned. Perhaps Bill makes $100,000 and Jane makes $50,000, but who knows? But whether or not Jane is wealthy would depend on whether Bill is perhaps a 10 year old with a summer lemonade stand on the lawn, or if Bill's last name is Gates.

So a ratio is problematic in many cases. There are cases, however, where it is more informative to know just a ratio instead of knowing both numbers. This is where we can describe a whole class of numbers. For example, we might say that a company had to cut all its salaries to 85%. Or we might say that all sounds with frequencies around 5000 Hz are attenuated by 10 db (to about 1/3) for every 100 meters of travel through air.

It must be recognized that decibels are not additive. For example, a person holding a party measured at 70 db might ask about the ordinary "ambient" noise in the neighborhood and be told it is 50 db, and then claim responsibility for only a modest increase of 20 db. Actually if you add the 50 db background to a 70 db party you get only 71db*, certainly not the (70+50=120) 120 db threshold of pain. A relatively quite background has only a tiny effect overall.

As a second example, if 60db is allowed, and one (legal) party is producing 60 db, while a second party is producing 75 db, and these combine at the street, you would get 76.4 db, so the louder party is producing most of the noise. When combining individual decibel levels that differ by say 15 db or more, the larger one pretty much tells the result. Note however that two parties at 60 db may combine to 66 db. Both added are likely in violation (this addition may be tricky to analyze exactly), and both would have to be reduced to 54 db if we are including combined parties.

In addition to this non-additivity, and the dominance of a sound if it is 15 db or more larger, there are a few other rules-of-thumb to consider. In general we think of any change of about 1 db (about 12%) as a "barely detectable" (by the ear) level change. An increase of 6 db is a doubling of level. An increase of 20 db is a factor of 10 increase. Zero db is barely audible. 120 db hurts. Ordinary conversation is about 60 db.

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* Example Calculation

$P_1/P_{ref}=10^{50/20}=10^{2.5} = 316.22$ $P_2/P_{ref}=10^{70/20}=10^{3.5} = 3162.28$

$(P_1+P_2)/P_{ref}= 3478.5$

$20 \text{ Log}_{10}(3478.5) = 70.83$

Frequency Aspects (Vibrations in Air, Weighting Curves: A vs. C)

Vibrations in Air

Sound waves are "longitudinal" pressure waves, generally considered to be directed along an axis that is a straight line between the source and the listener. The wave is not "transverse" as many waves are depicted. When we are pulling a garden hose along, and it hangs up on a rock or stump, instead of walking back to lift it, we often attempt to free it by giving it a sharp up/down jerk at the point where we are holding it, and this produces a transverse wave (a ripple) that propagates down the hose, and may jump the obstacle. We can demonstrate the longitudinal wave in the same hose. Suppose we are playing a joke on someone using the hose. We kink the hose, and after a slight delay, the user finds the flow slows or stops. As our victim becomes more curious, we may undo the kink and let through bursts which propagate down the water column in the hose, and result in some level of mischief.

A sound wave in air is a similar series of periodic overpressures and underpressure that bombard the eardrum. We can hear sounds for which the frequencies range from a low of about 20 Hz (deep "bass") to a high of about 20,000 Hz (high "treble"). The units Hz are "Hertz," formerly called by the much more meaningful units of "cycles per second." Obviously, the vibration rates of sound are much faster than we could ever achieve by kinking and unkinking a hose! This frequency range (pitch range if you wish) is, like the perception of loudness, logarithmic. Musically, we readily categorize pitches in 2:1 ratios, musical "octaves" (such as C to the C below, or a G# to the G# below). Accordingly, there are about 10 octaves in our hearing range, since $2^{10} = 1024$ is about the factor of 1000 we find between 20 Hz and 20,000 Hz (20 kHz).

Because of the octave nature of pitch perception, we are often astounded to learn what the actual pitches of various tones we hear really are, relative to what we intuitively consider to be high pitches and low pitches. The so-called "A-440" (440 Hz) to which an orchestra tunes, seems to us like mid-range. Indeed, "Middle C" on the piano is only 262 Hz. These frequencies, relative to a full range from 20 Hz to 20 kHz seem to be way down near the low end (bottom 5%!), but are actually the middle octaves for music.

Further examples: A person hearing a 2000 Hz tone will perceive it as "piercing" and suppose it is near the top, while it is only 10% of the way up. As we age our upper frequency range drops, and we may be shocked and very worried to learn that our upper range is only to 5 kHz (we lost 75%!). In fact, we have only lost the upper two octaves of about 10 total. Speech and most music will still sound much the same as before. A few bird songs may be missing (for persons who noticed then while younger).

In addition to a range of frequency for individual components tones (e.g., Joe is playing A=440 Hz and Sally is playing C=524 Hz), combinations of sound can vary greatly with regard to frequency content (called the "spectrum," closely analogous to the rainbow pattern achieved with light and a prism). Musical tones tend to have discrete frequencies in sets that are integer multiples called harmonics. Other sounds such as radio static, a tire leak "hiss," or wind through the trees is likely to have a continuous set of frequencies. Either harmonic sounds or "hiss" may have a frequency range (spectrum) that is narrow ("narrowband") or wide ("broadband"). As sound propagates from source to listener, its spectrum usually changes shape. Some seats in the concert hall may have poor high frequency response. Reflections may even cause broadbanded "hiss" to cancel some frequencies (the wierd evolving sound of a jet engine "hiss" as it reflects off a runway while it takes off). Music of many types is usually the most broadbanded sound we encounter. Speech has a much smaller bandwidth (100 Hz to 4 kHz).

The A and C Curves

One of the choices found on a sound level meter is the choice of A weighting or C weighting. These curves represent a manipulation of the sound, as captured by the meter's microphone, before it is analyzed. To the electrical engineer, these are electrical filters. They are essentially the same thing as the "frequency response" curves which may be used to advertise a stereo amplifier. Amplifier manufacturers often brag about the flat frequency response of their amplifiers. (Actually, this is not at all a difficult thing to achieve!) For example, an amplifier might be flat to within 0.1 db (about 1%) from 50 Hz to 18 kHz.

The C-curve on the sound meter is the one we consider to be flat (the most flat of the two). It is within about 2 db from 50 Hz to 5 kHz, nearly 7 octaves (Fig. 1). The C-curve is intended to be a "fair" curve, while in the same sense the A-curve is intentionally biased (Fig. 1). The A-curve has about the same high frequency response as the C-curve, and is by definition equal to the C-curve at 1000 Hz. But it rolls down by about 4 db (to 63%) as we lower the frequency to 500 Hz, by 11 db (to 28%) at 200 Hz, and by 30 db (to 3%) at 50 Hz. In short, the A-curve strongly attenuates low frequencies: note that it is strongly rejecting the fundamental frequencies of many (most?) musical tones (again think of A-440). Instructions for using sound level meters generally specify that the <u>C-curve should be used for music</u>.

So, if the C-curve is the fair curve, why would we ever want an A-curve? The basis of the A-curve is that <u>supposedly</u> it better represents the way the ear actually hears. This is based on some "equal loudness" experiments going back to Fletcher and Munson published in 1933. In essence, what the A-curve is supposed to do is to "model" the ear. This sounds like a good idea, but it must be remembered that these equal loudness measurements are made with pure tones (not broadbanded music), and that they are done with steady-state sound, not transients. The continued use of the A-curve is often

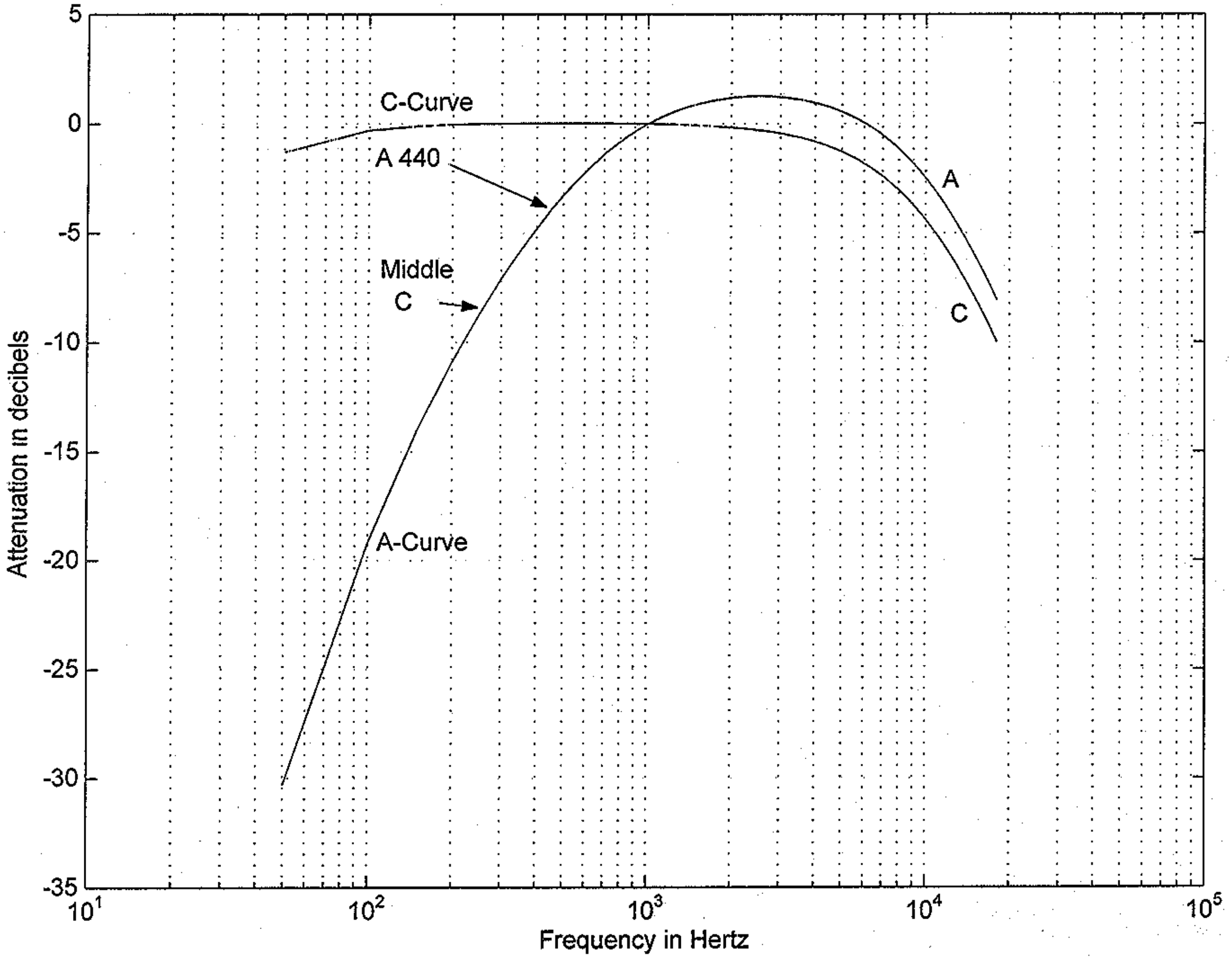

Fig. 1 Two standard curves, the A-curve and the C-curve are available alternatives for a sound level meter. The C-curve is the recommended (by the manufacturer) curve for music, and reasonably, for the measurement of musical events that are possibly too loud and thereby annoying. Note, for example, that if the A-curve is used for music, "middle C" on the piano (262 Hz) is attenuated by 8 db (to 40%). Use of the A-curve rather than the C-curve can result in readings that are 4 to 8 db too low.

discouraged in recent times, or even strongly discouraged when it is known that vary loud low-frequencies are present (e.g., aircraft noise) where physical damage to the ears may result.

For most music, readings using the C-curve may be 4-8 db higher than with the A-curve. The difference may of course be much more than that if the sound is largely low-frequencies.

Below we will discuss time aspects and distance aspects of sound measurements, and we will see that situations can arise where use of the A-curve is very misleading, relative to annoyance. In particular, a propagation path attenuating high frequencies leaves low frequencies which the A-curve then largely rejects (leaving very little) while the ear, always willing to scan, hears the residual clearly.

Time Aspects (Transients and Averaging)

In arranging for objective standards, we of course must be on guard for a failure to include factors that make highly significant differences. One important consideration is the length of time over which the sound level measurement is made. A sound waveform does not have a constant level, as is obvious, because at any location, we know that sounds are sometimes loud and sometimes soft. But what we also need to recognize is that the variations in sound occur on different scales of time. On the smallest time scale, the pressure wave goes up and down through zero many times per second. This is what makes it audible sound. The rate at which it goes up and down is called the frequency, closely related to what we call "pitch" in music. The famous "A-440" to which an orchestra tunes means that the pressure goes through a full cycle 440 times per second. As mentioned, we can hear frequencies from something like 20 Hz to something like 20,000 Hz (20 kHz). The cycle times are thus from about 1/20 of a second to 1/20000 of a second.

On the next scale of time, sounds levels vary to delineate individual musical notes, individual words of speech, individual barks of dogs, individual claps of thunder, etc. These "events" are typically substantial fractions of a second, or even several seconds in duration. Note that these times are long compared to the cycle length of pitched sounds.

On the longest time scales, we have events which may be on the order of minutes to hours (parties, concerts, lectures, thunder storms).

Over what time scale should we measure the sound pressure levels? Well, one guide is to recognize that the human perceptual system seems to have what is called a "time constant" of about 50 milliseconds (1/20 of a second). Notice that this is about the longest time between cycles for which we can hear pitched sounds (i.e., 20 Hz). Also, events which change more rapidly may be blurred, and it is this, as applied to visual perception, that causes us to see 24 frames per second of a movie as continuous motion. (Much slower and we start to see individual frames as "flicker.")

The accompanying Fig 2 shows a sketch of what we might consider a typical musical tone. We see that there are the fast vibrations which make the tone audible. (In reality, there would be far more of these cycles than we can sketch clearly here.) These cycles are "enveloped" by a much slower curve that defines the "amplitude" in a manner which is fairly obvious in its general nature. This particular player apparently started the sound with a much larger amplitude (musical "attack"), let it decay to a sustain level (held the note), and finally let it decay (ended the note). We need to measure something about the envelope. The sound level meter obtains and processes the envelope.

Let's assume the meter only sees this one musical tone. Our measurement would thus be something like one second in duration. One thing that is clear is that we have a well-defined maximum ("peak") value. We can also obtain an average value - perhaps as suggested in the sketch. Notice that the average must always be equal to or (much more generally) less than the maximum (like all averages). Further, if we averaged over longer times, and no new tones contributed, the average would continue to drop. Thunderstorms, averaged over a year, are inaudible, but get our attention on the much shorter time scale when lightning strikes a tree just outside our bedrooms. In general, if we took an arbitrary sound measurement, the longer the measurement time, the more consistent the average, and the greater the ratio between maximum and average. Maximum values are often, perhaps typically, 6-14 db above average. Further, the longer the time, the less significant the individual component events are relative to the human time constant and time scales of human importance. (When the party does ends at 2 AM, you can go to sleep, even though the average over the past hour remains very high)

A typical sound level meter flashes db levels, set to display either maximum or averages, as obtained over the previous second. This one second data time (sometimes called a "window" or "integration time") is quite reasonable. It is long enough (relative to human time-constant of 1/20 of a second) to exclude pitch related variations, and short enough (relative to, say, a song being played), to give a realistic representation.

So we could watch the meter and try to remember what happens. A bit tedious? But even the simpler meters are likely to have additional recording and memory functions. Thus we can select measurement times of a couple of minutes or so, and the instrument automatically monitors the sound, and then holds and displays the final results. Now we know how loud a song might be on a scale of time comparable to the way people listen to songs (to significant passages). Measurement times of something like 10 seconds to several minutes are likely to be the most closely related to the truth. In practice, a time of about 30 seconds is long enough to get to the truth, and it is short enough that confirming measurements (or replacement measurements - if some anomalous event such as a beeping car horn occurs) can be made in just a couple of minutes. This is particularly true for music that has a strong "beat" where the beats are something like one per second, and may be something like 5 times louder (14 db louder) than the material between the beats.

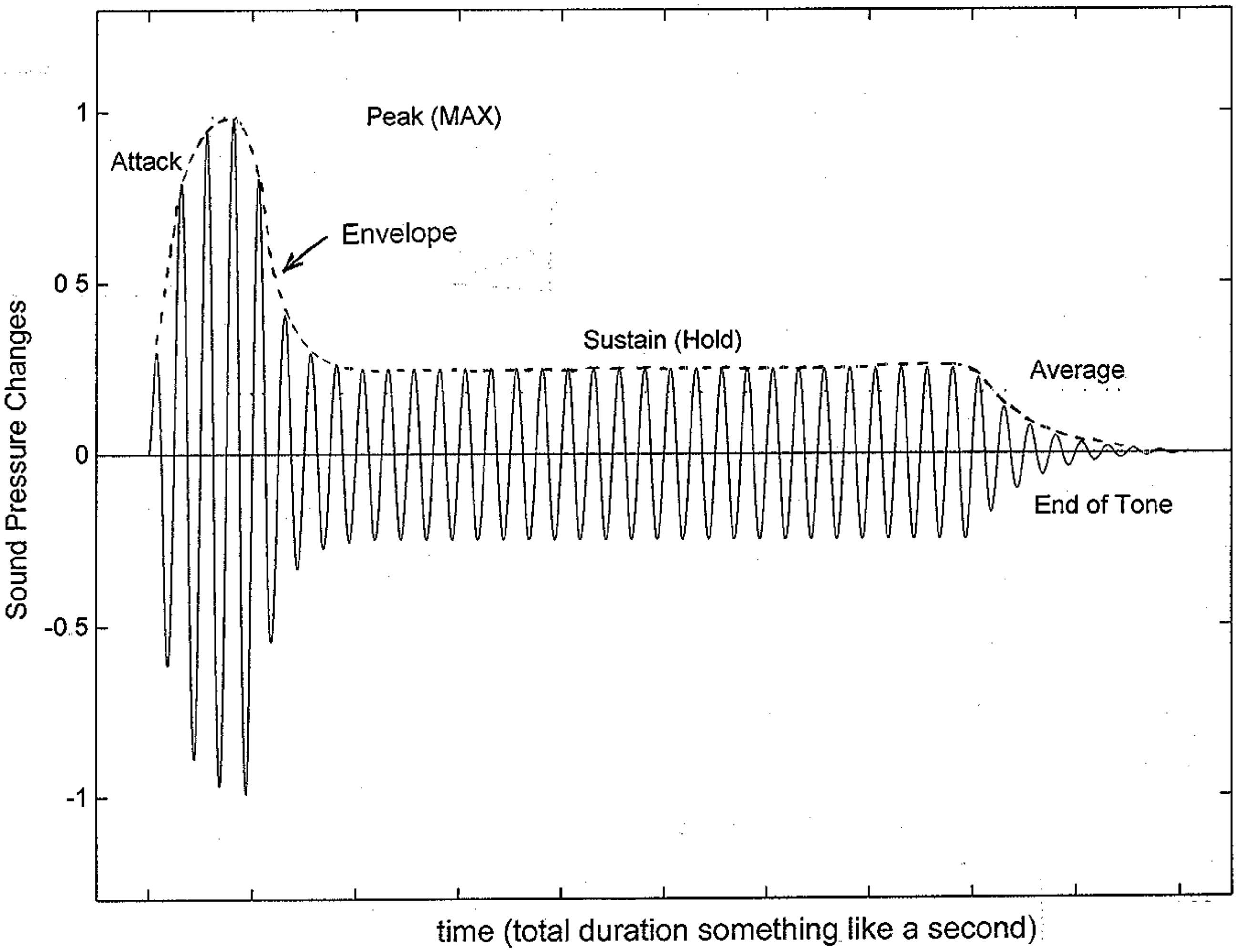

Fig. 2 A particular sound such as a musical "note" or tone, a dog bark, or a word of speech, etc., has a duration in time from a good fraction of a second up to several seconds. It consists of a vibration enclosed by an "envelope." Some portions may be much louder than others. In consequence, peaks (maximums) may be much greater than averages. Average readings may be up to 14 db too low relative to peak (maximum) values for some types of music (strong beats). [Note: For the diagram above, for clarity, we have shown only about 10% of the actual cycles that would be present on this time scale.]

Note that this idea of time of measurement is usually unrelated to instrument features of a "fast" or "slow" response, which relate to the update time of the display.

Distance Aspects

Sounds are modified as they travel over distance. In general (except as reflected sounds may recombine), they get softer over increasing distance, as we expect. One might expect the famous "inverse square law" to characterize the drop off as distance from the sound source increases, and this general trend may be approximated in some cases. But more generally, sound is much more influenced by physical objects in the environment and by atmospheric conditions. Sound can well be channeled between buildings and trees, and between air layers of different temperature.

Aside from the general trend that we expect to hear less if you move further from the source, the most important feature of distance is that low frequencies propagate very well over distance while high frequencies are much more attenuated. In our every day experience, this is why distant thunder storms rumble while the nearby strikes crackle. For an example more related to controlling noise, we experience the same thing in the case where a car stereo is heard to begins as a low "booming" while the car is a half mile away, and we only hear the high frequencies as the car subsequently passes nearby. Frequencies in the upper part of the hearing range, which we hear when we are close to the source, may be attenuated by as much as 10 db for each 300 feet of distance, just due to the damping effects of ordinary air. Vegetation increases this attenuation further. But there is very little damping of the low-frequencies which may disperse into a pulsation that we as much "feel in the pit of our stomachs" as hear.

Notice that if we combine this environmental attenuation of high frequencies over distance with the attenuation of low frequencies that we get by choice of an "A-curve," our sound level meters may show very little. The actual pulsations however clearly are heard, are recorded by the meter using the "C-curve" and are displayed on a "bar graph" display if the meter has one.

Masking (Hidden Noise)

Sounds can be masked (hidden by other sounds). A person who has a TV running and who is watching a program (or even not watching) is far less likely to hear the party next door, while someone else who is reading a book, may be unable to continue reading. This masking can be compared to similar cases with vision. When someone takes a picture of us with a flash, we likely see nothing for about a second. Yet specific visual regions can also be masked. For example, we may drive up a road into the setting sun and have an easy view to the sides of the road, but little idea of what is directly ahead.

With regard to sound perception by the ear, in general, very loud sounds mask very soft sounds, as we would expect. But, there is also a masking of sounds that are close in pitch, even for much more similar levels. Sounds also mask in time - our hearing can be overloaded pending a certain recovery time.

In the case of a relatively quiet local environment, the hearing mechanisms is nonetheless primed to respond to whatever is there. If the sound environment is extremely quiet, or extremely static statistically (e.g., a refrigerator "humming" along), we may even start to "hear voices." Even when the bandwidth of sound is reduced (i.e., by air and vegetative attenuation), we cannot ignore even distant low frequency booming.

Psychological Aspects (Accidental vs. "In Your Face")

Whether or not a sound is "annoying" is of course to a degree subject to psychological aspects. A mosquito humming in a dark bedroom is nearly inaudible, but certainly annoying for non-acoustic reasons. Loud (or even ordinary) talking by people walking the street at 3 AM makes us wonder what they are up to at that hour and if they might be about to stumble into our flower gardens, or worse.

Other sounds convey an "in your face" context. Guests departing a friend's residence at 3 AM so often seem to feel obliged to tap the car horn a couple of times, while they would not do that at 3 PM. Perhaps it is the anonymity of the darkness plus a desire to advertise the equivalent of "Hey - Mom let us stay up late!" More anonymity is afforded by large groups who can join in the noise without personal responsibility, while at the same time advertising membership in a supposed privileged group (we are special and can make noise). Cell phones (incoming or outgoing) even in a busy and relatively noisy restaurant are also potential "in your face" situations. In contrast, neither is it unusual for people who own a dog to be honestly unaware of its continuous barking, even when they are home.

On the other hand, even relatively loud sounds may not be annoying or even disturb us. We become accustomed to a furnace turning on in the middle of the night, and even if it is loud, after a few days in the fall, it usually does not even awaken us. The sound of a lawnmower is not annoying to many, except as it may remind us that we too should be mowing. The sound of children playing happily, even if loud, is wonderfully calming to many people.

Summary

A good measurement of sound level combines a reasonable knowledge of sound and its perception with a working knowledge of (and practice with) sound level meters, along with common sense. Proper use of the meter involves selecting the proper weighting curve (A or C, with C preferred), peak or averages (with maximum or peaks preferred over averages), and measurement times of about 30 seconds.

Proper selection of limits in db should be made with some care. We need to keep in mind that selection of a C-curve and/or selection of Max readings rather than average, will give db readings that are larger than those from the other choices. This may make some upward adjustment of db thresholds desirable.

Recommendations:

The strongest recommendation is that persons writing and enforcing noise ordinances learn the fundamentals of sound and its perception. Likely any organization will have at least one person who is a musician and/or audiophile and/or engineer who would be delighted to investigate sound more fully.

It is further recommended that persons involved with noise ordinances "play" with sound level meters for a while. Try the different settings. Talk to it. Sing to it. Clap your hands sharply. Set it in front of the TV. Check out some loud events. Check out your stereo by choosing some music you do not particularly like, and find a level in your room that you feel would not be annoying if it came from the house next door. Try to hold a conversation at that level. Try to read at that level. Learn to trust it, and "calibrate" its readings with what you think of as "reasonable" or "unreasonable." (Levels and methods used in other localities may have been in turn just copied from further away!)

It is strongly recommended that the C-curve rather than the A-curve be used as the standard. (The C-curve is further convenient in that most meters default to the C-curve when they are turned on.) Perhaps it would be reasonable to just keep the same db levels as standards, and specify the C curve rather than the A. However, the C curve should be chosen even if, in compensation, the maximum db levels are raised. It may turn out that 60 db nighttime with the C curve gives better relief from true annoyances than 55 db with the A curve (or even the 45 db some communities are using).

In addition, it is essential that an ordinance specify whether peak (MAX) levels are to be measured, or whether average levels are to be measured. While there is something inherently comforting when we involve averages, as emphasized, it is the peaks that matter. Choose maximums, again even if the db threshold is raised.

A measurement time of about 30 seconds is recommended.