COM-418 - Spring 2021 Mini-project

Building a Personalized Sound Meter

- The mini-project is due on April 18.
- You can work in groups to write the code but you will have to submit your own personalized weighting filter.
- You can use any programming language for the assignment, as long as your solution is readable and well explained. Jupyter notebooks are preferred.

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1 Objective

The objective of this mini-project is to create a personalized sound level meter that takes into account the loudness sensitivity of your own ears. To achieve this you will need to:

- write a program that generates a test tone and that allows you to interactively change the volume of the test tone,
- perform a series of listening tests with your program to determine your typical ear sensitivity curve,
- use the values in the curve to design a simple weighting filter,
- use the weighting filter to compute the perceptual loudness of an audio file.

2 Preliminaries

2.1 Sound Pressure Level (SPL)

Sound reaches our ears in the form of acoustic waves. An active sound source, such as a musical instrument or a loudspeaker, exerts a force on the surrounding air and the resulting deviation in the atmospheric pressure, that is the resulting *sound pressure*, propagates in the medium as an energy wave due to the interaction between neighboring air particles. Sound pressure values, whose unit is the pascal (1 Pa = 1 N/m^2), can be measured at any given point in space using a microphone, which converts sound pressure to a voltage.

The Sound Pressure Level L_p is defined as the ratio between the measured sound pressure and the smallest sound pressure detectable by the human ear (the so-called threshold of hearing). The latter is conventionally defined as $p_0 = 20\ \mu\text{Pa} = 20 \cdot 10^{-6}$ Pa so that

$$L_p = 20 \log_{10} \frac{p}{p_0}.$$

Normally, p is the root-mean-square (RMS) value of the sound pressure, computed over an observation window of appropriate length. Digitally, this can be computed as

$$p = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + \cdots + x_n^2)}.$$

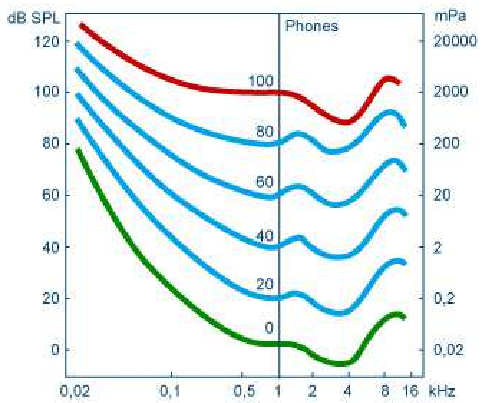
2.2 Equal-Loudness Curves

From a perceptual point of view, the subjective notion of *loudness* is a function of sound pressure, with larger sound pressure levels corresponding to louder sounds. But the function is complicated:

- it is nonlinear, with an approximately logarithmic characteristic;
- it depends on the sound's spectrum, because the sensitivity of the human ear changes significantly as we move over the range of audible frequencies;
- it depends on the sound's duration, although we won't consider this aspect much in the current context.

The spectral sensitivity of the human ear is experimentally determined using single-frequency sinusoidal test signals; the procedure is as follows:

1) The subject hears a 1 kHz reference tone at a pre-determined SPL value.
2) A test tone with different frequency and user-adjustable volume is played afterwards.
3) The subject is asked to adjust the volume of the test tone until its perceived loudness matches that of the reference tone.
4) The procedure is repeated using a new test frequency until the entire hearing range has been adequately covered.



The set of volume levels selected by the subject determines an *equal-loudness contour* for the nominal SPL of the reference tone; and, by further repeating the experiment with a different amplitude for the reference tone, a complete family of equal-loudness curves can be obtained. In practical applications, the standard reference set of curves is similar the one shown in this figure, obtained by averaging the results of many experiments using many different subjects.

A common unit of subjective loudness is the *phon*; an increase of 10 units on the phon scale corresponds to doubling the perceived loudness of the sound. By convention, the phon level of a 1 kHz sinusoidal tone is equal to its SPL; at other frequencies, the SPL necessary to induce a loudness sensation of s phons is given by the value of the s-phon equal-loudness curve at the chosen frequency.

2.3 Sound Level Meters

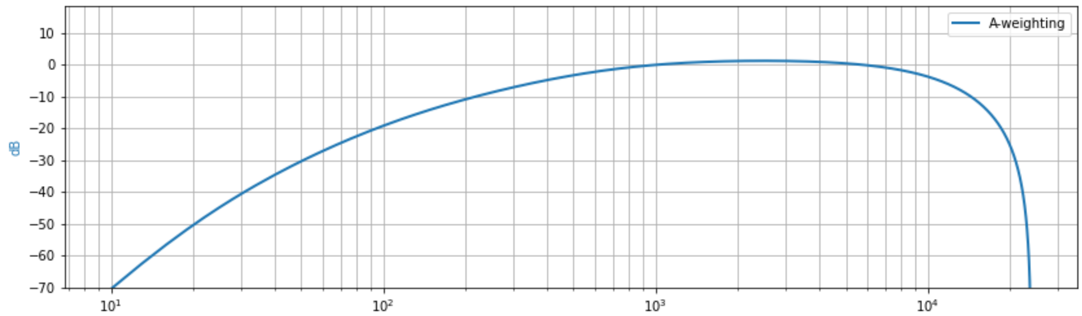
There are many situations that require an accurate estimation of "how loud" an enviroment is. A classic example is the need to ensure that industrial noise levels are not harmful to workers; similarly, legal requirements mandate that the volume of a rock concert must not exceed standard safety levels. A Sound Level meter uses a microphone to computer the RMS SPL over a user-definable analysis window. In order to provide a loudness reading that is closer to the subjective sensation experienced by a human listener, sound level meters include a prefilter that takes into account the uneven frequency sensitivity of the human ear as modeled by the equal-loudness countours.

A very common such filter is the so-called A-weighting, whose magnitude response mimicks the inverse of the 40-phon equal loudness curve. A simple implementation uses a 7-th order IIR filter with transfer function

$$H(z) = \frac{b_0 + b_1 z^{-1} + \ldots + b_6 z^{-6}}{1 + a_1 z^{-1} + \ldots + b_6 z^{-6}}$$

where the coefficients, for a sampling frequency of 44.1 kHz, are

n	a_n	b_n
0	1	0.234301792299513
1	-4.113043408775871	-0.468603584599027
2	6.553121752655046	-0.234301792299513
3	-4.990849294163378	0.937207169198054
4	1.785737302937571	-0.234301792299513
5	-0.246190595319486	-0.468603584599027
6	0.011224250033231	0.234301792299513



There are a few sound level meter applications, like this one, that you can download on your smartphone to get an idea of typical sound levels.

3 The Mini-project

3.1 The Psychoacoustic Experiment

In the first phase of the project, you will need to determine your own personalized 40-phon equal loudness curve. To this end you will need to write a program with a simple interface that allows the user to play either the reference tone at 1 kHz or the test tone at another random frequency in the 20 Hz to 15 kHz range; the user interface needs to provide a way to adjust the volume of the test tone and to store the volume value once the user finalizes their selection. A few remarks:

- although the hearing range spans a large interval, the number of test frequencies can be spaced logarithmically using K values per octave, with K small (e.g. $f_n = 22 \cdot 2^{n/K}$)
- the playback level of your tones will depend on many unknown factors (your soundcard, your headphones, etc) and so it will be impossible to ensure that the test tone is at 40 dB SPL. This is of little importance, however, since the actual phon level of the equal-loudness contour is not crucial. Just make sure that the volume of the test tone is constant throughout the experimental session and that its level is comfortable: audible but not loud.

3.2 The Weighting Filter

At this point your equal-loudness contour data will be a set of frequency-volume pairs $(f_n, v_n)_n$. In order to obtain a weighting filter, you need to design a digital filter that approximates the inverse of the contour. The simplest way is to design an FIR whose magnitude response interpolates the points $(f_n, 1/v_n)_n$. To achieve this, you can for instance look at the documentation for the routines `scipy.signal.firwin2` and `scipy.signal.firls` in SciPy.

The design of an IIR filter with an arbitrary characteristic will be much more difficult but the brave amongst you may have a look at some of the IIR least-squares design methods that are only a short web search away.

3.3 The Sound Meter

Finally, implement a sound meter that pre-processes the input via the weighting filter and then computes the time-varying RMS via an averaging filter with user-definable range (either a moving average or a leaky integrator). Compare the results obtained with pre-filtering to those without.