Tutorial 1: Specify Vibration Intensity in SL (Sensation Level)

In this tutorial, we use the terms "amplitude" and "frequency" to refer to the physical signal parameters, and "intensity" and "pitch" to refer to how people perceive these two parameters, respectively.

Measure Vibration Amplitude with an Accelerator

Let's start with the simple case of a single-frequency sinusoidal displacement signal:

$$x(t) = A\cos(2\pi ft) \tag{1}$$

where A denotes amplitude, f denotes frequency and t denotes time.

One way to measure the output of a tactor (tactile stimulator) is to attach an accelerometer (a sensor that measures acceleration) to it (see Figure 1 below).

The time derivative of $x(t)$ is the velocity $x'(t)$. The time derivative of $x'(t)$ is the acceleration $x''(t)$. It follows that

$$x''(t) = -A(2\pi f)^2\cos(2\pi ft) = -B\cos(2\pi ft) \tag{2}$$

where

$$B = A(2\pi ft)^2 \tag{3}$$

denotes the amplitude of the measured acceleration function. It follows that the amplitude A of the displacement function can be calculated from acceleration measurements, as follows:

$$A = \frac{B}{(2\pi ft)^2} \tag{4}$$

Figure 1: Photo of an accelerometer attached to the top of a (purple) C-2 tactor

Human Detection Threshold and Sensation Level

Vibrations with the same physical amplitude A but at two different frequencies f_1 and f_2 may not feel equally intense. This is because human sensitivity to vibrations is frequency-dependent.

Human detection threshold, an inverse to human sensitivity, is defined as the minimum vibration amplitude at which the vibration is barely detectable. It is usually plotted as a function of temporal frequency (see Figure 2 below). Typically, the detectino threshold is expressed in terms of displacement amplitude A on a log scale (relative to 1 micron); i.e.

$$20 \times \log_{10}\left(\frac{A}{1\mu m}\right) \tag{5}$$

Sensation level (SL) is specified in dB above Human Detection Threshold. For example, at 200 Hz, the human detection threshold is about -15.0 dB relative to 1 micron. If the output of a tactor is measured at 1.0 g, or equivalently $9.81 m/s^2$, then the corresponding displacement amplitude is 6.21 micron, or equivalently 15.9 dB re 1 micron. Therefore the vibration intensity is 30.9 dB SL.

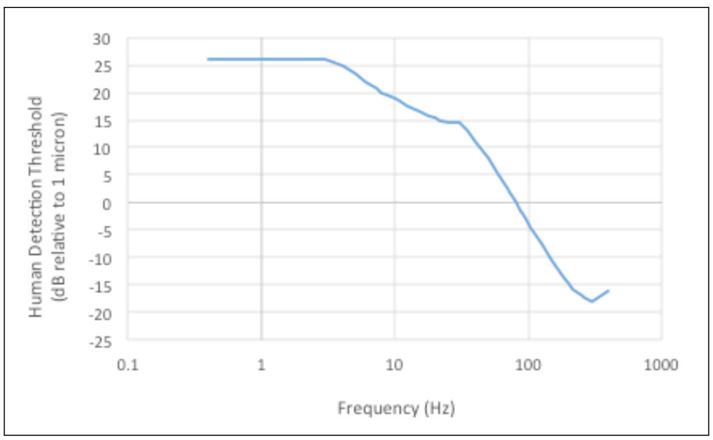

Figure 2: Human vibrotactile detection threshold in dB relative to 1 micron. *Data Source*: Bolanowski Jr., S. J., Gescheider, G. A., Verrillo, R. T., and Checkosky, C. M. (1988). "Four channels mediate the mechanical aspects of touch." *Journal of the Acoustical Society of America*, 84(5), p.1680-1694. (Data replotted from Fig. 1 in Bolanowski et al., 1988, measured at the thenar eminence (the fleshy part at the base of the thumb).

Sensation Level and Perceived Intensity

Figure 3 illustrates the perceived intensity of vibrations at different sensation levels. While vibrations at 0-10 dB SL are above the detection threshold, they take some effort to notice. Vibrations at 10-30 dB SL are noticeable and comfortable. At 30-50 dB SL, vibrations may start to feel too intense for some people. Most people find vibrations above 50 dB SL to be too strong and even painful.

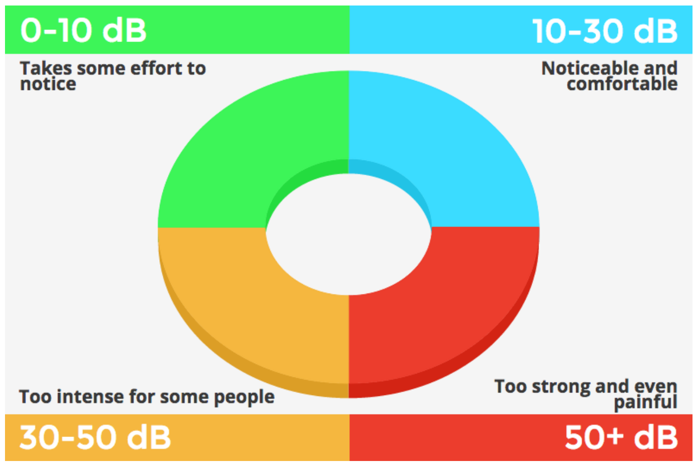

Figure 3: Relation between sensation level and perceived intensity

Factors affecting the Perceived Intensity of Vibrations

Many factors affect the human detection threshold, including body site, contact area, signal duration, skin-surface temperature, age, activity level (it is harder to notice the phone in the pocket vibrating when one is moving about), etc. The way a tactor is attached to the skin (via double-sided tapes, Velcro straps, rubber band, etc.) can also significantly alter the measured output of a tactor. All these factors affect the sensation level and the perceived intensity of vibrations.