Figure 1: Assessment of hand vibration on a blender container by using vibration sensors (accelerometers) attached to the container in three mutually perpendicular directions. *Source: Acentech*

A Vibration Primer for Appliance Designers

by david l. bowen

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Appliances and other motorized products all produce some amount of noise, and in many cases this noise results directly from vibration of structural or housing elements. In fact, reducing such vibration can be an effective approach to reducing the total radiated noise. For smaller appliances that require direct hand contact or larger appliances supported by wooden flooring, vibration that can be felt may be a concern. This article focuses on such "feelable" vibration, which tends to be low in frequency and distinct from the higher frequency, noise-producing vibration.

Some Vibration Basics

Vibration is, in essence, repetitive motion of an object about an equilibrium position. As with sound, two fundamental characteristics of that motion are its magnitude/level and the rate of the repetitive fluctuations about equilibrium (its frequency). The vibration motion at a given location is commonly described in terms of either the displacement of that location from its equilibrium position, its velocity, or its acceleration. The frequency of this motion can be simple, consisting of purely sinusoidal motion at a single frequency, or complex, consisting of multiple periodic components along with non-periodic, random "broadband" components (picture a basketball slowly bouncing up and down while at the same time its surface is vibrating—at much higher frequencies—right after striking the floor). In addition, the magnitude of the vibration occurring at any given frequency can be significantly different than at other frequencies, and both its magnitude and frequency can change over time.

Some degree of vibration will occur in any elastic (non-rigid) system when subjected to non-steady forces or moments, since this elasticity will provide restoring forces/moments that tend to pull any displaced points back to their equilibrium positions. Non-steady forces include not only the more obvious periodic examples like those arising from imbalance in rotating components or electromagnetics in motors, but also transient, impact-like forces (the latter are broadband in nature, meaning that since they contain many frequencies they can excite a wide range of responses). Structures will vibrate in response to these forces, with the magnitude of the response at a particular location dependent not only upon the magnitude of the force, but also the effective mass and dynamic stiffness of the structure at that location. This local mass and stiffness are governed by material properties and the geometry of the structure, and can vary substantially with position and frequency. In real systems there will always exist a finite amount of mechanical loss, providing energy dissipation that can serve to damp the vibration response and reduce its magnitude, especially at any resonances (resonance refers to the condition where an excitation frequency matches a structure's natural frequency). Such damping can arise from properties of the materials that make up the structure, from added materials or devices, and/or from the fastening together of various parts that go into a built-up structure like an appliance.

Feelable Vibration

Although many structures may appear to be "rigid," in the sense that if you push on them there is no obvious deformation, they will actually exhibit a minimal degree of flexibility if the frequency of the (non-steady) forcing is high enough. This flexibility, small as it might be, is enough to lead to vibration, which usually cannot be seen or felt because it takes place at frequencies beyond which we can detect it by seeing or feeling. However, such vibration does lead to something which we can detect, and that is sound. Vibrating surfaces radiate sound much like loudspeakers. This "structure-borne" sound is intimately related to vibration, and can often be responsible for much of the noise radiated by an appliance.

Sometimes the concern is with lower frequency vibration that does not necessarily radiate audible sound, but is feelable and thus may affect consumer acceptability. Examples include vibration in hand-held devices like hairdryers and floor-care appliances, food blenders that require the container be held down during operation, and larger white goods such as front-loading washing machines. People are generally most sensitive to vibration at lower frequencies—roughly speaking in the 0.5 Hz to 80 Hz range for whole-body vibration (and below 0.5 Hz for motion sickness), and in the 10 to 400 Hz range for finger/hand/arm vibration—but can feel it up to about 1,500 Hz. This sensitivity also depends on the level and duration of the vibration, as well as its direction and location on the body, and it varies considerably among individuals (and also with age and gender).

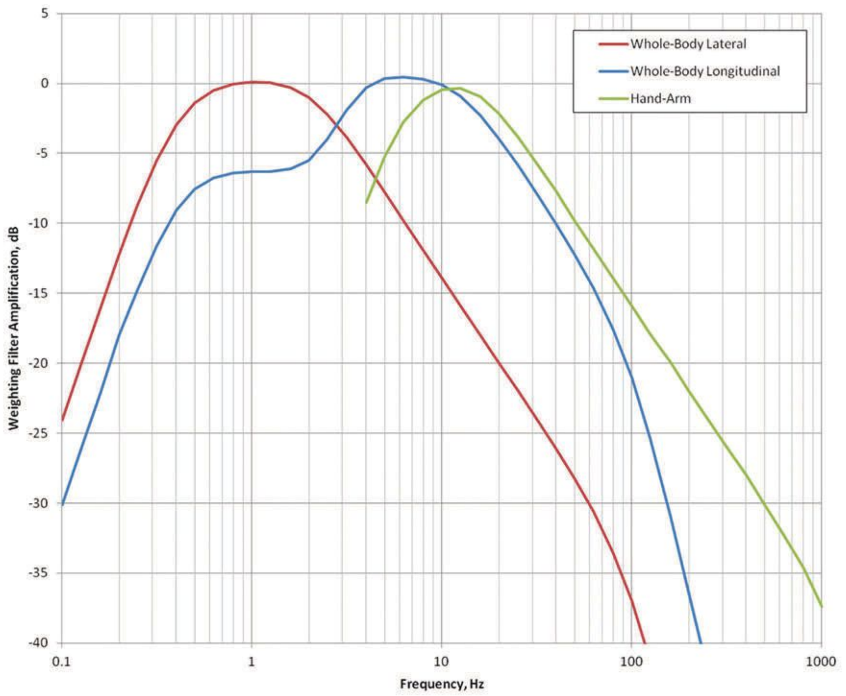

Figure 2: ISO frequency weighting functions for human sensitivity to vibration.
Source: Acentech

Another area of concern regarding vibration, which will not be discussed here, is the possible failure of components due to structural fatigue or to impacts related to vibration.

Quantifying Vibration

The most straightforward way to measure vibration on a device like an appliance is usually with a small accelerometer, although non-contact sensors such as laser vibrometers can also be used. The mass of the accelerometer should be low enough so that it does not impose a significant load at the measurement point, which could influence the vibration response at that location. Although small accelerometers are generally less sensitive than larger ones, the levels of concern for feelable vibration are sufficiently high that sensor sensitivity is usually not an issue. For the lower frequencies involved in feelable vibration, a small accelerometer can be adhered to the appliance in a convenient manner using, for example, double-stick tape, or even wax (if elevated temperatures are not an issue).

To characterize vibration at a particular location, it is usually necessary to measure in three orthogonal directions (full characterization would also require the three additional rotational motions). This can be accomplished either by using a dedicated triaxial accelerometer (or three accelerometers mounted to a small aluminum cube adhered/clamped to the appliance), or by using three accelerometers located near each other and with their axes oriented approximately orthogonal to each other, such as shown on the blender container depicted in Figure 1. Sometimes it may be desirable to evaluate the vibration of, say, a handle when gripped by a hand if the hand has the potential to load the handle enough to significantly influence its vibration. A specialized glove with built-in sensors can be utilized for this purpose, so that realistic hand-loadings are applied during the measurements.

Many of the standards having to do with human exposure to vibration (such as ANSI S2.70, ISO 5349 and ISO 2631) are mainly written from the standpoint of preventing physiological problems like "Hand-Arm Vibration Syndrome" (HAVS), and offer guidelines for maximum overall acceleration levels (obtained from the vector sum of the spectral levels in the three directions, frequency-weighted according to weighting functions like those shown in Figure 2 for hand-arm or whole-body vibration) and exposure duration. For someone holding a hand tool for 30 minutes/day, for example, the maximum recommended acceleration level for avoiding HAVS is 4 meters/sec2 in each of the 1/3 octave frequency bands up to 16 Hz. This limit doubles every octave, rising to 200 m/sec2 in the 800 Hz band. Data on vibration exposure, as it may affect comfort or annoyance, is more sparse (especially for hand/arm vibration), but these levels are generally at least an order of magnitude below the limits cited for avoiding complications like HAVS.

An accelerometer, of course, provides a direct measure of acceleration. In some situations, such as inside buildings where people may be exposed to whole-body vibration due to floor motion or where vibration-sensitive equipment is a concern, vibration limits are occasionally expressed in terms of velocity rather than acceleration (the threshold of perception for feelable floor vibration, for instance, is often expressed as an rms velocity level of about 0.1 mm/sec.). If needed, measured acceleration spectra can be readily converted to velocity spectra.

Common Sources of Vibration and Strategies for Reduction

The most common sources of feelable vibration in handheld appliances are rotating imbalance forces, creating vibration at the rotation rate (and sometimes at multiples/harmonics of this fundamental frequency). For feelable vibration, this means rotational speeds of up to about 24,000 rpm are potentially of concern if we consider the most sensitive range to be up to around 400 Hz. Imbalance in motor shafts or in their driven components can be a source of imbalance, and proper dynamic balancing of these components is the most effective approach for minimizing such vibration. Even if components are initially balanced, wear and dirt accumulation can eventually introduce significant amounts of imbalance. Bent or misaligned rotor shafts can also create vibration at the rotation rate and its harmonics. The magnitude of this type of vibration can be greatly amplified if a rotation speed happens to match a vibration resonance frequency of the assembled system. Such resonances, and whether they will be excited, can be difficult to predict accurately. Hence, a resonance problem will often not become apparent until prototype versions are available for test. Another potential source of feelable vibration can arise from electromagnetic forces in A/C motors, due to magnetostriction for example. These forces are usually not related to rotation rate but instead occur at harmonics of twice the line frequency of 60 (or 50) Hz.

Aside from reducing vibratory forces at their source, such as by increasing balance quality, the primary means for reducing vibration experienced by a user is isolation of the vibrating component from the rest of the structure. The goal here is to attenuate vibration at locations where a user may interface with the appliance. This approach involves selecting an appropriately compliant material and/or spring system to use as part of a mount or cradle, which will reduce, above a certain frequency, the vibration transmitted from the vibrating component to the structure to which it connects. Care must be taken to ensure the isolation system is not "short circuited" by, for example, a fastener. The effectiveness of the system depends not only on the mount stiffness and the frequencies involved, but also the local mass and dynamic stiffness of the structure at the mount attachment points (basically becoming less effective as these three latter quantities decrease). While this approach can often be effective, the low frequencies of concern for feelable vibration can sometimes require mounting systems that are impractically soft, especially for smaller appliances.

Larger appliances like washing machines, however, do usually make use of isolation mounting systems to reduce vibration transmitted to the floor, which in this case is the main "contact point" for the consumer. In typical homes, where the laundry center may be located within the living space and not on grade, a wooden floor can be quite responsive to vibration from an appliance like a washing machine. Front-loading washers can generate especially high levels of imbalance at the drum rotation rate during spin, leading to noticeable floor/wall vibration and sometimes rattle noise (and even wall cracking). Many of these washers incorporate various self-balancing mechanisms and drum isolation systems in an attempt to reduce the severity of imbalance to begin with. Even so, the dynamic response characteristics of the floor will have a large influence on the amount of residual vibration transmitted from the feet of the washer into the floor, and sometimes it is necessary to increase the mass and stiffness of the floor itself underneath the washer feet.

Another approach for reducing vibration, generally applicable only in those situations where the vibration is dominated by a single tone at a fixed frequency, is to incorporate some form of "tuned mass" (dynamic) absorber. These devices include a mass mounted on a spring-like element, designed so that at the frequency of concern this mass-spring system vibrates at its resonance, producing an oscillatory force that opposes motion at its point of attachment, thus reducing the high amplitude vibration of the primary system. Finally, there is the related approach of active vibration control, which can either take the form of a dynamic vibration absorber adaptively tuned to changing frequency, or the more general form of utilizing active elements attached to the structure at strategic locations, and adaptively controlled so as to counteract existing vibration. These active approaches, however, can often be cost-prohibitive to implement and support on consumer appliances. ■