Proposal:
Laser-Doppler Vibrometer Studies on a Loudspeaker

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1 Introduction

This note outlines the use of laser-Doppler velocimetry to study the motion of loudspeaker cones, as proposed to two M.S. candidates, first to Zi-jing Wang and later to Corbin Grimsley. The operation of the laser-Doppler vibrometer[1] was to be verified, date-analysis instrumentation was to be tested, and two properties of the mechanical response of the loudspeaker to electrical input were to be investigated:

A. Temporal distortion: the generation of harmonic distortion at large amplitudes of motion; and

B. Spacial distortion: the radial deformation of the speaker cone at high frequencies.

Pilot experiments were carried out on a large woofer, using up to two laser beams to detect the velocity of the cone surface.

2 Experimental Set-up

For the initial experiments, a 15-inch Radio Shack Cat. No. 40-1301A bass loudspeaker was mounted in a two-foot square wooden baffle. Small patches of silver-colored reflective tape, and later water-based non-glossy white paint were used to brighten the surface of the cone. The speaker was driven by a hundred-watt Optimus MPA-125 public-address amplifier, which was supplied with sinusoidal-wave signals from a Protek B-850 audio generator covering 10 Hertz to 1 MHz. Each of the two laser-Doppler vibrometers consists of a Polytec OFV 350 sensor head incorporating a 1 milliwatt Class II HeNe-laser and a Nikon projecting/collecting lens; each sensor head is connected to a Polytec

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[1] see "Laser Vibrometers" in Chapter 12 of Peter M. Moretti, *Modern Vibrations Primer,* ISBN 0-8493-2038-0

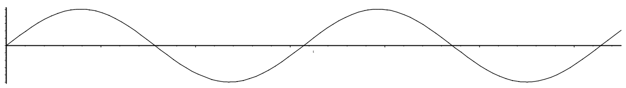
OFV 2600 velocimeter controller which converts velocity measurements to voltage signals. Three ranges can be selected: 5, 25, or 125 mm/sec/Volt. Initially, the output signals were processed with an Analogic/DataPrecision DATA 6100, which provides both time-traces like an oscilloscope as well as frequency spectra like a frequency analyzer. Other digital oscilloscopes and spectrum analyzers are also available.

3 Large-Amplitude Harmonic Distortion

Harmonic distortion can be detected by focusing a single vibrometer's laser beam at the center of the speaker cone. Low-frequency sinusoidal excitation is applied to the speaker coil, and the amplitude increased until harmonic distortion occurs. Harmonic distortion of the motion can be detected in four different ways:

1. The velocity output can be integrated electronically to obtain and display the displacement of the speaker's center:
    (a) At low displacement amplitudes, the response is linear and the displacement trace is sinusoidal like the excitation:

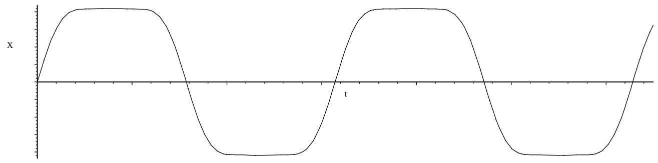
    $$x = A \sin(2\pi f_1 t)$$

    assuring us that the voice-coil windings remain in a consistent magnetic field.

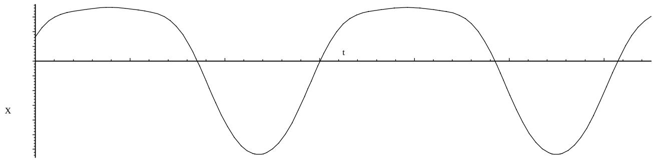
    (b) At higher amplitudes, the displacement trace can become either flattened symmetrically for both positive and negative peaks (odd-harmonic distortion), appearing to be "clipped" as in this exaggerated graph:

    $$x = A_1 \sin(2\pi f_1 t) + A_3 \sin(2\pi \times 3 f_1 t) + A_5 \sin(2\pi \times 5 f_1 t) + \ldots$$

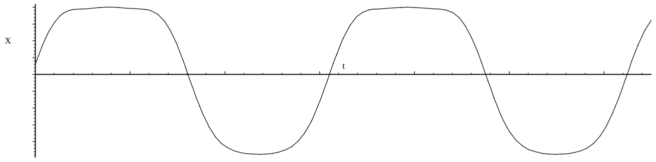
    or flattened un-symmetrically for only outward or only inward extremes of motion (even-harmonic distortion):

    $$x = A_1 \sin(2\pi f_1 t) \pm A_2 \cos(2\pi \times 2 f_1 t) \pm A_4 \cos(2\pi \times 4 f_1 t) + \ldots$$



or a mixture of both:

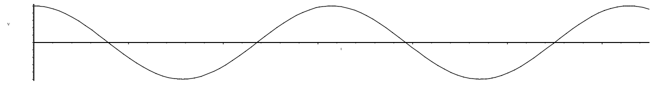
$$x = A_1 \sin(2\pi f_1 t) \pm A_2 \cos(2\pi \times 2f_1 t) + A_3 \sin(2\pi \times 3f_1 t) + \ldots$$



The amplitude display is attractive for showing voice-coil amplitude limitations graphically.

2. More directly, the velocity output of the vibrometer can be displayed on an oscilloscope:
    (a) The velocity trace is sinusoidal at low amplitudes:

    $$v = 2\pi f_1 \times A \cos(2\pi f_1 \times t)$$

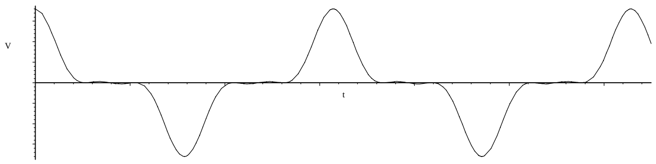
    

    The corresponding fundamental displacement amplitude x_{max} depends on the maximum velocity v_{max} and the excitation frequency f_1, and can be obtained from

    $$x_{\mathrm{max}} = \frac{v_{\mathrm{max}}}{2\pi f_1}$$

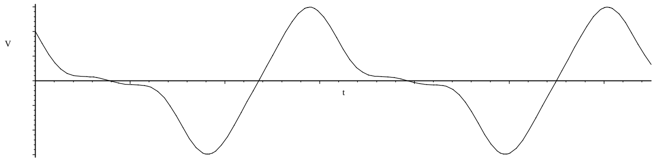
    (b) At higher amplitudes, the velocity trace becomes distorted either with odd harmonics, appearing to stay on near zero-velocity in this exaggerated plot:

    $$v = 2\pi f_1 A_1 \cos(2\pi f_1 t) + 6\pi f_1 A_3 \cos(2\pi \times 3f_1 t) + 10\pi f_1 A_5 \sin(2\pi \times 5f_1 t) + \ldots$$



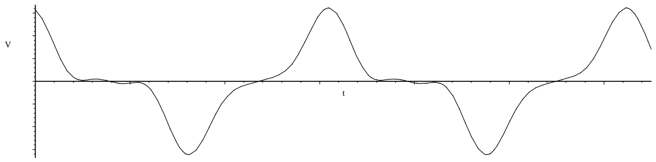
or with even harmonics:

$$v = 2\pi f_1 A_1 \cos(2\pi f_1 t) \mp 4\pi f_1 A_2 \sin(2\pi \times 2 f_1 t) \mp 8\pi f_1 A_2 \sin(2\pi \times 4 f_1 t) + \ldots$$



or a mixture of both:

$$v = 2\pi f_1 A_1 \cos(2\pi f_1 t) \mp 4\pi f_1 A_2 \sin(2\pi \times 2 f_1 t) + 6\pi f_1 A_3 \sin(2\pi \times 3 f_1 t) + \ldots$$



The velocity plot is more sensitive to harmonics than the amplitude display, showing non-linearities more dramatically.

3. The velocity output of the vibrometer can be processed with a Fast-Fourier Transform (FFT) analyzer to obtain its frequency spectrum display:
    (a) At low displacement amplitudes, only a single spike at f_1, the excitation frequency, will appear in frequency spectrum.
    (b) At higher amplitudes, smaller additional spikes will show up at $f_3 = 3f_1$ and possibly $f_5 = 5f_1$ for symmetrical amplitude limitations, and/or at $f_2 = 2f_1$ and possibly $f_4 = 4f_1$ for unsymmetrical amplitude limitations.

   Frequency spectra are convenient for quantifying the harmonic content. Operating an FFT analyzer requires careful choice of frequency range (see

Chapters 18 & 33 in Peter M. Moretti, *Modern Vibrations Primer,* ISBN 0-8493-2038-0). Note also that the magnitudes in a Power Spectral Density (PSD) display are proportional to the square of the motion.

4. The integrated-velocity (displacement) signal could be processed with an FFT analyzer, with similar results as with the raw velocity signal, except that the higher harmonics are less prominent relative to the fundamental, because each harmonic's displacement amplitude turns out to be its velocity amplitude divided by that harmonic's frequency—therefore this method is less sensitive for detecting harmonic distortion.

In our initial tests, methods (2.) and (3.) were used to analyze vibrometer output. It was demonstrated harmonic distortion due to non-linear electromechanics of the speaker can be verified using a laser-Doppler vibrometer, and the maximum acceptable voice-coil amplitudes can be determined.

4 High-Frequency Cone Deformation

The deformation of the speaker cone at high accelerations can detected by focusing two vibrometers' laser beams onto different spots on the speaker cone. Either the center of the speaker, or preferably an edge of the voice coil, is chosen as one of the location, the reference location. For a circular loudspeaker, deformation shows up as different motions at different radial locations. The amplitude and phase differences of displacement or velocity at two different locations can be obtained by comparing the velocity traces for the two locations on an oscilloscope, or by carrying out a cross-FFT to obtain the cross-spectrum. By moving one of the laser-Doppler vibrometers to different locations on the cone (but leaving the reference-location vibrometer in place), the motion of the entire cone can be investigated.

Tests should be carried out at voice-coil displacements within the linear range. The magnitude of the cone deformation is proportional to the acceleration $a_{\max}$ of the voice coil, which depends on the measured maximum velocity $v_{\max}$ and the excitation frequency f_1

$$a_{\max} = 2\pi f_1 \times v_{\max}$$

so that testing at increasing frequencies results in larger deformation effects.

At low frequencies, the ratio of amplitude at the cone perimeter to amplitude at the voice-coil should be about unity. Wide-range speaker cones are sometimes designed to have reduced edge-amplitude at higher frequencies. At very high frequencies, beyond the design specifications of the speaker, the edge of the speaker may have smaller or larger amplitudes than the center, and may even move in the opposite direction, affecting the pattern of acoustic radiation. Plotting the relative amplitudes for different locations at a given frequency of excitation will show the modal pattern for that given frequency, including the location of the nodes for that given frequency. Plotting the amplitudes ratios at a given location for a range of frequencies of excitation will show zeros whenever the node passes through that given location. These results can be compared with numerical analysis or used to improve cone design.

Preliminary experiments demonstrated that cone distortion can be measured using two laser-Doppler vibrometers, and the high-frequency-limits of a speaker can be determined. This should be done with the speaker mounted as intended, since the enclosure may affect cone distortion.

5 Conclusions

We propose the use of vibrometer measurements on loudspeakers:

A. The use of one a laser-Doppler vibrometer to measure harmonic distortion of loudspeaker motion at the large voice-coil amplitudes required for low frequency power; and

B. The addition of a similar second vibrometer to measure speaker-cone deformation at high frequencies.

Such measurements can form a valuable adjunct to acoustic microphone measurements of speaker output, because they show not only the degradation of performance with amplitude and frequency, but also the causes of this degradation:

A. The temporal-distortion analysis shows the actual forward and rearward voice-coil positions where the voice-coil windings no longer remain in a consistent magnetic field; and

B. The spacial-distortion analysis shows the nature of the speaker-cone deformation which interferes with acoustic propagation at high frequencies.

This information could be used to identify and correct specific deficiencies in the magnet, voice-coil windings, or speaker-cone design.