

Dynamic Linearity and Power Compression in Moving-Coil Loudspeakers*

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All loudspeakers exhibit changes in their performance characteristics as the input drive level is increased. The most pervasive of these effects is the rise in voice-coil resistance which accompanies coil heating due to inefficiency of power transfer. Comparative measurements of various loudspeaker designs at multiple drive levels will demonstrate reduction in efficiency, change in fundamental parameters, and other distortion mechanisms which transducers exhibit at high power inputs.

0 INTRODUCTION AND TERMINOLOGY

Changes which occur in a loudspeaker's input-output transfer characteristic with different input levels can be described as the dynamic linearity of the device. Since the loudspeaker is considered as an electroacoustic transducer, converting electric input power to acoustical output power, this characteristic can also be called the power linearity of the device. The terms "dynamic" and "power" both have the additional advantage of implying large inputs, usually the case of greatest interest.

The dominant mechanism of change which takes place in moving-coil loudspeakers at high input drive levels is the loss of efficiency caused by increased voice-coil resistance. The resistance increases in proportion to the temperature rise which accompanies increased current flow at higher power inputs. For this reason the effect is also referred to as the thermal linearity of the loudspeaker. Since all loudspeakers suffer to a greater or lesser degree from a reduction in efficiency at high power inputs compared to low inputs, a compression effect, the reduction characteristic can be referred to as power compression.

A distinction is made between nonlinear changes in the fundamental output amplitude alone, and changes in the harmonic, intermodulation, transient (phase), and other distortion characteristics of the loudspeaker. While any transfer characteristic nonlinearity is, strictly

speaking, a distortion, it is usual to describe level differences alone as separate from the generation of spurious output at other frequencies. Similarly, within the fundamental output, changes caused by voice-coil heating alone, as separated from those caused by nonlinearities in other parts of the loudspeaker, can be identified.

Dynamic linearity may therefore be defined as the extent to which a loudspeaker maintains a linear input-output transfer characteristic considering all aspects of its performance; power linearity or power compression may be synonymous or may refer only to the transfer characteristic of the fundamental amplitude; and thermal linearity implies changes resulting only from temperature, primarily the voice-coil resistance rise resulting from increased current flow.

These terms and their variations have been used both in the published technical literature and in manufacturers' technical notes, specification sheets, and advertising copy. King referred to "power nonlinearity" due to voice-coil heating [1, p. 42]. Colloms discusses the "power compression effect" and describes commercial measures that have been devised to combat it [2, p. 109]. Technical notes and white papers from major manufacturers have attempted to educate the public as to the existence of power compression, in a commercial competitive context [3, p. 14], [4, p. 17]. Some professional studio monitor loudspeaker system specification sheets show power compression curves of fundamental output at progressive input levels as a matter of course [5]. Professional high-level high-fidelity monitoring and sound-reinforcement low-fre-

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quency reproducers are said to be designed to assure "improved heat transfer which reduces thermal dynamic-range compression" [6]. Hi-fi loudspeaker specification sheets have used the terms as major sales features and benefits. One manufacturer shows fundamental output at progressive input levels and uses the term "power linearity" [7]. Another describes its loudspeakers as having "linear power response" and shows curves of both fundamental output and second and third harmonics at progressive levels [8]. Another describes an entire loudspeaker line with the term "linear response," making the distinction between both "power linearity," the "response linearity" of the fundamental acoustic pressure to the input, and the "dynamic distortion" characteristics of the systems [9]. One manufacturer even began to trademark the term "dynamic linearity" [10].

1 GRAPHIC DISPLAY FORMATS

Various graphic means can be employed to display compression and linearity characteristics. The most common is to display multiple frequency-versus-amplitude response curves taken at different input levels on a single graph. The input levels are progressive steps, typically 1, 3, or 10 dB. Deviation from equal separation can be easily viewed on the graph (Fig. 1) [7]–[9]. Alternately, output versus input can be plotted at a discrete frequency to show the deviation from linear transfer performance [11, p. 722]. An alternate method is to adjust the amplitude scale on each successive curve equal to the change in input, such that if the loudspeaker were perfect, the curves would exactly overlap. Any deviations can then be easily noted as separate, nonoverlapping traces. This method is particularly convenient for 10-dB input scaling (Fig. 2) [3, p. 14], [5]. If not only compression but other nonlinearities as well are to be studied dynamically, these

data may be generated in the same way. Usually second- and third-harmonic-distortion components are of the most immediate interest, but impedance, intermodulation, and other characteristics may each be run at separate levels and plotted to observe nonlinear characteristics [8]. When multiple types of plots are made at multiple input levels on a single two-dimensional graph, confusion in identification can result. One alternative is to employ a three-dimensional display plot, with the input levels differentiated on the third axis for clarity [9]. Alternately, individual plots with each type of data can be run at each chosen input level, and the curves compared individually.

2 VOICE-COIL RESISTANCE INCREASE

As previously stated, the dominant nonlinearity affecting loudspeakers with increasing input levels is the loss due to increased resistance from voice-coil heating. Moving-coil loudspeakers typically have voice coils wound of copper or aluminum wire. Their temperature resistance coefficients, the change in resistance with changing temperature, are not wholly linear but are on the order of $0.004/^{\circ}\text{C}$ [12, p. 2355]. The resistance of the voice coil R_T at some elevated temperature T_T can be compared to the resistance R_i at room temperature T_i by

$$R_T = R_i[1 + \alpha(T_T - T_i)] \quad (1)$$

where α is the temperature resistance coefficient. Room temperature is normally 20°C , and it is not uncommon for voice-coil temperatures to reach the range of 200°C (400°F). A voice coil operating at this temperature, which had a resistance of $6\ \Omega$ at 20°C , would have a resistance of $10.3\ \Omega$, a 70% increase. The effect of temperature in reducing the efficiency is theoretically

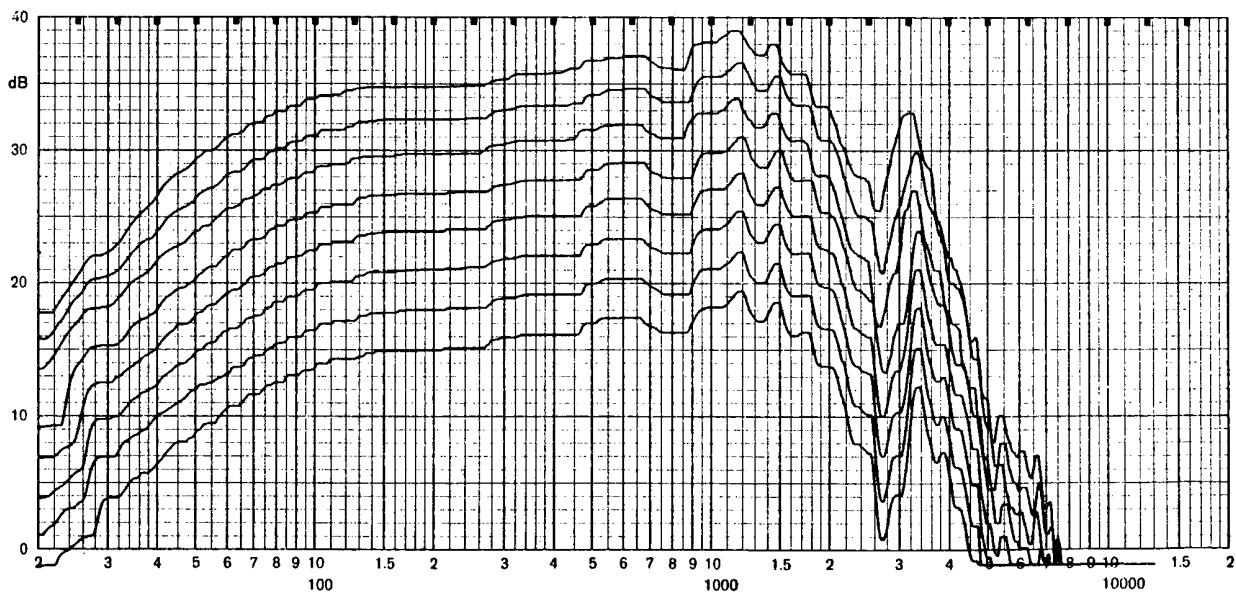


Fig. 1. 380-mm (15-in) loudspeaker driven with 3-dB successively larger input levels from 0.8 W (2.53 V rms) to 100 W (28.3 V rms) mounted flush in a 2π ground platform, 280-L (10-ft^3) sealed rear chamber, microphone 1 m on driver axis. 0-dB bottom line is 80 dB SPL re $20\ \mu\text{N/m}^2$.

fidelity system woofer is less than 1% efficient. These low efficiencies indicate that most of the electric power delivered to a loudspeaker must be dissipated as losses rather than converted to acoustical power. The mechanical frictional losses within a loudspeaker are normally much less than the electrical resistive losses, so the majority of this power is converted to heat in the voice coil. The degree to which a loudspeaker is able to dissipate this heat determines both the power handling capacity and the degree to which it will maintain a linear transfer characteristic.

The most thorough study of moving-coil loudspeaker heat transfer mechanisms has been done by Henriksen [16]. The most important element in keeping temperature low is the voice coil itself; next the air gap; then the heat-sinking effect of the pole tips, the magnet structure, and the rest of the loudspeaker. Heat can flow from the voice coil by conduction across the air gap or through the moving structure and into the loudspeaker/heat sink, by radiation into the air, or by forced convection venting due to diaphragm motion.

The voice coil itself will pass high currents more easily, and hence stay cooler, the lower the resistance per unit length and the larger the heat transfer area. For voice coils of equal dc resistance and equal axial lengths, then, a larger voice-coil diameter will inherently stay cooler than a smaller one. If the voice-coil diameter is doubled while axial length and dc resistance are maintained, the wire size will decrease 1½ gauges for $\sqrt{2}$ greater cross-sectional area, at a proportional decrease in resistance per unit length. Less resistance means more current capacity, hence lower heat. Also affecting the heat transfer area of the coil is its axial length. While a coil equal to or less than the axial depth of the magnetic gap will encounter maximum heat sinking, linearity requirements in the design may dictate a voice coil that overhangs the magnetic gap. This greater axial length will also decrease wire gauge and hence resistance and heat, and the voice-coil form may be made of thermally conductive rather than thermally resistive material, to both increase radiation of heat into the air and improve heat conduction from the coil ends to the central portion within the gap.

The air gap can be considered as a boundary layer across which heat can be conducted to the pole tips of the top plate and center pole. To minimize the thermal resistance, coil clearance must be as small as possible. Counter demand for larger clearance can be necessitated by practical manufacturing tolerances, or the requirements of high-compliance long-throw suspensions [1, pp. 40–42]. Thermal expansion of the coil and subsequent variations in concentricity must also be accounted for [14, p. 296].

The pole tips provide the most important heat conduction path through to the magnet structure and, ultimately, the entire loudspeaker physical structure. As with the voice coil, the heat transfer area should be maximized, so that large gap diameters as well as large axial depths are desirable. Both these requirements add to loudspeaker cost: gap depth will affect design linearity

constraints, and gap (voice-coil) diameter will affect diaphragm stability. Blackening of the pole tips can slightly improve radiation transfer through increased thermal emissivity [1, p. 42], [16, pp. 6–7]. Fluid-magnetic particle suspensions can reduce conduction resistance, but have other performance liabilities [16, p. 4], [17].

Forced convection can be provided by the diaphragm pumping air past the coil and pole tips [16, pp. 8–9]. This can be improved by vent holes in the coil form as well as a vent through the center pole of the magnetic structure [14, pp. 297–298]. The open area in the pole piece will trade off for a reduction in thermal mass, as will an undercut center pole for linearization of fringe flux. The presence of short rings for inductance or flux modulation reduction at or near the gap can improve conduction transfer, and may be placed solely for that purpose.

The magnet, back plate, and frame act as the final thermal mass, to sink heat from the coil and radiate it into the air. Fins, covers, and other assemblies only improve heat transfer insofar as they increase the radiating area [16, p. 10]. Natural convection heat transfer is dominated by the mass and area of the loudspeaker structure. Large magnets, cast frames, and thick back plates are therefore preferable to small, thin, stampings for increased thermal mass and radiating area.

5 DURATION EFFECTS—THERMAL TIME CONSTANT

The other key element in thermal compression is the duration of the applied signal. The thermal time constant is the product of the mass, specific heat, and thermal resistance of the element for 63% of its asymptotic level [16, pp. 9–10]. A typical voice coil will have a thermal time constant of less than a second, while a massive magnet structure and frame can take an hour or more to reach equilibrium between heat input from the coil and heat outflow to the air. The coil temperature will continue to rise along with the magnet structure, maintaining an approximately constant differential [14, pp. 295–296]. Data can be taken at a fixed input level at successive time increments to view thermal duration effects (Fig. 3).

6 OTHER THERMAL EFFECTS

Increased heat from the voice coil can cause other changes in the loudspeaker at high inputs. Heat can cause mechanical stress to paper and cloth parts and adhesives. Glue bonds can heat and become pliable compliances rather than rigid connections, or fracture and give way if pushed past their cure point, causing catastrophic failure. Magnetic materials change with temperature. Metals increase their reluctance, reducing their flux-carrying efficiency. Magnets will suffer reversible losses with elevated temperature, as well as irreversible losses if they have not been prestabilized [18, pp. 339–350]. For heating of the magnet to 100°C (212°F), Alnico V will suffer less than ½% irreversible

loss and also less than ½% reversible loss in remanent induction. Typical barium ferrite suffers no irreversible loss, but 15% reversible loss of remanence at the same temperature. In high-power loudspeaker designs, a ferrite magnet is larger in thermal mass and is typically placed on the outside of the magnet structure as compared to an Alnico magnet design, and so will not reach as high a temperature; however, some flux loss will occur.

7 OTHER DISTORTION MECHANISMS

In addition to thermal effects, other forms of distortion can become significant with the high voltages, forces, and excursions present at high inputs. Venting of the center pole or dust cap, or the lack thereof, can cause nonlinearities due to trapped air stiffness and turbulent air flow [19, pp. 73–75], [14, pp. 297–298], [16, pp. 8–10]. Cones and diaphragms can flex or “break up” due to the increased forces generated by high accelerations present with high inputs [14, p. 298], [20], [21]. Since

$$P = I^2 R \quad (2)$$

$$F = (Bl)I \quad (3)$$

$$F = ma \quad (4)$$

$$a_{\text{peak}} = \sqrt{2} a_{\text{rms}} \quad (5)$$

we have, combining Eqs. (2)–(5),

$$a_{\text{peak}} = \frac{\sqrt{2}(Bl)\sqrt{P/R}}{m} \quad (6)$$

Therefore a 0.050-kg moving-mass loudspeaker with a Bl factor of 10 N/A with 3.5-A input (100 W at 8 Ω) will undergo a peak acceleration of 1000 m/s² or over 100g (1g = 9.8 m/s²). These same forces can cause mechanical deformation in the frame, coil and form, suspension elements, and adhesive bonds, particularly if excursion motion is significant.

The Bl factor, or flux-linked turns, of a moving-coil loudspeaker motor can change with excursion. The only topology which prevents this is that of the short voice-coil/deep gap, and at long excursion this too changes as the coil turns begin to exit the gap. The greater the voice-coil overhang or underhang, and the more controlled and symmetrical the fringe flux, the more linear the Bl versus displacement characteristic will be [22, pp. 11–12].

Mechanical stress can cause changes in the stiffness characteristics of the suspension elements—the surround or compliance, and centering spider(s). The stiffness is usually greater statically than dynamically, and is displacement dependent [23], [24, pp. 2–3]. It is also frequency dependent, exhibits hysteresis, and its damping resistance loss may also be frequency and displacement dependent [25, pp. 3–4]. Change in

damping at high drive may cause the appearance of the classic surround self-resonance, or rim resonance, previously under control at lower drive, or cause its effect to shift in frequency or amplitude [26, pp. 83–86]. The stiffness characteristic can change with time, decreasing due to stretching of the material or increasing due to hardening and reforming of the material [20], [27, p. 4]. The increasing suspension stiffness with excursion can limit excursion capability, increasing third-harmonic distortion if symmetrical and second-harmonic distortion if single ended [20, p. 11]. It can, however, also be used to balance and cancel the non-linearity caused by a decrease in Bl with excursion [12]. This is possible since the increase of stiffness force is a third-order phenomenon and opposite in direction to the increase in coil force with decreasing Bl [28]. A carefully chosen and matched progressive suspension can also reduce dc components generated by the motor force [29]. The interaction of these effects can cause changes in the peak linear displacement of the diaphragm x_{max} with both level and frequency [22].

The coil motion away from its rest position is also subject to dc offset phenomena. Electromechanical rectification can cause the moving assembly to tend to move out of the gap toward a position of minimum Bl [19, pp. 245–251]. This “jump out” is another artifact of constant voltage rather than constant power excitation of the loudspeaker [30]. Solenoidal forces causing dc offset are also generated between voice coil and center pole, dependent on both coil position and center pole saturation level [31], [32]. Conductive voice-coil formers can add dynamic damping due to an eddy-current brake effect [1, p. 39].

Degaussing, magnetization, and modulation effects can result from the strong field generated by high voice-coil currents. The magnet may be discharged by a voice-coil field of opposite polarity, shifting its operating point to a position of lower energy product [1, pp. 42–43]. Alnico magnets centrally placed within long coils with many turns are most susceptible to this potential loss. Original flux levels can only be recovered through recharging of the magnet, and will still be subject to repeated loss if similar field levels are again encountered. The coil field can also tend to magnetize the pole tips, causing third-harmonic distortion through the cycling of a minor magnetic hysteresis loop. Constructing the pole tips of material with a very linear magnetization characteristic can tend to reduce this distortion [33]. Constructing the pole tips with laminated layers will also reduce this mechanism [34]. A conductive ring forming a short-circuited turn within the gap can reduce this magnetization distortion, and will also reduce voice-coil inductance and hence inductance modulation with coil position [32].

Short-circuited turns elsewhere within the magnet structure are also used to reduce the modulation of the permanent field by the voice-coil field, first identified by Cunningham and described in detail by Gilliom [31], [35]. This flux modulation causes levels of second-harmonic distortion, which can be the dominant mid-

lining, and potentially affect enclosure walls and joints as well. The high force amplitudes transmitted through the frame to the enclosure walls can increase absorption and leakage losses through vibration, as well as through the high pressures generated within the enclosure.

If driver excursion is significant, sufficient volume can be displaced through cone excursion within the isolated environment of the enclosure to cause nonlinear air compression [42, pp. 160–161], [43, p. 459]. It is well known that air is increasingly nonlinear at levels above the 150-dB range [44, pp. 215–217]. Too often this phenomenon is only associated with horn loudspeakers [45]. If an enclosure is small and the displacement capabilities of the driver are large, pressures reaching and exceeding these levels can be generated [46, p. 805], [47, p. 443]. To prevent excessive pressures of these magnitudes and subsequent distortion, minimum enclosure volume for a driver should be such that the driver's linear displacement volume (or the displacement volume that will be utilized) is no more than about ½% of the total net effective enclosure volume. This will prevent internal box pressures in excess of 150 dB sound pressure level, and should guarantee less than 1% distortion from air nonlinearity. A 5% displacement volume will yield 10% distortion [48, section 10.2], [49].

Port losses can increase dramatically at the high volume velocities required for large acoustic power outputs at low frequencies. Viscous losses can increase and the port can effectively close up at high system drive levels. One of the most common system failings is the choice of a vent area which is adequate at low level but is not examined at high-level inputs. Some commercial designs actually recommend that step-down and/or equalized alignments be executed by blocking off part of the port for alternate lower tuning [6]. This problem has been encouraged by Small's published guideline for minimum vent area [47, p. 442]:

$$S_v \geq 0.8 f_B V_d \quad (7)$$

or

$$d_v \geq (f_B V_d)^{1/2} \quad (8)$$

where S_v is the vent area in square meters, d_v is the diameter of a circular vent in meters, V_d is the driver linear displacement volume in cubic meters, and f_B is the vent tuning frequency in hertz. While this recommendation correctly indicates a larger vent area for larger driver displacement volumes, it also indicates a smaller port area for lower vent frequencies, clearly counter to intuitive knowledge of fluid mechanics and the requirements of laminar flow. More recent work, attributed to one of Small's students, has yielded the following equation [50]:

$$d_v \geq \frac{20.3 \sqrt{V_d}}{\sqrt[4]{f_B}} \quad (9)$$

and in U.S. customary units of inches,

$$S_v \geq \frac{8.25 V_d}{\sqrt{f_B}} \quad (10)$$

Both sets of equations yield equal results for box tunings of 55 Hz, but the revised equations demand greatly increased port areas for low tunings of large linear-displacement drivers. This can require long and cumbersome port lengths, but the validity and necessity is borne out by empirical measurements (Fig. 4). Passive-radiator systems have proportional requirements for vent-substitute displacement capability, and an additional loss term for the passive-radiator suspension losses [51].

10 PASSIVE NETWORK AND MULTIWAY SYSTEM EFFECTS

Resistors, capacitors, and inductors in loudspeaker system networks can also be subject to changes with dynamic input. These components are seldom the ideal elements assumed in a first design approximation [52, pp. 186–198]. Resistors are subject to heating and inductance changes causing distortion with increasing drive level [53, p. 3]. Inductors, whether air core or ferrite or iron core, have dc resistances that are subject to the same heating and inductance changes as resistors. Ferrite or iron cores can saturate with excessive drive and exhibit hysteresis effects dependent on the characteristics of the core materials [52, pp. 204–206]. Air cores can generate excessive stray fields, which can interact with nearby components [54]. Capacitors have been studied extensively for audio applications to identify various dissipation and hysteresis characteristics depending on composition and construction [55], [56].

With multiple-driver loudspeaker systems employing multiple-component crossover networks, different distortions can be exhibited at different drive levels to present an extremely complex dynamic signature. Designs employing further active processing such as equalization, compression, limiting, and bandwidth shifting for increased output levels may be able to improve the linearity or may merely exacerbate the problems.

11 SUBJECTIVE DESIRABILITY OF DISTORTION EFFECTS

While it is normally assumed that any deviation from linearity is an undesirable distortion, there are applications where certain distortions can create a desirable effect. Musical-instrument loudspeakers, in particular, are not necessarily designed to be accurate reproducers of sound, but may in many applications be thought of as sound producers, an integral part of the electric musical instrument. Manufacturers may categorize certain of their loudspeakers as sound reproducers with stress on smooth, linear, low-distortion response for maximum-accuracy sound-reinforcement application, and

others as sound producers with selectively engineered distortion colorations for musically or subjectively desirable effects [3, pp. 15–17].

The basic pressure-amplitude (frequency) response curve of the loudspeaker can be engineered to have certain characteristics based on the choice of cone size, shape, and composition, voice-coil material and size, cone suspension details, magnetic gap geometry, dome, and venting [3], [4], [57]. Flux modulation can be left unchecked in the loudspeaker for subjective effects [4, p. 12], [57, p. 2]. Conversely, flux modulation may be consciously eliminated if the subjective decision has been made that it is undesirable [3, p. 15]. Suspension bias or dc offset can be allowed to occur for certain transient dynamic effects [3, p. 15]. Thermal power compression can act as a built-in limiter for dynamic effects.

It remains for educated users to analyze for themselves whether a given loudspeaker has the objective or subjective characteristics, “the sound,” which they desire for their particular applications. The fact that a manufacturer has labeled a loudspeaker a reproducer is no guarantee that its performance characteristics are any different from one labeled as a musical-instrument loudspeaker.

12 COMPARATIVE MEASUREMENT

In order to evaluate the dynamic linearity and power compression of actual moving-coil loudspeaker units, random samples of various commercial units were measured at multiple drive levels. All units were high-quality 380-mm (15-in) designs utilizing cast frames, large ferrite magnets in vented structures, flat-wire voice

coils, and power ratings in the 200–400-W range. Swept sine-wave sound-pressure amplitude-versus-frequency curves were taken on an outdoor ground platform with the measurement microphone directly above the test loudspeaker at a distance of 1 m on axis. The platform had no substantial obstructions for a distance of at least 15 m in all directions along the ground surface so as to effectively provide a half-space 2π sr measurement environment. The backs of the loudspeakers were enclosed in a 280-L (10-ft³) well-braced enclosure extensively lined with damping material. Four curves are presented for each loudspeaker. The first is at 1 W with constant voltage set based on minimum impedance, with a 10-mA constant-current impedance curve. The second and third curves are at 10 and 100 W inputs, respectively, with individual second- and third-harmonic distortion sweeps raised 20 dB in all cases for display convenience. The final curve shows both the 1-W and the 100-W curves with a 20-dB display offset to view compression directly, again with impedance. Pen writing speed was 80 mm/s and paper speed 3 mm/s to ensure measurement accuracy, yielding a total sweep time of 75 s per pen trace. It should be noted that some slight skewing of the compression representation inevitably occurs due to the duration of the test. Drivers were initially at room temperature, and the timing of all data taking was consistent to within seconds to ensure fair, comparable, and repeatable results.

Peak linear diaphragm excursion displacement x_{max} was directly computed from the second- or third-harmonic plots for 10% (–20-dB) distortion at both 10- and 100-W inputs. This was possible since the radiation load and measurement distance are known, and given the sound pressure, frequency, and piston radius [22,

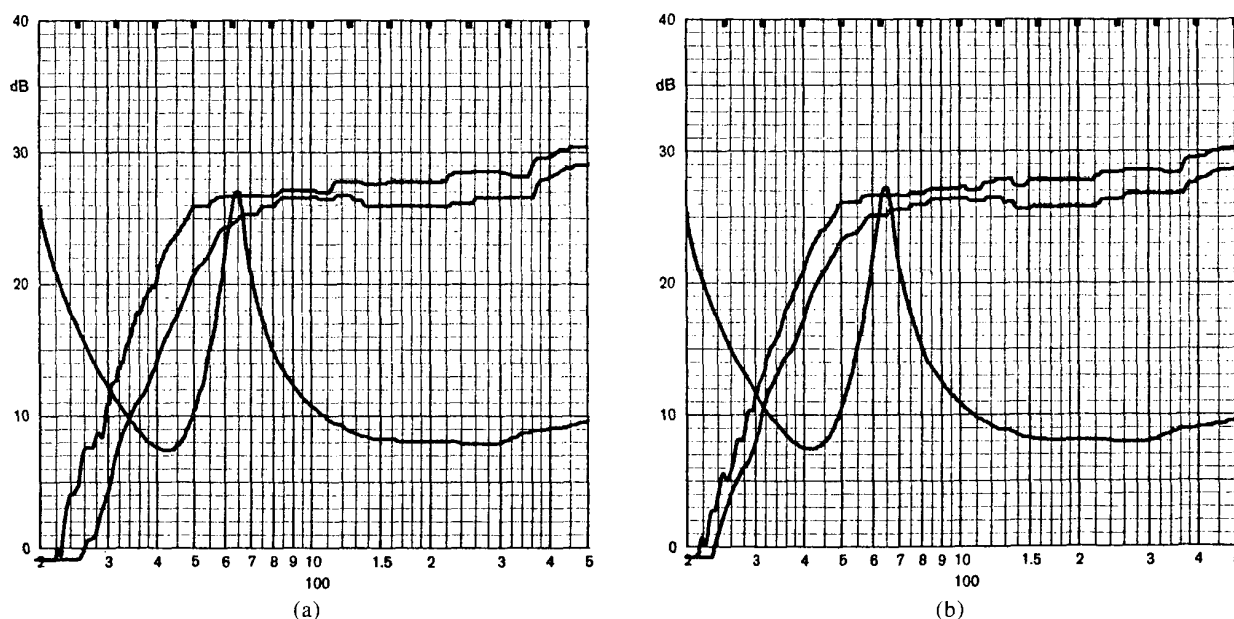


Fig. 4. 380-mm (15-in) loudspeaker mounted in 125-L (4.5-ft³) vented enclosure driven with 1-W (2.83-V rms) and 100-W (28.3-V rms) inputs, with 10-mA constant-current impedance showing 42-Hz tuning. (a) Enclosure tuned with 110-mm (4 $\frac{3}{8}$ -in) diameter simple circular hole in 19-mm ($\frac{3}{4}$ -in) thick baffle, 97-cm² (15-in²) port area. (b) Enclosure tuned with two 110-mm (4 $\frac{1}{8}$ -in) diameter ports, each with 125-mm (5-in) long ducts, 173-cm² (27-in²) total port area. While 1-W plots show no difference, 100-W plots show 3 $\frac{1}{2}$ -dB increased output at port resonance with larger port area. 0-dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W, 3.16 Ω (20 log Z) for impedance.

pp. 15–16]. For a 2π sr radiation load and 1-m measurement distance the formula is

$$x_{\text{peak}} = \frac{(1.18 \times 10^3) 10^{\text{SPL}/20}}{f^2 a^2} \quad (11)$$

where f is the frequency in hertz and a is the piston radius in millimeters.

The first commercial example is a unit sold for bass-guitar musical-instrument use as well as low-frequency sound-reinforcement applications. It features a 100-mm (4-in) diameter copper-wire voice coil, 11.2 mm (0.44 in) tall in a 7.1-mm (0.28-in) magnetic gap with undercut pole piece for gap fringe linearity and a short-

ing ring at the bottom of the center pole for control of flux modulation. A heavy, shallow, straight-sided cone with circumferential reinforcing ribs is fitted to a double half-roll treated-cloth surround and an aluminum center dome matching the 100-mm (4-in) coil diameter. Fig. 5 shows a rising response with response peak in the 1–2-kHz range, 2-kHz rolloff, and final 3–4-kHz peak. Fig. 6 at 10 W shows low-distortion performance up to 1 kHz, where second-harmonic-distortion spikes begin to occur due to the response peak cone breakup. 10% harmonic distortion occurred for the third harmonic at 25 Hz, with a fundamental output of 91 dB. For a piston radius of 167 mm (6.575 in) Eq. (11) yields a peak diaphragm displacement of 2.4 mm (0.09 in). At

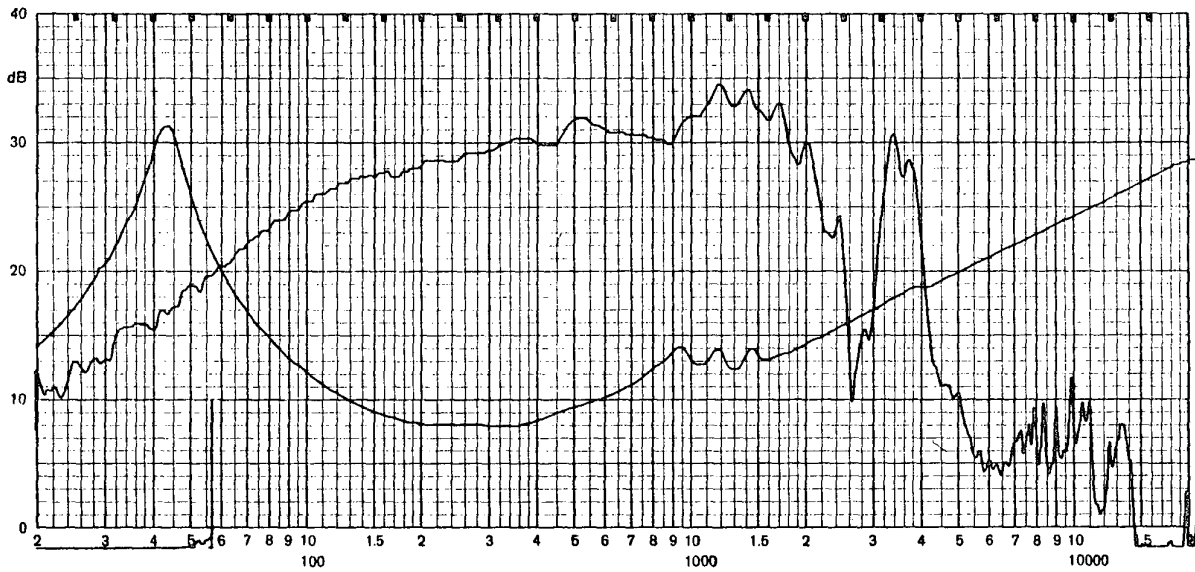


Fig. 5. 1-W response and impedance of 380-mm (15-in) nominal diameter musical-instrument loudspeaker with 100-mm (4-in) diameter voice coil. 0-dB bottom line is 70 dB SPL re $20 \mu\text{N}/\text{m}^2$ and 3.16Ω ($20 \log Z$).

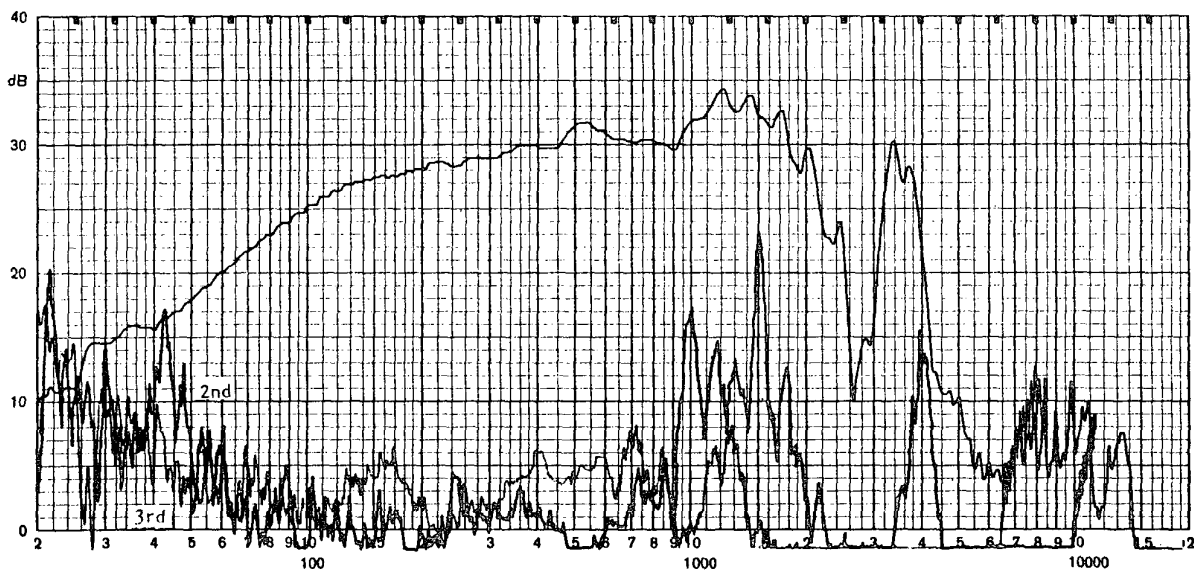


Fig. 6. 10-W response with second- and third harmonic-distortion components of loudspeaker of Fig. 5. 0-dB bottom line is 80 dB SPL for fundamental, 60 dB SPL for harmonics.

the 100-W input of Fig. 7 the spikes have increased slightly, but the most striking feature is the high second harmonic below 150 Hz, reaching 10–15% distortion. This can be attributed to the dc offset “jump-out” phenomena, and will impart a definite sound character to low-frequency transients. 10% second-harmonic distortion occurred for 116-dB fundamental output at 25 Hz, giving a peak displacement of 2.1 mm (0.08 in). If the dc offset is ignored, the third harmonic reached 10% at 63 Hz, with a 110-dB fundamental, for a peak displacement of 3.4 mm (0.13 in). Comparing the 1-W and 100-W curves in Fig. 8, the unit exhibits approximately 1 dB of overall average compression, with a maximum of 2½ dB at 350-Hz minimum impedance.

The next example is a similar unit by the same man-

ufacturer recommended solely for low-frequency sound-reinforcement use. It has the same features, with the exception of a longer 16.0-mm (0.63-in) voice coil, stiffer and more “progressive” suspension elements, and 1 dB less magnet flux. The same cone is used, this time with a paper rather than aluminum center dome. Comparing its 1-W response and impedance in Fig. 9 to the previous unit in Fig. 5, the decreased flux and coil turn density has reduced low-frequency damping and hence increased sealed-box low-frequency output by 1 dB in the 40-Hz resonance range. Similarly, the reduced motor force and increased moving-mass and voice-coil inductance have reduced midband efficiency and high-frequency output. The high-frequency peaks have been reduced, the bass-to-midrange balance has

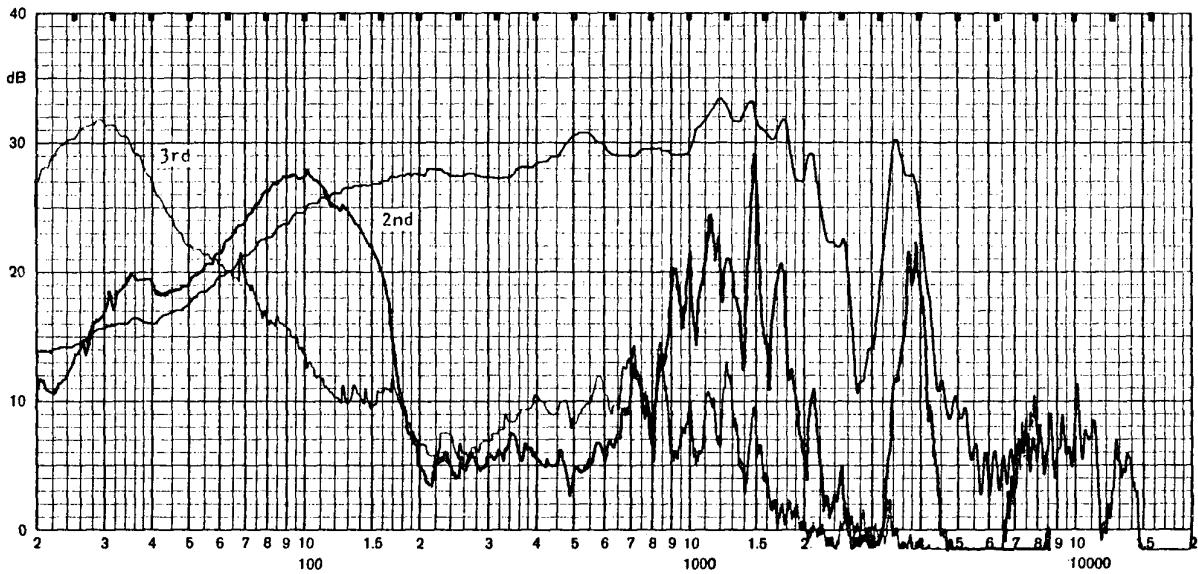


Fig. 7. 100-W response with second- and third-harmonic-distortion components of loudspeaker of Fig. 5. 0-dB bottom line is 90 dB SPL for fundamental, 70 dB SPL for harmonics.

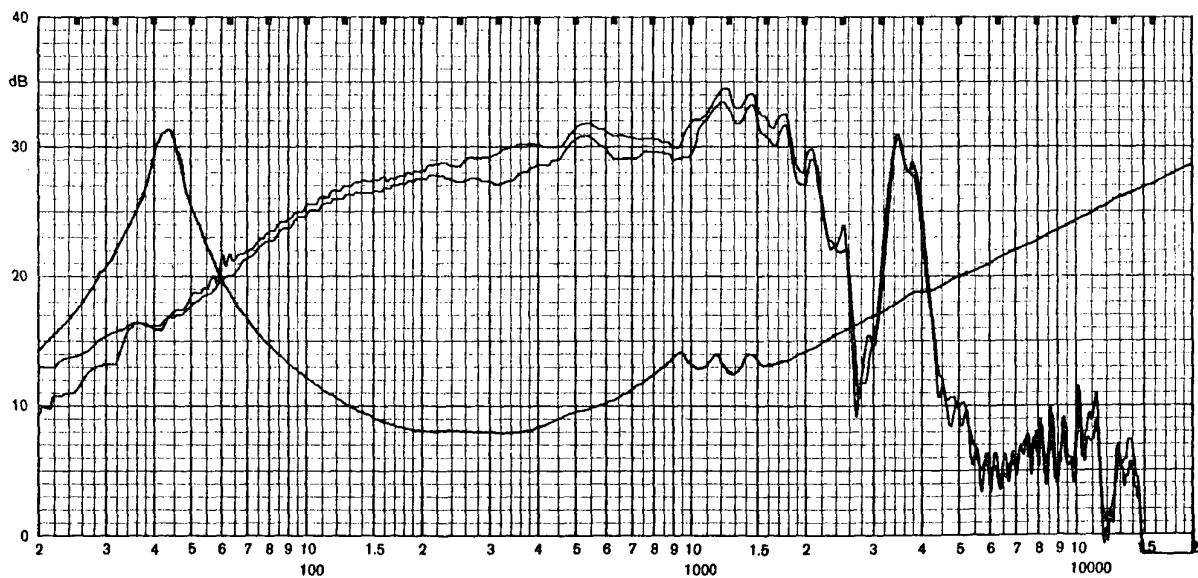


Fig. 8. 1-W and 100-W response of loudspeaker of Fig. 5 with impedance, reference levels scaled 20 dB so that compression can be easily viewed. 0-dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W, 3.16 Ω for impedance.

a unit from a third manufacturer, recommended for extended-bass application and using a 105-mm (4 $\frac{1}{8}$ -in) diameter voice coil, was measured. The design utilizes a double spider design spaced apart on the voice-coil tube between the voice coil and cone neck, a straight-sided ribbed cone, and an undercut-center-pole magnet structure, but without shorting ring. The voice coil is long for extreme travel, approximately 19 mm ($\frac{3}{4}$ in) deep in a 7.1-mm (0.28-in) gap, and is wound on a thick aluminum former. Fig. 21 shows a low mid-band efficiency for good bass balance, but bass damping is quite high. The output level at 40 Hz may also be contributed to by the eddy-current brake action of the conductive former. Upper end response shows a large

dip and peak related to the surround and cone configuration, and the beginnings of associated distortion are visible in the 10-W plot of Fig. 22. The peak excursion linearity for 10% third harmonic at 29 Hz, 96 dB, and an assumed piston radius of 165 mm (6.5 in) is 3.3 mm (0.13 in). The most significant distortion visible in the 100-W data of Fig. 23 is a high level of second harmonic throughout the midband, which is characteristic of flux modulation of the magnet structure due to the many voice-coil turns and no shorting ring. The excursion linearity at 110 dB and 54 Hz is 4.7 mm (0.19 in). The 1-W to 100-W compression curve of Fig. 24 does show excellent thermal compression performance of less than 1 dB in the minimum-impedance

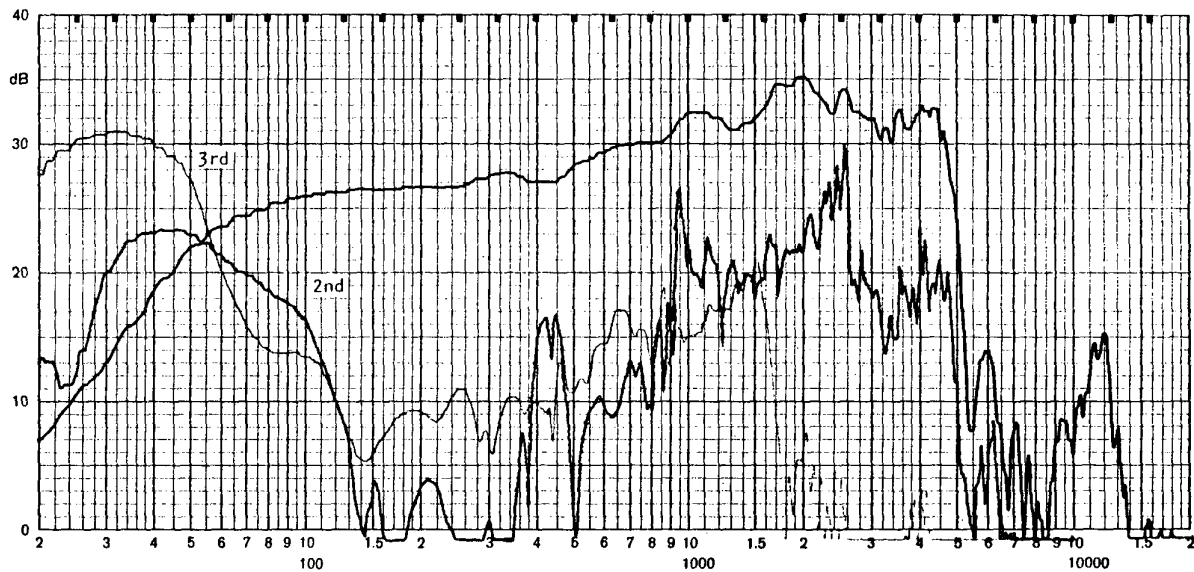


Fig. 15. 100-W response with second- and third-harmonic-distortion components of loudspeaker of Fig. 13. 0-dB bottom line is 90 dB SPL for fundamental, 70 dB SPL for harmonics.

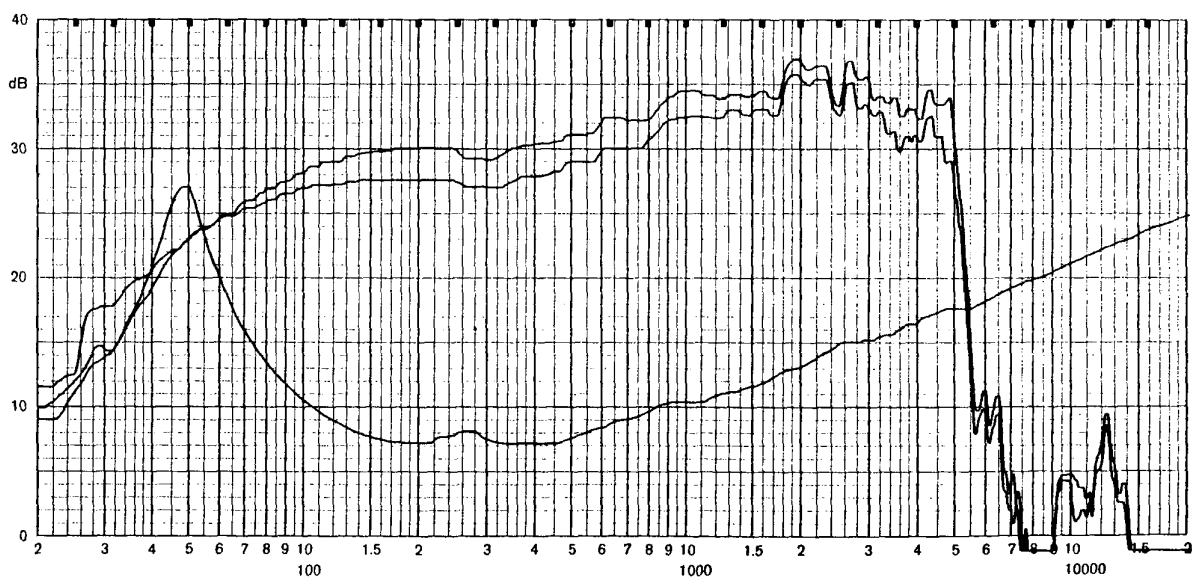


Fig. 16. 1-W and 100-W response of loudspeaker of Fig. 13 with impedance, reference levels scaled 20 dB so that compression can be easily viewed. 0-dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W, 3.16 Ω for impedance.

region, but this is unfortunately marred by suspension stiffness and resonance changes of up to 2½ dB above and below this range.

13 SUMMARY AND CONCLUSIONS

Moving-coil loudspeakers exhibit changes in their linearity with dynamic input. The most common and significant is the loss of sensitivity and efficiency from increased resistance due to voice-coil heating at high power. This is manifested as a compression in the input-output transfer characteristic. Better power transfer both acoustically and thermally can improve this situation, with increased voice-coil size of primary thermal importance. Other forms of distortion in the loudspeaker, its enclosure, and associated components can also in-

crease at high power, and various methods can be employed to correct or reduce them. Diaphragm excursion linearity usually increases with large inputs due to motor and suspension interaction. Measuring and comparing loudspeaker performance at multiple levels can reveal the existence and degree of these problems, and allow objective judgment of suitability of the loudspeaker for sound-production or sound-reproduction applications.

14 ACKNOWLEDGMENT

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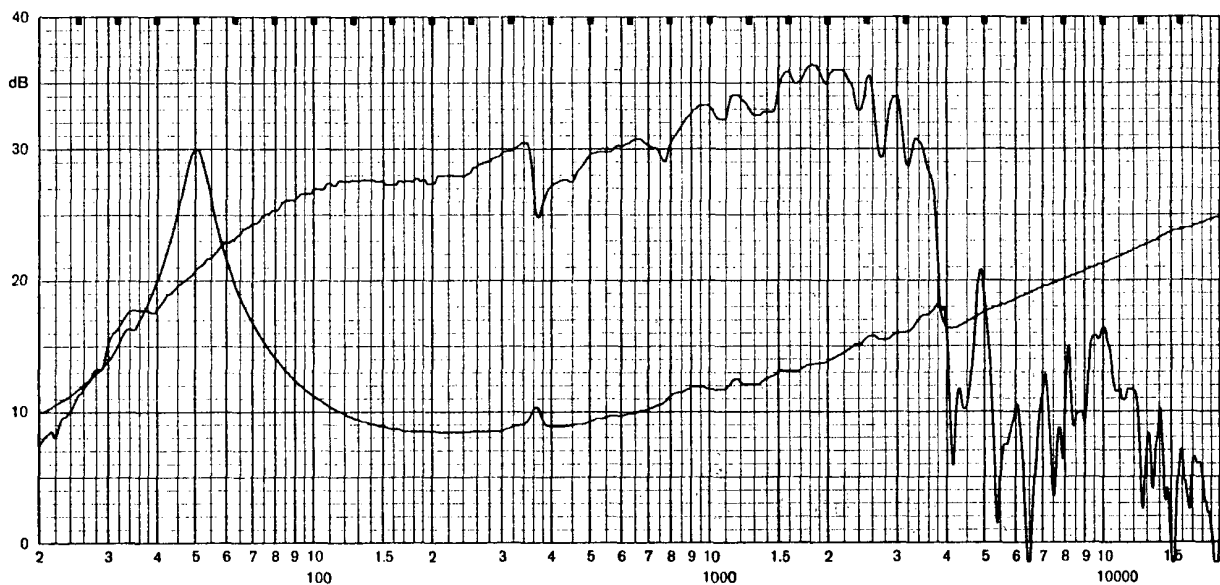


Fig. 17. 1-W response and impedance of 380-mm (15-in) nominal diameter sound-reinforcement loudspeaker with 63.5-mm (2½-in) diameter voice coil. 0-dB bottom line is 70 dB SPL and 3.16 Ω.

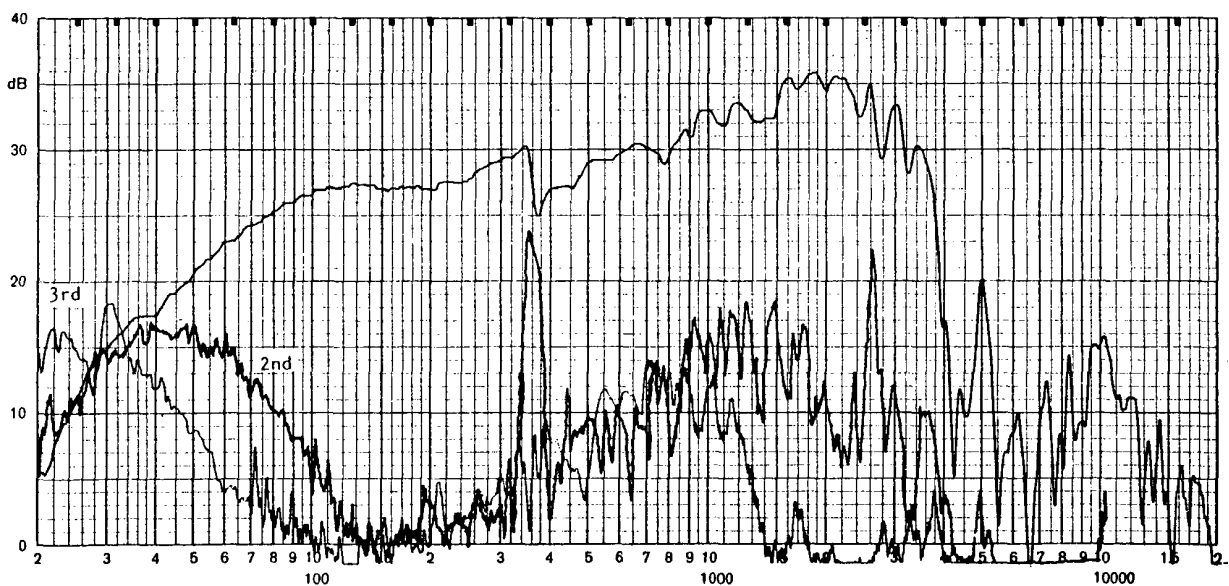


Fig. 18. 10-W response with second- and third-harmonic-distortion components of loudspeaker of Fig. 17. 0-dB bottom line is 80 dB SPL for fundamental, 60 dB SPL for harmonics.

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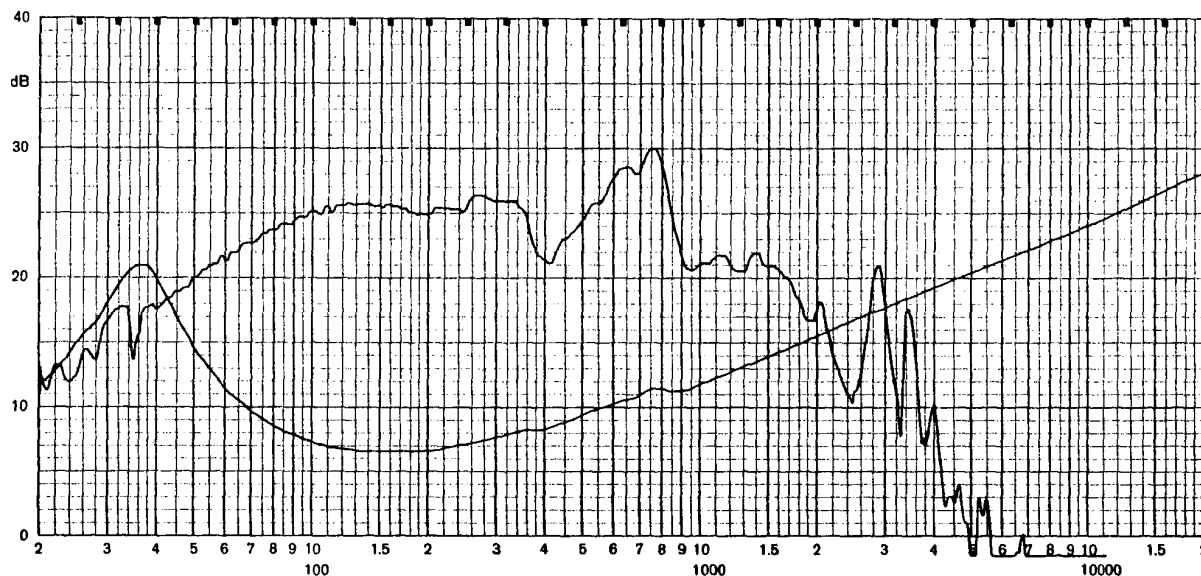


Fig. 21. 1-W response and impedance of 380-mm (15-in) nominal diameter extended-bass loudspeaker with 105-mm (4 1/8-in) diameter voice coil. 0-dB bottom line is 70 dB SPL and 3.16 Ω .

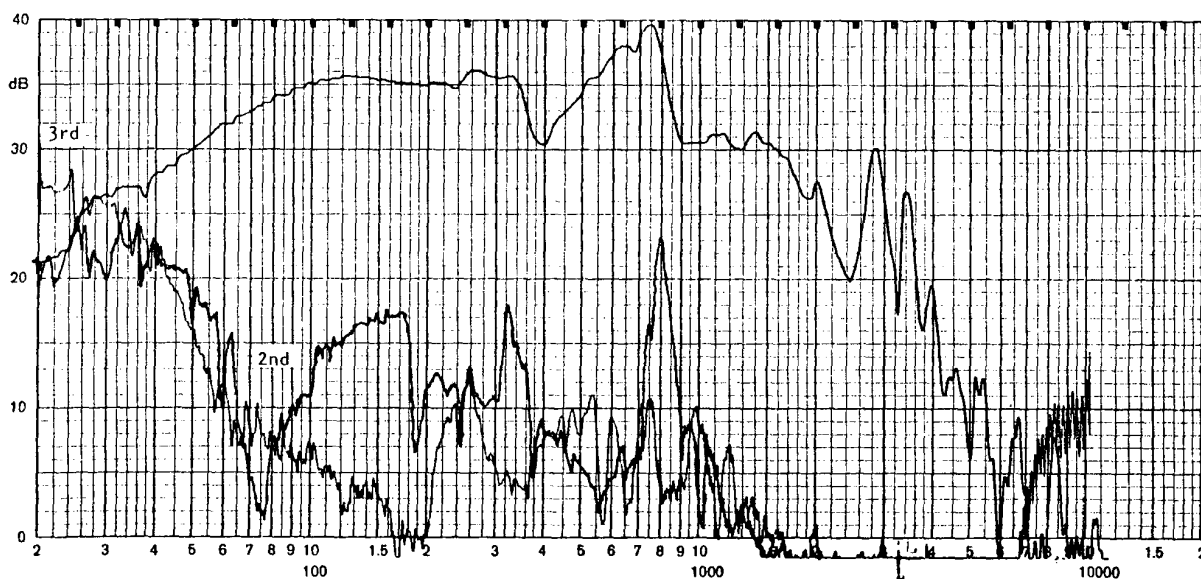


Fig. 22. 10-W response with second- and third-harmonic-distortion components of loudspeaker of Fig. 21. 0-dB bottom line is 70 dB SPL for fundamental, 50 dB SPL for harmonics.

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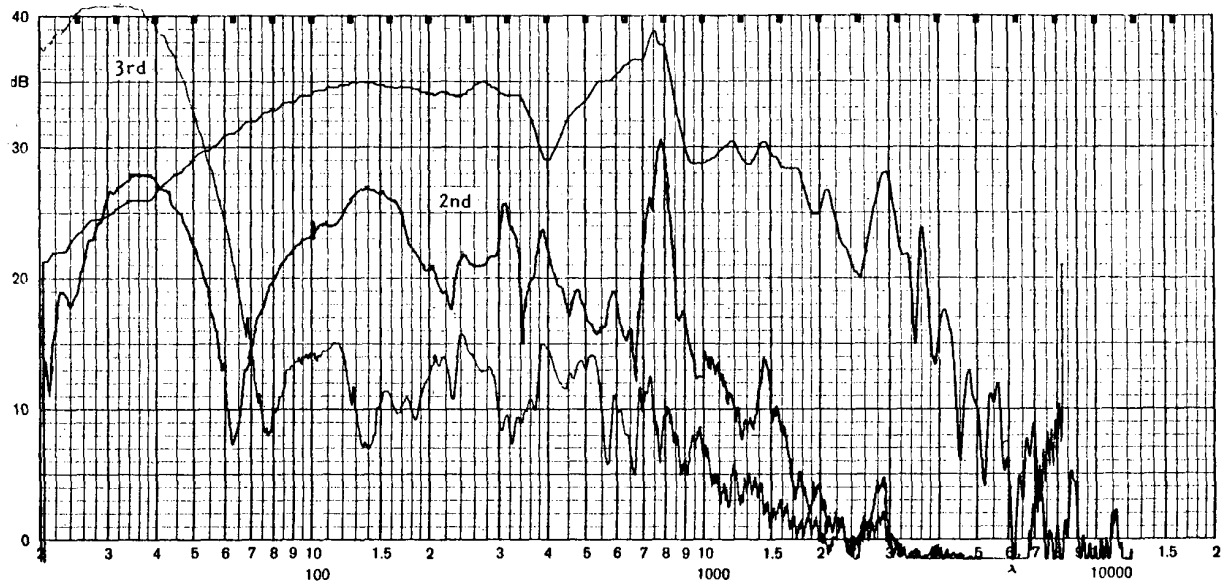


Fig. 23. 100-W response with second- and third-harmonic-distortion components of loudspeaker of Fig. 21. 0-dB bottom line is 80 dB SPL for fundamental, 60 dB SPL for harmonics.

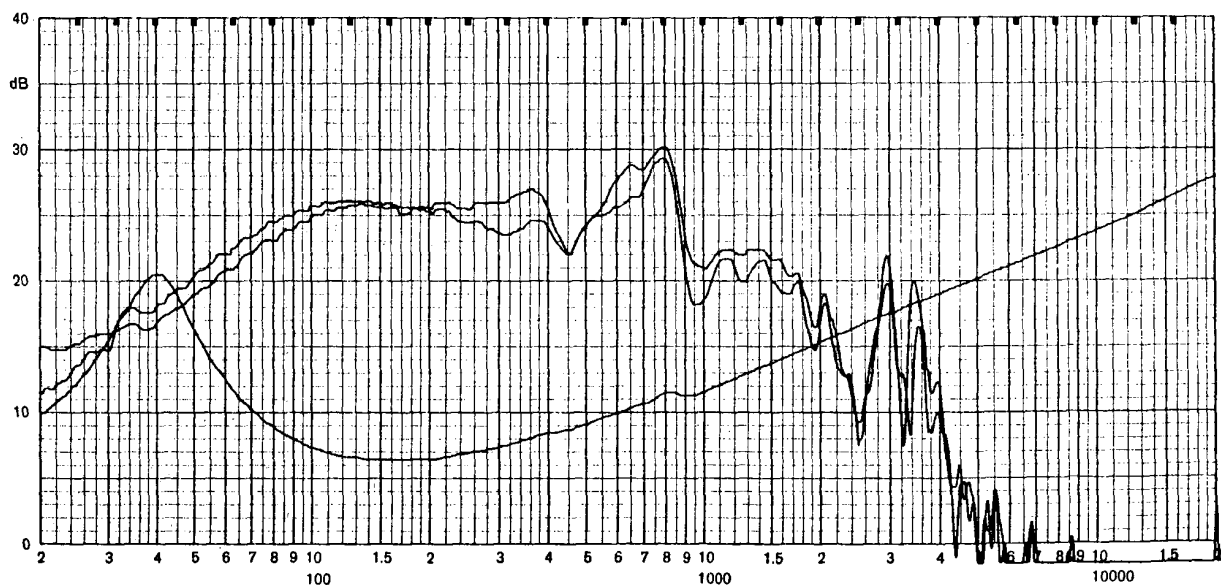


Fig. 24. 1-W and 100-W response of loudspeaker of Fig. 21 with impedance, reference levels scaled 20 dB so that compression can be easily viewed. 0-dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W, 3.16 Ω for impedance.

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