DYNAMIC LINEARITY AND POWER COMPRESSION IN MOVING-COIL LOUDSPEAKERS

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All loudspeakers exhibit changes in their performance characteristics as 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.

INTRODUCTION AND TERMINOLOGY

Changes which occur in a loudspeaker's input-to-output transfer characteristic with different input levels can be described as the dynamic linearity of the device. Since the loudspeaker is considered as an electro-acoustic transducer, converting electrical input power to acoustical output power, this characteristic can also be called the power linearity of the device. Both the terms dynamic and power 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 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, a compression effect, the reduction characteristic can be referred to as power compression.

A distinction is made between non-linear 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 non-linearity 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 non-linearities 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 synonomous 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 in both published literature, and manufacturers technical notes, specification sheets, and advertising copy. King referred to "power non-linearity" due to voice-coil heating (1, p. 42). Colloms discusses the "power compression effect", and describes commercial measures which 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-frequency 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 feature/benefits. One manufacturer shows fundamental output at progressive input levels and uses the term "power linearity" (7). Another describes their speakers as having "linear power response" and shows curves of both fundamental output and second and third harmonic 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).

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 dB, 3 dB, or 10 dB. Deviation from equal separation can be easily viewed on the graph (Figure 1)(7, 8, 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, non-overlapping traces. This method is particularly convenient for 10 dB input scaling (Figure 2) (3, p. 14; 51). If not only compression but other non-linearities as well are to be studied dynamically, this 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/or plotted to observe non-linear 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.

VOICE COIL RESISTANCE INCREASE

As previously stated, the dominant non-linearity 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/°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_t, at room temperature, T_t, by:

$$R_T = R_t\left[1+\alpha(T_T-T_t)\right] \tag{1}$$

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 ohms at 20°C would have a resistance of 10.3 ohms, a 70% increase. The effect of temperature in reducing the efficiency is greater the lower the efficiency of the loudspeaker (13, pp. 154-155). High power handling voice coils may be called upon to operate at temperatures in the region of 270°C (520°F). At these temperatures the voice-coil resistance will have doubled.

The increase in coil resistance has a double effect on the output of the loudspeaker. Since the coil resistance is inversely proportional to the piston band efficiency of a loudspeaker, a coil resistance increase creates a decrease in loudspeaker efficiency. However, loudspeakers are not driven from constant power sources, they are driven from constant voltage sources. With a fixed voltage set at the loudspeaker terminals, as the loudspeaker voice coil heats up the power delivered by the source amplifier goes down. This voltage effect is further complicated by the fact that it is most noticeable in the region of the minimum impedance of the loudspeaker. At other points the effect can be somewhat shielded by the reactive components of the complex loudspeaker impedance, such as the motional impedance and coil inductance. These facts not only contribute to compression, but also to changes in frequency response with increasing input power (14, pp. 295-296). Further, the major concern is often with the pressure output at some position and distance rather than the true acoustical power output of a loudspeaker. This places primary importance on the voltage versus pressure transfer characteristics or voltage sensitivity of the loudspeaker and its linearity, rather than the actual power transfer characteristics. If the loudspeaker has doubled its coil resistance, it is not only half as efficient as it was, it is drawing half the power that it was. Actual voltage sensitivity will have been reduced by 6 dB.

POWER HANDLING VS. POWER TRANSFER EFFICIENCY

The marketeer in his advertising copy and the end user in his purchase requirements stress power handling, with less regard for efficiency or sensitivity and little or none for reductions at high power inputs. These are almost always assumed not to occur, with many manufacturers quoting a derived rather than measured maximum acoustic output specification for products which is merely the addition of the power handling rating to the one watt sensitivity rating.

Obviously there is a difference between power capacity of a speaker and power output (acoustical output at high power input). Heat transfer away from the voice coil is more important than heat resistance, the ability of the coil to operate at high temperatures (14, p. 296). It does little good if a 3 dB handling increase only yields a 1 dB output increase, or worse yet, no increase. The intelligent designer will focus first on power transfer into acoustic output, next on heat transfer away from the device, and lastly on the heat resistance of the device.

HEAT TRANSFER MECHANISMS

Loudspeakers generate heat because they are inefficient transducers of electrical energy into acoustical energy. Even the most efficient horn loudspeaker is only approximately 25% to 30% efficient. The most efficient cone speakers can approach 10% efficiency, but 1% to 2% is far more common. The typical home high-fidelity system woofer is less than 1% efficient. These low efficiencies indicate that most of the electrical 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 Henricksen (15). 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, radiation into the air, or forced convection venting due to diaphragm motion.

The voice coil itself will pass high currents easier, 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 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 which 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 desireable. 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; 15, pp. 6-7). Fluid-magnetic particle suspensions can reduce conduction resistance, but have other performance liabilities (15, p. 4; 16).

Forced convection can be provided by the diaphragm pumping air past the coil and pole tips (15, 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 tradeoff for a reduction in thermal mass, as will an undercut center pole for linearization of fringe flux. The presence of shorting rings for inductance and/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 radiating area (15, 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.

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 (15, 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 equalibrium 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 (Figure 3).

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, reduce their flux-carrying efficiency. Magnets will suffer reversible losses with elevated temperature, as well as irreversible losses if they have not been pre-stabilized (17, 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 remanance 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.

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 non-linearities due to trapped air stiffness and turbulent air flow (18, pp. 73-75; 14, pp. 297-298; 15, 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; 19; 20). Since:

$$P = I^2R \tag{2}$$

$$F = (B\ell)I \tag{3}$$

$$F = ma \tag{4}$$

$$a_{peak} = \sqrt{2}\, a_{rms} \tag{5}$$

Combining (2), (3), (4), and (5):

$$a_{peak} = \frac{\sqrt{2}\,(B\ell)\sqrt{\frac{P}{R}}}{m} \tag{6}$$

Therefore a 0.050 kg moving-mass loudspeaker with a $B\ell$ factor of 10 N/A with 3.5 amperes input (100 W @ 8 ohms) will undergo a peak acceleration of 1000 m/sec^2 or over 100 G's (1 G = 9.8 m/sec^2). 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 $B\ell$ 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 $B\ell$ versus displacement characteristic will be (21, pp. 11-12).

Mechanical stress can cause changes in the stiffness characteristic of the suspension elements, the surround or compliance and centering spider(s). The stiffness is usually greater statically than dynamically, and is displacement dependent (22; 23, pp. 2-3). It is also frequency dependent, exhibits hysteresis, and its damping resistance loss may also be frequency and displacement dependent (24, 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 (25, 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; 26, p. 4). The increasing suspension stiffness with excursion can limit excursion capability, increasing third harmonic if symmetrical and second harmonic if single ended (21, p. 11). It can, however, also be used to balance and cancel the non-linearity caused by decrease in $B\ell$ 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 $B\ell$ (27). A carefully chosen and matched progressive suspension can also reduce dc components generated by the motor force (28). The interaction of these effects can cause changes in the peak linear displacement of the diaphragm, x_{max}, with both level and frequency (21).

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 $B\ell$ (18, pp.245-251). This "jump out" is another artifact of constant voltage rather than constant power excitation of the loudspeaker (29). Solenoidal forces causing dc offset are also generated between the voice coil and center pole, dependent on both coil position and center pole saturation level (30, 31). 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 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 (32). Constructing the pole tips with laminated layers will also reduce this mechanism (33). A conductive ring forming a shorted turn within the gap can reduce this magnetization distortion, and will also reduce voice-coil inductance and hence inductance modulation with coil position (31).

Shorted 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 (30; 34). This flux modulation causes levels of second harmonic which can be the dominant mid-band distortion mode in long-coil ferrite-magnet loudspeakers without shorting rings for prevention. Placement of the rings is critical, as they are most effective within the voice coil but can then incur the previously mentioned inductance changes and modulation with coil displacement position. The shorted turn can also increase the magnet assembly's resistance to demagnetization from the coil field.

DRIVER PARAMETER AND SYSTEM ALIGNMENT VARIATIONS

Since changes occur in the fundamental electro-mechano-acoustical parameters of a moving-coil transducer, so too must other representations of driver parameters change, as well as the system characteristics in which the transducer is to be used. The filter-theory approach to categorization of transducers and systems devised by Thiele and Small has become extremely popular due to its ease of understanding and application (35, 36). Since their approach uses a Q figure for the loudspeaker, combining both resistive and reactive characteristics into a single figure of merit, individual and interactive changes in each physical parameter will have a complex effect on the Thiele-Small parameters. Various authors have attempted to come up with complete equations to describe the complete loudspeaker including non-linearities, with limited results due to the extreme complexity of solving the non-linear differential equations involved (37, 38). Thiele and Small recommend "small-signal" parameters be taken at nominally 1 volt or less than 0.1 watt inputs, implying linearity up to the limits of "large-signal" parameters, including maximum thermal input power and piston displacement volume (35, P. 479; 36, P. 395).

One author has addressed the concept of identifying the loudspeaker parameters under conditions more closely related to actual use (26). It would clearly seem wise to measure the "small-signal" parameters at what will be the nominal operating power for the driver under typical use, and use these parameters for system alignment calculations. In the absence of this data, a simple approximation can be made by measuring or predicting the actual dc resistance of the voice coil during typical operation and raising the driver Q in accordance with Small's equations for adjusting the Q of a driver (39, p. 550). Even this will be overly optimistic, since it only accounts for voice-coil heating and no other non-linearities, which are almost always in the nature of additional loss factors. The net result is that a driver which has been designed into a maximum-flatness alignment based on its low-level parameters will often exhibit an underdamped response when operated at high levels still well within the specified maximum input. Conversely, if a driver is designed with typical operating conditions in mind, the alignment chosen will be one that is slightly overdamped but smooth and well-behaved, and which will yield an approximately flat characteristic when the actual operating driver Q is realized.

ENCLOSURE NON-LINEARITIES AND PORT COMPRESSION

The enclosure in which a moving-coil loudspeaker is mounted can itself be subject to dynamic non-linearities which will affect the entire system. Small has identified and isolated the resistive losses in a typical direct-radiator system as those related to leakage losses, absorption losses, and, for a vented system, vent losses (40, pp. 365-367). Heat from the driver can change the absorption characteristics of enclosure filling and 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 non-linear air compression (41, pp. 160-161; 42, p. 459). It is well known that air is increasingly non-linear at levels above the 150 dB range (43, pp. 215-217). Too often this phenomena is only associated with horn loudspeakers (44). If an enclosure is small and the displacement capabilities of the driver large, pressures reaching and exceeding these levels can be generated. 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 which 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 SPL, and should guarantee less than 1% distortion from air non-linearity. A 5% displacement volume will yield 10% distortion.

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 step-down and/or equalized alignments be executed by blocking off part of the port for alternate lower tunings. This problem has been encouraged by Small's published guideline for minimum vent area (45, p. 442):

$$S_V \geq 0.8\, f_B\, V_d \qquad (7)$$

or

$$d_V \geq (f_B\, V_d)^{\frac{1}{2}} \qquad (8)$$

where S_V is the vent area in m^2 or d_V is the diameter of a circular vent in meters, V_D is the driver linear displacement volume in m^3, and f_B is the vent tuning frequency in Hz. 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 (46):

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

and in English units of inches:

$$S_V \geq \frac{8.25\ V_d}{\sqrt{f_B}} \tag{10}$$

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 (Figure 4). Passive-radiator systems have proportional requirements for vent-substitute displacement capability, and an additional loss term for the PR suspension losses (47).

PASSIVE NETWORK AND MULTI-WAY 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 (48, pp. 186-198). Resistors are subject to heating and inductance changes causing distortion with increasing drive level (49, p. 3). Inductors, whether air cored, or ferrite or iron core, have dc resistances which 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 (48, pp. 204-206). Air cores can generate excessive stray fields which can interact with nearby components (50). Capacitors have been studied extensively for audio applications to identify various dissipation and hysteresis characteristics depending on composition and construction (51, 52).

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.

SUBJECTIVE DESIREABILITY OF DISTORTION EFFECTS

While it is normally assumed that any deviation from linearity is an undesireable distortion, there are applications where certain distortions can create a desireable 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 for maximum accuracy sound reinforcement application, and others as sound producers with selectively engineered distortion colorations for musically or subjectively desireable effect (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 (53, p. 1). Flux modulation can be left unchecked in the loudspeaker for subjective effect (4, p. 12; 53, p. 2). Conversely, flux modulation may be consciously eliminated if the subjective decision has been made that it is undesireable (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 effect.

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

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 W to 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 each loudspeaker unit were enclosed in a 280 liter (10 cu. ft.) well-braced enclosure extensively lined with damping material. Four curves are presented for each loudspeaker. The first is at 1 watt with constant voltage set based on minimum impedance, with 10 mA constant current impedance curve. The second and third curves are at 10 watt and 100 watt 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 100 W curves with a 20 dB display offset to directly view compression, again with impedance. Pen writing speed was 80 mm/sec and paper speed 3 mm/sec to ensure measurement accuracy. Drivers were initially at room temperature and 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 W 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 (21, pp. 15-16). For a 2π sr radiation load and one meter measurement distance the formula is:

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

where f is the frequency in Hz and a is the piston radius in mm.

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 shorting 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, a double half-roll treated cloth surround, and an aluminum center dome matching the 100 mm (4 in) coil diameter. Figure 5 shows a rising response with response peak in the 1 kHz to 2 kHz range, 2 kHz roll-off, and final 3 kHz to 4 kHz peak. Figure 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 break-up. 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) equation (11) yields a peak diaphragm displacement of 2.4 mm (0.09 in). At the 100 W input of Figure 7 the spikes have increased slightly, but the most striking feature is the high second harmonic below 150 Hz, reaching 10% to 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 Figure 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 manufacturer 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 and impedance response in Figure 9 to the previous unit in Figure 5, the decreased flux and coil turns 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 mid-band efficiency and high-frequency output. The high-frequency peaks have been reduced, the bass-to-midrange balance has been made more linear and the overall response is smooth. Figure 10, the 10 W distortion response, shows similar low-distortion response below 900 Hz, and the peak diaphragm displacement for 10% third harmonic is 2.1 mm (0.08 in) for 94 dB fundamental at 32 Hz and a 167 mm (6.625 in) piston radius. In Figure 11, the 100 W distortion response is devoid of the high second-harmonic dc-offset distortion. The peak diaphragm displacement for 10% third harmonic at 54 Hz and 109 dB fundamental output is 4.1 mm (0.16 in). The longer coil and progressive suspension have controlled the offset and increased linearity for more accurate reproduction. Comparing 1 W to 100 W in Figure 12, compression is quite consistent at just over 1 dB across the full usable range.

The next example is a unit by a different manufacturer sold as a musical instrument loudspeaker but also utilized for low-frequency sound reinforcement. It has a 63.5 mm (2½ in) diameter aluminum wire voice coil, equal in height to the 10.9 mm (0.43 in) top plate, with no undercut on the center pole, or shorting ring. A light, deep, curvilinear cone is employed, with a multiple cloth-roll accordion-pleat surround, and an oversize 100 mm (4 in) paper dome. Figure 13 shows smooth, extended response all the way to 5 kHz. Because of the smaller coil, low-frequency damping is reduced 3-4 dB over the previous 100 mm (4 in) coil examples in Figure 5 and Figure 9, yielding increased output in the 40 Hz range in this sealed-box measurement. Mid-band piston efficiency in the 200 Hz to 400 Hz range is about the same as the unit in Figure 5 and about 3 dB greater than that of Figure 9. Figure 14 shows the 10 W distortion response dominated by high-frequency cone break-up and a bias yielding higher low-frequency second than third. The peak displacement for 10% third harmonic at 30 Hz, 96 dB, and a piston radius of 165 mm (6.5 in) is 3.0 mm (0.12 in). The suspension bias is confirmed in Figure 15 at 100 W, as the second harmonic remains slightly higher than the third. This could be caused by a suspension bias, some dc-offset effect, the non-symmetrical gap geometry, or a combination. The suspension definitely exhibits a progressive characteristic, since for 10% third harmonic at 113 dB and 56 Hz the peak displacement is 6.2 mm (0.24 in), double that at 10 W drive. Figure 16 reveals this design's major compromise, a consistent 2½ dB of compression from 1 W to 100 W throughout the region of minimum impedance with a differing curve shape and Q relative to resonance.

The fourth example is a similar design from the same manufacturer sold specifically as a low-frequency reproducer. It uses the same basic cone, suspension, and magnet structure, with additional enhancements designed to increase linear travel, power handling and reduce thermal compression. The voice coil is longer, 15.2 mm (0.6 in) deep, so that it overhangs the top plate, and a shorting ring is placed so as to effectively extend the center pole to control drive inductance and improve heat transfer from the top of the coil. The top-plate pole tip is also coated with a thermal lubricant to protect and insulate against coil expansion rubs. Figure 17 reveals this unit to have a piston-band response very similar to the competitive unit of Figure 9 in terms of mid-band sensitivity and low-frequency damping. However, this unit has a broad high-frequency response peak more like the musical instrument drivers of Figure 5, and also appears to suffer from a surround self-resonance due to insufficient damping in the 350 Hz range. This is borne out in the 10 W distortion plot of Figure 18, which shows the spike of second-harmonic distortion associated with the resonance. Both Figure 18 and the 100 W distortion curve of Figure 19 display a low-frequency bias similar to that of the previous unit in Figure 14 and Figure 15. The 10 W 10% third-harmonic peak diaphragm displacement is 2.5 mm (0.10 in) for 96 dB, 33 Hz, and a 165 mm (6.5 in) piston radius. At 100 W, 10% second harmonic gives 6.0 mm (0.24 in) for 113 dB and 57 Hz, and 10% third harmonic gives 6.4 mm (0.25 in) for 112 dB and 52 Hz. The suspension bias and limiting action appears to have prevented any excursion linearity increase from that of the previous speaker. Figure 20 shows 1 W to 100 W compression at about the same 2½ dB level at minimum impedance and with the same characteristics as the musical instrument loudspeaker in Figure 16. The linearization methods employed do not appear to have made significant improvement insofar as thermal compression and distortion characteristics are concerned.

Lest anyone think that the use of a large voice coil is itself alone a panacea for all dynamic-linearity ills, a unit from a third manufacturer, recommended for extended-bass application and using a 105 mm (4 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. Voice coil is long for extreme travel, approximately 19 mm (3/4 in) deep in a 7.1 mm (0.28 in) gap, and is wound on a thick aluminum former. Figure 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 Figure 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 Figure 23 is a high level of second harmonic throughout the midband, 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 Figure 24 does show excellent thermal compression performance of less than 1 dB in the minimum impedance region, but this is unfortunately marred by suspension stiffness and resonance changes of up to 2½ db above and below this range.

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 increase 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 speaker performance at multiple levels can reveal the existence and degree of these problems, and allow objective judgement of suitability of the loudspeaker for sound production or sound reproduction applications.

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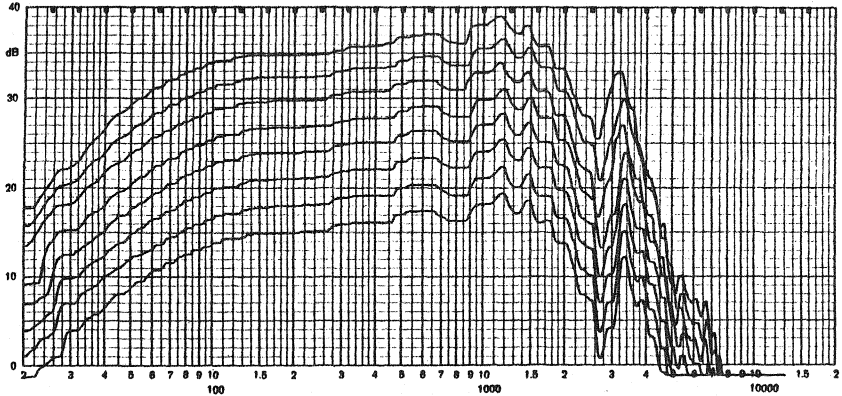

Figure 1. 380 mm (15 in) loudspeaker driven with 3 dB successively larger input levels from 0.8 W (2.53 Vrms) to 100 W (28.3 Vrms) mounted flush in a 2π ground platform, 280 liter sealed rear chamber, microphone 1 m on driver axis. 0 dB bottom line is 80 dB SPL, re 20 $\mu N/m^2$.

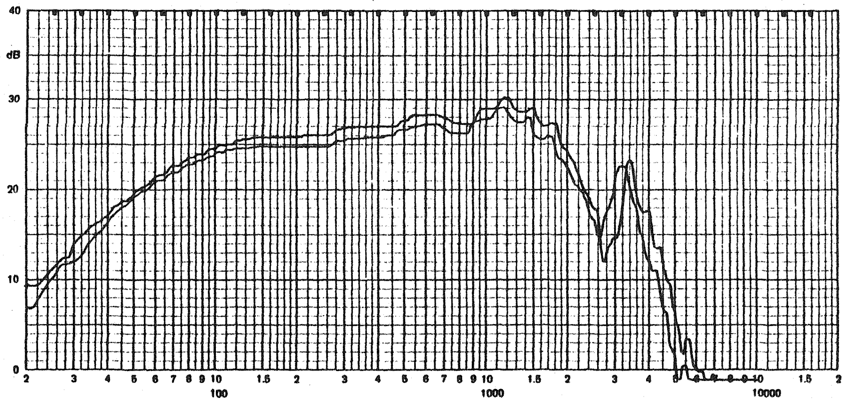

Figure 2. Same loudspeaker and measurement environment as Figure 1 driven with 1 W (2.83 Vrms) input and 100 W (28.3 Vrms) input, with reference level scaled 20 dB such that for no power compression, curves would overlay exactly. A reasonably consistent 1¼ dB of compression is evident over most of the loudspeaker's usable range. 0 dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W.

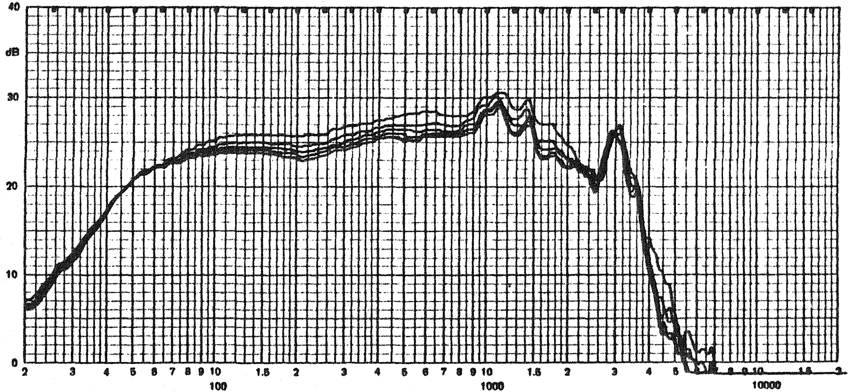

Figure 3. Same loudspeaker and measurement environment as Figure 1 driven with a 200 W (40 Vrms) input, with subsequent curves taken through 100 minutes at 20 minute intervals. The 80 minute and 100 minute curves overlay identically, since by that time the loudspeaker had reached thermal equalibrium within this particular measurement environment. 0 dB bottom line is 90 dB SPL.

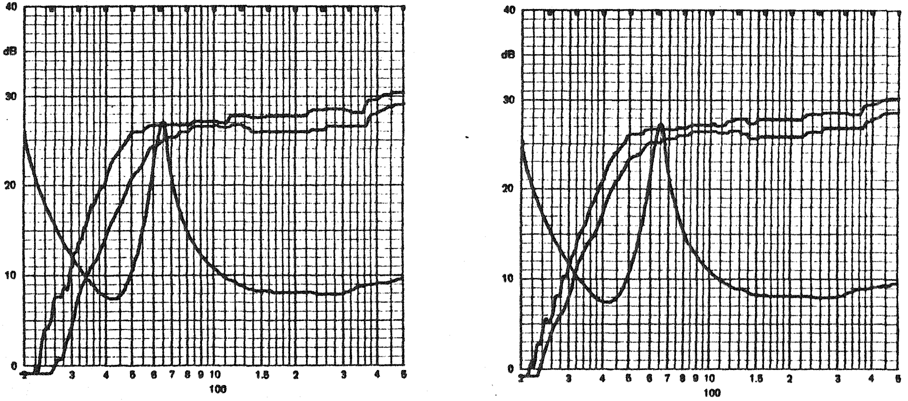

Figure 4. 380 mm (15 in) loudspeaker mounted in 125 litre (4.5 cu. ft.) vented enclosure driven with 1 W (2.83 Vrms) and 100 W (28.3 Vrms) inputs, with 10 mA constant current impedance showing 42 Hz tuning. Left hand plots show enclosure tuned with 110 mm (4 3/8 in) diameter simple circular hole in 19 mm (3/4 in) thick baffle, 97 cm^2 (15 in^2) port area. Right hand plots show enclosure tuned with two 110 mm (4 1/8 in) diameter ports, each with 125 mm (5 in) long ducts, 173 cm^2 (27 in^2) total port area. While 1 W plots show no difference, 100 W plots show 3½ 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 ohms (20 log Z) for impedance.

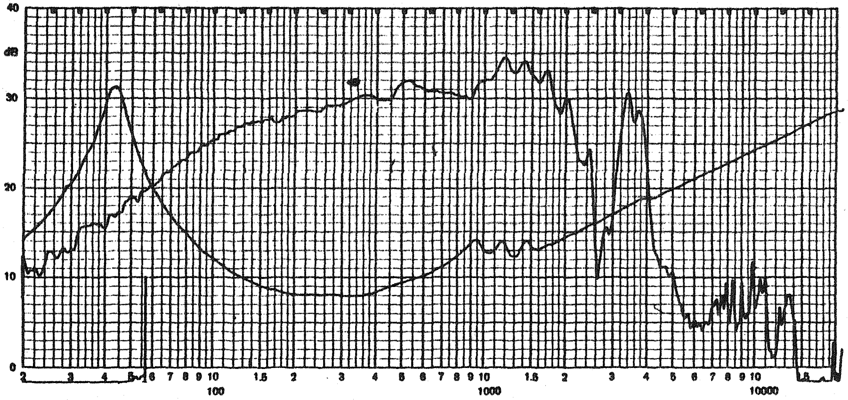

Figure 5. 1 W response and impedance of 380 mm (15 in) nominal diameter musical instrument loudspeaker with 100 mm (4 in) diameter voice coil. 0 dB bottom line is 70 dB SPL re 20 $\mu N/m^2$ and 3.16 Ohms (20 log Z).

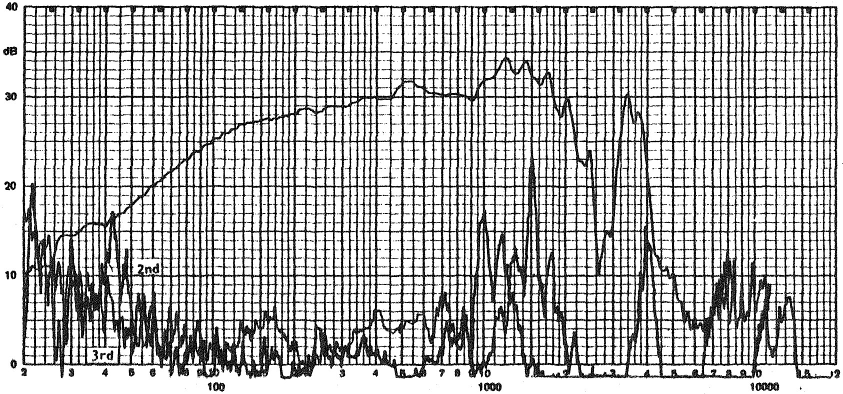

Figure 6. 10 W response with second and third harmonic distortion components of loudspeaker of Figure 5. 0 dB bottom line is 80 dB SPL for fundamental, 60 dB SPL for harmonics.

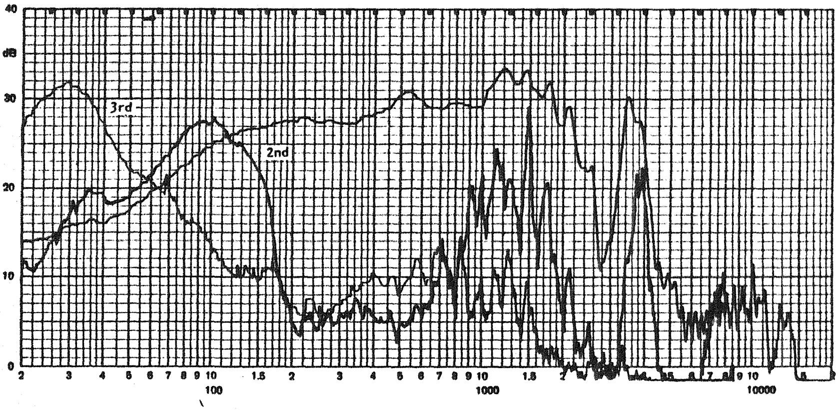

Figure 7. 100 W response with second and third harmonic distortion components of loudspeaker of Figure 5. 0 dB bottom line is 90 dB SPL for fundamental, 70 dB SPL for harmonics.

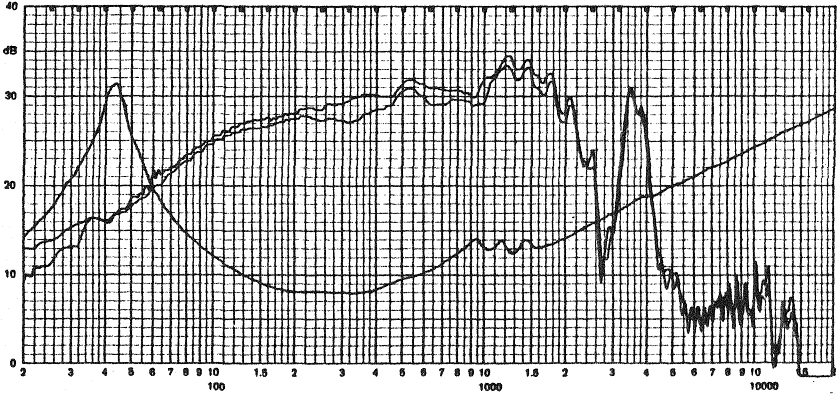

Figure 8. 1 W and 100 W response of loudspeaker of Figure 5 with impedance, reference levels scaled 20 dB so that compression can be easily viewed. 0 dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W, 3.16 Ohms for impedance.

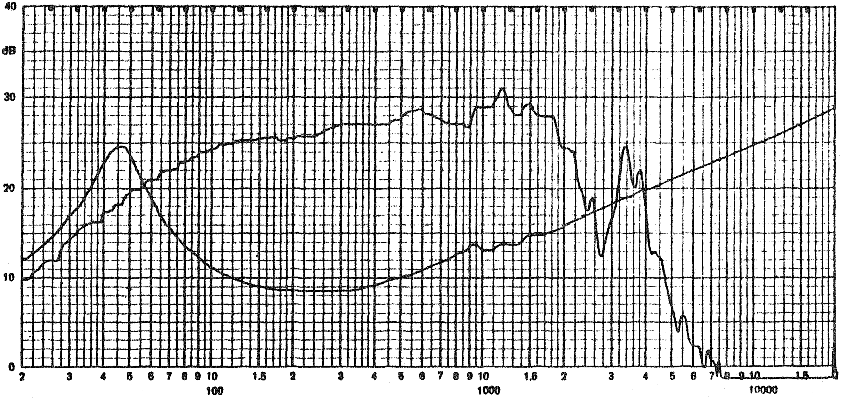

Figure 9. 1 W response and impedance of 380 mm (15 in) nominal diameter sound reinforcement loudspeaker with 100 mm (4 in) diameter voice coil. 0 dB bottom line is 70 dB SPL and 3.16 Ohms.

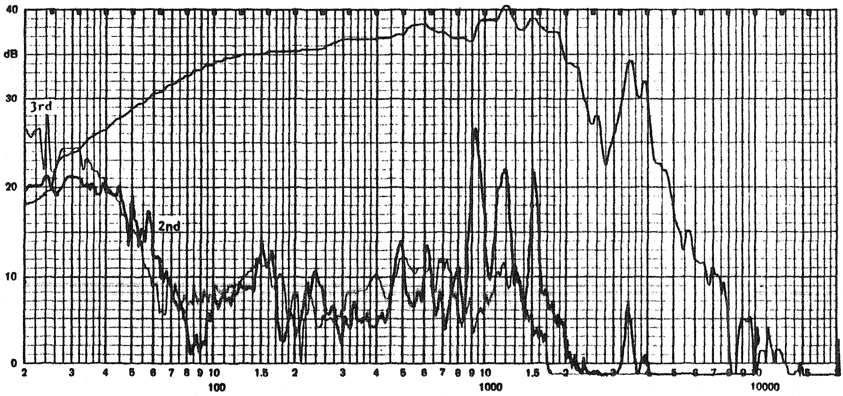

Figure 10. 10 W response with second and third harmonic distortion components of loudspeaker of Figure 9. 0 dB bottom line is 70 dB SPL for fundamental, 50 dB SPL for harmonics.

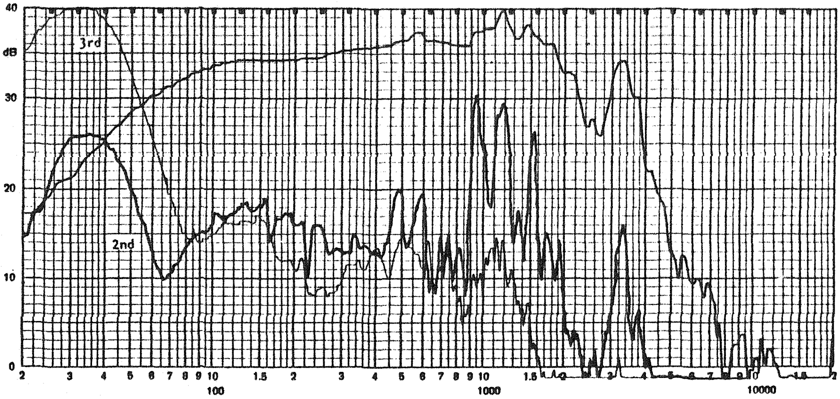

Figure 11. 100 W response with second and third harmonic distortion components of loudspeaker of Figure 9. 0 dB bottom line is 80 dB SPL for fundamental, 60 dB SPL for harmonics.

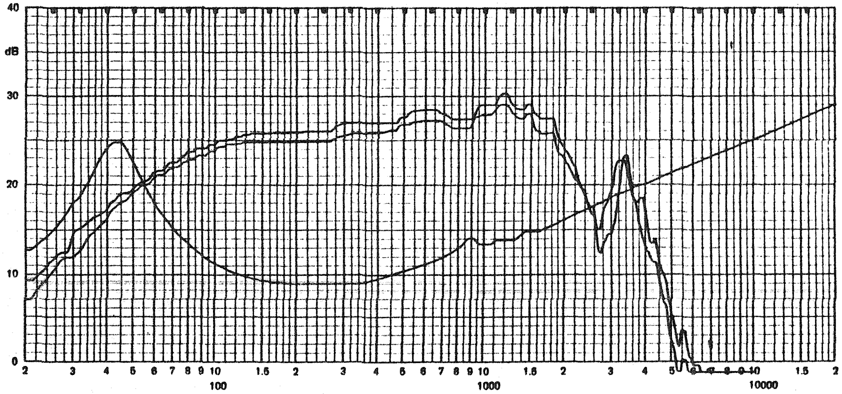

Figure 12. 1 W and 100 W response of loudspeaker of Figure 5 with impedance, reference levels scaled 20 dB so that compression can be easily viewed. 0 dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W, 3.16 Ohms for impedance.

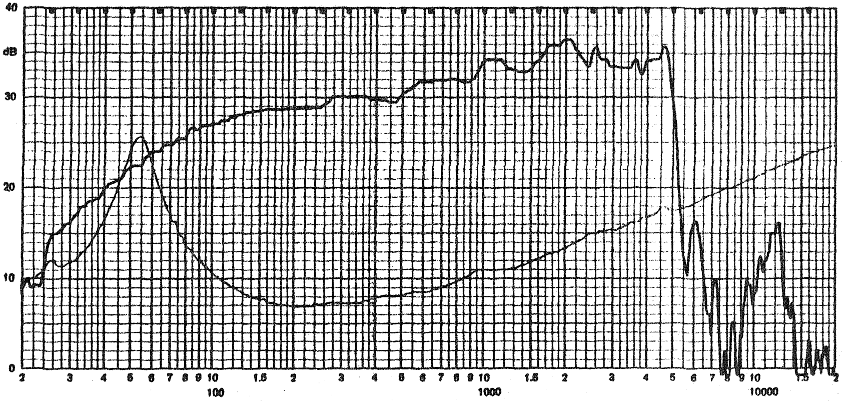

Figure 13. 1 W response and impedance of 380 mm (15 in) nominal diameter musical instrument loudspeaker with 63.5 mm ($2\frac{1}{2}$ in) diameter voice coil. 0 dB bottom line is 70 dB SPL and 3.16 Ohms.

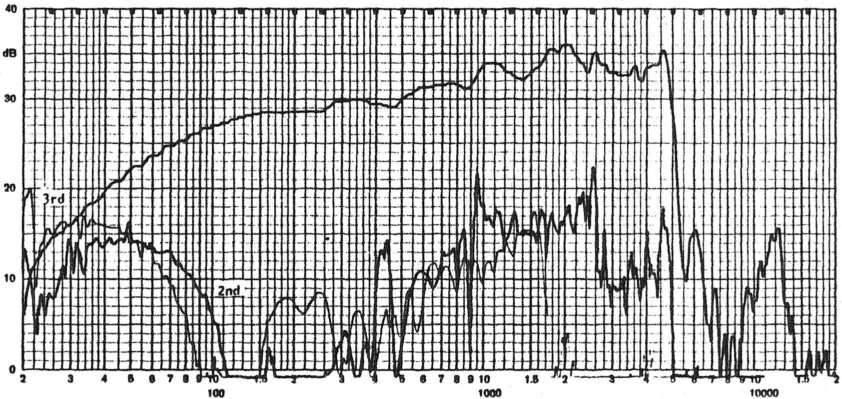

Figure 14. 10 W response with second and third harmonic distortion components of loudspeaker of Figure 13. 0 dB bottom line is 80 dB SPL for fundamental, 60 dB SPL for harmonics.

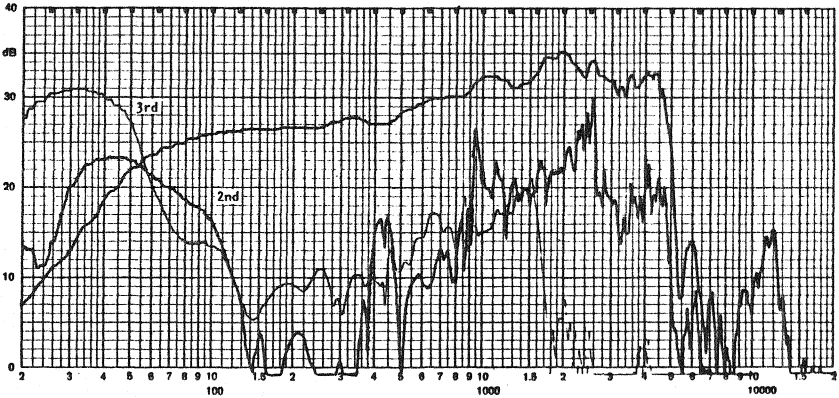

Figure 15. 100 W response with second and third harmonic distortion components of loudspeaker of Figure 13. 0 dB bottom line is 90 dB SPL for fundamental, 70 dB SPL for harmonics.

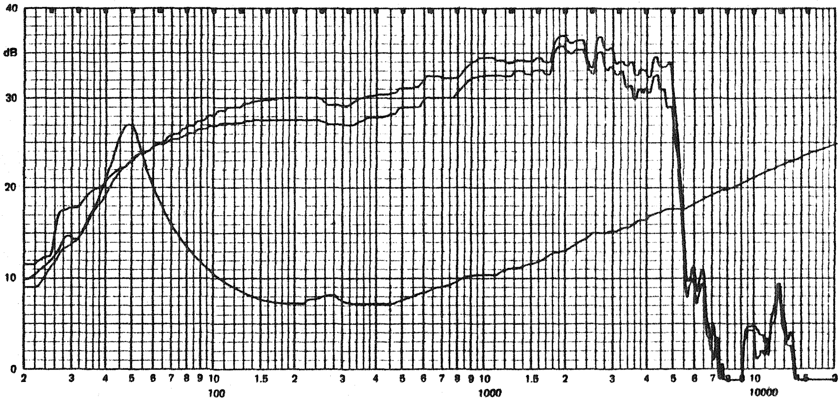

Figure 16. 1 W and 100 W response of loudspeaker of Figure 13 with impedance, reference levels scaled 20 dB so that compression can be easily viewed. 0 dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W, 3.16 Ohms for impedance.

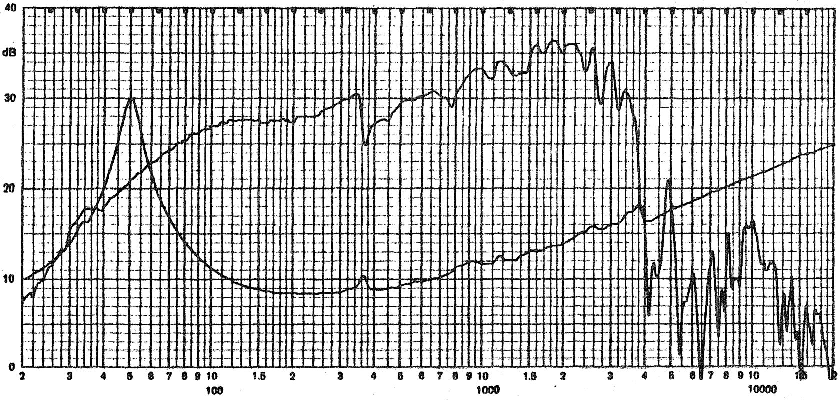

Figure 17. 1 W response and impedance of 380 mm (15 in) nominal diameter sound reinforcement loudspeaker with 63.5 mm (2½ in) diameter voice coil. 0 dB bottom line is 70 dB SPL and 3.16 Ohms.

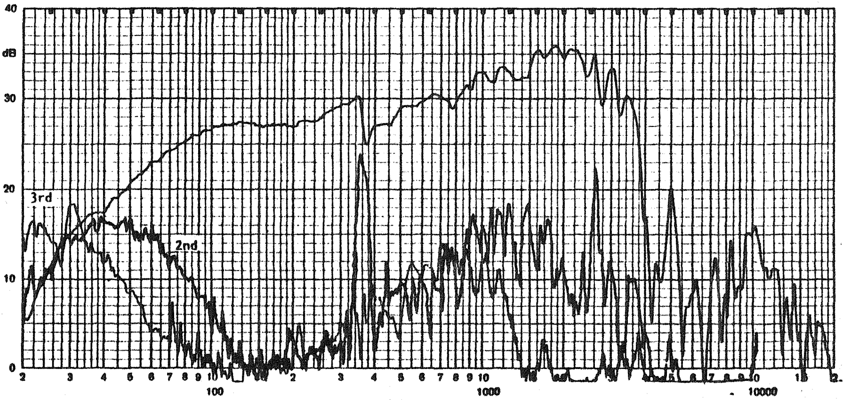

Figure 18. 10 W response with second and third harmonic distortion components of loudspeaker of Figure 17. 0 dB bottom line is 90 dB SPL for fundamental, 70 dB SPL for harmonics.

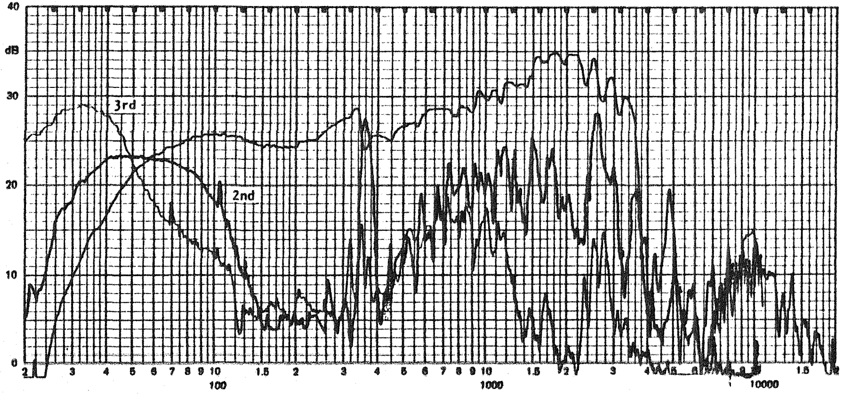

Figure 19. 100 W response with second and third harmonic distortion components of loudspeaker of Figure 17. 0 dB bottom line is 90 dB SPL for fundamental, 70 dB SPL for harmonics.

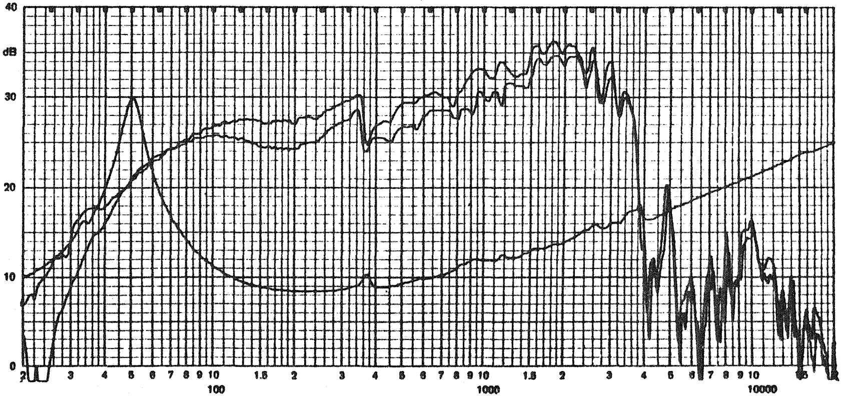

Figure 20. 1 W and 100 W response of loudspeaker of Figure 17 with impedance, reference levels scaled 20 dB so that compression can be easily viewed. 0 dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W, 3.16 Ohms for impedance.

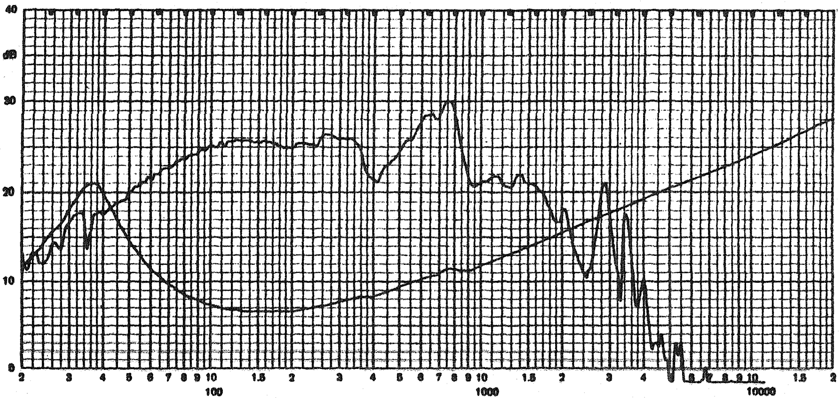

Figure 21. 1 W response and impedance of 380 mm (15 in) nominal diameter extended bass loudspeaker with 105 mm (4 1/8 in) diameter voice coil. 0 dB bottom line is 70 dB SPL and 3.16 Ohms.

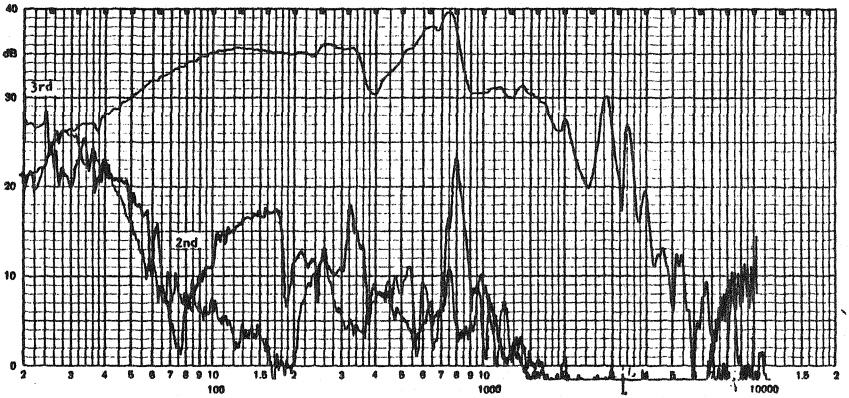

Figure 22. 10 W response with second and third harmonic distortion components of loudspeaker of Figure 21. 0 dB bottom line is 70 dB SPL for fundamental, 50 dB SPL for harmonics.

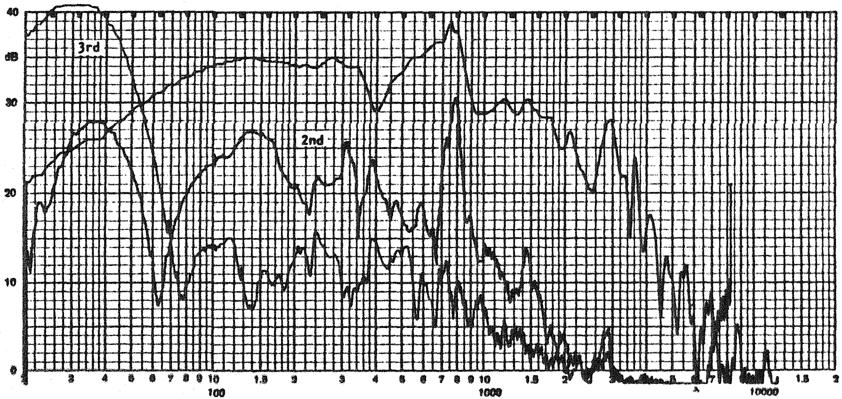

Figure 23. 100 W response with second and third harmonic distortion components of loudspeaker of Figure 21. 0 dB bottom line is 80 dB SPL for fundamental, 60 dB SPL for harmonics.

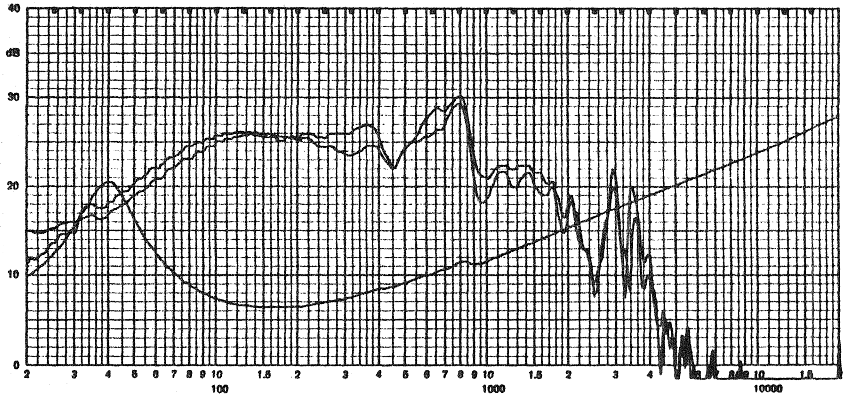

Figure 24. 1 W and 100 W response of loudspeaker of Figure 21 with impedance, reference levels scaled 20 dB so that compression can be easily viewed. 0 dB bottom line is 70 dB SPL for 1 W, 90 dB SPL for 100 W, 3.16 Ohms for impedance.