Institute of Acoustics

DYNAMIC LOUDNESS COMPENSATION

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INTRODUCTION

The desirability of applying 'loudness' compensation to playback systems, to compensate for the ears' differing tonal sensitivity against SPL, has been evident since Fletcher & Munson published the first experimental data in 1933. To date, however, the practical implementation of loudness compensation in all kinds of sound reproduction equipment has been indiscriminate, since the applied equalisation has lacked any explicit reference to both the original and playback Sound Pressure Levels. This paper describes the development of a purpose-built automatic loudness-compensation unit, discusses the consequences; and posits the simultaneous correction of dynamic tonal abberations in loudspeakers.

THE VOLUME PROBLEM

Since the dawn of sound systems, volume control adjustments have come hand-in-hand with changes in tonal balance. If a playback system is 'tuned' to reproduce instruments' timbre accurately at live SPLs, music becomes 'thinner', more distant and 'muddy' when the volume is turned down. The psychoacoustic effects of 'loudness' leads discerning users of sound equipment into a clear preference to listening at a specific SPL. In recording studios, for example, producers and engineers are forced into monitoring at a set level, to maintain a definate reference of instrumental tonality, throughout production and mixdown. By contrast, in everyday life, it's often impractical to replay recorded music at it's original SPL. In the home and in night-clubs for example, music originally performed and recorded with 'C' weighted SPLs of 95 to 115dBC may have to be replayed at levels not exceeding 80dBC SPL or below, for the sake of allowing sociable conversation, or avoiding disturbance to others.

LOUDNESS Vs. SPL CONTOURS: THE DATA

The original and well known Fletcher-Munson [1] contours (Figure 1) clearly display the scope of the ears' changing tonal sensitivity against SPL. To recap, each contour's SPL label is referenced to 1kHz. The contour itself traces the commensurate SPL required for an equal sensation of loudness, at any other frequency. In the past, the majority of electronic loudness 'compensation' circuits have been developed from this data [2]. Yet the accuracy and relevance of the contours is questionable, since the data was gathered long before accurate, low distortion sound generation and measurement equipment had been perfected over 20Hz to 20kHz, for the indicated SPLs; figure 1 plots measurements up to 130dBC! Low distortion is important, insofar as 54 years later, it's now well known that small doses of harmonics and intermodulation products can exaggerate an individual's assessment of a tone's loudness or nuisance level, particulary at high SPLs, above 90dBC rms.

A RE-DETERMINATION Figure 2 shows a critical redetermination of the equal loudness contours, carried out by Robinson & Dadson in England, twenty years later [2]. With the benefit of more sophisticated equipment, and more powerful statistical techniques, the contours arrived at differ from previous work. Most notably, the ears' insensitivity below 400Hz is seen to remain relatively constant at all SPLs. This contrasts markedly with the original contours plotted by Fletcher & Munson in 1933, and with Churcher & Kings' [3] evaluation in 1937 (Figure 3). In both cases, the ears' relative insensitivity to LF is seen to flatten out above 60dB. This is surely the consequence of a steep rise harmonic distortion at high SPLs, in the transducers (particulary loudspeakers) available pre-1945, making a tone sound louder than it would otherwise. Similary, a look at the HF contours (those above 5kHz) in figures 1, 2 & 3 reveals a distinct development in detail over 1933 to 1954, the period more than any other when HF sound-reproduction technology was developing rapidly, from 5kHz upwards.

Although the Robinson & Dadson contours are (like their predecessors) derived in the free-field, ie. anechoically, they have the status of an ISO recommendation [4], and may be taken as a broadly valid representation of what the 'average' ear percieves. This is a resonable assumption, since subsequent studies involving presentation with bands of noise, or with earphones and other variables haven't revealed any major ambiguities in the contours. It can be argued that measurements made in anechoic space are unrepresentative of practical listening environments. Yet prior to the development of loudspeakers exhibiting constant-directivity over a substantial part of audio's bandwidth, a nominally free-field measurement was at least preferable to allowing loudspeaker 'Q' anomalies to underpin the results.

In 1972, Stevens at Harvard University's Dept. of Psychophysics wrote [5] .."*No single isolated study appears quite capable of evaluating all of the variables that may exert an effect on the frequency weighting function. It is therefore reassuring that most of the 11 studies conducted in the past 25 years show generally close agreement with a single composite contour.*"

Stevens' work involved the development of a series of loudness contours under varied conditions, culminating in Mk.VII, itself an ISO-standard, being an amalgamation of data from a variety of loudness measurement methods.

Irrespective of implied accuracy, all the modern data broadly shows a standard deviation of ± 5dB. In other words, an individuals' perception of the 'correct' degree of loudness-contour compensation at a given frequency and level is uncertain to this degree. In domestic listening, personal taste can be accomodated by ad-lib adjustment. But for professional applications, whenever music heard by diverse groups of, or crowds of people, is subject to loudness-compensation, the degree of tonal equalisation for any given condition is arguably valid provided it's within ± 5dB of recognised, modern (post 1954) contours, and is self-consistent.

PRACTICAL LOUDNESS COMPENSATION - A CONCISE HISTORICAL & TECHNICAL ASSESSMENT

Over the past half century, there have been many attempts to overcome the tonal abberations of reproducing sound at (principally) lower SPLs than the original, using a variety of electronic equalisation techniques.

Because loudness compensation has never found widespread favour with professional users, whether PA contractors, installers - or recordists, the practice of forwarding the state-of-the-art in loudness compensation technology has been left in the hands of large-scale domestic equipment manufacturers. Of the many thousands of 'consumer grade' audio/radio products which have featured loudness compensation since 1945, the majority have been configured with no pretence of psychoacoustic accuracy.

Some circuits have been brought into play by a single button, allowing only the indiscriminate boosting of extreme 'bass' and 'treble' frequencies. The better examples allow progressive tonal equalisation to take place, with or without being ganged to the volume control. Of these circuits, the majority appear to be loosely based on Fletcher & Munsons' contours, despite 33 years of obsolesecence. Worse still, many are apparently based on a mistaken idea, that of cancelling the equal-loudness contour outright, rather than deriving the differential change in amplitude from an SPL baseline! Figure 4 depicts a typical example of this genre: The 20dB lift in response at 40Hz can't at any point be justified by modern data. Equally, the progressive response boost above 10kHz is uncalled for by a differential assessment.

To develop differential contours, we have to take a baseline, namely the SPL at which the reproduced music was originally performed. For this SPL, the compensation is nil, and the response curve is flat. At all other SPLs, the response should then develop with increasing inflection. In practice, music is but rarely reproduced at SPLs above the original, so commercial examples of differential compensation contours take on the general 'flat-topped' appearance of figure 5, itself one of few examples of potentially accurate loudness compensation, gleaned from an advanced Hi-Fi Preamplifier of the early 1970's. The contours are brought into play by the volume control setting, and broadly follow the Robinson-Dadson differential: Observe how the degree of LF compensation progressively increases to around +11dB at 20Hz, as the volume control's attenuation increases to -60dB. Contrast this with the same degree of boost engaged at only -25dB attenuation in the preceeding figure 4.

As long ago as 1937 [5], M.G. Scroggie, reporting on the consequences of Fletcher & Munson's paper in the British journal 'Wireless World', postulated that the degree and balance of loudness compensation required was intimately related to the style and content of the music, not to mention the playback SPL. If loudness compensation is to attain credence in the hands of professional users, and be of practical benefit, three further obstacles now remain:

(1) The contours in figure 5 are only correct for a specific original SPL. In effect, they are correct for one style of music, but quite possibly wrong for another: They lie within the tolerance of deviation and remain acceptably accurate over $\pm$ 10dB range of recorded SPLs (over which the contours themselves vary by < $\pm$ 5dB), but this by no means encompasses the full range of live music's average SPLs, ranging in the extreme over 50dB, from 70 to 120dBC. In effect, a loudness controller with pretensions to accuracy needs to be adjustable to accomodate a 50dB range of original average levels. However, if primarily one kind of music is to be reproduced, then the range of reference setting could be relaxed.

(2) The contours in figure 5 only 'move' with the volume control setting. Even if the contours' reference SPL were to accord with the SPL of any original recording, the compensation applied would become progressively incorrect in quiet or loud passages, whenever the SPL deviates by more than 10dB from the nominal alignment.

(3) The baseline defines the replay SPL against any combined volume-cum-loudness control. For example, if the baseline is 100dBC SPL (The recorded level), then the -60dB contour in figure 5, would spell, by implication, an SPL of 40dBC. It follows that the actual playback SPL has to be trimmed to correspond to the volume-cum-loudness control's setting. This requires a subsidary overall volume control, easily achieved in a domestic preamplifier, but possibly awkward to implement and prone to disruption in a large scale sound system or installation.

AUTOMATIC DYNAMIC DIFFERENTIAL LOUDNESS COMPENSATION

Having spotted the flaws in 'loudness compensation' - as traditionally achieved, our curiosity was aroused. "What" we asked "would loudness compensation achieve, if orchestrated correctly ?" So we began to consider the design of a commercial product for pro-audio applications, one which could undertake accurate, consistent and above all, automatic tonal compensation:

DERIVING THE CONTOURS The first requirement is a workable set of differential contours. The Stevens' data (Figure 6) makes no provision for tonal equalisation above 400Hz, holding it to be unneccessary - since the contours are very nearly parallel above this frequency. But preliminary listening tests suggested otherwise: some adjustment to mid and high frequencies was found to be neccessary, as the replay SPL descended.

It's interesting to note that differential derivations from the Robinson-Dadson contours support the need for small deviations in mid and high audio frequencies, circa ± 5 to 8dB over a 50dB range of SPL. This amount of compensation is small enough to be substantially hidden in the range of standard deviation. This may account for its absence in Stevens' contours. Another possibility is the need to compensate for the dynamic tonal anomalies, inherent to some extent, in all moving-coil loudspeaker drive-units. We shall return to this point.

At low frequencies, between 30 and 200Hz, the Robinson-Dadson and Stevens' contours are broadly in agreement, lying within the ± 5dB envelope of statistical uncertainty, over a wide range of SPL's. Overall, we decided to mould our equalisation curves around the Robinson-Dadson contours, making adjustments, where required, on the basis of extensive listening tests, in conjunction with a variety of state-of-the-art PA loudspeakers.

AUTO INFLECTION The next requirement was to arrange for the compensatory equalisation to **inflect**, according to the actual replay SPL, without manual intervention. It was immediately obvious that the provision of a continuously variable equaliser would be prohitively expensive, since the need for reasonably tight matching between different frequency bands, channels and units would call for a precise and costly control element like a Blackmore-VCA.

Instead, we experimented with incremental equalisation, and found that step changes were inaudible, provided they lay within the standard deviation. As a result, we were able to control the equalisation by means of simple binary switching techniques. This technique is economical by comparison, and consistent matching between different channels and units is inherent by design, being defined by fixed resistors.

LINE DERIVATION Having designed an apposite and controllable equaliser, the next step was to derive a control signal which reflected the replay SPL. In the majority of professional sound-system installations, the mean line level (expressed in dBu or dBV) immediately prior to the power amplifiers tracks the room's mean SPL within ± 2dB, provided the loudspeakers and power amplifiers respectively aren't subject to significant thermal or V-I compression, or to waveform clipping. In a competently engineered sound system for music, the relationship holds, up to SPLs where loudness compensation is no longer required.

The block diagram in figure 7 consolidates our design so far. On the left, a summer (Σ) reads, combines and weights the incoming stereo signal, the one that's about to be subjected to loudness compensation. The summer's output is converted into an rms voltage (TRMS). The rms line level that corresponds to the room SPL is aligned with the equaliser's switching-steps by subtracting an incremental level from the rms signal. A reference generator (REF) produces a series of voltage levels corresponding to 10dB steps, in conjunction with a fine adjustment, spanning ± 5dB. Once the appropiate reference is set accurately with the aid of an rms responding dBC SPL meter, the unit then goes on to track the room SPL within ≤ ± 2dB over a range of 60dB, from 65 to 125dBC, and adjust the equalisation accordingly. As a commercial accessory, we went on to develop a low-cost acoustic sensor, which has the benefit of measuring the room's mean SPL **directly.** This method of controlling a dynamic loudness compensator is more expensive, but again more foolproof when a sound systems' back-end gain structure is insecure, eg. when amplifier gain settings might be tampered with.

ANALOG COMPUTATION Once offset, the rms signal is applied directly to an A-B convertor, which converts the linear (analog) signal into a binary buss code. In this way, a common control signal adjusts the equalisation of any number of audio channels in sync. The binary buss is also made to drive an LED bar, which displays the average line-level signal level. The LED thresholds correspond to a defined dBC SPL level when the unit is correctly aligned, and the LED's readout is accordingly scaled in dBC SPL.

One tier of the control process couldn't reasonably be automated, namely the adjustment of the contour-set relative to the recording's original SPL, since this information is not explicitly contained within the signal. To overcome this objection, we set the baseline (at and above which equalisation is nil) at the average SPL at which (for example) Rock music is generally recorded. This technique is effective for a defined style of music, since ± 10dB variations in mean recording level lie within the bounds of the contours' allowable tolerance, ie. ± 5dB

EXPERIMENTAL RESULTS

The finished product, a multi-channel dynamic loudness compensator was dubbed 'The Inflexor'. Since its purpose is inherently psychoacoustic, the only proving ground was that of listening. Basic A/B comparisons were easy to implement, as the equipment was designed with an integral bypass switch, a routine standard in pro-audio signal-processing equipment. We then set about evaluating the practical effects of dynamic loudness compensation against a wide variety of speaker systems, types of music, and SPL replay levels. The contours and other vital parameters were kept constant during the tests. A body of tests were conducted by independent associates, to lend objectivity to our conclusions. These were:

1) Everyone involved with evaluating 'The Inflexor' preferred the results when the compensation was engaged: On the majority of speaker systems, and over the range of compensated SPLs, the accuracy of tonal rendition and instrumental timbre was judged to be improved.

2) In all cases, with the compensation engaged, all kinds of music were held to be subjectively louder and more immediate, than the measured SPL would suggest. These results are to be expected, yet the obvious practical benefits for the 'psychological' restraint of SPLs in discotheques do not appear to have been recognised by previous researchers.

3) When pre-production samples of 'The Inflexor' were applied to high-power speaker systems incorporating bass drive-units with large (>12") cones, the effect of compensation at low frequencies was judged less satisfactory, compared with conventional domestic and smaller studio loudspeakers. To account for the discrepancy, we posited [6] that *"..the electrodynamic 'torque'.. of conventional moving-coil drive-units fades disproportionately, with descending power input. In heavy duty bass drivers, with weighty pulp cones, the moving force eventually becomes insufficient to shift the full mass of the cone. This happens at.. SPLs lying some 40 or 50dB below the driver's rated maximum. Accurate motion is ultimately limited to the centre of the piston, effectively attenuating.. the lowest octaves."*

To overcome the discrepancy, we modified the unit in production, so that extra LF boost could be progressively engaged as the drive level is reduced. A preset 'LF trim' control maintains the Robinson-Dadson contours when set counter-clockwise, but when turned up, additional LF boost, up to 12dB extra at 30Hz, can be brought into play as judged neccessary, according to the speaker system in use. In tests, our modification enabled 'The Inflexor' to be adjusted for satisfactory results when evaluated against a wide range of loudspeakers optimised for PA, studio and Hi-Fi applications.

CONCLUSIONS AND FURTHER WORK

Our practical work raises questions, and shows that further fundamental research is required. In particular, we feel that Equal Loudness Contours beg further re-evaluation, taking into account both the diverse dynamic tonal anomalies of real loudspeakers, and the ambiguities of deriving differential compensation contours above 400Hz.

ACKNOWLEGEMENTS

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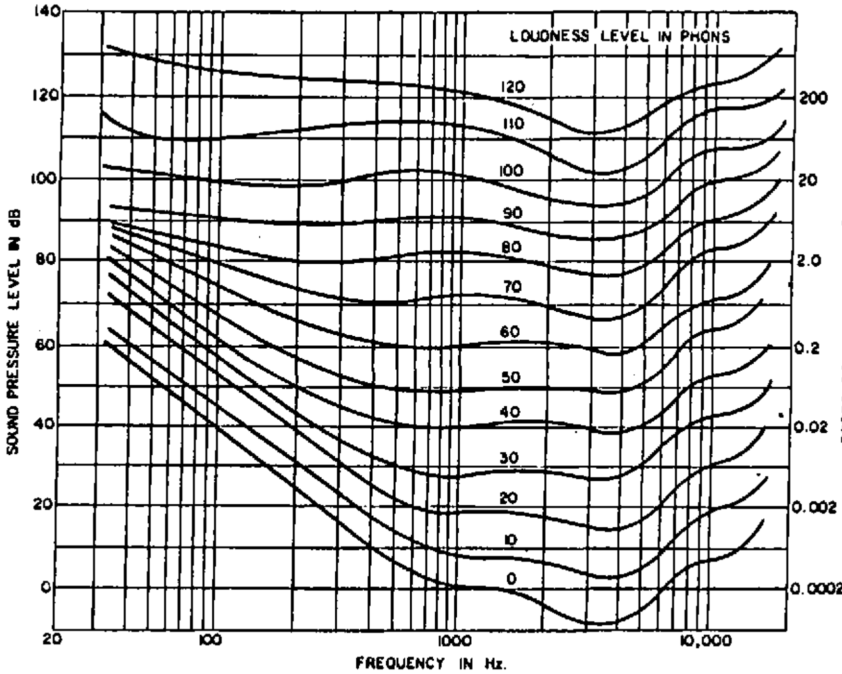
Figure 1.



Fletcher-Munson curves (USA).

Figure 2.

ROBINSON & DADSON EQUAL LOUDNESS CONTOURS

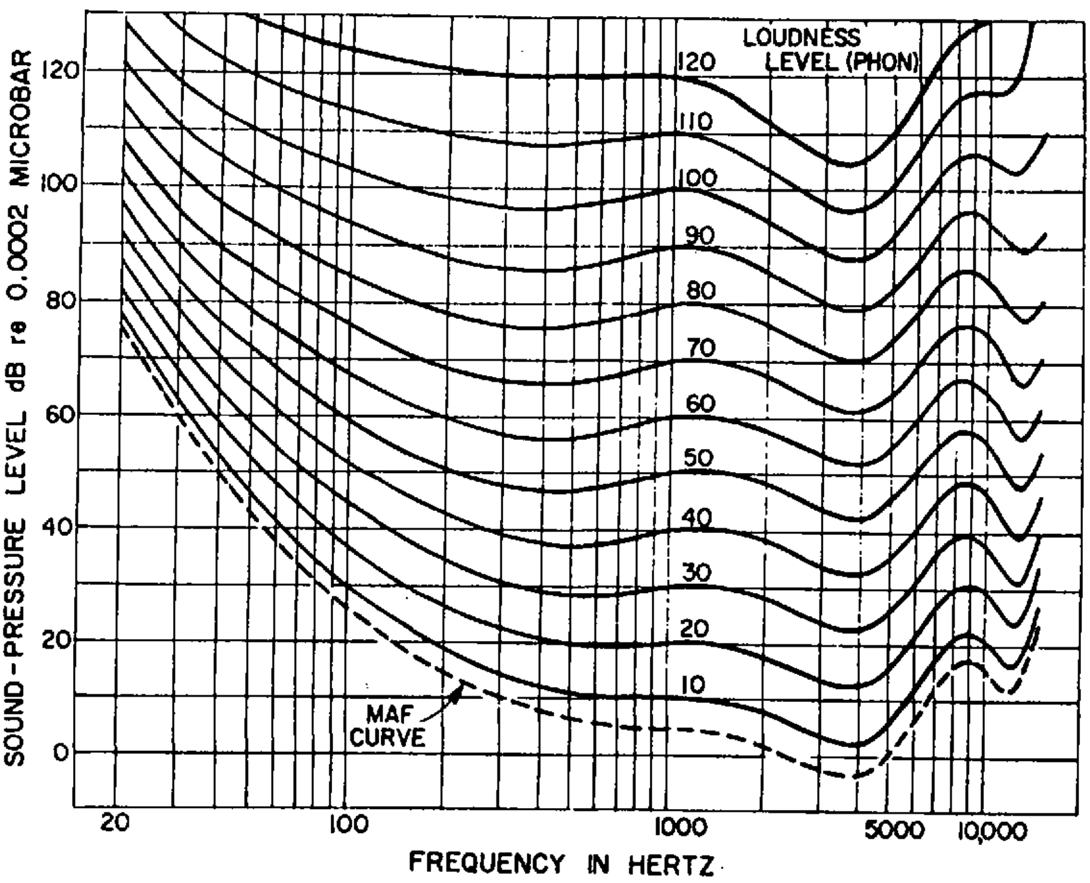
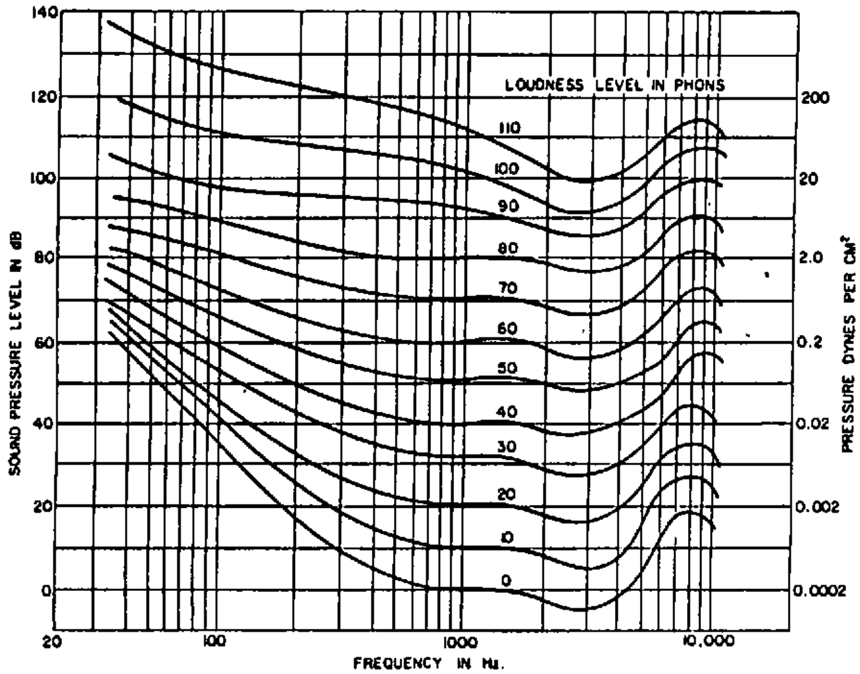
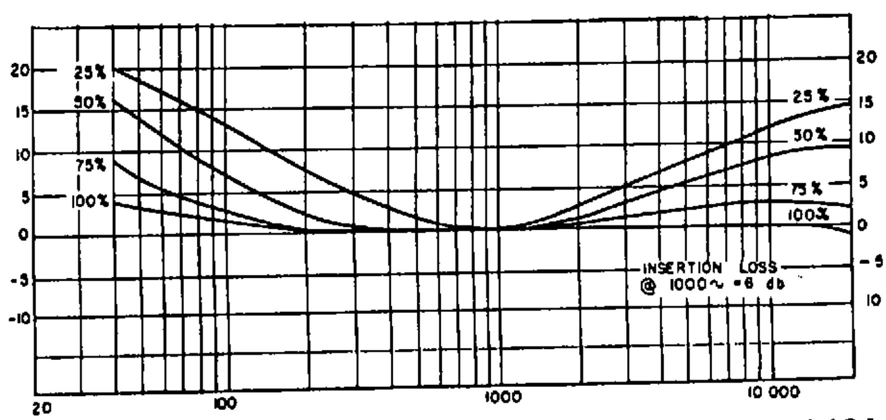


Figure 3.



Churcher-King curves (England).

Figure 4.



Frequency characteristics of the IRC loudness control Model LC-1.

Figure 5.

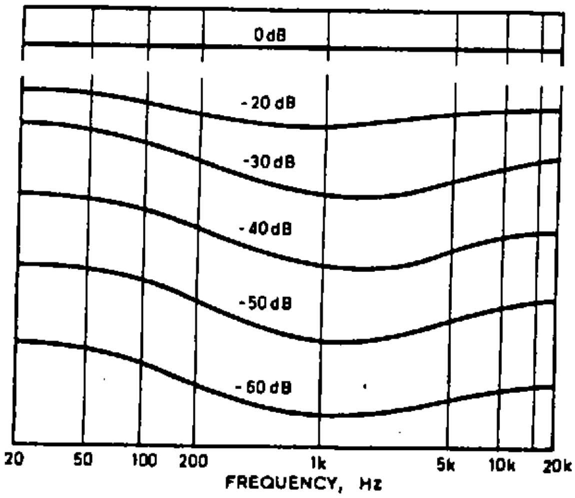


Figure 6 Examples of Differential Compensation, After S.S. Stevens

Original Level: 105dBC SPL
Replay level: 85dBC SPL
SPL differential = 20dB

Frequency:	20	30	50	80	100	200	400 Hz
Applied EQ:	+6.3	4.5	2.1	0.0	0.0	0.0	0.0 dB

Original Level: 105dBC SPL
Replay level: 70dBC SPL
SPL differential = 35dB

Frequency:	20	30	50	80	100	200	400 Hz
Applied EQ:	+12.2	9.1	5.2	1.6	1.4	0.7	0.0 dB

Abstracted from 'Loudness Compensation - Use & Abuse' J.AES, July '78.

Figure 7 **'The Inflexor' – A simplified block schematic**