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EXPERIMENTAL MODAL ANALYSIS OF A PORTABLE GRINDER DISK

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ABSTRACT

This paper reports about experimental investigations conducted on disks for portable grinders: the main goal is to state the benefits obtainable with a new type of "damped" disks, that have been developped to reduce the high noise levels caused by the operation of the machine. The results obtained from the modal analysis are useful to understand the noise emission mechanism, and show that the damped disk exhibits a large reduction of the high frequency modes.

NOMENCLATURE

f_v (Hz) Natural frequencies of the disk

f_r (Hz) Revolution frequency (8500 r.p.m.)

f_m (Hz) Modulation frequency

f_c (Hz) 1/3 Oct center-band frequencies

RT60 (s) Reverberation time (60 dB decay)

η () Loss Factor

INTRODUCTION

Portable grinders are widely used tools, that are suited both for cutting metal profiles or for finishing the surfaces after welding. One of the main problems of these tools is the high noise emission, that can give levels at the user's ear in excess than 110 dB(A).

To reduce this unacceptable noise level, a new type of grinding disk has been developped, made with an internal highly damped layer. These damped disks (commercially denoted "Silentium") have shown a reduction of the noise at the user's ear of about 8 dB (A-weighted).

The present works concern with the experimental modal analysis of the vibrations in the disk, that has been performed on both a standard undamped disk and on a damped one.

The research was expected to give informations about the noise emission mechanism, and particularly to explain the strong peaks found in the acoustic spectrum. Furthermore, the direct evaluation of the loss factor is capable to state the damping properties of the material inserted in the new disk versus frequency. In parallel, a theoretical study of the same problem has been conducted by the same authors ([1]).

The comparison of the experimental results given here with such theoretical findings enable the computation of the dynamic Young's Modulus and Poisson's Ratio of the material, as well as a better understanding of the modal shapes, and gives the capability of predicting the natural frequencies.

EXPERIMENT

The experiments concerned with disks having a diameter of 178 mm and a thickness of 7 mm: this size was the one that gave the better acoustic performances employing the damping material.

To reproduce the mounting conditions of the disk as close to the actual working conditions as possible, the disk was fixed to a shaft dismounted from a grinder. The shaft was then pressed between two angulars, clamped in the jaws of a vice. The disk, mounted as explained, is visible in fig. 1.

Two different excitation techniques have been used: hammer excitation has been chosen for the measurements of the decay time and subsequent calculation of the loss factor, while an electrodynamic shaker has been employed to accurately measure the modal frequency and shapes.

The force applied to the disk in the excitation point have been sampled through a B&K type 8200 load cell, mounted on the hammer (B&K type 8203) or the shaker (B&K type 4810). The acceleration of the disk's surface have been measured with a B&K type 4393 accelerometer (mass=2.4 grams).

The excitation point chosen is on the edge of the disk, and the direction of the applied force is normal to the disk surface: this simulate the force due to the impact of the disk on the surface under grinding. The other two component of such a force (radial and tangential) have been neglected, because the vibrations excited by them are not capable of radiate efficiently the noise.

An orthogonal grid of measuring points have been fixed on the disk's surface, assuming a square frame divided in 7 rows and 7 columns. Obviously, 12 points of such a square grid fall out of the disk, and so they have not been measured.

The transducers were connected, through two B&K type 2635 charge amplifiers, both to a two channel FFT spectrum analyzer (OnoSokki CF920), and to a PC fitted with an A/D board (A2D160, DRA laborat.).

The noise excitation was produced by the A/D board, that incorporates an MLS (Maximum Lenght Sequence) pseudo-random noise generator ([2]). The analysis of the signals made on the PC benifits of the deterministic nature of the test signal, that allows fast computation of the impulse response between the excitation and both the input channells through a fast Hadamard transform, that yields directly the response in the time domain with only additions and subtractions. On the other hand, the FFT analyzer was working in the traditional way, computing the Frequency Response Function (FRF) by the FFT spectra.

The FFT analyzer was limited by its FFT size of 1024 points, so two separate measurements were needed for the low frequency (FS=2 kHz) and high frequency (FS=10 kHz) bands; the PC, instead, is able to compute impulse responses up to 32768 points, so it was possible to take a single, 10 kHz sample for each measurement point, containing good resolution also at the lower frequencies.
The damping of the material is however quite high, so the impulse response goes quickly to zero in about 50 ms also for the undamped disk, as it is shown in fig. 2. For this reason, there is no matter to acquire more than 4096 points at a sampling rate of 30 kHz, because this correspond to a lenght of about 130 ms.

Comparing the effectiveness of the two acquisition instruments with shaker excitation, it can be said that the MLS A/D board gives significant benefits over the standard FFT analyzer both in terms of acquisition speed (no averaging is required) and frequency resolution. Furthermore, the support software of the board is capable to perform useful analysis in the time domain, like the evaluation of reverberation times in frequency bands of 1/3 octave. When used with hammer excitation, the acquisition time becomes the same (an 8 events average has been employed). but the other advantages still exist.

MODAL EXTIMATION

The analysis of the measured FRFs has been performed by a simple three point circle fitting code, written expressly for this research. Fortunately the modes are well separated, and so it was possible to manually identify and analyze separately the peaks, as it can be seen by the fig. 3. For a given frequency range, centered on a peak found in many of the measurement points, the code extract the modal amplitude and the phase relative to that of the excitation point. The code itself produce a graphic animation of the disk, moving accordingly to the identified mode shape.

In the fig. 4 the first six mode shapes have been reported, as obtained from CRT printouts of such animations: the mode shape is substantially the same for the damped and undamped disk, but the maximum displacement and the mode frequency are both lower for the damped one, as it is clearly readable under the drawings.

These low frequency modes are very useful for the comparison with the theoretical analysis, but they don't give reason for the high acoustic emission at frequencies well beyond 2 kHz. Nevertheless, the measurement grid is too coarse for an accurate spatial identification of the high frequency modes (also in the space domain, an insufficient sampling causes aliasing...). So the identification of the modes that produce the acoustic peaks must be conducted looking directly at the FRF curves, taking account for the frequency shift due to the disk rotation.

EFFECTS OF DISK ROTATION

The actual measurments were conducted on disks clamped in a vice, while the real word disk are rotating at a speed of about 8500 r.p.m. during the grinding. This high rotational speed cause two different effects:
1) The disk is subjected to centrifugal forces, that strain the material, making it stiffer for the flexional vibrations, and increasing the natural frequencies (like a violin chord). This effect can produce a frequency increase of about 3% for the first modes.

2) The rotation frequency combines with the vibration frequency, so that the acoustic radiation arise at frequencies different from that of the not rotating disk.

The second effect need more investigation, because also the mode shape is involved in its behaviour. Let us consider a mode shape characterized by a certain number of nodal diameters, say 3. When the disk is vibrating without any rotation, an air particle near the disk surface is pumped forth and back at the same frequency f_v of the vibration surfaces, for example 1730 Hz for the undamped disk. Some points will be at the absolute maxima, while other points, being near the nodal lines, will not be acoustically loaded at all.

When the vibrating disk is bring in rotation, all the points are repeatedly passed by maxima and nodes, so the vibrational radiation at frequency f_v is modulated from a sinusoid, having an angular frequency f_m that is 3 times the rotational frequency f_r. At 8500 r.p.m., it corresponds to $f_m = 425$ Hz.

Taking the Fourier transform of such a modulated signal, one find two peaks at $f_v \pm f_m$ (1305 and 2155 Hz), as it is shown in fig. 5. Now if one looks at the acoustically measured spectrum, as reported in fig. 6, he discover that effectevely two peaks are present for each vibration natural frequency.

The same approach can be applied to explain also the higher frequency peaks, taking into account the number of diametral nodes of each modal shape, that act as a multiplier of the rotational frequency that modulates the vibration. On the other hand, the number of radial nodes does not affect the frequency shift due to the rotation.

In the table below the results of this analysis are summarized for the undamped disk: for each vibration mode, the resonance frequency and the two degenerated frequencies are indicated, in comparison with frequency of acoustically noticeable peaks.

Number of diam.nodes	Nat. Freq. f_v (Hz)	Degener. freqs	Acoust. Peak
1	475	333 617	
0	735	735	
2	910	627 1193	917 1090
3	1730	1305 2155	1728 2175
4	2950	2383 3517	2901 3447
5	4425	3717 5133	4340 5158

It is interesting to note that, while the frequency degenerated upward is always clearly visible in the acoustic spectrum (at least for four modes, see fig. 6), the downward degenerated one isn't present at all; however, the fundamental (undegenerated) frequency always appear as a peak in the acoustic spectrum but its level is lower than the corresponding upward degenerated peak. No explanation for this fact has still be found.

For the damped disk, the same considerations can apply, also if beyond 2 kHz the peaks are not so well pronounced as in the undamped disk. Fig. 2 shows the comparison between a FRF measured in the same point of both disks: it is clear that over 2 kHz the damped disk exhibits only modes with a very low magnification factor, so the sides of each peak are overlapped with the adiacent ones.

MEASUREMENT OF DAMPING

While the previously described modal analysis was based on data collected with the disk subjected to stationary excitation through a shaker, the damping measurement required the hammer excitation, to avoid that the damping contained in the shaker itself reduce the decay times of the vibrating structure.

This effect is clearly visible comparing two impulse responses obtained with hammer excitation and with MLS deconvolution: fig. 7 shows the response measured with the hammer, in the same point of the undamped disk where the response of fig.2 was obtained. The response measured with the shaker (fig. 2) is shorter than the other one, measured with the hammer excitation.

To obtain the decay times from the impulse response, it must be noted that the decay time is frequency-dependent: in fig. 8 it is shown a waterfall representation of the time-frequency decay. At the modal frequency the decay is usually slower than at frequencies out of resonance.

The standard approach is to measure only the decay at the natural frequencies of the vibrating structure. In this work a different approach has been used: the impulse response is digitally filtered with band-pass filters of 1/3 octave. Each filtered response is then backward integrated, as initially suggested by M.R.Schroeder ([3]). In such a way, the decay of an interrupted stationary band-pass noise signal is reconstructed, as it is shown in fig. 9 (the original response is reported in fig. 7). The slope of the decay curve gives the reverberation time RT60 (defined as the time required for a 60 dB decay): from it, the band-average loss factor can be computed as:

$$\eta = \frac{1}{2\pi}\left(1 - 10^{\left(-\frac{6}{RT60 \cdot f_c}\right)}\right) \qquad (1)$$

The loss factor measurement has been repeated for each frequency band upon all the measurement points, and then an average value has been computed at each frequency f_c for both the normal and damped disk. Fig. 10 shows the comparison between these loss factor measurements, that points out the substantial increase of the damping obtained with the new type of grinding disks. On average, it can be stated that the damped disk has a loss factor 2.5 times greater than the undamped disk, but in the most noisy region of 2 - 4 kHz the increase in loss factor exceeds a factor of 3.

In terms of magnification factor of resonance peaks, this result allows the prevision of a peak amplitude reduction in the order of $20 \cdot lg(3) = 9.54$ dB, that has been effectively achieved both on FRF measurements, both on acoustically measured spectra. It is noticeable that the insertion of the damping layer does not affect the grinding capability of the disk. nor its average consumption.

CONCLUSION

The comparative measurements conducted over two types of grinding disks (damped and undamped) have been depicted. From a set of FRF curves, measured along a grid on the disk, a simple modal estimator was able to extract the modal frequencies and the modal shapes: the damped disk make both the frequencies and the modal amplitudes to become lower.

The acoustic emission spectra have also peaks that don't match the natural frequencies found. This discrepance has been explained in a large extent with the effects due to the disk rotation at a very high speed. In such a way, it was possible to identify the modes that cause the great noise emission of these grinding tools.

The analysis of the decay curves, reconstructed from hammer impulse responses, was used to measure the loss factor of the material versus frequency. As it was expected, the loss factor of the damped disk is about 2.5 - 3 times greater than the undamped one. This increase in loss factor explains perfectly the overall noise level reduction achieved with such disks, that is in excess than 8 dB (A-weighted).

The new type of grinding disks is a valuable tool to reduce earing damage for workers and noise pollution of the environment; a further research will be started to state the benefits obtainable also in terms of hand-arm vibrations, that should be highly effective according to the results of the present work.

ACKNOWLEDGEMENTS

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(2) D.Rife and J.Vanderkooy, "Transfer Function Measurements with Maximum-Lenght Sequences", *Journal of the Audio Engineering Society (JAES)*, vol. 37, No. 6, pp 419-443, 1989 June.

(3) M.R.Schroeder, "New method of measuring reverberation time", *Journal of the Acoustic Society of America*, vol. 38, pp 329-361 (1965) and vol. 40, pp 549-551 (1966).

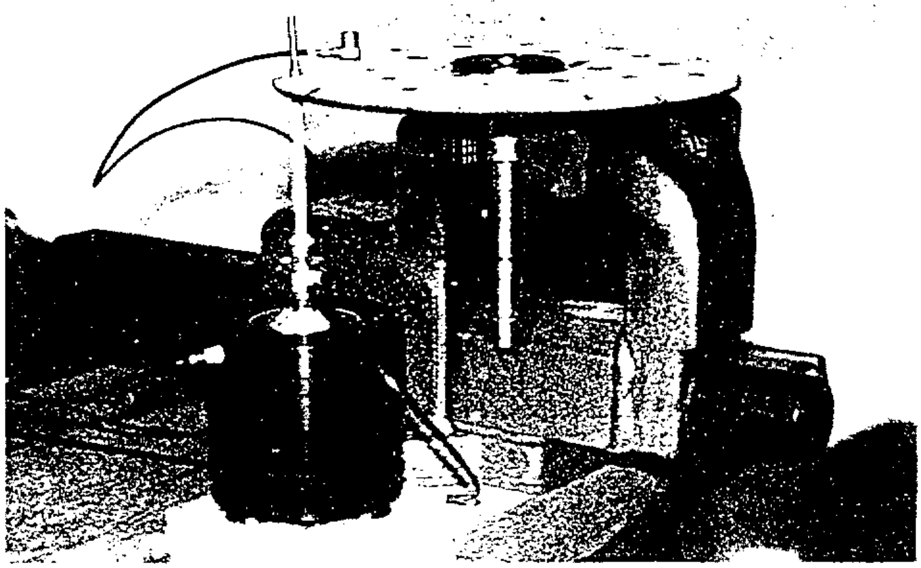


Fig. 1 - The disk mounted in a vice.

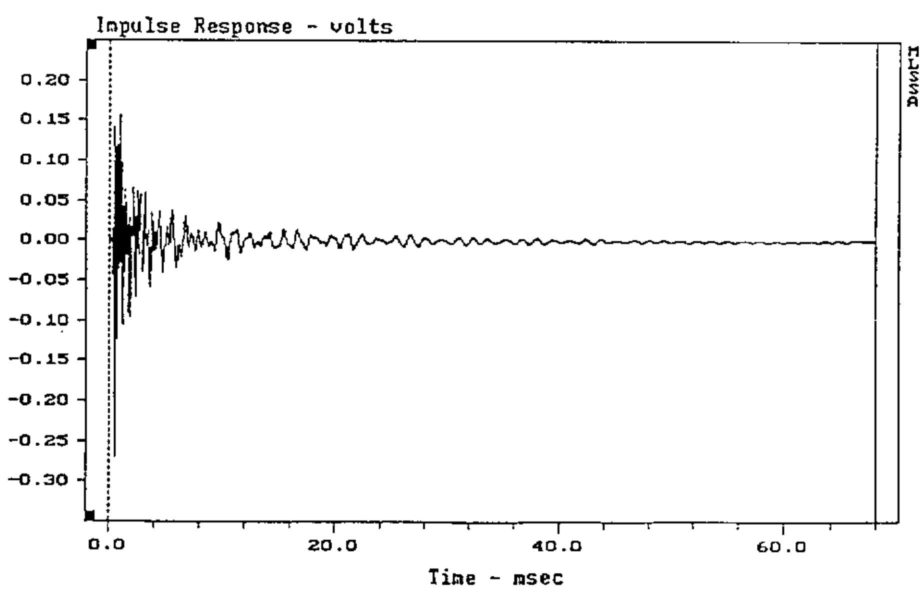


Fig. 2 - Impulse response obtained with MLS deconvolution.

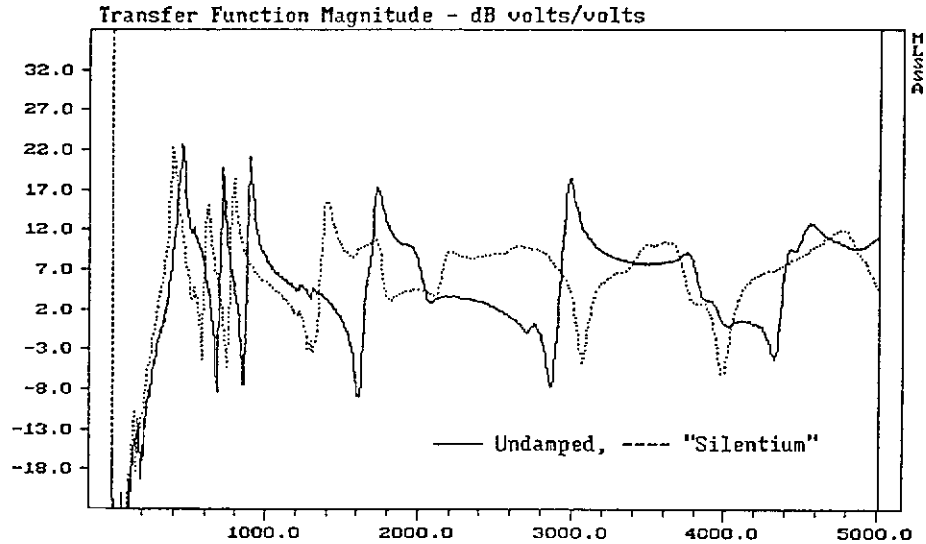
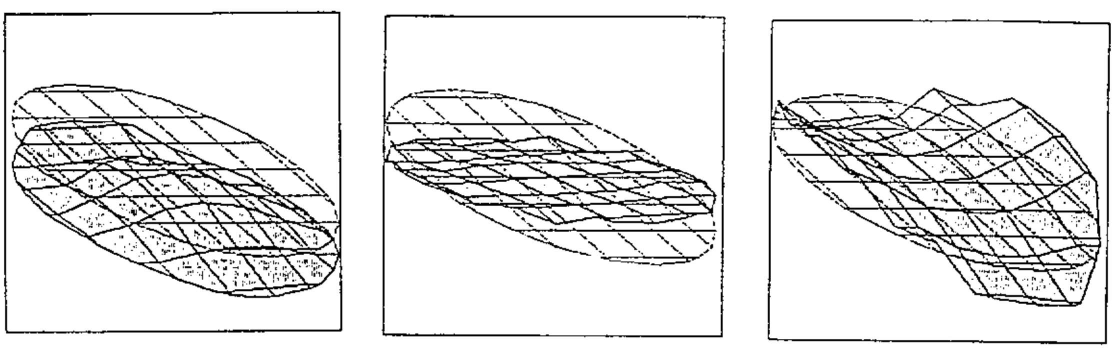
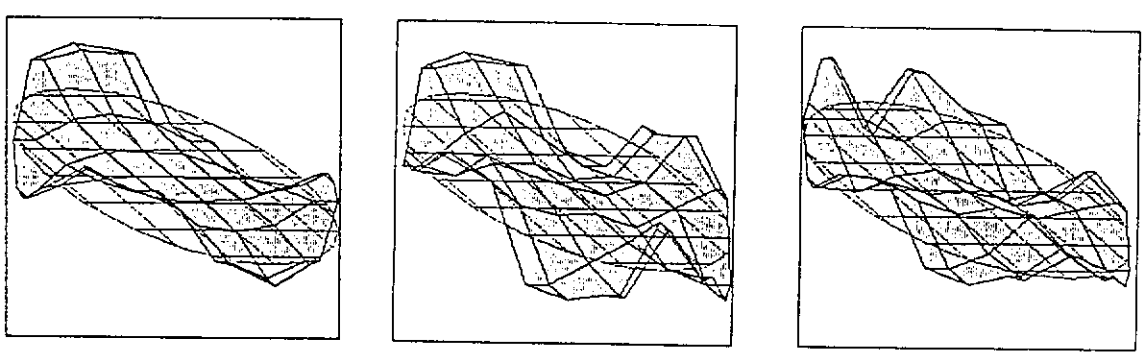


Fig. 3 - FRF curves for undamped and "Silentium" disk.



Undamped: 735 Hz	Undamped: 505 Hz	Undamped: 915 Hz
"Silentium": 635 Hz	"Silentium": 440 Hz	"Silentium": 815 Hz



Undamped: 1730 Hz	Undamped: 2950 Hz	Undamped: 4425 Hz
"Silentium": 1420 Hz	"Silentium": 2395 Hz	"Silentium": 3610 Hz

Fig. 4 - Plot of the first mode shapes, with natural frequencies of both disks.

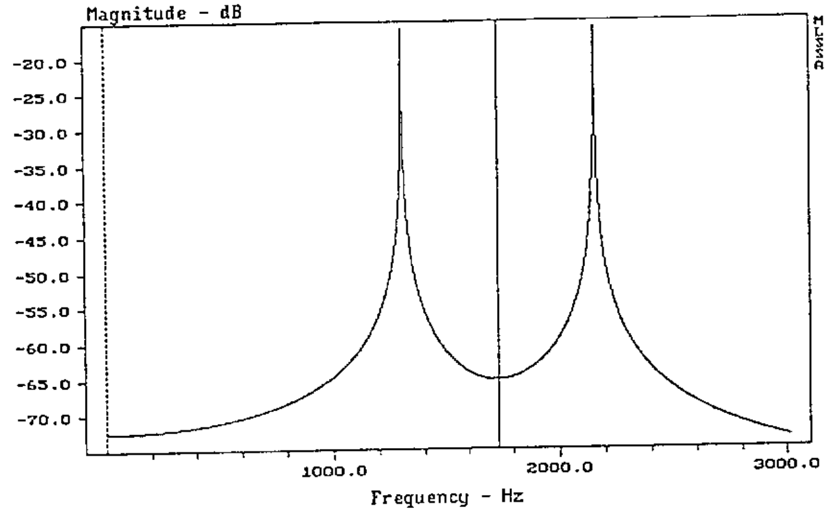


Fig. 5 - Degeneration of a single natural frequency due to disk rotation.

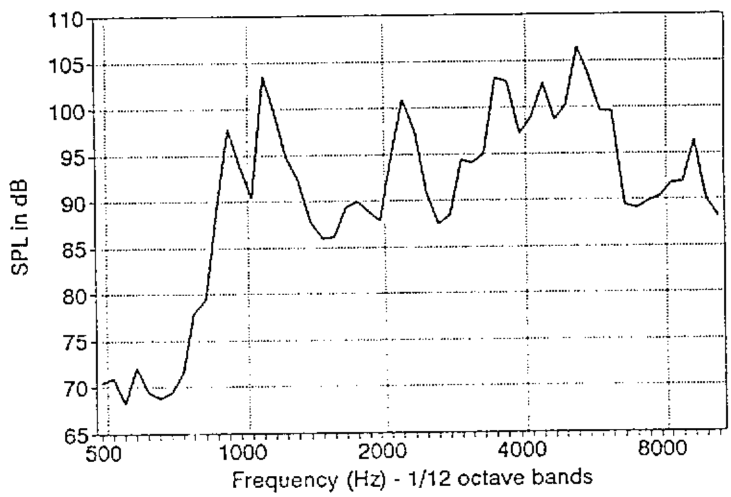


Fig. 6 - Acoustical noise spectrum.

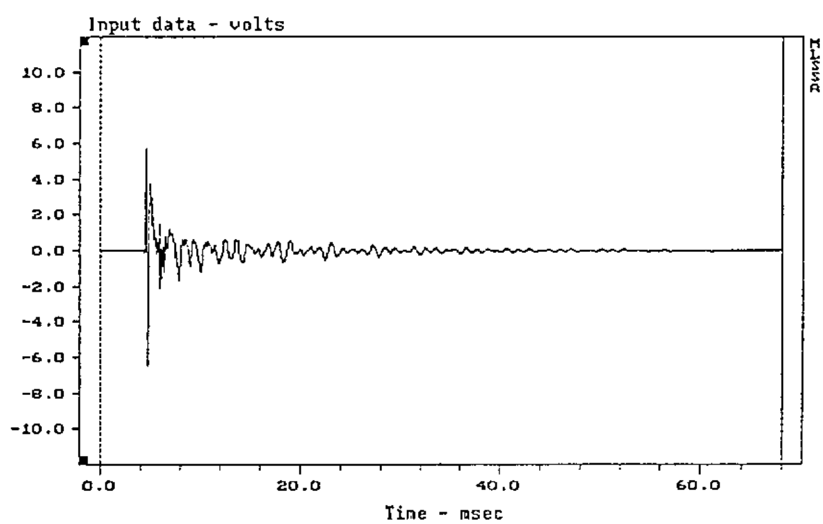


Fig. 7 - Impulse response obtained with hammer excitation.

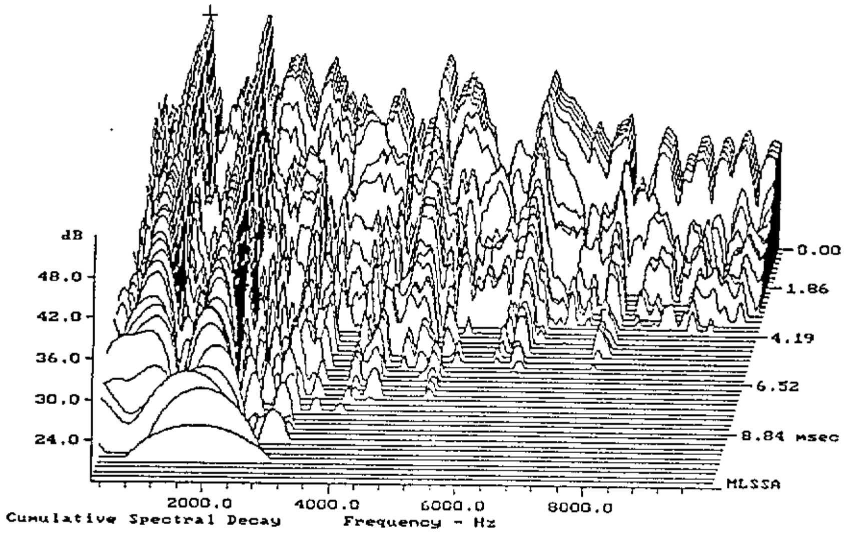


Fig. 8 - Waterfall of the vibration decay.

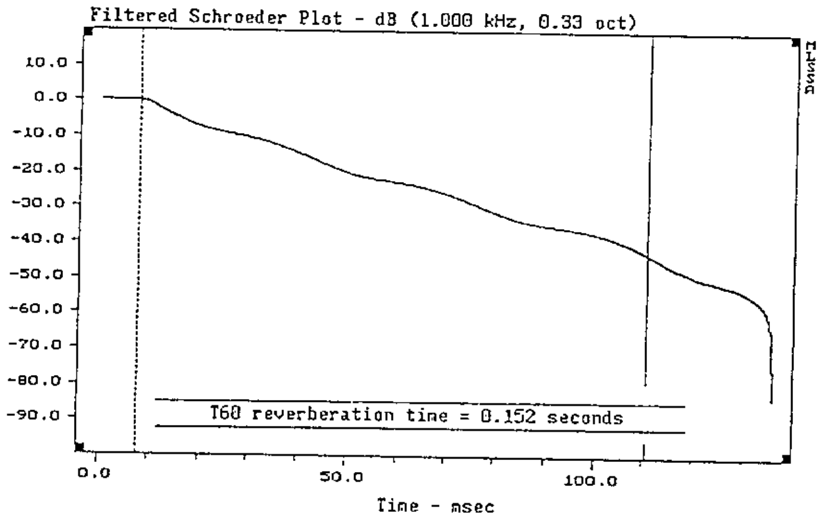


Fig. 9 - Backward integrated decay curve.

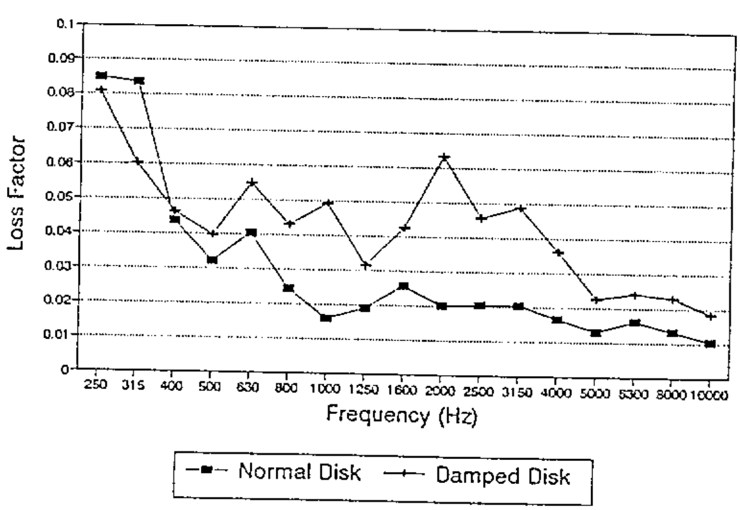


Fig. 10 - Loss factors of undamped and "Silentium" disks