THE RESPONSE OF PLAYED GUITARS AT MIDDLE FREQUENCIES.

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SUMMARY

We present long-time-average measurements of acoustical power density spectra of music played on a classical guitar. The spectrum is integrated to give the distribution of acoustical energy with frequency. This function reveals that most of the acoustical energy radiated from the guitar is due to the first, the third and to the fourth top plate resonances.

INTRODUCTION

In this article, we deal with the acoustical response of played guitars. The problem we want to address is to find which tonal ranges are most important, i.e. give most contribution to the radiated acoustical energy under normal playing conditions. And which resonances of the instrument are the sources of this energy? With such a knowledge luthiers can focus the attention on trimming the resonances which contribute most to the acoustical energy.

METHOD

The method used here starts with the electrically measured acoustical signal. In most cases, this was taken from a grammophone recorder. This is an easy method to get a signal since it relies on a grammophone record rather than on a player. In a few cases, the author was playing, and the signal from a microphone was used directly. The influence of the room together with microphone response suppressed bass response somewhat in the latter case. This is of minor importance for the qualitative results presented here. In both cases, frequencies above the maximum analyzed were filtered off. The signal was sampled on a PDP-11/34 computer in records of 1024 data points and Fourier transformed to obtain the Acoustic Power Density Spectrum (APDS) of the signal. The spectra of many (60 - 200) data records were added to give a long-time-average APDS. No weighting was used in processing the data.

In the upper part of **Fig. 1** is shown such an APDS. At a given frequency, the ordinate gives the amount of acoustical energy at that frequency. The energy contained in a frequency interval is found by integrating the APDS over this frequency interval. Spectra of this kind are difficult to interpret and compare due to the occurrence of many peaks. The peaks are partly due to the resonances of the guitar and partly to the excitation at discrete frequencies under playing conditions. In order to get the information in the spectrum presented in a more manageable fashion, it is customary (Jansson [1]) to find the average sound pressure level in prefixed frequency intervals. This procedure condenses all information in the spectrum into rather few figures and consequently, a great deal of more detailed information is lost. We have instead calculated the <u>acoustic energy distribution</u> from the spectrum. The energy distribution function [E(f)] at frequency f is the amount of energy in the spectrum [S(f)] contained below this frequency. In mathematical terms E(f) is given by

$$E(f) = \int_0^f S(f)\,df \Big/ \int_0^\infty S(f)\,df$$

The denominator in this expression accounts for normalization so that **E**(f) is the percentage of the acoustic energy found below frequency f. k1**E**(f) has thus properties of a statistical distribution function. In the lower part of **Fig. 1** is shown **E**(f) (= % of radiated energy) corresponding to the spectrum at the upper part of the figure. Thus for instance 80% of the acoustic energy is contained below 600 Hz in this case.

RESULTS

In **Fig. 2** is shown the energy distribution function for various

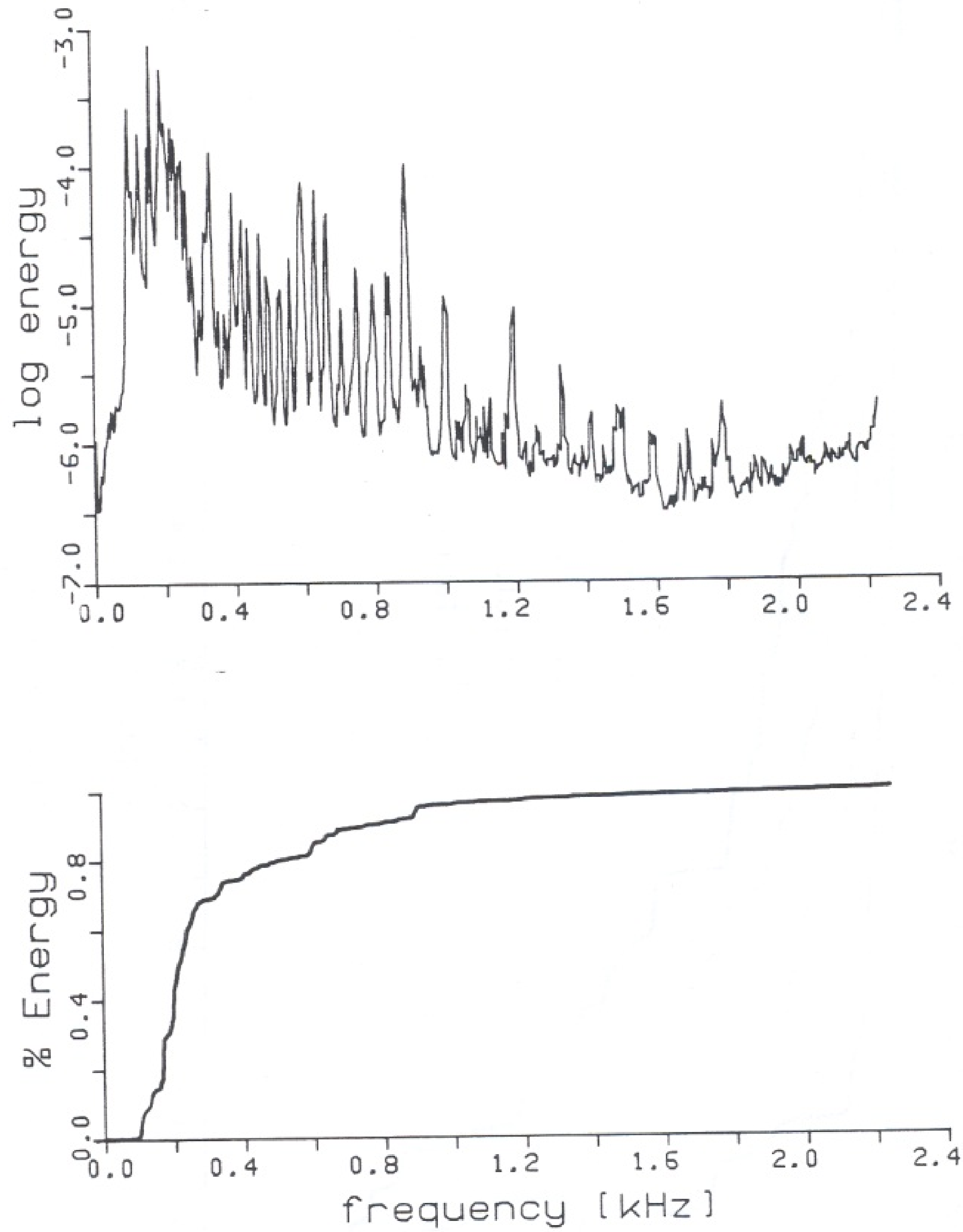

Figure 1. Upper part is logarithm of acoustical energy content at given frequency (actually square of sound pressure) in arbitrary units versus frequency for a guitar, measured from grammophone recordings. Lower part is the corresponding energy distribution function, normalized to unity at the highest analyzed frequency. At any frequency, it gives the fraction of the total acoustic energy contained below that frequency.

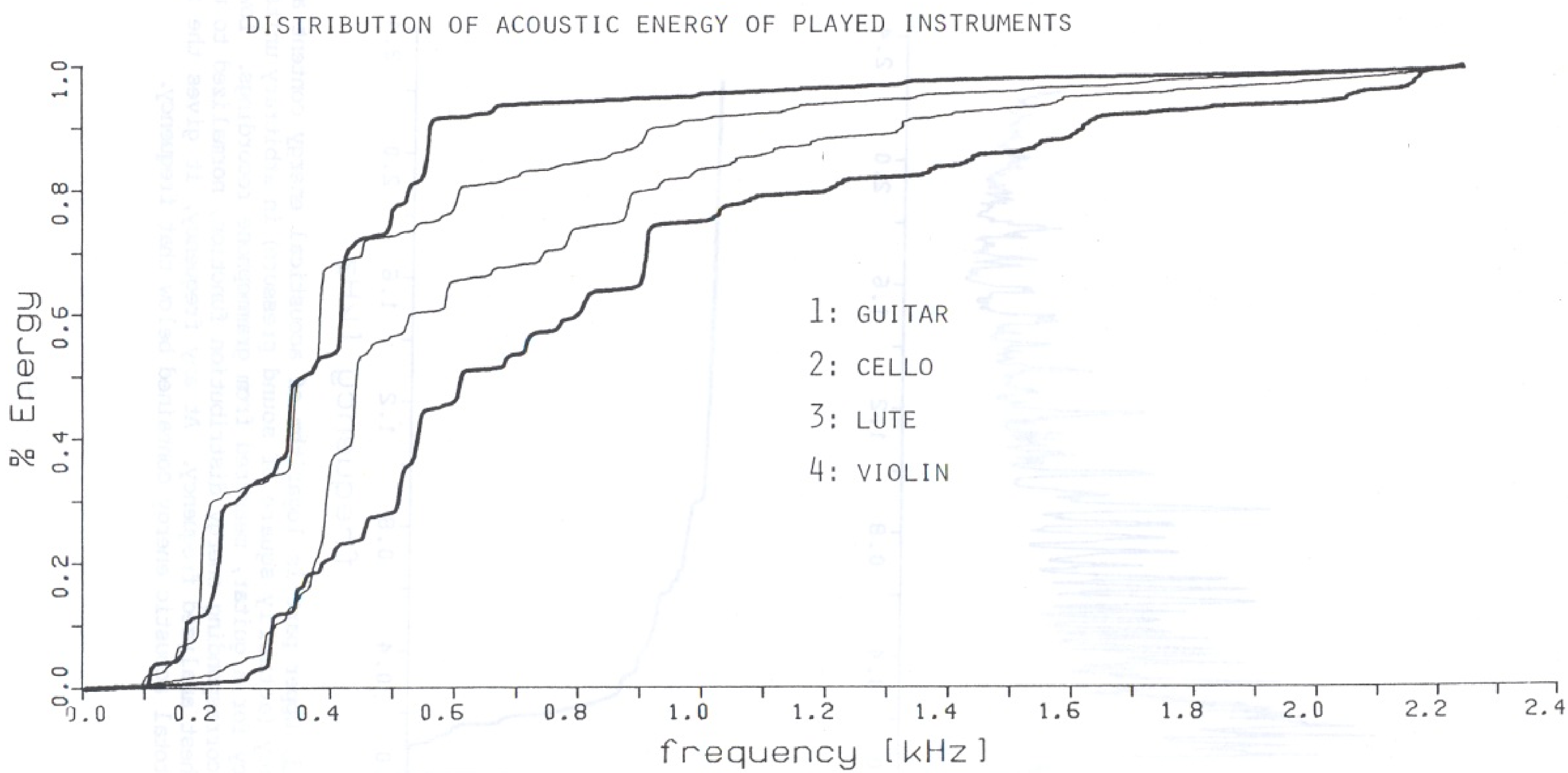

Figure 2. Distribution of acoustical energy for different stringed instruments.

instruments obtained from grammaphone recordings. The maximum analyzed frequency is 2.2 kHz. It is obvious that the large subjective difference between for instance guitar and cello is represented by the contribution to energy at higher frequencies for the cello where the human ear is more sensitive.

If the signal from a grammophone recorder is filtered electronically before it is passed on to a stereo set one can get an impression of he subjective importance of different frequency intervals for the guitar. Thus frequencies below 300 Hz roughly account for the 'depth' or 'warmth' of tone; frequencies from 300 to 1000 Hz account for the brilliance of tone. Frequencies above 1 kHz account for the instrument-characteristic accentuation of tone and usually have much shorter duration than the lower frequencies. the contribution to sound of frequencies above 1 kHz is anyhow difficult to control on a guitar. The sound here is dominated by multipole radiation from higher order modes of the top plate which are difficult to control individually because they become more closely spaced at higher frequencies. So far no general measure has been found to control this contribution as is for instance is the case for the violin family where tuning of the bridge controls the high frequency response. It seems therefore reasonable to focus the investigation on the frequency region below 1 kHz.

In **Fig. 3** is shown the energy distribution function for different musical pieces played on the same guitar by the author. The maximum analyzed frequency here is around 1 kHz since **Fig. 2** showed that only a very small fraction of radiated acoustical energy is found above this frequency. Different musical pieces, chromatic scales and tap tones produce energy distribution functions with the same characteristic shape. The major features of the energy distribution function is the stepwise jump from one plateau to the next at certain frequencies. In **Fig. 3** most of the acoustic energy comes from regions around 225 and 445 Hz. The similarity between curves obtained under different playing conditions allow us to conclude, that the major features of the energy distribution function are independent of the music played and therefore represent characteristic features of the instrument.

In the following, we focus on the details of the energy distribution function for the guitar shown in **Fig. 4**. The curve is characterized by 'small steps' which build up to 'large steps' around certain frequencies.

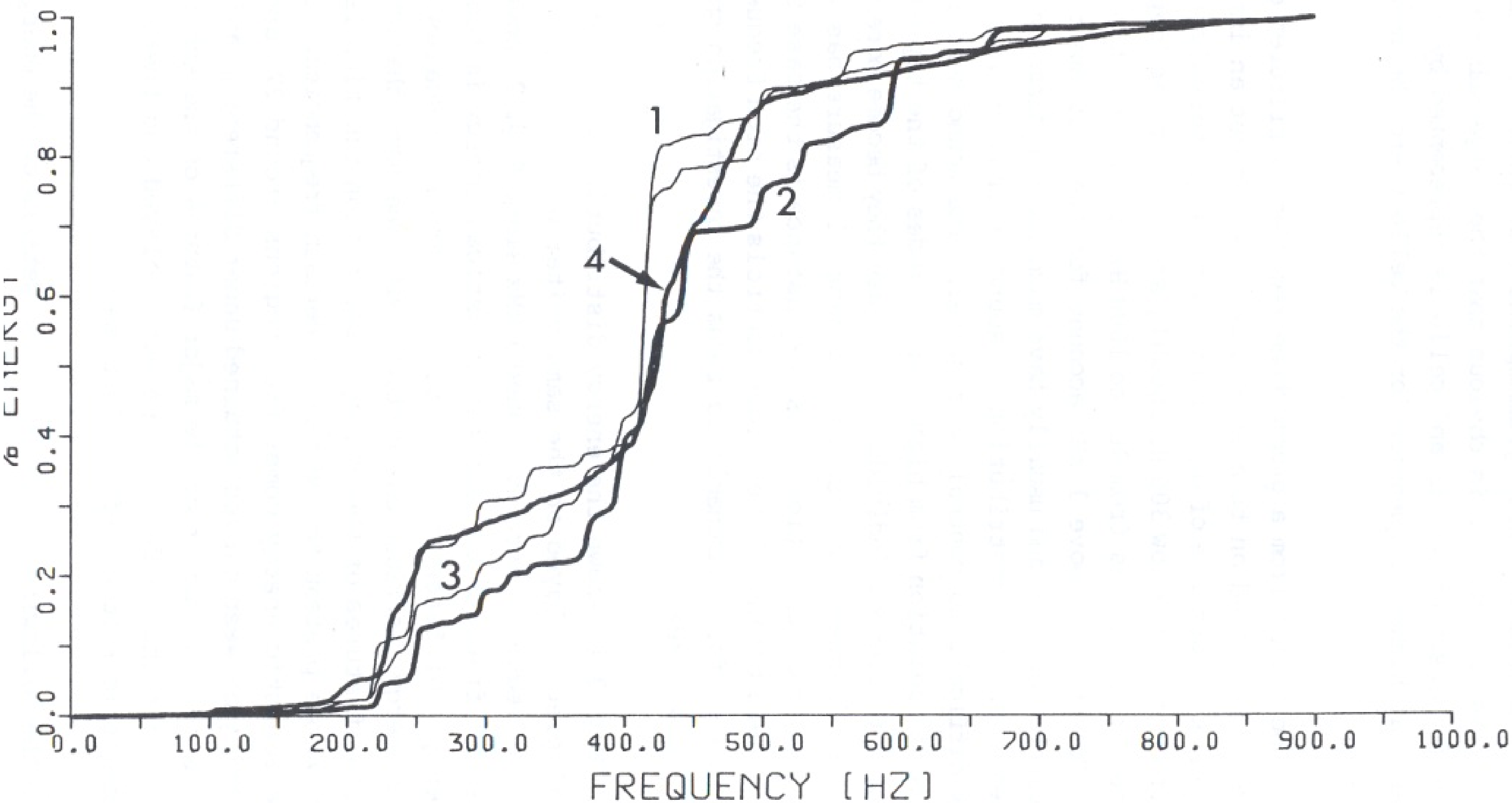

Figure 3. Energy distribution functions for different musical pieces and tap tones, played by the author on the same instrument. 1 - Bach: Kantate 147; 2 - Pernambuco: Son des Papillons; 3 - Chromatic scale; 4 - Tap tones.

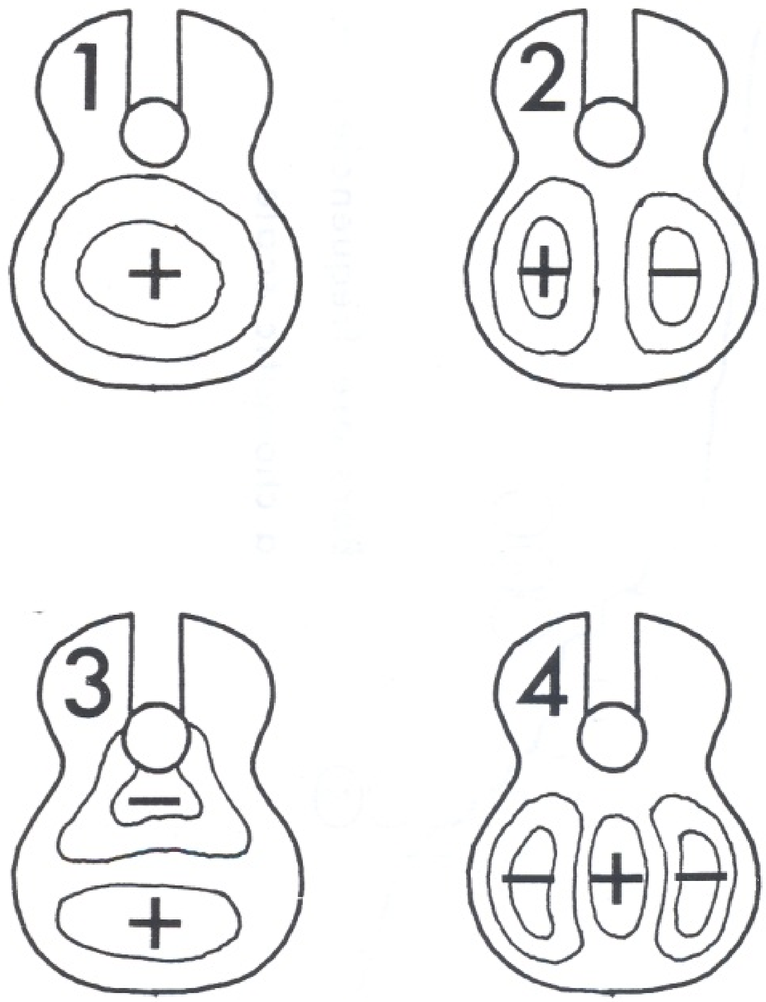

Figure 5. The vibrational configurations of the four lowest top plate modes found in most classical guitars. Typical resonance frequencies are 200, 300, 400 and 500 - 550 Hz. Contours of same vibrational amplitude are indicated. The relative direction of vibration (up/down) is indicated with (+) and (-).

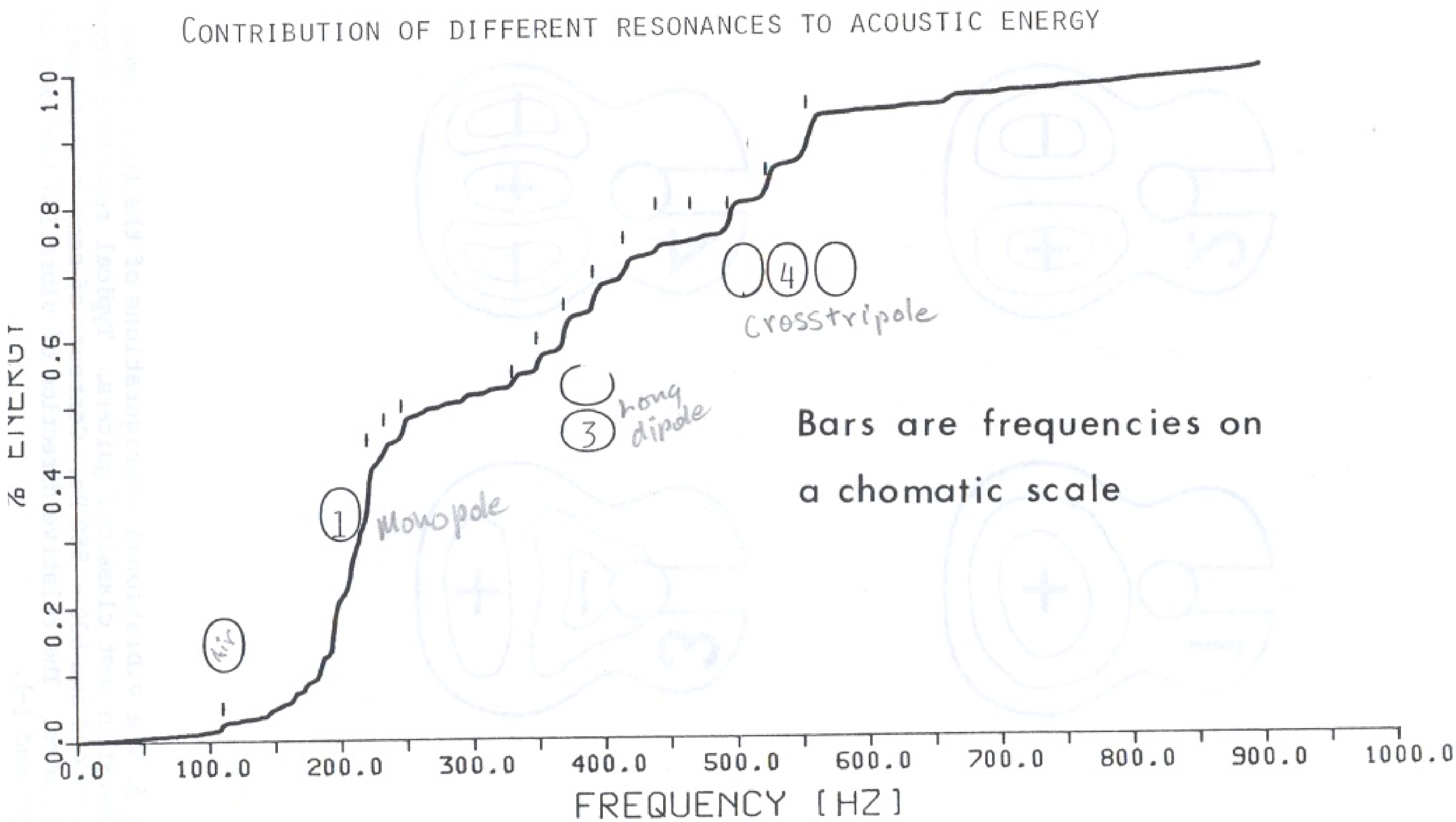

Figure 4. Contribution of top plate resonances to the acoustic energy. The small bars are frequencies on a chromatic scale. The large steps in the curve represent contributions from the first, third and fourth top plate resonance modes as marked by symbols in the figure.

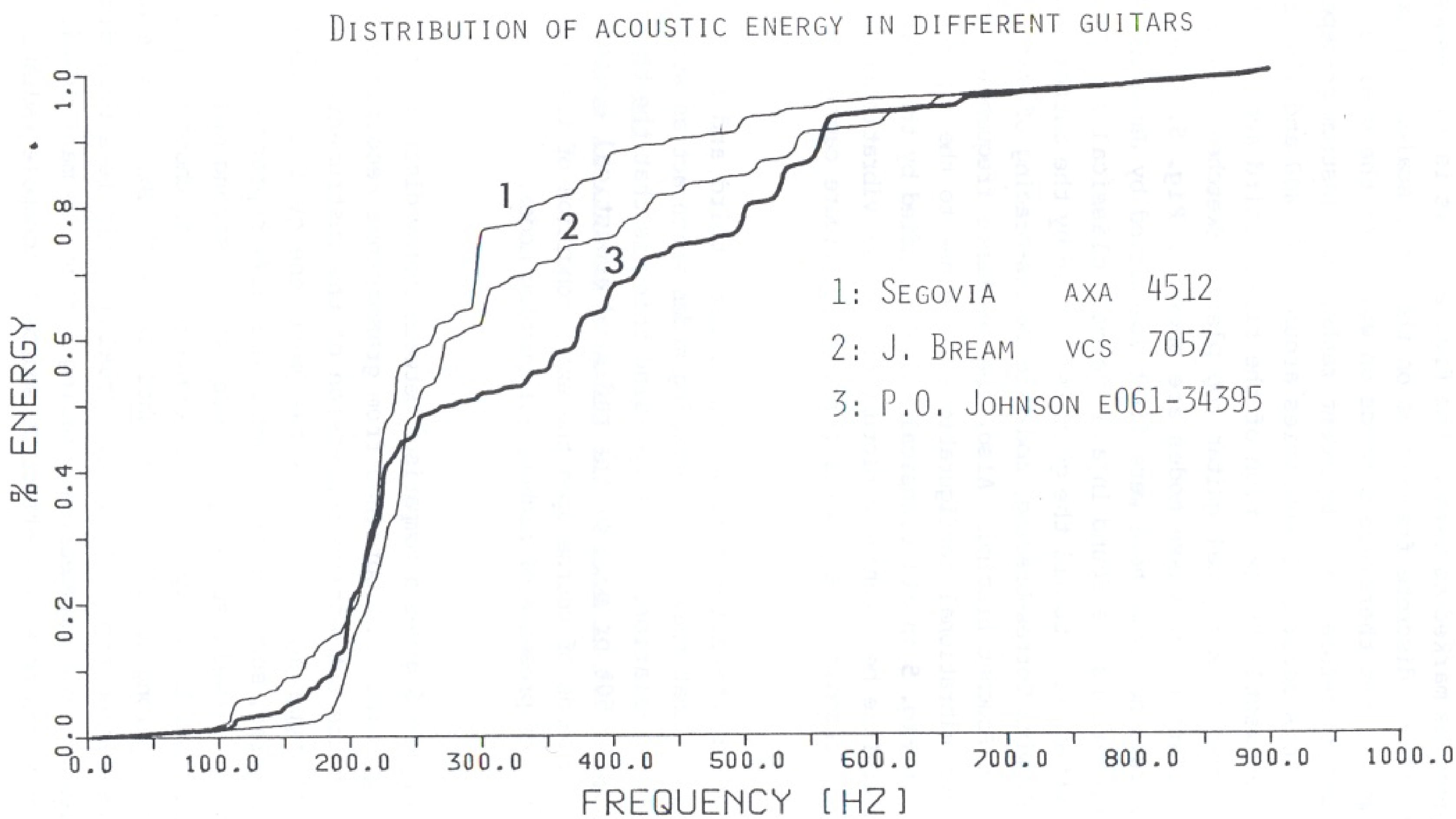

Figure 6. Comparison between distribution of acoustical energy in guitars played by the recitalists shown in the figure.

The small steps on the figure coincide with the chromatic scale frequencies marked as bars on the figure. This is a consequence of the excitation at discrete frequencies on the tonal scale. The exact size of the small step therefore depends on which key the music is played in. They are therefore music-dependent rather than instrument-dependent. The large steps occur at frequencies around 200, 400 and 550 Hz in **Fig. 4**. This is exactly the position of the first, third and fourth resonance frequencies of a typical guitar top plate. Sketches of the vibrational configurations of these modes are shown in **Fig. 5**. The vibrational configurations shown here were first identified by Jansson [2]. Similar configurations are found in all 'normal' classical guitars. The term 'normal' applies to all the guitars studied by the author and comprises guitars with Torres-bracing, modified Torres-bracing of various types and also the Bouchet bracing. Also, the resonance frequencies corresponding to these vibrational configurations are close to the typical frequencies given in **Fig. 5** in all classical guitars studied by the author. Figure 5 may therefore be taken as a picture of typical vibrational configurations with the resonance frequencies given in the figure caption.

It is characteristic of the first, third and fourth top plate resonances that they are air-pumping modes which act as strong sources of monopole radiation. The surprising thing is that **the third and fourth mode carry 50% or more of the radiated acoustical energy**. The exact figure depends of course upon the exact condition of these resonances and also on the presence of higher, air-pumping modes.

Figure 6 gives a comparison between energy distribution functions for three guitars, all obtained from grammophone recordings. The curves reflect the subjective impression of the instruments: #1 is a 'dark' Spanish type and #3, which has more energy distributed at higher frequencies, sounds more 'bright'. Guitar#2 represents an intermediate case. #1 is well suited for pieces with a strong melodic line. #3 is well suited for polyphonic music and for clear chord separation. Guitar #1 has a strong contribution slightly below 300 Hz. This is probably due to the second top plate mode. Usually, this is a pure dipole but in instruments with asymmetrical bracing - found in many Spanish guitars - this mode can be a very efficient source of monopole radiation.

An overwhelmingly large part of the acoustic energy radiated from the guitar comes from the first, the third and the fourth top plate resonances in the frequency range from 200 to about 600 Hz. It is therefore important to assess what we really know about these modes.

The first top plate resonance, the Helmholtz resonance and in some guitars the resonance of the back, are all coupled together and are by now well understood. Thus Meyer [3] has given a technical description of this system with much practical information for the instrument builder. Firth [4], Caldersmith [5], Dickens [6] and the author (Christensen and Vistisen [7]) have presented studies of these resonances so that one can now quantitatively predict the low frequency response of the guitar.

Now let us turn our attention to the third and fourth top plate resonances. Meyer [8] has shown that a distinct and strong third resonance correlates well with a high score in a subjective quality evaluation in accordance with the present finding that this resonance accounts for a substantial fraction of the acoustical energy. However there is considerable difficulty in constructing a guitar to get a strong third resonance, mainly because the bridge is usually very close to the nodal line of this resonance (see Jansson [2]). The situation is complicated because there probably is a coupling between this top plate mode and the standing half-wave resonance in the cavity (Meyer [3]), (Jansson [9]).

The situation is better for the fourth resonance. The excitation efficiency is much greater because the bridge is at anti-node for this resonance. Recently Walther Kruger [10] has published a paper which indicates that enhancement of acoustic output from the middle frequency range results when the lobes of the top plate are tapered down to smaller thickness. This is the only general technical information which deals with the very important middle frequency range. It is the author's belief, that further progress in guitar making could be achieved by concentrating some efforts in understanding the anatomies of the third and fourth top plate resonances.

Although the present study is done on the classic guitar, the method may be tried out on other string instruments. The use of the energy distribution function instead of the power spectrum has the advantage of greatly simplifying the information in the power spectrum of sound pressure. Especially, it allows the user to sort the music-dependent features from the more interesting instrument-dependent ones while at the same time providing detailed frequency information to allow a direct identification of the more important resonances of the instrument.

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