

# Acoustic Cues from Shapes between Spheres and Cubes\*

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## Abstract

*Solids of different shapes resonate according to their peculiar geometry. Although physics, for some fundamental shapes such as the cube and the sphere, provides explicit formulas for determining the modal frequencies, a general resonance analysis of 3-D shapes must be conducted using numerical methods. In this paper, Waveguide Meshes are used to model intermediate geometries between the cube and the sphere. This example is paradigmatic of the general problem of morphing 3-D shapes.*

*We are interested in understanding how smooth shape transitions from sphere to cube translate into a migration of the resonating modes. This work is aimed at assessing the suitability of the waveguide mesh as a tool for such a research, and it is preliminary to further investigations involving human subjects.*

## 1 Introduction

Acoustic rendering is an emerging research field, whose growth is stimulated by two, somehow opposite factors: an increasing interest for applications of multi-modal virtual reality on one side, and inevitable constraints in cost and technology of the equipment on the other side. These factors, together, lead to looking for rendering methods which are realistic and computationally efficient at the same time. Under these assumptions, a method which is capable to acoustically render objects, or enclosures, will move the listener to virtually experience a scenario without reproducing all its characteristics.

Important studies have already been conducted in the visual field, and remarkable results have been achieved in rendering shadows, textures, lightings, and object movement. This encourages to looking for audio counterparts of those methods.

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Perception of shapes from acoustic cues is a matter of investigation for researchers in psychophysics (Lakatos et al. 1997) and object modeling (Rocchesso and Ottaviani 2001a). A listener could experience, by hearing, to stay for example in the middle of a semi-spherical enclosure, or in front of a large cube, without seeing any of them (McGrath et al. 1999). Tests have been conducted to investigate whether or not listeners discriminate simple shapes such as cubes and spheres (Rocchesso and Ottaviani 2001a). Such experiments show that shape labels can be reliably attached to sounds, regardless of their pitch, and that the distribution of low-frequency resonances play the prominent role in this task. As a side result (Rocchesso and Ottaviani 2001b), it was shown that non musicians tend to equalize pitches of resonators as if they resulted from equal-volume shapes. This gives us a simple criterion that can be used to minimize the influence of pitch when experimenting with 3-D objects of varying shapes.

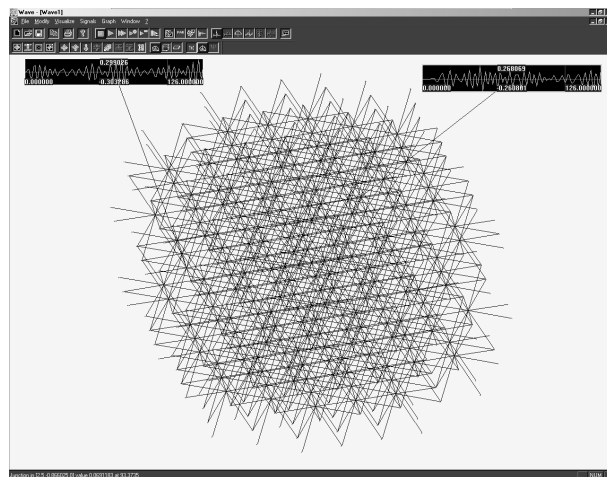


Figure 1: User interface of the application running the mesh models.

In this work we investigate on the “spectral continuum” holding when a cube morphs into a sphere, through specific geometries called superquadrics (Kumar et al. 1995). We

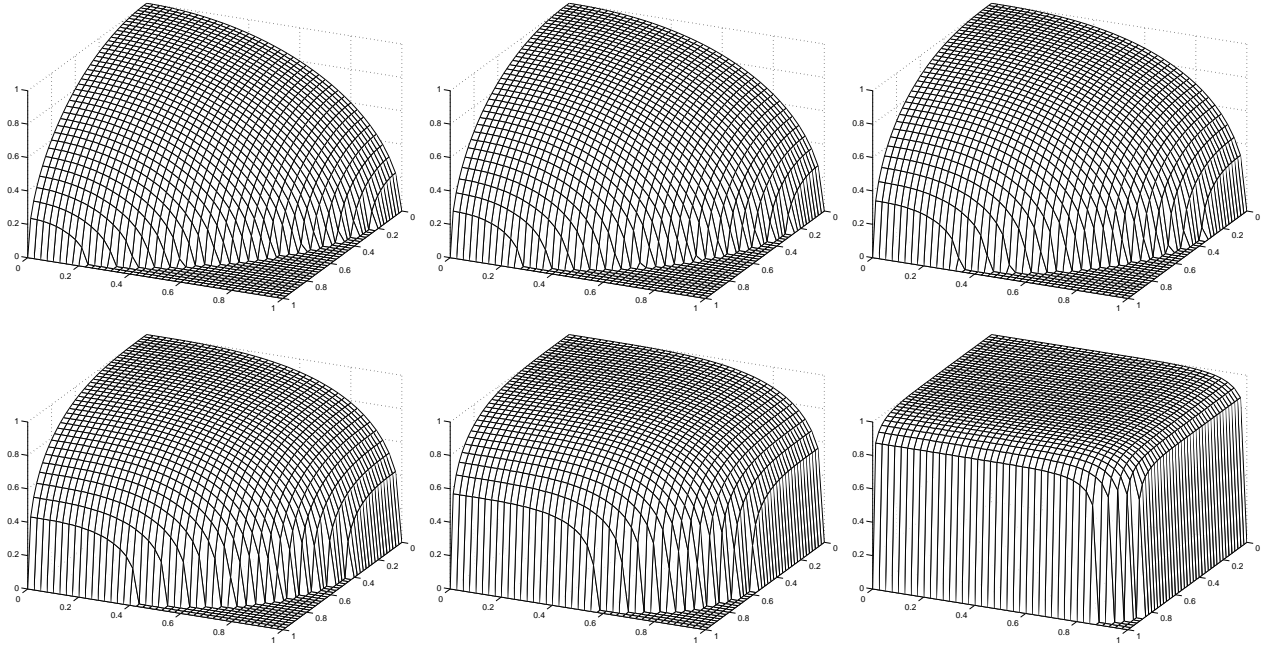


Figure 2: Positive sections of superquadrics obtained using (1).  $\gamma$  has been set to  $\{2, 2.2, 2.5, 3, 4, 10\}$  starting from left above, respectively.

look for specific cues to check out if there are “footprints” which acoustically label each intermediate shape, and, hence, the whole morphing process. We will show that these cues exist, although only listening tests could demonstrate a real sensitivity of human beings to shape variations.

A numerical method is needed for studying the ellipsoidal shapes. In our work, all resonators are modeled using waveguide meshes (Van Duyne and Smith 1993). In particular, the 3-D triangular waveguide mesh (3DTWM) has been adopted, for its low dispersion characteristics and good approximation in modeling boundaries (Fontana et al. 2000).

All the simulations have been conducted working with an application written in C++, whose user interface can be seen from the screenshot in figure 1. This application simplifies the construction and initialization of the mesh, and performs all needed processing. A pre-release of the executable program is available from the Web site of the SOb European Project (<http://www.soundobject.org>) for public experimentation.

## 2 From Spheres to Cubes

One possible morphing from spheres to cubes can be easily realized if we restrict any possible geometry to be an ellipsoid. Superquadrics are, in this sense, a versatile family which is defined by the following equation (Kumar et al.

1995):

$$\left|\frac{x}{a}\right|^{\gamma_x} + \left|\frac{y}{b}\right|^{\gamma_y} + \left|\frac{z}{c}\right|^{\gamma_z} = 1 \quad (1)$$

Changes in shape are then performed by varying only the three parameters  $\gamma = \gamma_x = \gamma_y = \gamma_z$  together, and constraining  $a, b, c$  to condition  $a = b = c$ :

- sphere:  $\gamma = 2$
- ellipsoid between sphere and cube:  $2 < \gamma < \infty$
- cube:  $\gamma \rightarrow \infty$ .

We consider six shapes, including the sphere and the cube, which are built according to (1). Their positive section (i.e., their volume limited to  $\{(x, y, z) : x > 0, y > 0, z > 0\}$ ) is depicted in figure 2, where, starting from left above, parameter  $\gamma$  has been set to

$$\begin{aligned} \gamma_1 = 2 & \quad \gamma_2 = 2.2 & \quad \gamma_3 = 2.5 \\ \gamma_4 = 3 & \quad \gamma_5 = 4 & \quad \gamma_6 = 10 \end{aligned}$$

respectively. Note that  $\gamma_6$  is large enough to represent the cube. This is true because the discrete boundary, which will be modeled by the 3DTWM, does not change for  $\gamma \geq 10$ .

Accordingly, waveguide mesh models are built. Taking advantage from the application presented above, 3DTWM’s are constructed so that they match, as close as possible, the geometries coming from the selected ellipsoids. Perfect reflection of the signal holds at the boundary.

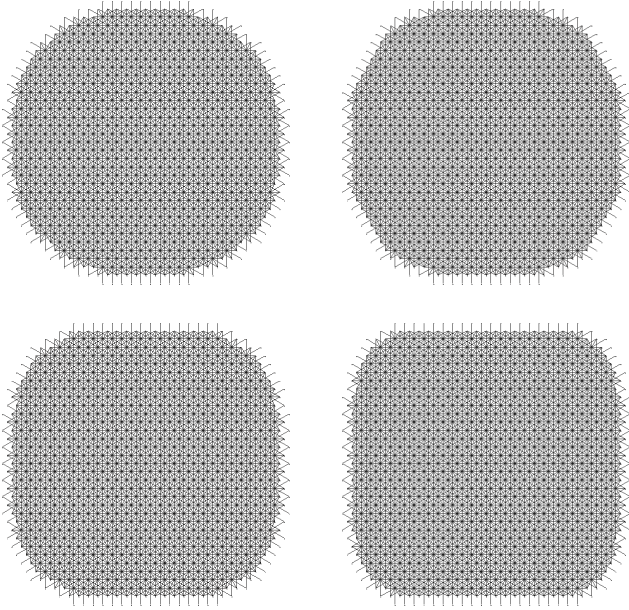


Figure 3: Projections, orthogonal to the  $z$ -plane, of 3DTWM models closely matching the intermediate shapes given in figure 2.  $\gamma$  has been set to  $\{2.2, 2.5, 3, 4\}$  starting from left above, respectively.

Figure 3 depicts orthogonal projections to the  $z$ -plane of the mesh models, in the same order given in figure 2, for intermediate shapes. Inevitable mismatching between ideal geometries and 3DTWM models can be noted, even if the scattering junction density was guaranteed to provide a minimum distance equal to 20 junctions between surfaces located on opposite sides.

Moreover, the 3DTWM models flat surfaces with lower accuracy due to its own topology. This causes some blur in the definition of the resonance peaks, especially in the case of the cube. This will be evident in the spectral analysis.

### 3 Spectral Analysis

For each geometry, one spectrum was calculated from a signal obtained by exciting (using an ideal impulse) the resonator on three points, i.e., the center plus two points close to the boundary. The output signal was picked up on a position which was located near the boundary, for capturing most of the resonances. For non-spherical shapes, the excitation and output junctions were located near one corner. Since the corner geometry varies together with shape, inevitable variations in the excitation and acquisition positions occur during the experiment. For this reason, the dynamics of the output signals varies with shape.

Signals have been damped offline. Offline damping en-

sures that the resonances do not move due to imperfect internal modeling of attenuation mechanisms.

Each spectrum should be rescaled in the frequency axis, holding the condition of volume constancy. Table 1 (second column) shows, according to the chosen geometries, volume ratios for resonators having the same size<sup>1</sup> in the sense of figure 2. In the third column, size ratios for resonators having the same volume are shown. Clearly, frequency rescalings for constant volume morphing should comply with the values in column three<sup>2</sup>. Volume normalization of signals will be used in future research, devoted to investigate the perceptual aspects of shape variations.

$\gamma_i$	$\text{Vol}(\gamma_i)/\text{Vol}(\gamma_1)$	$\text{Size}(\gamma_i)/\text{Size}(\gamma_1)$
2	1	1
2.2	1.0923	0.970
2.5	1.2086	0.940
3	1.3560	0.900
4	1.5406	0.865
10	1.8157	0.815

Table 1: Volume ratios for equal sizes (second column), and size ratios for equal volumes (third column). Geometries given by  $\gamma_1, \dots, \gamma_6$ .

We can analyze a portion equal to  $1/16$  of the band of the output signals. Once the sampling frequency has been set to a nominal value of 8 kHz, frequencies up to 250 Hz are hence taken into account.

Figure 4 shows plots of the spectra discussed above, from the sphere (top) to the cube (bottom). Frequencies are expressed in Hz, and gains in dB. The lower resonances exhibited by the sphere are sparser, as one would expect from theory (Moldover et al. 1986), and define a clear mode series where each mode accounts for a precise portion of the whole band.

As shape morphs to squareness, the mode series shrinks and shifts to lower frequencies. At the same time, new resonances arise in between the existing ones, so that the density of modes increases as the resonator approaches the cubic shape.

Both shifting of the modes to lower frequencies, and rising of new modes in between, are events which do not depend on the excitation and listening positions. Of course, these positions determine the modes which appear on the spectra or, likewise, the resonances which are audible.

From the previously shown plots, we can extrapolate a clear evolution of the low-frequency modes. This kind of description is especially useful when someone wants to recreate

<sup>1</sup>say, diameter of the sphere, and side length of the cube

<sup>2</sup>Note that an alternative approach for obtaining resonators of equal volume would consist in modeling each geometry using meshes having, more or less, the same number of scattering junctions. This way is in practice harder to follow than numerically computing the ratios presented in table 1.

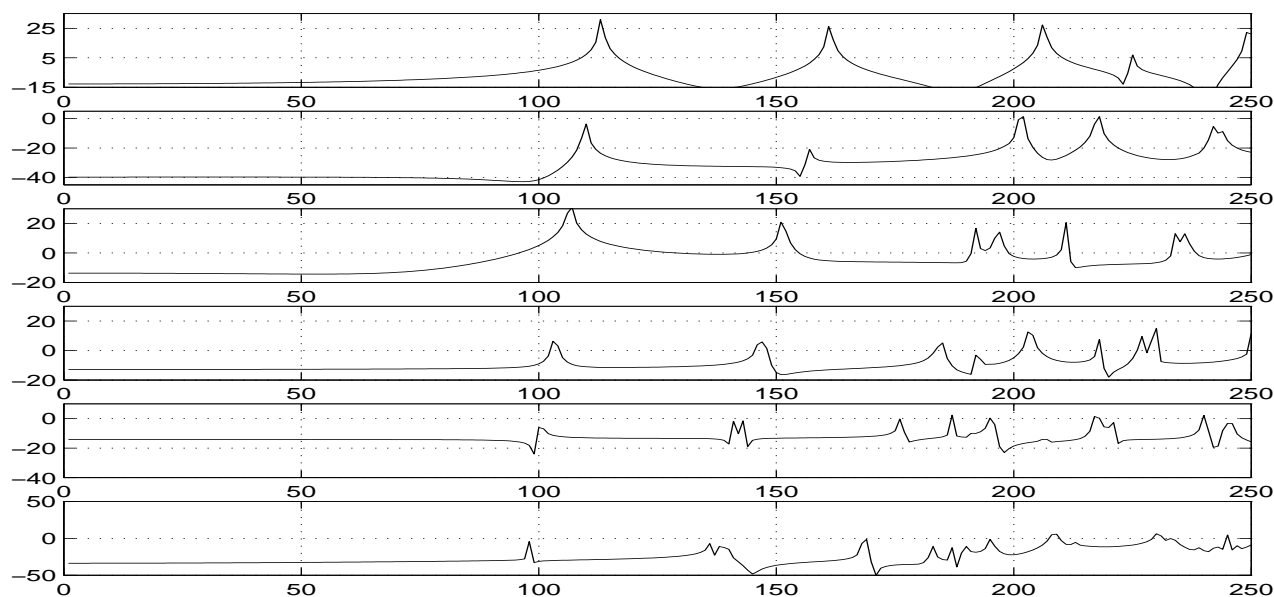


Figure 4: Low-frequency portion (1/16 of the nominal band) of the output signals taken from the resonators. Top: sphere. Bottom: cube.  $x$ -axis: frequency (Hz).  $y$ -axis: gain (dB).

the low-frequency resonances of a shape such as the ones presented here, for instance using additive synthesis, or render a shape by processing a signal with a series of tunable (second-order) equalization filters, whose peak frequencies follow the positions of the modes during changes in shape.

These characteristics of the spectra have a counterpart in the sound samples which are obtained from the corresponding signals. As a resonator approaches the shape of a cube, pitch becomes less evident (or more ambiguous) and, at the same time, a sense of growing brilliance in the sound is experienced by the listener. Although pitch, if sensed, decreases as shape migrates to squareness, a proper resampling of the signals which respects volume constancy should equalize the pitch and balance the brightness to a homogeneous value.

## 4 Conclusion

A study on the spectral modifications of sounds produced by resonators, whose geometry morphs from a spherical to a cubic shape, has been presented. It has been shown that a “spectral continuum” exists such that listeners could in principle be sensitive not only to roundness and squareness, as shown by previous results, but also to certain intermediate situations.

Listening tests using sounds whose spectra are properly rescaled, will verify whether the spectral cues provided by such shapes have a perceptual counterpart.

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