

# THE ENIGMA OF VITRUVIAN RESONATING VASES AND THE RELEVANCE OF THE CONCEPT FOR TODAY

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## ABSTRACT

The clarity of sound within any Greek or Roman theatre (without any form of enhancement) is impressive to any visitor. The seats arranged in curved rows around the circular orchestra form large horizontal reflecting surfaces. This ensures that the path of the sound waves travel from the source (the actor or singer) to each of the listeners in a direct path (i.e. without reflection). Vitruvius, however, claimed further enhancements could be made.

*In theatres, also, are copper vases and these are placed in chambers under the rows of seats in accordance with mathematical reckoning. The Greeks call them Echeia. The differences of the sounds which arise are combined into musical symphonies...*

*... it becomes fuller, and reaches the audience with a richer and sweeter note.*

***Vitruvius, on Architecture, Book I, – on training of architects, Loeb***

This paper explores the notion of intent and purpose behind the Vitruvian concept and also addresses an arguably more complex issue, that of a potential fusion between archaeology, science and music.

## 1. INTRODUCTION

### 1.1 Vitruvius – the person

Marco V. Pollio Vitruvius studied Greek philosophy and science around the 1<sup>st</sup> Century BC. A practical exponent of his craft, he gained experience through his professional work and was the architect of at least one complete unit of buildings for Augustus in the reconstruction of Rome. As an indication of his diverse talents, he also oversaw developments in the imperial artillery and military engines – making Vitruvius an important figure in his day.

In modern times, Vitruvius has been regarded primarily as an architect but his explorations of science and art in the widest sense shouldn't be forgotten. The emphasis of books I-V

is on architecture in the traditional sense of the word. The second five books contain information relating to Greek science demonstrating the background Vitruvius had during his studies and younger days. The inspiration of science was at one with art and literature (although this was not a philosophy specific to Vitruvius).

*The science of the architect depends upon many disciplines and various apprenticeships which are carried out in the art.*

***Vitruvius, on Architecture, Book I – on training of architects, Loeb***

### 1.2 The Ten Books on Architecture

*De Architectura* is a collection of ten books detailing his practical experience with traditional Greek theory of the time. Exact dates for the composition remain uncertain but it is believed to have been written around 27 BC (towards the latter period of his life).

The complete treatise is detailed as follows:

**Book 1:** Architectural Principles

**Book 2:** Evolution of Building, Use of materials

**Book 3:** Ionic Temples

**Book 4:** Doric and Corinthian Temples

**Book 5:** Public Buildings, Theatres (and music), Baths and Harbours

**Book 6:** Town and Country Houses

**Book 7:** Interior Decoration

**Book 8:** Water Supply

**Book 9:** Dials and Clocks

**Book 10:** Mechanical and Military Engineering

There are a number of surviving manuscripts that have been used to create the current published translations. These date from as early as the 8<sup>th</sup> Century (London, British Museum). The text was rediscovered in the fifteenth century and has been studied by renaissance architects to a wider range of student in the current day. A number of translations of the text exist and are available in print. The three used for the purpose of this paper (Dover, Loeb,

Cambridge publications) are referenced in the bibliography.

## 2. THEATRE DESIGN

The design of a Roman theatre has much in common with its Greek counterpart. Before discussing the differences, it is worthwhile thinking about terminology. It is a common mistake to name the semi-circular Greek and Roman theatres as amphitheatres. They are not! An amphitheatre is circular (think about the Coliseum in Rome) and a theatre is semi-circular (or at least close to it). The amphitheatre and theatre have vastly different uses.

The theatre of the Greeks was built on the slope of a hill, securing sufficient elevation for the back row from the naturally occurring landscape. The tiers were either cut directly into rock or if the land was soft an excavation was made in the hillside and lined with rows of benches. The steps were often faced with marble (as in the theatre of Dionysus at Athens). The theatre of the Romans and hence Vitruvius, was potentially a freestanding structure and therefore a much more complex design.

## 3. GREEK/ROMAN MUSIC

Before exploring the reasoning behind Vitruvius' concept of the resonating vases in Roman theatres it is important to have an understanding behind music principles of the time.

*Harmony is an obscure and difficult musical science, but most difficult to those who are not acquainted with the Greek language; because it is necessary to use many Greek words to which there are none corresponding in Latin. I will therefore explain, to the best of my ability, the doctrine of Aristoxenus, and annex his diagram, and will so designate the place of each tone, that a person who studiously applies himself to the subject may very readily understand it.*

***Vitruvius, The Ten Books on Architecture, Book V, Dover***

The systems as described by Aristoxenus and Pythagoras are different in terms of technical specification but particularly in terms of philosophy. Vitruvius (as can be seen from above) follows the theory of Aristoxenus and it is this that the acoustic vases are based upon.

Aristoxenus sets out a theory of scale structure and a method for analysis. His definition of *interval* is somewhat different to that of the Pythagoreans (which is based on ratio and proportion) in that he describes two pitches as being bounded or marked off by two notes of different pitch (*Landels*). A *system* is a construction of intervals, the smallest group of which is known as a *tetrachord*.

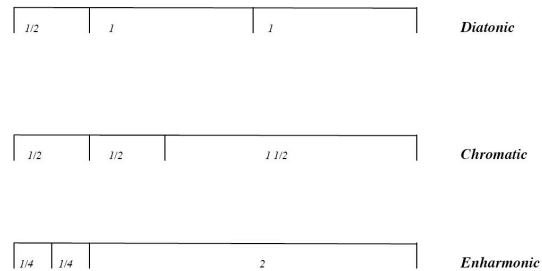


Figure 1

The groups of four pitches in each tetrachord are always surrounded by the interval of a fourth. Aristoxenus demonstrates three different types (diatonic, chromatic, enharmonic). He uses the term *hemitonion* to describe an interval of a semitone and more complex term of *diesis* for any interval smaller than a semitone (*Landels*). He does use mathematical ratios to assist with the concept of microtones but also spoke of them in terms of colour and other descriptive methods.

To make more complex pitch systems it is a simple matter of placing one tetrachord on top of another (giving tetrachords based on cycles of fourths). This developed into the *Greater Complex System* giving a two-octave construction and this is the method that Vitruvius follows for the tuned vases.

## 4. ACOUSTICS

### 4.1. Problems, vases...

A greater understanding of acoustics can be identified as early as the beginning of the 5th century BC (Dionysos at Athens and the theatre at Syracuse). Ironically, the shape of the theatres was not based on scientific understanding but rather by accident. A site on the side of a hill, sloping down at approximately 45 degrees gave a good acoustic result. Other portable solutions also helped the acoustic. Backdrops helped high-frequency reflections (provided by painted skins). It is believed the propagation of sound to the audience was aided by the megaphone effect of the masks worn by the actors.

Further developments in the shape of theatres are all thought to have been due to attempts at improving the acoustics. An increased length of the seating area (whilst maintaining overall proportion) brought more of the audience close to the stage and thus improved the acoustics, especially as less of the sound could escape at the sides of the orchestra. However, the direction in which the actors were facing became of greater importance, and the height of the stage building was increased and made of stone to provide more reflection from behind and improve the distribution of the sound. A few centuries later, and with the aid of his knowledge derived from Aristoxenus, Vitruvius was

attempting to solve other acoustical problems still prevalent in Roman theatres.

The Pythagoreans formulated the modern science of acoustics in Greece in the 6th century BC. Aristoxenus examined the study of musical sounds further by going beyond the source and propagation of sound to consider issues of perception. The work concerning acoustics of Vitruvius is largely based on Aristoxenus' writings.

*In theatres, also, are copper vases and these are placed in chambers under the rows of seats in accordance with mathematical reckoning. The Greeks call them **Echeia**. The differences of the sounds which arise are combined into musical symphonies or concords: the circle of seats being divided into fourths and fifths and the octave. Hence, if the delivery of the actor from the stage is adapted to these contrivances, when it reaches them, it becomes fuller, and reaches the audience with a richer and sweeter note.*

**Vitruvius, on Architecture, Book I, – on training of architects, Loeb**

Vitruvius' understanding of acoustics is extremely impressive for its time. He was aware of an acoustical problem caused by the reflection of sound waves, namely that interference to the original source is created by reflections making the original less clearly audible or defined. Vitruvius called this reflection of sounds *resonantia* (which differs somewhat from our modern day meaning of the word resonance which implies a sound being bounced back and forth repeatedly at a specific pitch). Although such reflections were kept to a minimum by the very design of Roman and Greek theatres, the *resonantia* would still have been seen as a considerable problem. If any extraneous strong reflections come back to a listener at slightly different times, then speech, for example, would have become difficult to understand. As Vitruvius pointed out, an inflected language such as Latin is difficult to understand when the final syllables of words arrive at slightly different times. These theatres were outdoor venues often built into the side of a hill. The apparent dryness of the resultant acoustic was also a problem for Vitruvius when dealing with music and he went to considerable effort to invent a system that would counteract it. Resonating bronze vases were his solution to this problem.

*...let bronze vases be made, proportionate to the size of the theatre, and let them be so fashioned that, when touched, they may produce with one another the notes of the fourth, the fifth, and so on up to the double octave.*

*...the voice, uttered from the stage as from a centre, and spreading and striking against the cavities of the different vases, as it comes in contact with them,*

*will be increased in clearness of sound, and will wake an harmonious note in unison with itself.*

**Vitruvius, The Ten Books on Architecture, Book V, Dover**

How well these vases may have worked? It remains unclear.

#### **4.2 Musical theory within the theatre, placement**

Whilst there are no known original resonating vases in existence, a number of sites show evidence of spaces (niches) where the vases would have been positioned.

*12 pairs of compartments corresponding to those described by Vitruvius have been found in the supporting wall of the uppermost row of seats of the Greek theatre at Aizani in Phrygia, eight in the podium of the Roman theatre at Nicopolis, and seven in the Greek theatre at Scythopolis in Syria. There are 20 niches in the upper part of the Greek theatre of Gerasa in Jordan; at Ierapetra and Gortyn in Crete the theatres have 13 niches each; and at Lyttos, also in Crete, there are three rows of 13 niches each.*

**Grove Dictionary (Belli, 1854, Müller, 1886).**

Vitruvius clearly states that the vases are to be placed freestanding.

*... so that they touch no walls and all around them have empty space and place above their heads. Set them upside down, and on the side facing the platform put wedges underneath them, no less than half a foot high, and opposite these chambers leave openings along the footings for the lower tiers of seats...*

**Vitruvius, The Ten Books on Architecture, Book V, Cambridge**

Different numbers of vases should be used depending on the size of the theatre.

*The method of marking out the positions in which the jars are to be placed is as follows. If the theatre is not very large, a horizontal line should be marked out, halfway up the slope [of the auditorium], and 13 vaulted cubicles built, with 12 equal intervals between them: then the sounding jars as described above are placed in them.*

*So by this arrangement, the voice, radiating from the stage as from a centre, spreads itself around [the auditorium]: and, by exciting resonance in particular vases, produces an increased clarity and a series of notes which harmonize with itself.*

**Vitruvius, The Ten Books on Architecture, Book V, Dover**

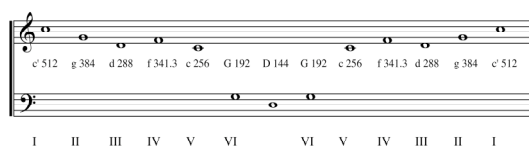


Figure 2 - vessel pitches for a small theatre

I	nētē hyper bolaiōn
II	nētē die zeugmenon
III	paramese
IV	nētē synhemmenōn
V	mesē
VI	hypatē meson
in media	hypatē hypatōn

Figure 2 shows the pitches (with Greek names) of the vases for a small theatre as specified by Vitruvius. Vase I (*nētē hyper bolaiōn*) would be placed at either side of the theatre with the *in media* vase (D 144) placed centrally. All others would be equidistant between.

Larger theatres required a greater number of vases arranged in three horizontal rows (one for the *harmonia*, a second for the *chromatic* and a third for the *diatonic*).

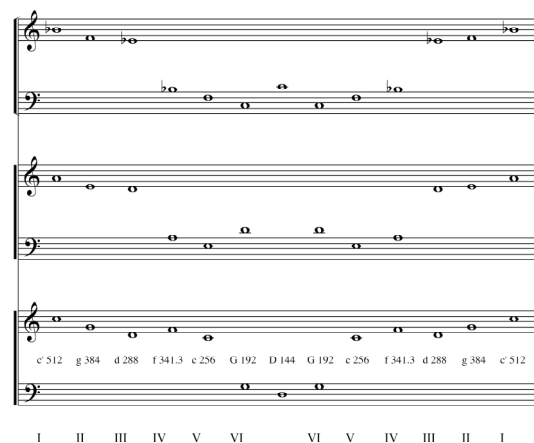


Figure 3 - vase pitches for a large theatre

Vitruvius discusses why acoustic vases were not used in the theatres of Rome. Owing to their wooden construction, singers who wished to increase the projection of their sound could direct their voices towards the scene doors (*valvae*). When a theatre is made of solid materials (such as stone) then it should be equipped with the vases as specified. Vitruvius states that there are many examples in Greek cities (Corinth). The expense of the bronze vases is also considered by Vitruvius:

*‘many clever architects who have built theatres in small cities, from the want of others have made use of earthen vases, yielding the proper tones, and have introduced them with considerable advantage’.*  
**Vitruvius, The Ten Books on Architecture, Book V, Dover**

### 4.3 How did the vases sound?

It is likely that the function of the vases would have been to make some sounds louder than others by allowing them (or the air within them) to sympathetically vibrate when certain harmonics ‘hit’ them. So, when a singer performs a perfectly in-tune scale, a number of vases would ring creating a harmonic chord. An artificial reverberation (RT60 time estimated as 0.2–0.5 seconds, *Landels*) containing only those harmonics listed in the vases pitches would be produced in an open-air theatre that would otherwise have none.

There may be another purpose for the vases other than those already mentioned. Some believe the acoustic jars helped singers and those relying on ear for maintaining pitch to keep to proper pitch. As indicated, the resonance of the vases would have given emphasis to important pitches leaving the others silent. If the artificial reverberation concept is difficult to accept, the assisted resonance idea is perhaps a little more attractive.

No definitive answer has been found to the question of authenticity and intent with regards Vitruvian resonating vases. It is known that many of the original bronze vases were later used for other purposes and even melted down. The earthenware vases are obviously more prone to damage making them more unlikely to survive the ravages of time.

We have only limited information as to how large and what shape they were and this information varies depending on which translation you use of the Vitruvian text. As a result, a lot of reasoning and occasional down right guesswork is required in order to begin piecing together the enigma of function and intent. However, we do have much greater knowledge of Helmholtz resonators and bass-traps and a comparison is useful when attempting to predict the shape and size of the Vitruvian vases.

Various suggestions for shape and design are cited in *Grove, Dictionary of Music (Acoustics) 2002*. Particular attention should be paid to neck shaping and proportion.

### 4.4 Helmholtz resonators and bass-traps

There is a clear relationship in terms of function between the Vitruvian vases and Helmholtz resonators and bass-traps. Helmholtz resonance deals with air resonance in a cavity with the name being taken from Hermann von Helmholtz (the 19<sup>th</sup> Century Physicist). The sound created when air is blown across the top of an empty bottle is a much cited example of Helmholtz resonance. In acoustic string instruments, the resonance curve has the Helmholtz resonance as one of its peaks (further peaks can be found from resonances within the physical body of the instrument).

There are two principle types of bass traps (resonating and porous). Resonating absorbers

generally absorb a narrow range of frequencies and porous absorbers absorb sound all the way across audible frequencies. Clearly, examples of the resonating type of bass trap include Helmholtz resonators. Many examples of Helmholtz resonators can be found throughout the world but a particularly fine set of spherical resonators can be seen in the Department of Physics, University of Toronto, Canada.

Whilst a detailed account of Helmholtz resonators and bass-traps is outside the scope of this paper, it is clear many similarities exist between them and Vitruvian vases.

## 5. VIRTUAL RECONSTRUCTIONS

### 5.1 Touching the vases...

We can assume that the word 'touch' as used by Vitruvius means to make the vases (or the air inside them) ring sympathetically when the vibration of a sound source with a particular frequency in its harmonic series comes into contact.

A number of methods for experimentation were attempted including building banks of resonant filters within Max/MSP. Detailed below are methods of using impulse responses and a more 'creative' use of additive synthesis.

### 5.2 Impulse response method

By clapping your hands in a church, you are listening to the church's response to the impulse your palms have made. Commercially available convolution reverb software is available to emulate such responses. What this means is that it is possible to 'sample' an acoustic and use it as a plug-in of your choice. Audioease have developed *Altiverb*<sup>™</sup>, software that allows the user the opportunity of combining a dry input sound with an impulse response created in a real acoustic environment.

From conversations with Stephen Morris (Department of Physics, University of Toronto, Canada) at the Subtle Technologies Conference, Toronto, May 2005, we believe that the material of the vase itself is relatively unimportant. It is the air inside the vase that would resonate and not the physical material of the vase (Vitruvius does state that bronze or 'earthenware' options would work and also suggests that the use of different material is largely down to economic practicalities). Helmholtz had used a variety of materials as resonators, including glass cylinders and tubes. He later asked Koenig to make metal resonators.

Ironically, the closest modern day vases to match the patterns suggested by archaeologists, historians and acousticians (*Brüel 2002*) were found recently in a farm shop close to the author's home! A Greek farmer is importing a variety of vases from

Crete and selling them as garden ornaments, water-features...

By spending some time singing into the vases, it soon became clear that these objects resonated quite effectively at certain frequencies, and that these frequencies could be changed by placing material (sand, water etc.) into the vase to change its' volume. The shape and depth of neck also proved important as can be seen from measurements on Helmholtz resonators.



Figures 4a and 4b

Modern earthenware vase (manufactured in Crete). Approximate dimension are 60cm high with a neck 18cm wide. The close-up of the neck shows a loudspeaker with a 5-inch driver suspended within the vase.

### 5.3 Physical Modelling method

Dr. Richard Polfreman (Music Centre, University of Hertfordshire) has investigated the potential for physical modelling of the Vitruvian vases. Using *Modalys*, he has created an aural and visual representation of a vase that will also provide an impulse response. Initial findings from this research have given strong indications of the effectiveness of functionality. Currently, these are based on a model of a single vase. Potentially, an entire theatre with vases could be modelled to test the relationship

between these vases themselves. This research is in an early stage of development.

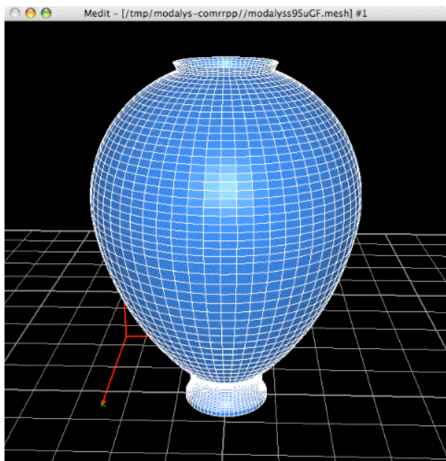


Figure 5

### 5.4 Additive synthesis method

The author began designing software based upon the concepts of Vitruvius in 1999. The experiments began by building a synthesizer using the ratios specified by Vitruvius to explore the types of sound to be generated. A number of assumptions were made as to how the vases would have sounded - a principle assumption being that the harmonics would be largely sinusoidal.

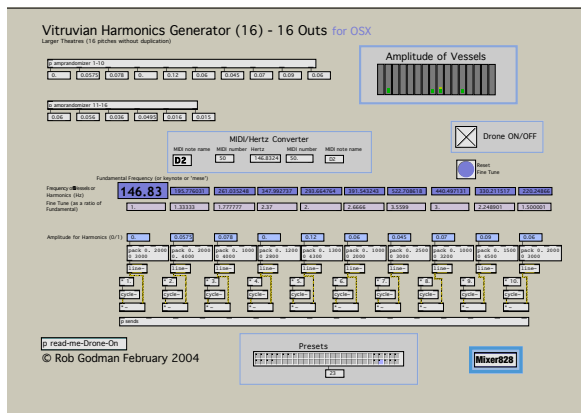


Figure 6 – additive synthesis patch

No attempt was made at modelling the amplitude envelope of the vessel, although it would have been relatively simple to do. This proved to be a very enlightening way to proceed as it made the author address issues of authenticity in the modelling process. Clearly this was an artistic reconstruction based upon the Vitruvian principle where many of the physical constraints (decay time and other naturally occurring acoustic phenomena could be largely ignored as a result of being in the digital domain).

The patch shown is an early additive synthesis patch consisting of sixteen oscillators (ten

shown here). The programme can be used to trigger the oscillators via external sound (using percussive or pitch detection objects, [bonk~] or [fiddle~] for example), which would be close to the original function of the Vitruvian vases. Video input via SoftVNS or Jitter, other sensor input or via a quasi-random process for automatically ‘sounding’ the oscillators are also possible.

Ironically, what began as an experiment produced some very interesting musical results. The quasi-assisted resonance approach has featured in most of the author’s work over the past six years.

## 6. ANALYSIS

A variety of impulse responses were created using the *Altiverb*™ Impulse Response Pre-Processor software. Sinusoidal sweeps gave the best results when a good quality loudspeaker was placed around 150cm from the neck of the vase (attempts were made at placing sound sources directly inside the vase as indicated in the images). The microphone used to record the sweep was also placed in a variety of positions - the most dramatic result being produced when placed several centimeters into the neck of the vase.

The analysis took place within the anechoic chamber at the University of Hertfordshire.

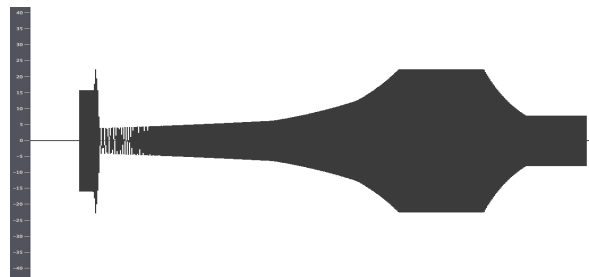


Figure 7 - The sweep used to create the impulse response.



Figure 8

A waveform of a recording of the impulse (sweep). A number of resonant peaks can be seen. The frequencies of these peaks for this vase are as follows (the vase can be ‘transposed’ by changing its volume by placing sand or other solid objects within it):

(Hz)	
683	3130
3913	3211
1070	3518
1407	4956
1790	5035
2150	5627
2465	
2759	

It is likely that there will be many higher harmonics, but these gave an accurate rendition of the resonance of this vase. Interestingly, it is far from obvious what the fundamental of the vase is!

The impulse responses within Altiverb gave interesting results when different sounds were played through them. Speech gave strong resonant results (male voice). Some of my existing synthesized drones were also played back. Obviously, those that contained a high number of frequencies close to those listed above gave strong resonant results.

### 6.1 Physical reconstructions

Early in his career, Per Brüel attempted to duplicate the resonating vase concept by physically building a series of vases to experiment with. None of Vitruvius' original diagrams illustrating the size and shape of the bronze vases survive so Brüel's experimental vases were made of clay in a wine-beaker shape. The depth and diameter of the neck is significant. In depth readings on Helmholtz resonators demonstrates the mathematical reasoning behind these findings. Brüel claims his experiments showed that they enhanced reverberation at the resonant frequency (although the vases were not tested in a real theatre or in an anechoic chamber).

Ideally, a complete set of vases needs to be made. However, the sheer cost of a minimum of ten bronze vases has presumably prevented most researchers from pursuing the project. A combination of all available methods (physical and digital) may provide a truer picture that is realizable commercially, scientifically and artistically.

## 7. THE CONCEPT AS COMPOSITION

### 7.1 Halo for piano and responsive electronics

Receiving its US premiere at the ICMC, New Orleans, 2006, *Halo* uses an additive synthesiser to 'emulate' the Vitruvian resonances, triggered by a microphone detecting transient dynamic changes ([bonk~]). *Halo* was recorded by Philip Mead and the author for the UH Record Label.

### 7.2 inside the eye of silence

#### - a collaboration with Vivienne Spiteri

The following is a programme note by Vivienne Spiteri for *inside the eye of silence*. It demonstrates their preoccupation with the Vitruvian concept and how they pushed the principle away from a purely practical 'problem-solving' idea. By focusing on the resonance of the harpsichord, the piece explores the inner most world of the instrument, removing the effect of time and physical barriers through the use of granular synthesis.

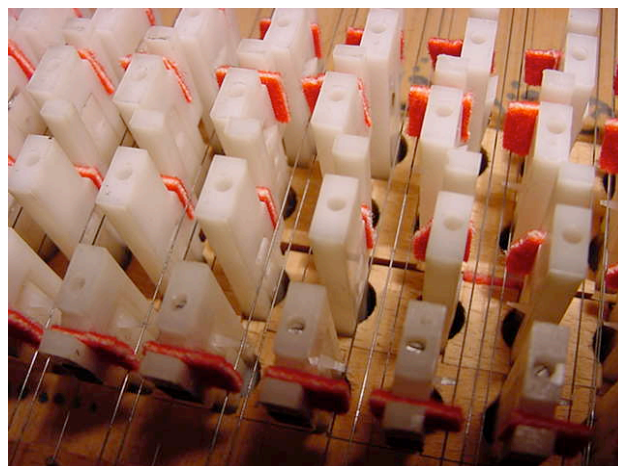


Figure 8 - image from the documentary DVD version of *inside the eye of silence*.

*where does sound stop and silence begin, end,  
sound, begin?*

*one of the harpsichord's best kept secrets lies hidden within her  
chambered spaces between the notes, between those plucked  
strings (the sound of a harpsichord is like two skeletons making  
love on a corrugated iron roof) whose piercing sting obliterates  
all potential revelation of the secret : her resonance juices.*

*to isolate a single sound, to let the time-life of a solitary plucked  
string linger, live and rise through to its natural end, is to reveal  
all : birth, breath, life, death and rebirth. all swell with  
song. skeletons no more this full-bodied dancing sound,  
laughing and rejoicing, these rich spectra liberated, escaped  
from their string prison, these wingéd frequencies, free as air.*

*air  
ah, air  
space  
air-space  
and time*

*where do air, space and time unite?*

*"and time is the space your mind moves through" (Gwendolyn MacEwen :  
"vacuum genesis" from afterworlds 1987-88)*

*sound. sound becoming silence through air-travel, through open  
air, through air within a space. an enclosed space? of time?  
time, ah time. sound's phantom vessel.  
where does it wander? what is its voyage?  
what is its voyage, never lowering anchor?*

*to step inside the eye of silence is to listen deeply, to feel it at  
your ear. for as long as air and time give it wing, sound-in-  
silence-in-sound births and breathes itself, expanding,  
contracting, like the lungs of a whale, huge and light as air.*

*enter vitruvius, ah vitruvius. he who knew the secret of the  
wingéd. his siren-song, embodied in resonating bronze inside  
semi-circular spaces of another place, another time, drew forth,  
beguiled and captured the wild and wandering waves, colouring  
them lively : live, alive, life. long life. longer still. unending*

*enter the spider, weaver of webs, silent siren temptress, vitruvius-  
collaborator inside the eye, along her radii.*

*toronto. chemistry building. hanlan's point. harpsichord as  
siren temptress inside the eye, weaving through space,  
resonating her chambers.*

*listen, dive, fly, let the air wing you  
around  
space*

is time  
is sound is  
silence  
is

infinity's music

© Vivienne Spiteri August 2002

Commissioned by New Adventures in Sound Art for Sign-Waves, *inside the eye of silence* was first shown in a multi-room environment using an octaphonic system at The Chemistry Building, Toronto Island, Canada in August 2002.

## 8. CONCLUSIONS

Vitruvius understands and addresses problems faced by performers and audiences in Roman Theatres. Vase placement is derived from an understanding of acoustics and musical theory of the day. Authenticity and intent are still arguable and we should at some point be brave enough to ask (and potentially answer) a simple question – did the vases as specified by Vitruvius actually do their intended job? There is now a large amount of evidence to support the concept. Other resonating vases have been found throughout history and some are still in use. There is no doubt that Vitruvius was the source for vases used in medieval churches. In Europe there are examples found in St. Clements, Sandwich, Kent, St. Peter Mancroft, Norwich, Fountains Abbey, York, UK and St. Martin, Angers, Bjerresjoe, Sweden. Most of these jars are between 20 cm and 30 cm in length with fundamental frequencies of between 90 to 350 Hz (not far away from the pitches specified by Vitruvius). However, some of these examples of vases used in churches may have been used to *reduce* reverberation and echoes by absorbing resonance (*Landels*). Many were cemented into place and not placed loose as with the Vitruvian examples. So, with these many contradictions, it is hardly surprising that archaeologists are wary of the function of the vases.

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