Towards a New Method for the Evaluation of the Tonal Colouring of the Japanese *koto* using COMSOL Multiphysics.

COMSOL Multiphysics による日本の箏の音色理解への展望

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ABSTRACT

This paper investigates the potential for a multidisciplinary approach using finite element models of COMSOL Multiphysics for the evaluation of the tonal colouring of the Japanese *koto* (13-stringed zither). It uses Ando's classic acoustic studies (1986; 1996) as a benchmark for the analysis of the natural resonant frequencies and design of the sounding body of the *koto*. It reports on the development of the model and initial results of simulations. It concludes that COMSOL Multiphysics and finite element analysis can contribute to a multidisciplinary approach to an investigation of the tonal colouring of the *koto* and that further development of the model is warranted.

INTRODUCTION

Dr Kimi Coaldrake received the performance name Reiku Hirowakyō [麗久博和京] from the Living National Treasure, Nakada Hiroyuki and is a Professor of Koto (sōkyoku kyōjū)[箏曲教授]. She has performed at The National Theatre in Tokyo and is currently Associate Professor of Music at The University of Adelaide, Australia.

The *Koto* (箏): Definition and History

The *koto* is classified as a 13-string plucked zither. A zither has strings stretched the length of the sounding body. The sounding body of the koto is a rectangular box which is 186 cms, by 25 cms by 7 cms. It has the properties of a resonant acoustic box.

The *koto* has its origins on continental Asia as found in instruments in the Shōsōin collection dating from the 8th century. It was brought to Japan when court music (*gagaku*) was introduced from T'ang China in the 8th century although indigenous zithers such as the *wagon* are also known to have existed. The *koto* has been central to traditional musical culture especially in the Edo period (1603-1867).

Historical sources document the construction of *koto* e.g. *Sōkyoku Taiishō* (1772) (Fig. 1). Images of *koto* are also found in Japanese art e.g. *ukiyo-e* woodblock prints (Coaldrake 2012).

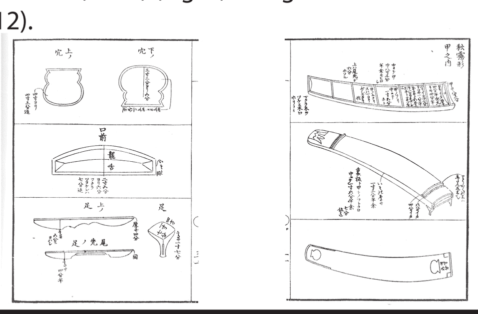


Fig. 1 *Koto* Diagrams from *Sōkyoku Taiishō* (1772)

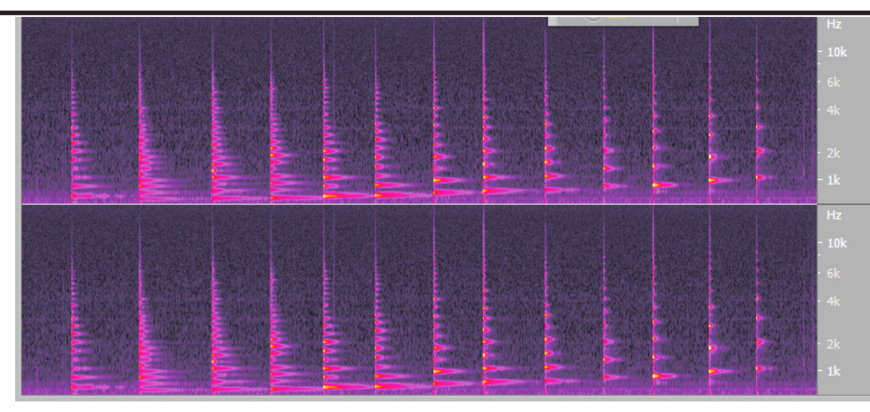


Fig. 2 The frequency spectrum of the 13 notes shows a rich pattern of sound in addition to the expected simple harmonics.

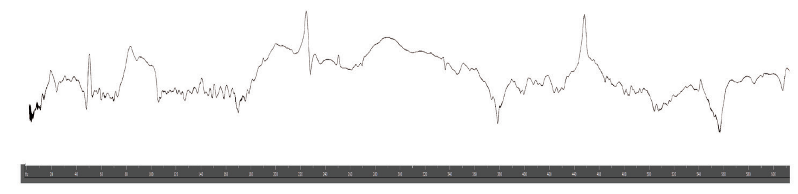


Fig. 3 A single note, A^3, 220 Hz, again shows a rich and complex frequency spectrum whose origin is not understood.

The *Koto*: Its Tonal Colour

Tonal colour (音色), also known as timbre, is a defining characteristic of Japanese music.

The Tale of Genji (*Genji monogatari*) talks about the sabi (侘び) or 'seasoned' qualities of the sound of the *koto*. This reflects the complex overtones of the sound (Figs. 2 and 3) especially when compared with the highly regarded clear, pure tones of Western melodic instruments such as the flute (Kikkawa1984, Galliano 2002).

1. RESEARCH PROBLEM and METHODOLOGY

Research Problem: Can we establish a methodology that provides a quantitative approach to analyze the sounds of the *koto* and helps to create a more refined vocabulary for discussing the tonal colour of the *koto*?
What insights into the behaviour of the instrument can be achieved using this methodology?

Methodology: The methodology developed for this study involves three stages:

1. *Creating a Heuristic Model using Ando (1986)*:The creation of a heuristic model in the COMSOL Multiphysics Acoustic module to examine general concepts and make discoveries about the sound and tonal colouring of the *koto*. The model is informed by knowledge of Japanese musical culture and traditional performance practice. Simulation of the Ando (1986) *koto* and its performance using the model is then undertaken. This stage also acts as a test and calibration of the method.
2. *Creating a Heuristic Model using Coaldrake's koto*: The interpretation of discoveries from Ando (1986) is used to develop a more sophisticated understanding of tonal colouring of a *koto* of known provenance, sound qualities and dimensions.
3. *Refinement of the Model* : Results of Stage 2 highlight points for refining the model and direct attention to key areas for further study.

2. CREATING A HEURISTIC MODEL USING ANDO (1986):TEST and CALIBRATION OF METHOD

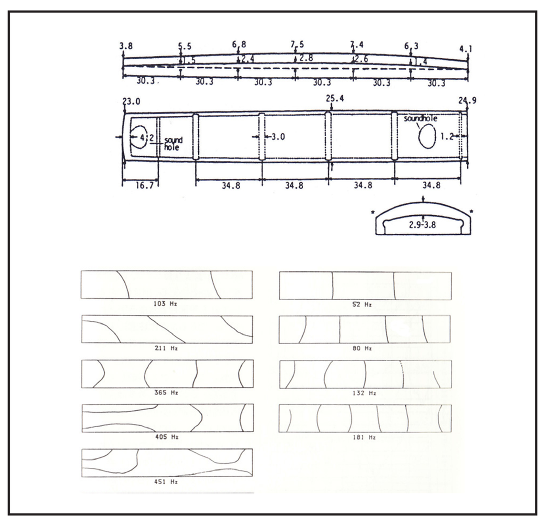


Fig. 2.1 Ando (1986) *koto* and results.

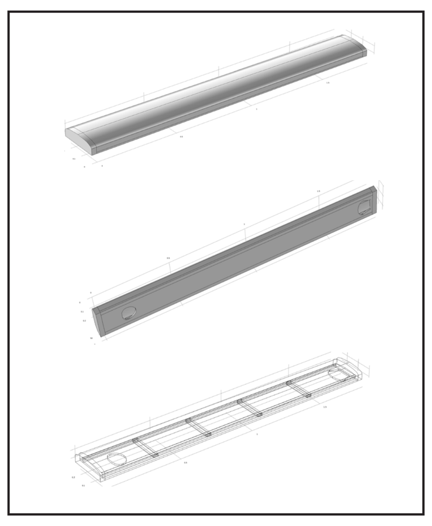


Fig. 2.2 Heuristic block model constructed in COMSOL based on Ando (1986) *koto*.

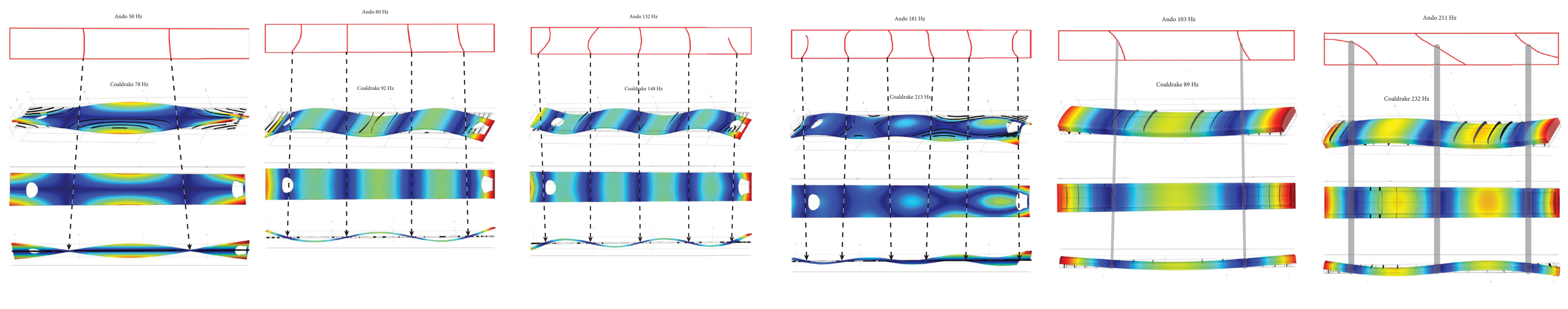


Fig. 2.3 COMSOL Results for Modal Shapes and Frequencies of Ando (1986) *koto* (Original Ando Chladni patterns presented in red)

The available data for *koto* in Ando (1986) consists of hand drawn sketches of structural dimensions and Chladni patterns (Fig 2.1). These are the only available representation of the acoustic properties of the *koto*. They have been subject to review and much speculation (Fletcher and Rossing 2010, Yoshikawa 2010).

A Block Model with COMSOL was constructed using assumptions based on the best interpretation of Ando (1986) and this author's experience with the instrument (Fig 2.2).
Using the COMSOL Block model, we were able to reproduce and identify six of the ten Chladni patterns obtained by Ando (Fig. 2.3). Provisional matches were investigated, but we were less confident in assigning our eigenfrequencies and modal shapes to those of Ando, noting that these discrepancies could in all probability be attributed to the advances with technology over the intervening 25 years.
This convinced us that the methodology could work and shed light into tonal colouring. We therefore proceeded to the next stage.

3. CREATING A HEURISTIC MODEL USING COALDRAKE'S *KOTO* :THE WOOD and ITS PROPERTIES

Fig. 3.1 A core of wood was removed from the side of the *koto*.

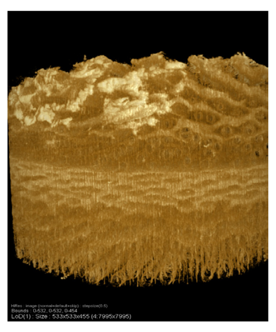


Fig. 3.2 CAT scan of the wood showing the complex layering.

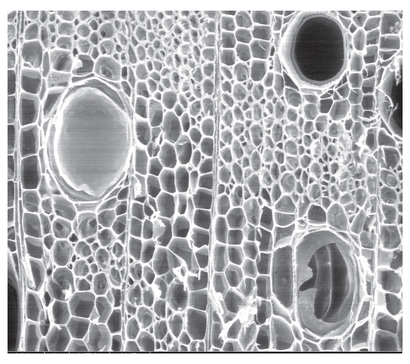


Fig. 3.3 Scanning Electron Microscope (SEM) view of the wood, demonstrating its highly anisotropic nature.

0.2207*e*9	0.1260*e*9	0.1563*e*9	0	0	0
0.1260*e*9	0.5115*e*9	0.2376*e*9	0	0	0
0.1562*e*9	0.2376*e*9	8.5605*e*9	0	0	0
0	0	0	0.8192*e*9	0	0
0	0	0	0	0.6491*e*9	0
0	0	0	0	0	0.0680*e*9

Fig 3.4 Provisional Anisotropic Elasticity Matrix for Paulownia Wood (Voigt notation).

The *Koto*: Physical Properties

The sounding box of the *koto* is made of paulownia (*kiri*) (桐). It is indigenous to East Asia (Akyildiz and Kol 2010). Paulownia is used traditionally in Japan for storage boxes and is flame retardant (Li and Oda 2007). To gain insight into this unusual wood, a sample core was professionally extracted by the Director of the South Australian Woodcarving Academy from a practice instrument (Fig. 3.1) and taken to The University of Adelaide's Microscopy Centre where it was subjected to an array of modern scanning instruments to observe the microstructure (Figs. 3.2 and 3.3).

Paulownia wood is believed to be both anisotropic and viscoelastic. In the present study, the wood was modelled as an elastic solid using an anisotropic elasticity matrix. (Fig. 3.4). Future studies will attempt to incorporate aspects of viscoelasticity.

4. CREATING A HEURISTIC MODEL USING COALDRAKE'S *KOTO*

Fig. 4.1 The heuristic model of *koto* built within COMSOL was "blocky", but still useful. Meshing shown.

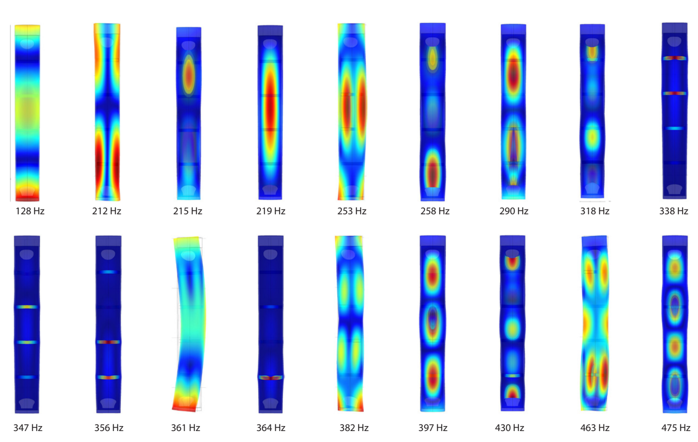


Fig. 4.2 Some Results

Using the model as an experimental tool.

Q. How significant is wood grain orientation?
A. The grain orientation is very significant (see Fig.4.3).

Q. What is effect of making the instrument of a different length?
A. The frequencies are significantly lowered as the instrument is made longer (Fig.4.4). This corresponds to known practice to make a bass (17-string) koto.

Q. Does the curvature of the instrument really make a difference?
A. By extruding the koto body along a defined curve it was possible to make a normally curved instrument, a hypercurved and a hypocurved version. The eigenfrequencies were found to be significantly altered for some parts of the frequency range and not for others. The significance of this is not known at present. It does imply that the curve is not purely ornamental as some suggest but does makes a difference. This work is not shown here, but is being extended in future models.

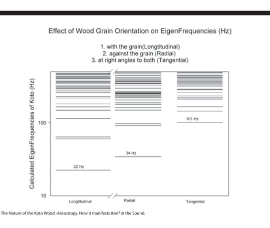


Fig. 4.3 Wood grain orientation.

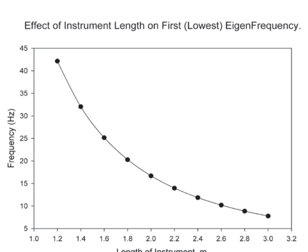


Fig. 4.4 Effect of instrument length. The longer the instrument, the lower the frequencies in line with known practice.

Q. What parts of the instruments contribute which natural resonances? Would we be able to make changes here?
A. It proved possible to break down the model into its component parts and examine where many of the resonances originated (Fig. 4.5). This will become an important part of the work in the next stage.

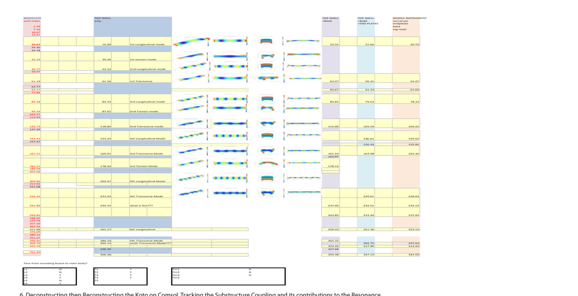


Fig. 4.5 Resonance of Component Parts

5.COALDRAKE'S *KOTO*:ACOUSTIC COUPLING WITH AIR

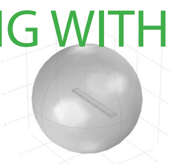


Fig. 5.1 *Koto* in a Sphere of Air

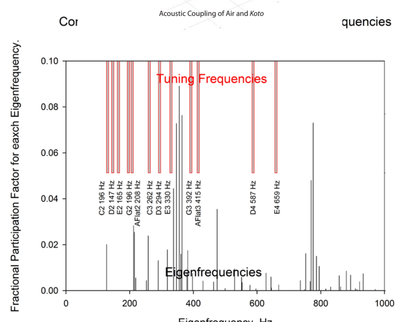


Fig. 5.2 Comparison of Eigenfrequencies and Tuning Frequencies

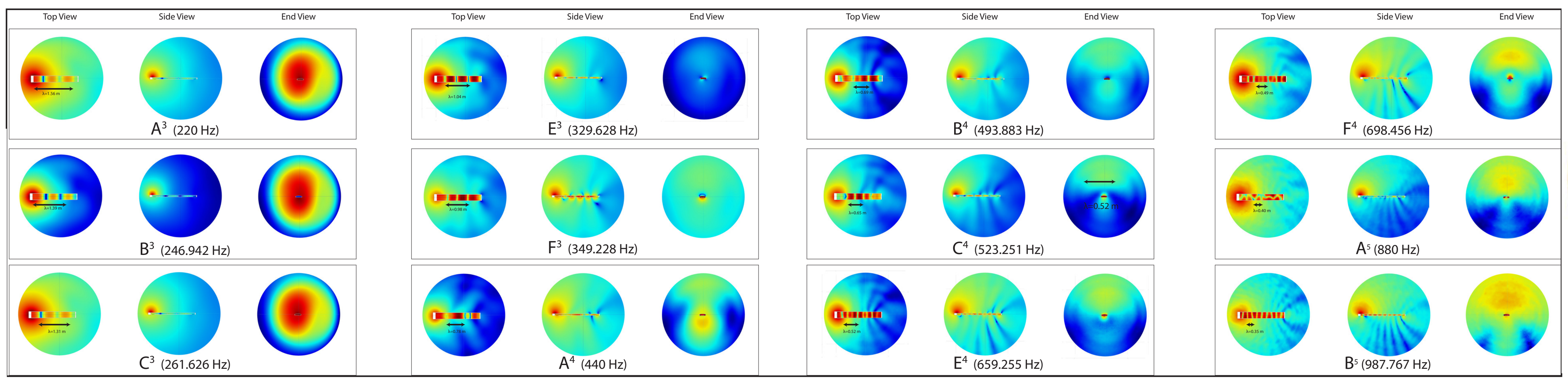
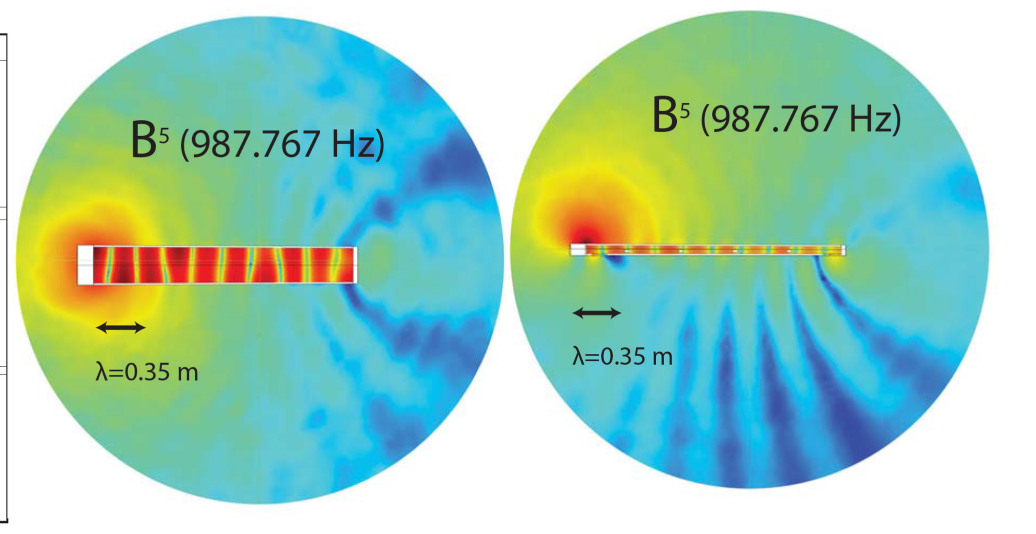


Fig. 5.3 The 12 frequencies of the standard *koto* tuning viewed in each of three dimensions (top, side and end)

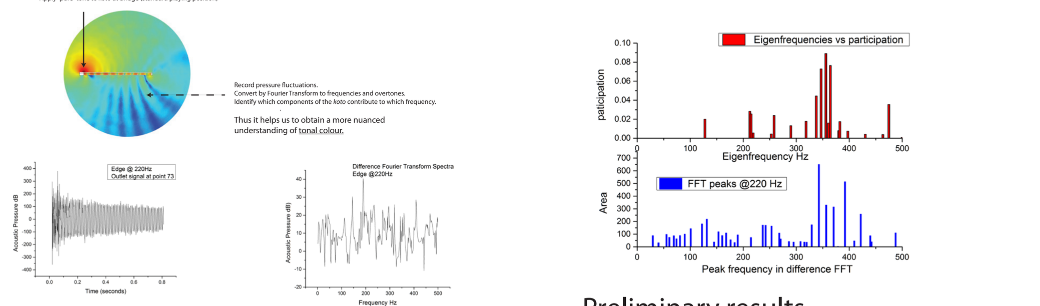


Figs. 5.4a and 5.4b Marked banding at high frequencies

The *koto* is placed in a sphere of air (Fig. 5.1) and a point power source (10^{-7} W) is then played for each of the 12 frequencies of the standard *hirajōshi* (平調子) tuning at a point that approximates where the performer plucks the string. The standard tuning results are compared with the eigenfrequencies of the instrument (Fig. 5.2). It shows that the tuning frequencies do not correspond with the eigenfrequencies. The 12 pitches of the standard tuning are simulated and top, side and end views are compared. The wave length (λ) is included in each diagram. (Fig. 5.3). The results highlight the intense activity taking place within the resonant cavity of the instrument with standing wave-like formations whose spacing varies with the wave length of the frequency in air. At higher frequencies very marked banding is observed (Fig. 5.4a and 5.4b).

6. REFINEMENT 1

THE NEXT STAGE: *Transient studies*. A pure note (220 Hz) is applied at the bridge, its inlet acoustic pressure measured at 0.1 ms intervals. The acoustic pressure (dB) in the air at 0.5 m below the instrument is also recorded. Its Fourier transform is subtracted from the inlet to yield a difference spectrum to analyze what the *koto* body does to a pure note. "Strings" are also being added.



Preliminary results

REFINEMENT 2

THE NEXT STAGE: *Refined model*. Development of an accurate "organic" *koto* model (based on x-ray of author's koto), reconstructed as "lofts" (cross-sections) in Autodesk 3DSMax, imported into Autodesk Inventor then "LiveLink"-ed into Comsol. Add more strings. WAV files output, Perception of listener. Historical reconstructions. New designs.

CONCLUSIONS

1. COMSOL Multiphysics and finite element analysis can contribute to a multidisciplinary approach to the investigation of the tonal colouring of the *koto* and its musical characteristics.

2. Further development of the model is warranted.

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