Proceedings of the Institute of Acoustics

SENSOR GRID DESIGN FOR HIGH RESOLUTION 3D ACOUSTIC MEASUREMENTS OF MUSICAL INSTRUMENTS

D Carugo Faculty of Technology, Design and Environment, Oxford Brookes University
K Hayatleh Faculty of Technology, Design and Environment, Oxford Brookes University
FJ Lidgey Faculty of Technology, Design and Environment, Oxford Brookes University
D Sharp School of Engineering and Innovation, The Open University.

1 INTRODUCTION

The mechanics and acoustics of musical instruments have been studied for centuries[1] and many aspects of sound production are well understood. Much of the recent research work in this area involves mechanical actuation of instruments in order to measure their acoustic output. The repeatability afforded by this approach is valuable as musicians are unlikely to be able to sound a note with the same consistency as with mechanical actuation[2]. However, this approach often does not take into consideration the presence of the musician on the acoustical behaviour of the instrument, particularly with regard to the acoustic radiation pattern in 3D space. If an instrument is mechanically actuated the measurement can be repeated many times in different directions to build up a detailed picture of the acoustic output in all directions. One approach might be to have a person present while the instrument is being mechanically actuated – but this would be tiresome and tedious for the person, as the measurement mic is moved to new positions and the measurement repeated as required.

Another approach is to have the musician present and sounding the note from the instrument themselves. The issue with this approach is that because of the musician's (unintentional) lack of consistency when sounding notes, the measurement of the sound radiation pattern cannot be done by measuring one position at a time – it must be done in all directions simultaneously[3]. This requires a sensor array consisting of a number of measurement microphones placed at the various positions from which the sound radiation pattern is to be measured. This paper, reporting some early results from a PhD research project, is concerned with the design of a sensor array which gives reasonable spatial resolution to 3D acoustic measurements of musical instruments (with the musician present and sounding the instrument) and presents some results taken from a small part of the sensor array in order to demonstrate the benefits of this approach.

This research essentially comes from the music recording engineer's perspective for enquiry – it is often useful to know how the sound of the instrument will change depending on where the listener or the recording microphone is placed in relation to the instrument in order to both optimize the recording process or to place microphones during recording for particular sonic effect, in order to accentuate certain timbral characteristics of the instrument being recorded. However, there are additional benefits to this work: having a 3D acoustic measurement system of sufficient spatial resolution would allow us to both verify or replicate existing data for known instruments which have been previously measured (for example [4,5]) , and also to generate novel data from instruments for which no data set or 3D acoustic measurement currently exists.

2 CURRENT DATA AND DATA SETS

The idea of taking 3-dimensional acoustic measurements from musical instruments is not in itself new – Jurgen Meyer's 'Acoustics and the Performance of Music'[4] from the 1960s includes basic directional plots for various frequency ranges for a variety of instruments, and also includes some frequency-amplitude response graphs for the sound radiating from different directions from the instruments. Work by Cook and Trueman[6] in 1998 used a small number of microphones at the vertices of an icosahedron to measure the radiation in all directions simultaneously, but with low spatial resolution. The issue with these data is that of resolution; and even studies done more recently (such as[5,7]) have been done with relatively few microphone sensors, which may lead to some high frequency inaccuracy in the measurements, where the short wavelengths are smaller than the spacing between the sensors.

While the frequency content of the radiated sound from any angle from an instrument can be interpolated from adjacent measured sensor data, a larger number of sensors will yield better high frequency interpolation. A larger number of sensors also allows a larger radius to the sensor array while maintaining small angular distance between sensors, and so can be used to measure the performance of larger instruments while maintaining a reasonable angular resolution.
Although much of the previous work in this area has yielded a good understanding of the acoustic radiation patterns of various instruments, the need for further measurements is threefold: to have data with better resolution which can confirm and verify existing data sets; to attain new understanding by measuring instruments for which no data set currently exists; and, to develop averages of typical data sets for instrument ‘types’ for example typical violin data, typical guitar data, etc.

3 PROJECT OVERVIEW

3.1 Project Introduction

This work is based upon a spherical microphone sensor array designed with a 2m radius which is to be placed around the instrument being analysed, with the instrument placed at the centre of the sphere. As the intention is to capture the data while a musician is sounding the instrument, a fully spherical radiation pattern in an anechoic chamber may not actually be optimal: in the real world, the musician will generally be playing on a floor, so taking data points from directly under the musician is not particularly relevant and some reflection from the floor may be appropriate.

3.2 Design of the Data Capture System

In order to capture the data from a large number of microphone sensors, a data capture system has been designed using multiple hard disk recorders, capable of 120 channels of simultaneous recording. These are sample-synchronised using an external word clock which also synchronises the analogue to digital convertors, one for each microphone. After pre-amplification the microphone sensor signals are converted to a digital signal, and sent to the hard disk recorders via optic fibres, each of which carries 8 channels to the hard disk recorder array.

3.3 Microphone Sensor Developments

A number of options for microphone sensors have been tested during this research project. While a custom designed system using B&K microphone sensors[8] or even the Sennheiser 4211 microphone sensor[9] could be used, it was originally considered to be more cost effective to design the microphone system specifically for this project. As the microphone preamplifiers are units which supply +48Volt dc biasing, the miniature capsules chosen for this project needed a much lower biasing voltage – so a circuit was designed which would allow the electret capacitor capsule to get the correct bias voltage derived from the +48Volt supply. The original design required that the microphone capsule and the biasing circuit should fit inside an industry-standard XLR connector shell, in order to be connected to the preamplifiers using readily available cables. This requirement resulted in a miniature design, using minimal components, which after some testing resulted in an acceptable response within the audio range as shown in Figure 1.

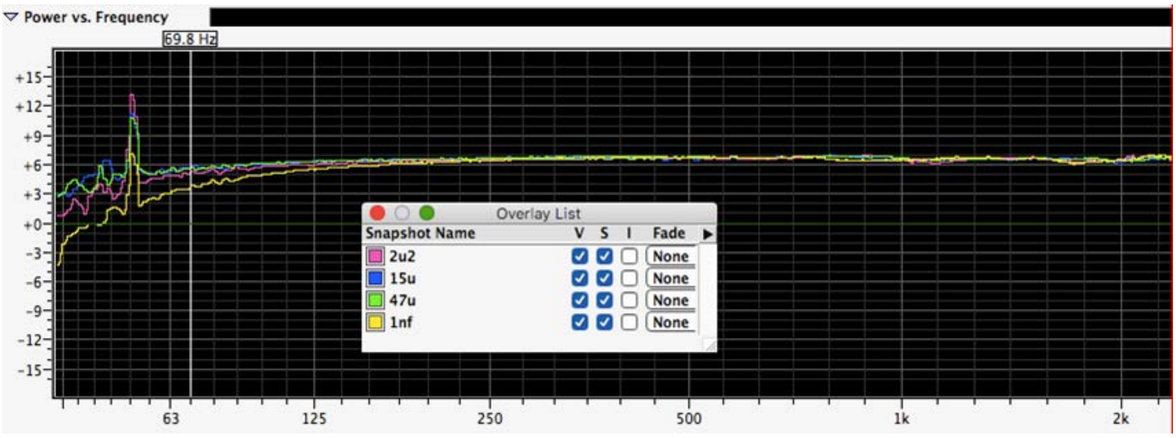


Figure 1. Test results of various bias circuit capacitor values showing frequency response.

However, although the design and testing process was successful (the 50Hz spike shown in Fig.1. is mains frequency interference due to the test capsule not being shielded), and resulted in a very cost effective solution, the decision was taken to use commercially available microphones to expedite progress, due to the inordinate amount of time it would take to assemble the large number of required microphones by hand.

3.4 Microphone Sensor Array Grid Spacing

The previously available literature in many cases shows sensor arrays with varying numbers of sensors – larger diameter arrays have more sensors in order to keep the angular / spatial resolution at a usable level. This project is based around a design which uses a higher number of sensors, based around an icosahedron which has additional sensors placed between the vertices, but at the same radial distance from the origin. Each edge is divided into 4 – this is sometimes known as a ‘4V’ geodesic sphere.

4 SENSOR GRID DESIGN

4.1 Prior Designs

Various spherical sensor arrays have been described previously, including by Zotter et al[10], Patynen and Lokki[7], Behler, Pollow, and Vorlander[5], and while good results have been obtained, it can be seen that these arrays have relatively low spatial density of the sensors, and as such there is the possibility that at high frequencies, some radiation lobes may have been missed, if the lobe passes between sensor positions. This cannot be recovered using interpolation, as the data for these high frequencies (with correspondingly short wavelengths, and thus narrow lobes) would not be captured in the first instance.

Other work by Hohl and Zotter[11] describes a 64 channel sensor array, which has a 2.7m diameter. There is still the possibility with this number of sensors that high frequency directivity lobes from the instrument can be missed if they radiate through the gaps between the microphone sensors.

4.2 Icosahedron-based 4-frequency geodesic array

This project uses an array design based on a 4-frequency icosahedral geodesic sphere – the original triangle edges of the icosahedron are divided into 4, and a set of 16 new triangles is formed from these sub-divisions of the original triangles (Figure 2.a). The vertices are then projected onto the sphere that has the same radius as the original icosahedron vertices to give the positions for the vertices of the 4-freqency icosahedron based geodesic grid (Figure 2.b).

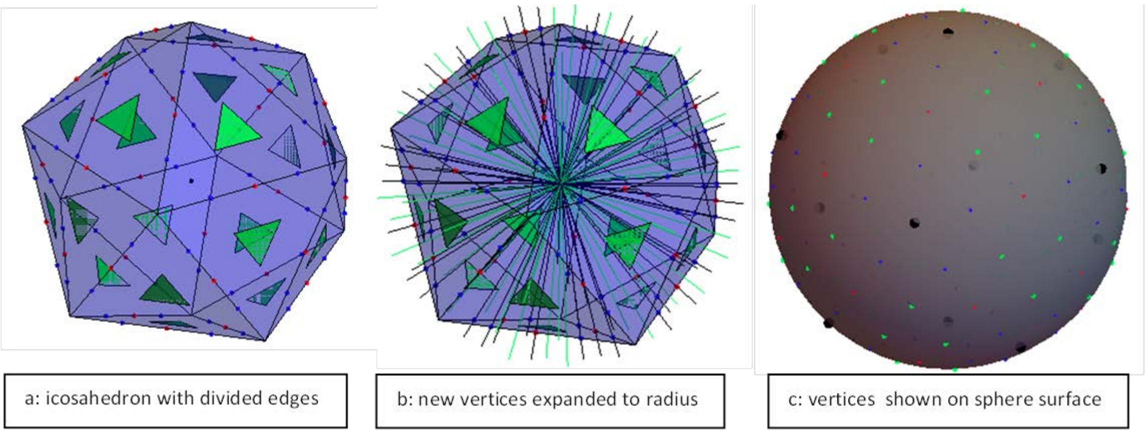


Figure 2. Icosahedron expanded to a 4-frequency geodesic sphere.

This gives a ‘4V’ geodesic sphere with 162 vertex points, as seen in Figure 2c. These vertices are the positions of the microphone sensors in this array, with the exception that some of the vertex points at the bottom of the sphere (what could be described as the ‘south pole’ of the sphere) will not be measured, as these points would be considered to be ‘under the ground’, and as the aim of this project is to measurement the instrument as sounded by a musician playing the instrument, these data points would not be relevant.

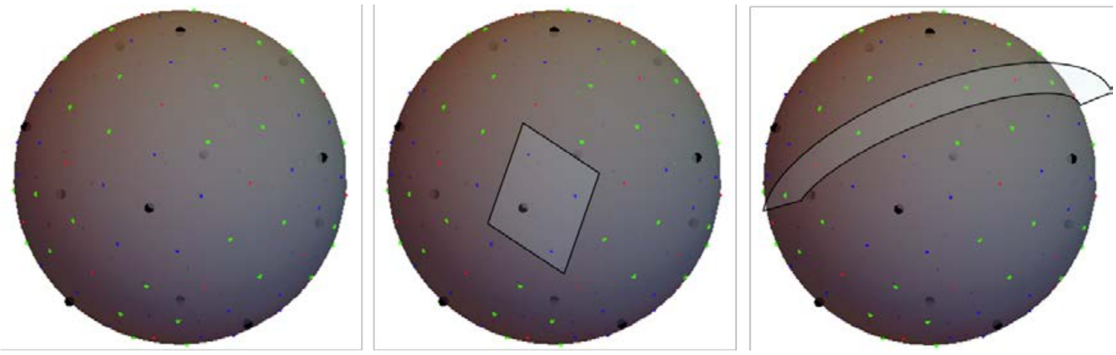
This sensor array design, using 120 data points out of the 162 available vertices on the 4V geodesic sphere, gives an inter-sensor angle or approximately 16 degrees. This will vary slightly as the vertex points are not perfectly evenly distributed on the surface of the sphere, but the variations are small with respect to the wavelengths of sound that are being measured. This design which uses a significantly larger number of data points on the sensor array should yield better high frequency data than prior studies, and thus should yield lower errors in interpolation between data points at high frequency, where the closer spacing of sensors in this array gives it a better chance of capturing narrow high frequency radiation lobes emanating from the instrument.

The distance between each sensor varies slightly due to the grid geometry (the difference is approximately ±9%). The radius of the sphere does not change the direction of each vertex, and thus the angle of each sensor. A sphere radius of 2m (giving a 4m wide sphere, large enough for most instruments) would give a maximum inter-sensor spacing of approximately 0.56m and a 1m radius sphere would have a maximum inter-sensor spacing of approximately 0.28m.

Athough the 4-frequency geodesic surface projection does not give perfect distribution of the sensors at the vertices, the spatial resolution performance is limited by the maximum distance and angle between sensors. Despite this, the 4-V design still yields a high spatial resolution compared to many of the sensor arrays used in these types of studies previously.

4.3 Data From Small Grid Section Tests

At the time of writing, the full sensor grid is under construction, but the spatial resolution has been tested using smaller segments of the sensor array. This includes 2 segments which were in a ‘diamond’ shape on the surface of the sphere, and in an ‘arc’ shape on the surface of the sphere, as shown in Figure 3.



Full array on sphere

Diamond shaped segment

Arc shaped segment

Figure 3. Array points and test segments on the surface of the sphere.

These tests were made at a 1m radius with angular spacing corresponding to the positions illustrated in Figure 3; the diamond-shaped segment and the arc-shaped segment.

4.3.1 Diamond shaped segment results

The test measurement involved a musician sounding an open A string on a small body steel strung acoustic guitar. The microphones were numbered as shown in Figure.4. The results of the frequency response analysis are shown in Figure.5. Although the responses look similar, there are subtle audible differences in the recorded samples, reflecting how close the microphone sensors were placed for the test.

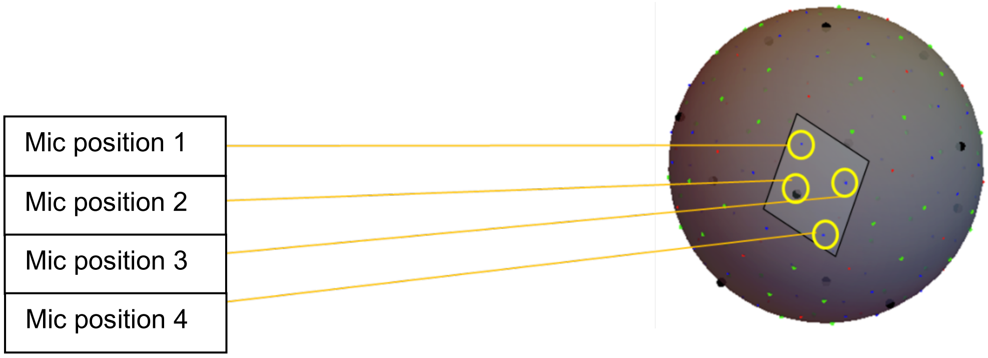


Figure 4. Microphone sensor positions in the ‘diamond shaped’ test.

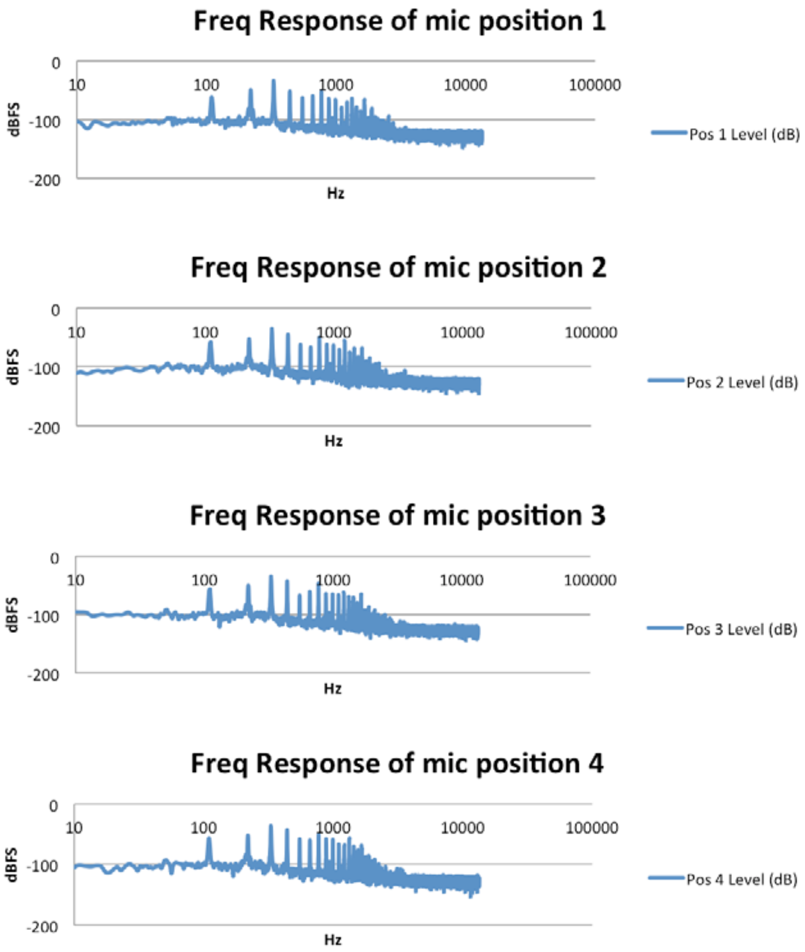


Figure 5. Frequency analyses of the test recording at different microphone positions

4.3.2 Arc shaped segment results

The test measurement for the arc section also involved the musician sounding an open A string on a small body steel strung acoustic guitar. The mic sensor positions were as shown in Fig. 6.
This gave a set of results whose frequency analysis can be seen in Fig.7. In this case, there is a noticeable difference in the high frequency response between positions 1 and 4 – which were the furthest sensor positions apart. This difference was also audible in the test recordings.

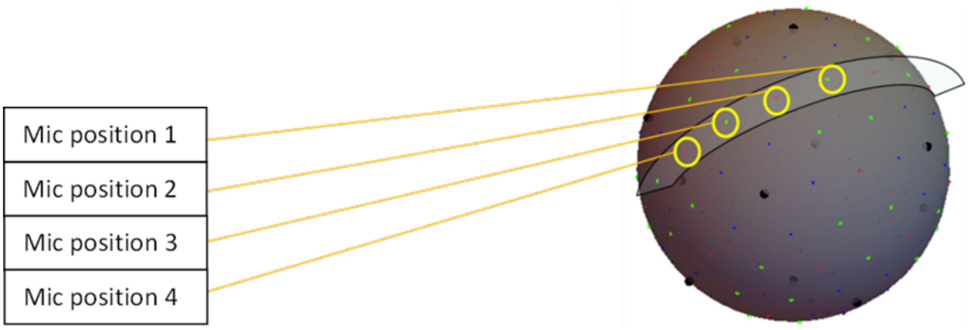


Figure 6. Microphone sensor positions in the arc segment of the sample test.

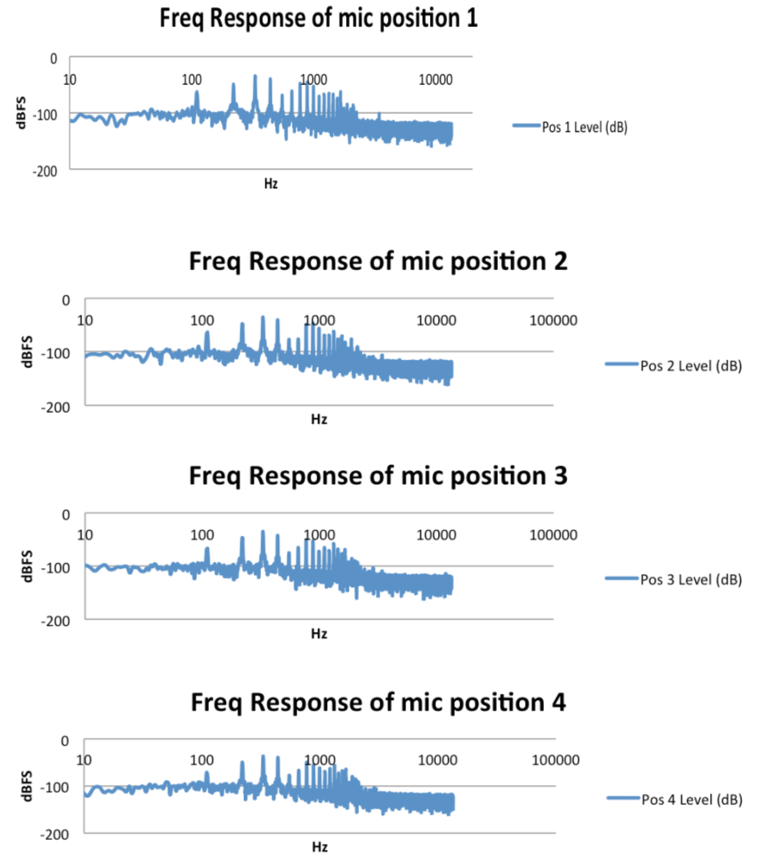


Figure 7. Frequency analysis of the test recordings in the arc segment at different positions.

5 APPLICATIONS AND FUTURE WORK

This work has potential applications in a number of areas. The data gathered can be compared to existing data sets for various instruments for verification and for comparing measurement techniques. This might also include determining if the actuated measurements without the musician present yield similar results to when the instrument is measured with the musician in place. Sound radiation data can also be measured for novel instruments, for which no data set currently exists within the literature; for example an analysis of different types of bagpipes may be useful to musicians, recordists, and even the instrument makers.

The ability to make multiple data sets of a number of different instruments of the same ‘type’ can offer instrument type attributes; for example a number of violins or a number of guitars could be analysed in order to find typical radiation characteristics, such as a particular radiation pattern being typical of many nylon string guitars, or finding that many violins share a particular sound radiation behaviour. These data sets could even be averaged out to offer an ‘expected’ or ‘common’ radiation pattern for this type of instrument.

Having data sets of one instrument will allow us to interpolate the data from the measured positions to infer the probable radiation pattern at any intermediate position, as shown by Nachbar et al[12], although for some purposes a weighted straight line interpolation on the FFT frequency points would be adequate. This will be accurate at low frequencies below the sensor spacing frequency limit, but this also depends on the radial distance of the measurement ‘sphere’. Transfer functions could then be generated between either measured sensor points or interpolated points to demonstrate the differences in sound quality or timbre (expressed as frequency-amplitude response graphs) which could be expected from a listener in these directions.

6 CONCLUSION

A high spatial density sensor geometry has been proposed and some sample measurements on the grid surface have been presented here. The small number of sensor points tested is representative of adjacent sensor positions on a 1m radius grid and demonstrate a small but measurable (and under optimal listening conditions, audible) change in the response of the instrument tested at each sensor location. Although the full sensor array grid is still under construction at the time of writing, the initial tests presented in this paper support the array grid design and establish a basis for ongoing work.

7 REFERENCES

1. A.H. Benade., Horns, Strings and Harmony. Dover Publications. New York (1992).
2. D.M. Campbell. ‘Non-linear dynamics of musical reed and brass wind instruments.’ In Contemporary Physics vol 40(6) pp 415-431. (1999).
3. D. Carugo et al., ‘Play That Funky Music: Making 3D acoustic measurements under performance conditions’. Proceedings of the Institute of Acoustics Vol37 Pt.2 (2015).
4. J. Meyer,. Acoustics and the Performance of Music, Springer, New York. (2009).
5. G.K. Behler, M. Pollow, M. Vorlander., Measurements of musical instruments with surrounding spherical arrays. Proceedings of the Acoustics 2012 Nantes Conference. (2012).
6. P.R. Cook, D. Trueman., A Database of Measured Musical Instrument Body Radiation Impulse Responses , and Computer Applications for Exploring and Utilizing the Measured Filter Functions. Proceedings of the International Symposium on Musical Acoustics 1998 (1998).
7. J.Pätynen, T. Lokki., ‘Directivities of symphony orchestra instruments’, Acta Acustica united with Acustica, vol. 96, no. 1, pp. 138-176, January/February 2010. (2010).
8. https://www.bksv.com/en/products/transducers/acoustic/ Accessed March 2019.
9. https://www.acoustic-camera.com/en/products/microphone-arrays.html/ Accessed March 2019.
10. F. Zotter, A. Sontacchi, M. Noisternig, R. Höldrich,. ‘Capturing the radiation characteristics of the Bonang Barung’. In Proceedings of the 3rd congress of the Alps Adria Acoustics Association, September 2007, Graz, Austria. (2007).
11. F. Hohl, F. Zotter., ‘Similarity of musical instrument radiation-patterns in pitch and partial’. Fortschritte der Akustik, DAGA, Berlin, 2010 (2010).
12. Nachbar, C., Nistelberger, G., Zotter, F. (2010) “Listening to the direct sound of musical instruments in freely adjustable surrounding directions” Proceedings of the 2nd International Symposium on Ambisonics and Spherical Acoustics. Paris 2010. (2010).