Final Report

Research Project to Reduce Sound Levels in the Pit

Royal Opera House Covent Garden Foundation/LSBU Studentship Agreement

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Executive Summary

London South Bank University and the Royal Opera House Covent Garden Foundation signed a joint agreement to fund a 3-year studentship signed on 17th December 2017. The aim of this project was to reduce the sound level in the orchestra pit. Mr Eric Ballestero was contracted to undertake the necessary research as part of his PhD programme.

A previously commissioned feasibility study to reduce the sound level in the pit had shown that traditional noise control approaches were both impractical and extremely expensive whilst having a minimal effect, 2 dBA. As such a new novel approach had to be found capable of delivering the ambition of the project.

New cutting-edge wave-based mathematical modelling, a collaboration with Edinburgh University, was used to demonstrate that the solution to the problem was to rapidly redistribute the music. This would allow the sound to leave the pit as soon as possible thus mitigating high pressure hotspots. An additional benefit of this solution would be that more of the music would reach the audience. An existing solution was found, a broadband quadratic residue diffuser. However, there was no space in the pit to retrofit such a solution due to the depth of the diffusers. The depth being necessary to accommodate the wide range of musical notes that need to be diffused.

To solve the diffuser depth issue an entirely new type of material was created, a metamaterial. The world's first acoustic metamaterial was designed using an optimised mathematical structure to create an ultra-thin diffuser. The ultra-thin diffuser was then prototyped using 3-D printing technology to create a 30cm by 30 cm panel. Acoustic tests were undertaken, a collaboration with Le Mans University, to verify the performance characteristics of the ultra-thin diffuser. This verification confirmed that strategically positioned ultra-thin metadiffusers would redistribute a wide range of musical notes in the orchestra pit.

The final step in the programme of research was to calculate how much and where to position the panels. The Edinburgh University model was used to calculate that 20m^2 of the 2 cm deep panels are required to rebalance the acoustic and mitigate against the hotspots. The panels would need to be installed on all the pit walls and beneath the overhang.

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1. Introduction

This document presents the research undertaken to provide a solution to reduce the sound level in the orchestra pit at the Royal Opera House.

The research focused on two aspects: firstly, identifying the issue in the pit and simulating a solution; and secondly, to create a solution which is compatible with the operation of the pit.

2. About Us

The Acoustics Group has a team with more than 40 years of experience in architectural acoustics and computer modelling. Between us we have helped create acoustic solutions for the Royal Academy of Music, Henry Wood Hall, and the London Philharmonic Orchestra. We offer education and training to the latest standards and guidance to help manage risk from excessive sound. We also offer hearing acuity testing using the newly proposed Otoacoustic Emission method

3. Background Information on the Project

Through the Acoustics Group work with the Royal Academy of Music we were approached in early 2017 by John Bernays of the Royal Opera House. Mr Bernays was tasked by the Royal Opera House to develop a team to develop solutions that would benefit the musicians. The team was named the Sound and Performance Study Group and considered of representatives from medicine, academia, vocal specialists, audiology, and the BBC. This was a direct response by the Royal Opera House to the High Court case, Goldscheider vs Royal Opera House. This case concerned hearing damage due to acoustic shock. The damage occurring during a 2012 rehearsal in the orchestra pit

A previously commissioned feasibility study to reduce the sound level in the pit had shown that traditional noise control approaches were both impractical and extremely expensive whilst having a minimal effect, 2 dBA. As such a new novel approach had to be found capable of delivering the ambition of the project.

On the 17th December 2017, the Royal Opera House Covent Garden Foundation agreed to co-fund a London South Bank University studentship with the aim to reduce the sound level in the pit. Mr Eric Ballestero was contracted to undertake the necessary research as part of his 3-year PhD programme.

4. Management of the Project

A team was immediately formed to assist with the project to progress the research due to the urgency of the issue. The team chaired by the Director of Human Resources met on a quarterly basis to be informed of progress, facilitate the research, and to steer the direction of the work. This team did authorise additional funding when need arose. Firstly, for the purchase of 3-D ink to allow the building of the prototypes, £2000. Secondly, for assistance with advanced computer simulations using experimental room acoustic software, £6,000.

5. Results of the Project

The project had positive results for the two main objectives to find a practical solution to this very challenging problem. First to predict how the sound behaves in the orchestra pit and what approach would optimally redistribute the music to mitigate acoustic hotspots. The second objective was to develop a practical solution which would be compatible with the operation of the orchestra and orchestra pit.

5.1 Room Acoustics Computer Simulations

To understand how sound behaves in the orchestra pit a completely new cutting-edge experimental wave-based room acoustic simulations had to be deployed. Edinburgh University assisted with the mathematical modelling which allowed a rapid and deep understanding of the acoustic in the pit.

The software identifiable acoustic hotspots in the pit, as do all orchestra pits. These hotspots occurred in specific locations and at specific frequencies. To mitigate this issue with the pit possible solutions were modelled. It was found that acoustic diffusers would redistribute the sound so that hotspots are minimised. This would have the additional advantage of allowing the music to leave the pit more rapidly. This should provide the audience with an improved musical experience.

Computer simulations were run to optimise the location and number of diffusers necessary to redistribute the sound in the pit. The Edinburgh University model was used to calculate that a total of $20m^2$ of diffusers would need to be installed on all the pit walls and beneath the overhang to mitigate the build-up of sound that creates the acoustic hotspots.

5.2 The Solution- Metadiffusers

An existing 1970's acoustic solution was found, a broadband quadratic residue diffuser. However, there was no space in the pit to retrofit such a solution due to the depth of the diffusers, 20 cm. The depth being necessary to accommodate the wide range of musical notes that need to be diffused to redistribute the sound. The maximum possible space available in the pit was deemed by operation staff to be 10 cm.

To solve the diffuser depth issue an entirely new type of material was created, a metamaterial. The concept of an acoustic metamaterial was only speculated upon in July 2017. The theory was developed to simulate a practical acoustic metamaterial, a metadiffuser. Then in February 2019 the world's first ultra-thin metadiffuser was designed and built using 3-D printing technology, a 30 cm by 35 cm panel. The metadiffuser was only a proof of concept and had a limited frequency range, 1500-3000 Hz. This metamaterial was immediately taken to the University of Le Mans for laboratory performance testing. The tests results showed excellent agreement between the computer simulations of the metadiffuser and the actual panel in terms of frequency response and the redistribution of the sound. The key advantage was that the panel was just 2 cm deep and hence could be installed on the walls and overhang in the orchestra pit. This compared to the original quadratic residue diffuser which was 14 cm deep. The metamaterial panel is now in a public science exhibition in Portugal.

Computer simulations were than run to widen the frequency response of the metadiffuser. The optimisation allowing the ultra-thin panel to be effective across a wide range of frequencies matching those played by the orchestra.

At this point the COVID-19 outbreak occurred stopping the development of the final panel.

6. Summary

The research programme produced a proven practical solution that was only a theoretical concept at the start of the project. The assistance of Edinburgh and Le Mans University is greatly acknowledged. The final steps of the project were planned but not implemented due to the COVID-19 pandemic.

The final three steps of the project are outlined. Firstly, a survey of the orchestral musicians to assess if they would accept the change to their environment using virtual reality technology and computer simulations. The second, was to manufacture the 20m^2 of ultra-thin metadiffusers according to the computer simulated designs. The third and final step was to install each panel in the optimise location on the walls and overhang of the pit in accordance to the room acoustics computer simulations used in the VR survey.

Finally, the panels were to be removeable so that if the layout of the orchestra changed the panels could be quickly changed in accordance. This would provide the best possible environment for the musicians.

7. Future Work

We propose, LSBU and Edinburgh University, to ask for funding from the government, UKRI, to complete the project. This will allow the solution, as given above, to be fully implemented between now and 2023. This would require the full and further cooperation of the Royal Opera House, but would not require additional funding.

Appendix

Journal Papers

1 Eric Ballestero*, Noé Jiménez, Jean-Philippe Groby, Stephen Dance, Haydar Aygun, and Vicente Romero-García, From Quasi-Perfect to Broadband Sound Diffusion Using Deep-Subwavelength Metasurfaces Applied Physical Letter (submitted January 2021)

2 Eric Ballestero*, B. Hamilton, Noé Jiménez, Jean-Philippe Groby, Stephen Dance, and Vicente Romero-García, Simulating Acoustic Subwavelength Metamaterials in Large 3D Finite-Difference Time-Domain Volumes Using Impedance Filtering, Physical Review Letters (submitted Jan 2021)

3 Eric Ballestero*, Noé Jiménez, Jean-Philippe Groby, Stephen Dance, Haydar Aygun, and Vicente Romero-García Experimental validation of deep-subwavelength diffusion by acoustic Metadiffusers, Applied Physical Letters, 115, 2019 doi: 10.1063/1.5114877.

Conference Papers

1. E. Ballestero, S. Dance, D. Shearer, H. Aygun, Acoustic Conditions in Orchestra Pits: Can metadiffusers a potential solution?, Proc. IOA, 2018
2. E. Ballestero and S Dance. Head tracked auralisation for a dynamic audio experience in virtual reality sceneries, Proc. International congress on Sound and Vibration, 24, July 2017, London