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Full-scale outdoor concert adaptive sound field control

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ABSTRACT

Outdoor musical events in urban environments are of large cultural importance, but they are also a source of noise, especially for non-participating neighbors. In an attempt to solve this, an Adaptive Sound Field Control (ASFC) system is under development. The purpose is to mitigate low-frequency noise annoyance for neighbors and simultaneously enhance the audience musical experience. The system uses a secondary array of loudspeakers, canceling out the sound in a dark zone. To do this, accurate estimates of the transfer function between the loudspeakers and the dark zone are necessary. A static version of the system has been tested in three events: a controlled pre-test, the Kappa FuturFestival in Torino, and Tivoli in Copenhagen. These deployments are reported and discussed, with special focus on the Kappa FuturFestival, where noise measurements were conducted in the neighborhood, supplementing the insertion loss measurement from the ASFC. The performance of the ASFC system is shown to strongly depend on the complexity of the setting. In the final stage, the system needs to be adaptive in order to adjust to changing weather conditions. The adaptive parts of the system are under development and will be tested in a series of events during 2019.

Keywords: Sound Field Control, Outdoor Concerts, IoT

1. INTRODUCTION

Outdoor concerts in urban areas are important cultural events. However, there are challenges due to noise exposure and fulfilling noise regulations in neighbor areas. Concert organizers want to give their performers and audience a good musical experience, which might be compromised due to the neighbor noise issues. In an attempt to solve this, an adaptive sound field control (ASFC) system is being developed to mitigate annoyance in residential areas nearby. The focus of the approach is on the control of low frequencies. The ASFC system is consisting of loudspeaker arrays developed as a sound zone system, integrated with the organizer's public address (PA) system into an acoustic closed loop system.

Most modern sound reinforcement systems are based on the line array principle, which allows for the control of directivity of the sound radiation of high and mid frequencies. However, the sound propagation of low frequencies cannot be as easily controlled, as sound waves at these frequencies are less attenuated by air and reflections from boundaries and are damped the least by the structures of buildings. Low frequencies are therefore the most critical frequencies in the noise problem of outdoor concerts. The subwoofers are often arranged in a horizontal array or as two left-right clusters. In the reported ASFC system, these systems (primary sources) are extended using additional low-frequency loudspeakers (secondary sources), which are controlled by the ASFC system. The secondary sources are placed behind the audience in between the primary sources and the neighboring region in which the sound from the event should be reduced (dark zone). The radiation from the secondary sources is optimized so that the sum of sound pressures from the primary and secondary sources effectively reduces the total sound pressure level in the dark zone. However, at the same time, the use of additional loudspeakers to control the sound in the dark zone must not negatively impact the sound experience in the audience area, the bright zone. For the computation of the secondary source control

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filters, transfer functions between each source (subwoofer) and each control position are needed. These transfer functions have so far been based on microphone array measurements for tuning the system before its deployment. One main challenge in developing a full-scale outdoor ASFC system is the changing weather conditions and their effect on the transfer functions. In order to take this into account, the final system is planned to incorporate an adaptive model-updating system, which adjusts for changes in the transfer functions.

The reported work is part of the MONICA project (https://www.monica-project.eu/), a large-scale demonstration of IoT techniques for a smarter living. The full project consists of demonstrations in six major European cities, of which two – Copenhagen and Torino – are considered in the present application and paper. The IoT technique is intended to provide real-time data for the adaptive model updating. Another use of the IoT is for monitoring the noise pollution of the concert in real time, and for accurate measurements of transfer functions before the concert. The work presented in this paper is reporting on ongoing research; the overall ASFC strategy [1], the overall MONICA project with a focus on the sound monitoring tasks [2], and the measurements conducted in 2018 (partly reported in [3, 4]; more details can be found in these publications). The present paper gives some more details in the technical implementation and results from the three full-scale outdoor events in 2018 with increasing complexity; these are 1) a pre-test at Refshaleøen in Copenhagen, 2) Kappa FuturFestival in Torino, and 3) Tivoli Fredagsrock in Copenhagen. It is shown that the chosen ASFC strategy, in its static version, gives a satisfactory result (>10 dB IL in the low-frequency range) when the complexity is low as in the pre-test, but that in the more complex situations the result is limited (6 dB IL in Torino) or even no reduction (Tivoli).

2. METHOD

2.1 Method overview

The overall concept of the ASFC system is illustrated in Figure 1 (see [1]). The music signal is taken from the mixer board to the sound field controller. The sound field controller is using a propagation model that estimates transfer functions used in the optimization process to find the appropriate loudspeaker filters. The goal with the optimization is to minimize the sound pressure level in the dark zone. In the non-adaptive version of the system, the transfer functions in the propagation model module are based on measurements before the concert; this is the version of the system that has been tested in full scale so far. In 2019 the adaptive version will be tested, using sensor data.

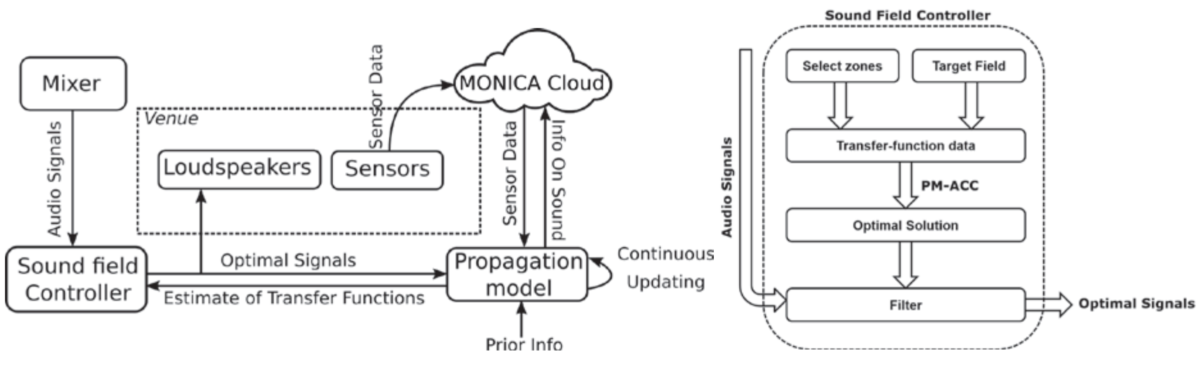

Figure 1 – Left: Information flow in the sound field control system, from [1]. Right: Signal processing flow of the Sound Field Controller module.

2.2 Loudspeaker array configuration

The ASFC system is based on the principle of sound zoning; the method used is a version of pressure-matching acoustic contrast control (PM-ACC), see [5]. The objective is to minimize the average SPL in the dark zone and the reproduction error in the bright zone. In the version of PM-ACC used in the present ASFC, only the secondary sources are controlled, see Heuchel et al. in [3]. The reformulated cost function consists of three terms,

$$\min_{\mathbf{w}^s} \kappa\|\mathbf{H}_B^s\mathbf{w}^s\|^2 + (1-\kappa)\left\|\mathbf{H}_D^s\mathbf{w}^s + \mathbf{H}_D^p\mathbf{w}^p\right\|^2 + \lambda\,\|\mathbf{w}\|^2 \qquad (1)$$

where $\mathbf{w}^s$ and $\mathbf{w}^p$ is the control weights for the secondary and primary loudspeakers, respectively. Moreover, $\mathbf{H}_B^s$, $\mathbf{H}_D^s$, and $\mathbf{H}_D^p$ are matrices containing transfer functions between secondary loudspeakers to bright zone, secondary loudspeakers to dark zone, and primary loudspeakers to dark zone, respectively. The first term in Eq. (1) minimizes the contribution from the secondary sources in the bright zoon (the audience area), the second term minimizes the total contribution in the dark zone, and the third term is a Tikhonov regularization term controlling the magnitude of the total loudspeaker filter weights. The parameter κ controls the balance between pressure matching and acoustic contrast and the parameter λ is the Tikhonov regularization parameter. In the full-scale tests reported in section 3, both parameters were tuned manually.

2.3 Signal chain configuration

The signal chain of the ASFC system is further described in Figure 3. The ASFC processing core calculates optimized control weights of the secondary sources from the transfer function set measured between the PA system of the stage and the bright and dark zones (see the monitoring paths 1, 2, 3a, and 3b in Figure 3).

All signal connections are enabled using DANTE (Digital Audio Network Through Ethernet) protocol. We selected a network-based protocol for connecting the ASFC system because the distances between the components can be over several hundred meters, far longer than the standard multichannel audio device setup. To ensure the reliable long-distance multi-channel signal transmission, signal routing over a single Ethernet cable the most reasonable approach. In addition, the ASFC system requires monitoring and playback of a high number of channels. The broadcast/subscription concept in network-based audio transmission has great advantages over a traditional one-to-one channel-based connection. Once the signals are on the DANTE network, any DANTE-enabled device are ready to transmit and receive signals.

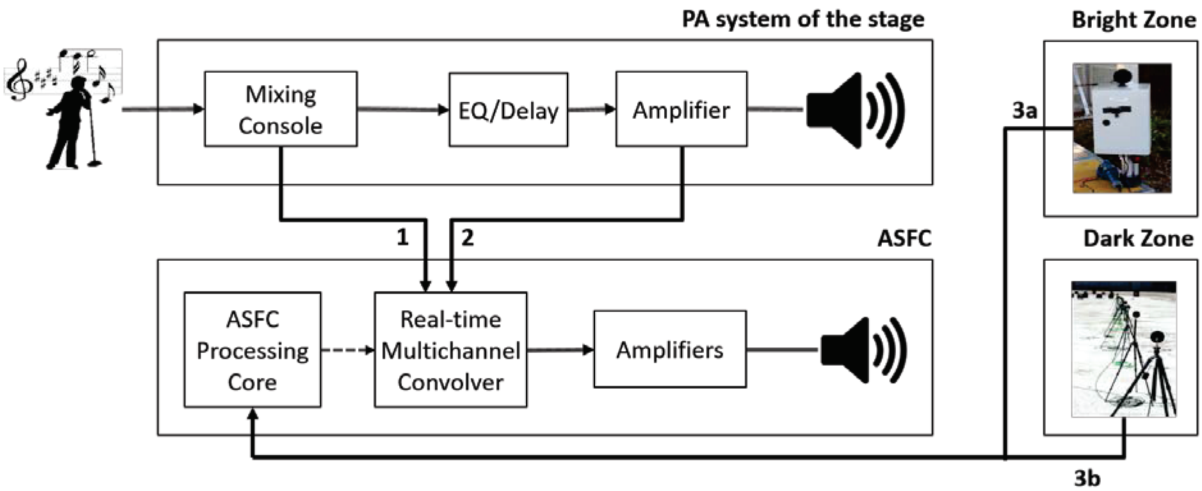

Figure 3 – Monitoring/Playback signal chain configuration of the ASFC system.

The ASFC requires real-time monitoring of the PA audio channels and monitoring of these channels can be done simply by connecting the mixing console. However, the signal outputs that passing the PA amplifier (what we need to know) can be quite different from the PA Mixing Console output. In general, after the music signal passes the mixing console, there are EQ/delay lines applied afterward which mean to adjust the sound fit to a specific venue. For accurate monitoring, it is recommended to monitor the whole electro-acoustic signal from the latest node (the monitoring path 2 in Figure 3). We have developed a device called Sniffer, which can monitor the high-voltage analog output from the PA amplifier. The sniffer is placed in the signal line between the PA amplifier and the PA loudspeaker, and thus monitor the signal actually provided to the loudspeaker. This signal is sent to the DANTE interface for further processing. Alternatively, the monitoring can be done at the previous nodes (the monitoring path 1) if the transfer function to the end node is known in advance. If there is no possibility of change in EQ/delay lines during the event, the latter approach can be practical but if not, the final node after the PA amplifier should be monitored.

Monitoring purpose of the sound in the bright zone is to minimize the reproduction error (unwanted sound due to secondary array activation) in the audience area. Because people can enter and exhibit the measurement area, it is wise to use IoT enabled sound level meter (IoT-SLM) instead of wired connection for the safe and secure measurement [4]. However, from the informal listening test that we have conducted in the pre-test at Refshaleøen (see the section 3.1), it was clear that people could hardly distinguish the secondary source activation from the deactivation even when the secondary array was just a few meters away from the audience area. Therefore, in the other two pilots – KappaFuturFestival and Fredagsrock - the bright zone monitoring (the path 3a) was removed.

In the controlled pretest at Refshaleøen, the dark zone connection was enabled by DANTE connection. However, the wired connection was not possible in the two following real concert cases because of roads and railways separating the concert area and the dark zone. Therefore, the sound in the dark zone was recorded remotely and data time alignment and synchronization were done with post-processing.

3. Results

In 2018 three full-scale outdoor tests were conducted, with increasing complexity. These tests are shortly reported below.

3.1 Refshaleøen, Copenhagen

In May 2018 a full-scale outdoor test with professional PA equipment was conducted at Refshaleøen in Copenhagen, with the purpose of investigating and testing the ASFC system in a more realistic setting, see Figure 4 and Ref. [3]. The area for the test consisted of a flat ground surface, and there were no obstacles (except for the secondary subwoofer array) in between the sources and the control zones. The temperature and wind were changing moderately. The experiment spanned a region of 80 m × 20 m. The primary sources comprised 10 subwoofers arranged in a line array with 2 m spacing. The secondary sources consisted of 20 subwoofers of the same type arranged in a double layer line array. The subwoofer model had an intrinsic cardioid radiation pattern and a nominal frequency range of 37 − 115 Hz (-5dB). The transfer functions to the bright and dark zones were sampled at 100 microphone positions in each zone, half of which was used for the computation of the control filters and the other half for the performance estimation.

The results of this test are presented in detail in Ref. [3], and are only briefly summarized here. A maximal insertion loss was estimated to be 12-14 dB between 45-85 Hz when using either two or just one layer of secondary sources. Thus, using a double layer does not significantly increase the insertion loss, but it does increases the primary-to-secondary ratio in the bright zone by 2-10 dB. However, the primary to secondary ratio is larger than 15 dB at all frequencies for both cases, suggesting that a single layer of cardioid secondary sources is sufficient for avoiding the secondary sources to be heard in the bright zone. This justifies the use of only one layer of cardioid secondary sources in the succeeding tests.

Measuring the system performance with a mismatch of temperature conditions between the transfer function measurements and the cancelation test – the temperatures had fallen by 6-8 °C between the two times – led to a reduction of the insertion loss of 2-10 dB.

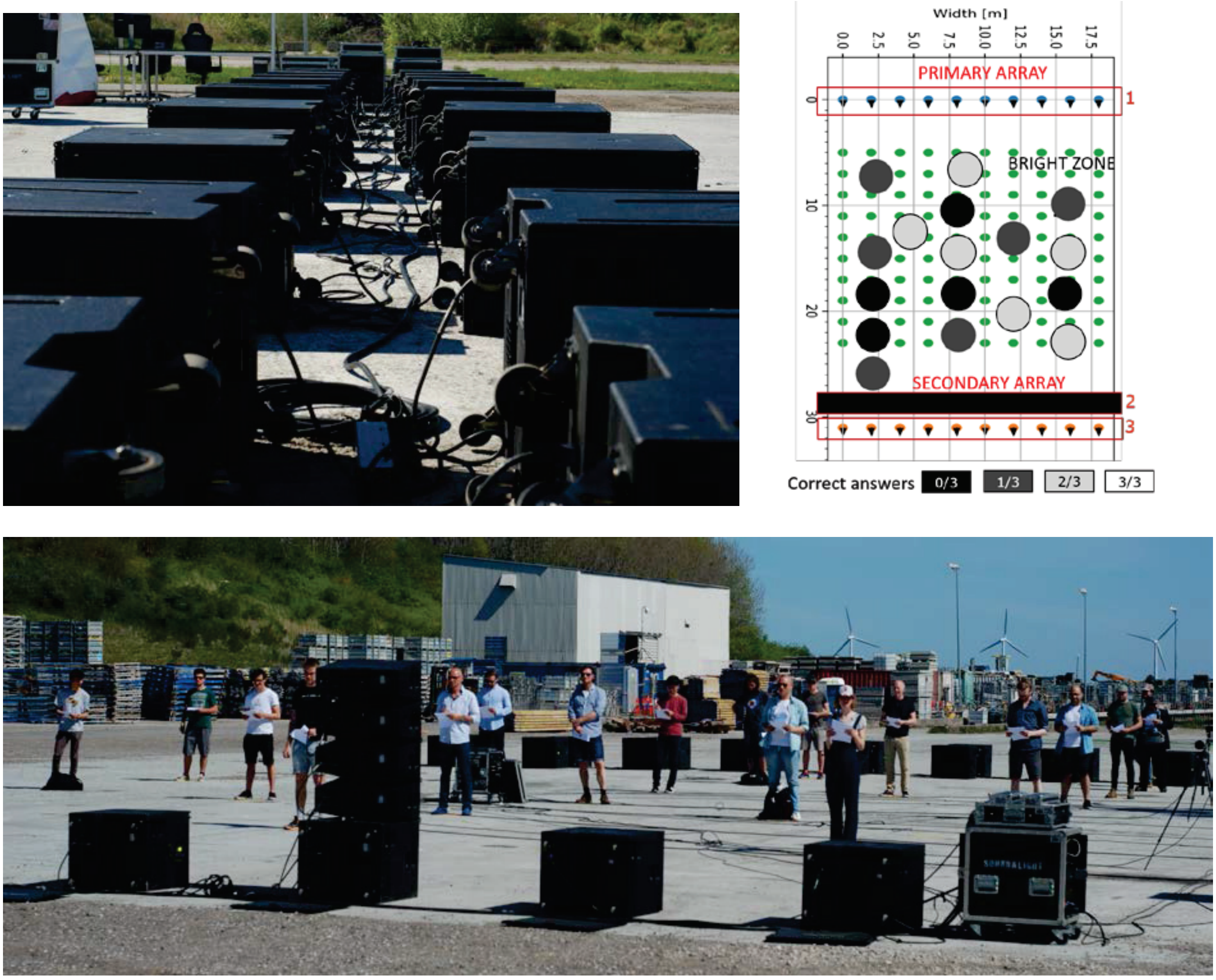

Figure 4 – The full-scale pre-test at Refshaleøen. Upper-left: Double array of secondary subwoofers. Upper-right: Result of the preliminary listening test in the bright zone (audience area). Darker circle means the subject failed to discriminate the difference. Lower: In the front the primary subwoofer array and complementary mid-high frequency line array, in the back the secondary subwoofer array. A listening test is conducted in the audience area (bright zone).

In addition, a preliminary listening test was conducted to check the audibility of the secondary array activation in the audience area (total of 17 subjects). Each subject was placed at different positions in the audience area (Figure 4 (upper-right)) and the Triangle Test (3-AFC) [6], was performed to discriminate the effect of the secondary array activation. Under the questionnaire of 'Which sample is most different from the others?', the subjects were asked to choose the sample from permuted three trials (BBA, BAB, ABB). Sample A represents the test case both primary and secondary arrays are activated and sample B is the reference sample where only the primary array is on. Only the single-layer secondary array was driven with simulated PM-ACC solution of Eq. (1) in section 2.2. Note that the level difference between the primary array and the secondary array was less than 3dB.

The result shows that out of 17 subjects (circles in Figure 4 (upper-right)), no one was able to make correct three choices for the test (the number of the correct answer is represented with a black-gray-white color difference). Even a subject within 5 m from the secondary array only scored 1 out of 3 questions. We have six participants who scored 2 out of 3 but note that the guessing probability is 2/9 for the test. Further investigation is needed but we are presuming that the late-arriving sound from the secondary array is masked by the first-arriving coherent sound from the primary array. In this pre-test, although the secondary array is placed very close to the audience area the audibility in the audience area was not clear. Therefore, we can expect that if ,the secondary array is placed further from the audience area, the effect would be negligible. This also implies that the optimization problem of Eq. (1) can be modified to neglect the reproduction error in the bright zone.

3.2 Kappa FuturFestival, Torino

The Kappa FuturFestival is an electronic music festival that takes place every summer at the beginning of July in Dora Park in Torino, Italy. The festival runs from noon to midnight for two days (Saturday and Sunday) on three or four stages and welcomes 12,000 spectators per day. The festival in 2018 was chosen as the first real-world and real-time test of the ASFC system, at the Futur stage. The main results are presented in detail in [3, 4], and is only shortly reported here. Compared to the previous experiments this scenario posed several new challenges: There is a complex, uneven terrain with many reflecting structures and surfaces around the venue and dark zone. Moreover, the dark zone has obstacles in the line of sight to both the primary and secondary sources. Due to practical limitations, fewer positions of the transfer functions in the dark zone could be measured. Finally, the environment was noisy (due to sound from other concert stages as well as road and tram traffic), resulting in a limited signal to noise ratio in the transfer function measurements. Also, note that here the control loudspeaker signals were convolved in real time. The secondary source array is shown in Figure 5 (left).

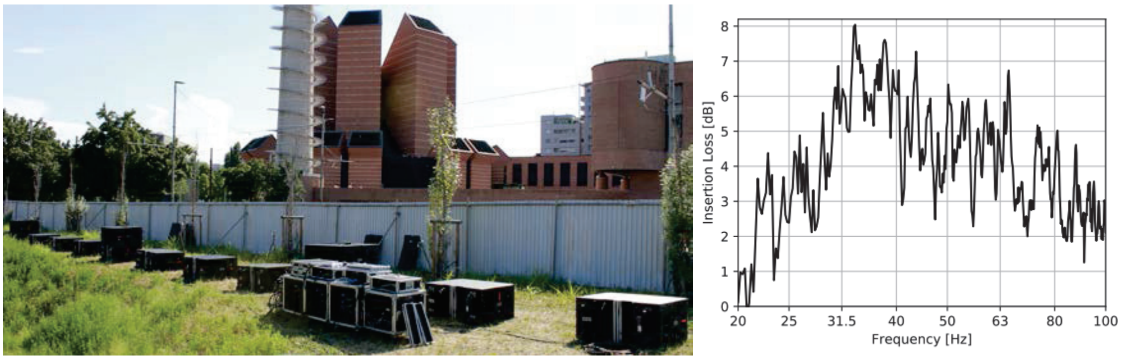

Figure 5 – The full-scale pilot test at Kappa FuturFestival. Left: In the foreground the 20 subwoofer secondary array. In the background is the church building that was used as the dark zone. Right: Estimated average Insertion Loss, from [3].

The part of the festival area that used for the test spans around 300 m in length, from the primary sources to the end of the dark zone. The primary subwoofer array consists of 20 cardioid subwoofers. The width of the secondary array is around 40 m, consisting of 16 cardioid subwoofers, facing the dark zone – it was judged that the secondary array had no noticeable effect in the audience area/bright zone. The width of the dark zone is also around 40 m, but not fully in line with the secondary sources. The stage sound system also featured two vertical line arrays for the higher frequencies, but these were not included in the sound field control system. The dark zone was approximately 100 m deep and 40 m wide, placed on an elevated courtyard and the roof of a modern church building. It was sampled at 20 microphone positions in the courtyard and 30 positions on the rooftop. After the measurement of the transfer-functions from all sources to all microphone positions, a set of control filters was computed, and the regularization parameter was chosen by hand such that the gain of the control filters was not overly extreme. Figure 5 (right) shows the estimated insertion loss of the system; an IL of around 6 dB is achieved between 31.5 Hz and 40 Hz, and in the range from 25 Hz to 100 Hz, an IL of above 3 dB is achieved. This shows that the system works, but the effect is significantly worse than in the previous experiment. Moreover, the effect of the system was not clearly audible in the dark zone; the reason for this is partly due to the limited bandwidth and low-frequency range of the effect, and partly due to the high background noise level from the other stages of the festival.

At the façade of one of the neighbor dwellings, from 4th to 9th floor, 200 m away from the secondary array, the effect of the system was not clearly audible, mainly due to noise from the other stages of the festival and traffic noise. In particular, the transfer function from the Main and Futur stage has been estimated to be more or less equal at these positions [7]. An analysis on one-third octave bands from 31.5 to 50 Hz confirmed the difficulty to properly detect an effect on such complex acoustic field with multiple sources, see Figure 6.

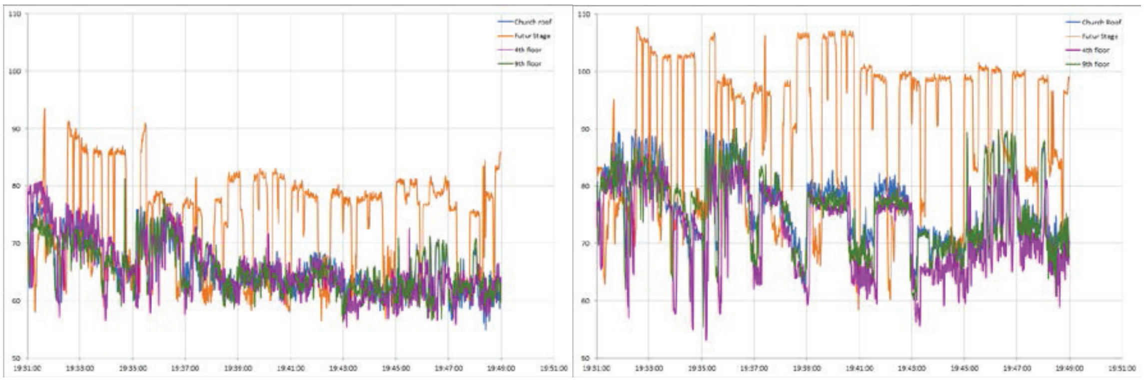

Figure 6 – One third octave band analysis of sound at façade of a neighbor building, compared with sound at the church roof (dark zone) and the Futur stage (bright zone). Left: 31.5 Hz. Right: 40 Hz.

3.3 Tivoli, Copenhagen

The ASFC system was also deployed at a third full-scale outdoor test at a concert at Tivoli, Copenhagen, in August 2018. Figure 7 left shows the secondary subwoofer array, located at the roof of the concert hall building at Tivoli. The dark zone was located in a city courtyard on the other side of the street, outside Tivoli. The geometrical and topological complexity is much greater than in the previous testy cases; there are multiple buildings that scatter the sound propagating from both primary and secondary sources, and there is as well a large building in the line of sight between the primary sources and the dark zone, etc. Moreover, time constraints, noise regulations, and weather conditions limited the possibility of measure transfer functions.

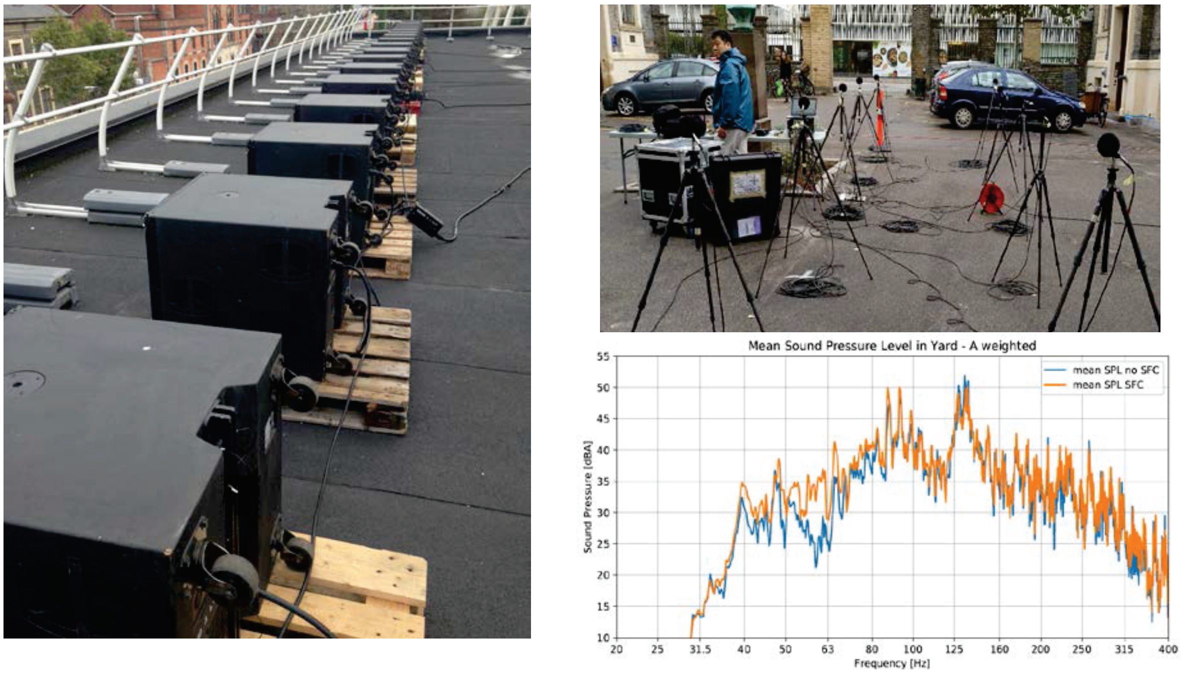

Figure 7 – The full-scale pilot test at Tivoli. Left: The subwoofer secondary array on the roof. Right-top: Microphone positions in the dark zone. Right-bottom: Average SPL in the dark zone.

The challenges faced at Tivoli all together led to an unsuccessful test result. The problems faced are here summarized: 1) There were problems during measurement of the transfer-functions: Due to the long distances and road traffic, wired cables could not be used. Instead, a system specially designed by B&K was used, using a GPS-NMEA signal for time synchronization (this system was also used in Torino, where it worked well). However, we experienced problems with the synchronization of the recording front ends connected to microphones and signal generators. This resulted in the measurements of the transfer functions were not aligned in time properly which makes it impossible to calculate the cancellation filter. Moreover, continuous rain during the planned transfer-function measurement session limited the time available. Therefore, only a subset of the measurements could be used. 2) There where a change in weather and audience conditions between the measurement of transfer functions and concert time. This is the purpose of the adaptive part of the ASFC, which was not tested at Tivoli. 3) The complex geometry did give a strongly reverberant and complex sound field in the dark zone, as the microphones were placed in a city courtyard. To describe this sound field properly, longer FIR filters and a denser grid of microphone positions would have been needed. 4) As compared to previous tests, the primary subwoofer system was driven by two separate audio systems. This was dealt with using an ad-hoc design without proper validation. Moreover, part of the low-frequency range (down to 65 Hz) was also produced by the hanging top line array loudspeakers. This led to a more complex configuration. 5) The signal to noise ratio was very low because of extensive road traffic between the park and the measurement location, increasing the background noise. In addition, the music signal was low compared to the level we could reach in Torino. As a result, as the measurements showed no effect or insertion loss of the system, as seen in Figure 7 (right-bottom).

CONCLUDING REMARKS

The paper present ongoing work developing an adaptive sound field control system for outdoor concerts. Three full-scale outdoor tests are reported, with increasing complexity, and still without the adaptive solution. The results show that the proposed system works satisfactorily in stable outdoor conditions and in sites of moderate topological complexity. Many practical challenges have been faced, which are reported too. The results show that the basic principles behind the sound field control work also in this scale; in the first pre-test experiment an insertion loss of more than 10 dB (the effect was clearly audible on-site). However, when the complexity of the situation increased, the performance was compromised. In the final test at Tivoli, Copenhagen, which is by far the most complex of the three tests, no insertion loss was achieved. Thus, it seems as the adaptive part of the system seems necessary, and that still a large set of measured transfer functions of good quality is essential for good results. Moreover, from the pre-test, it can also be concluded that if using cardioid subwoofers, the spillover from the secondary sources to the audience in the bright zone is minimal, only online of secondary sources is needed, and that the emphasis of the cost function shall be on controlling the dark zone.

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