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ABSTRACT

The Early and Late Support parameters (ST\textsubscript{early} and ST\textsubscript{late}) are used to describe acoustic conditions on stage. Recently, extended Support parameters have been introduced which can be measured at various distances: ST\textsubscript{early,d} and ST\textsubscript{late,d}. This way, the amount of reflected sound energy can be studied for sound paths with distances between source and receiver larger than 1 meter. Occasionally, Early and Late Support are also used to investigate orchestra pits. Using the extended Support parameters, the mutual support from reflections between the positions in the open and covered part of the orchestra pit has been investigated. It is found that, when plotting ST\textsubscript{early,d} as a function of distance, three different trends are found each having a distinctive shape for different types of source and receiver positions: both positions in the open part; both positions in the covered part; and just one of both positions in the open or covered part. When comparing the different trends, a large increase is found in early reflected sound energy when either source or receiver or both are in the covered part of the pit. In the covered part, at 1 meter distance the level of reflected sound can even be in the same order of magnitude as the direct sound. When considering the late reflected sound energy it was found that ST\textsubscript{late,d} was not dependent on the source to receiver distance and less difference was found between the open and covered part of the orchestra pit.

1. INTRODUCTION

A typical modern orchestra pit is partly covered by the stage floor and partly opened to the auditorium. Because of that, the orchestra pit can be an acoustically challenging environment for orchestra musicians. Typically, the louder instruments (brass instruments, wind instruments and percussion) may be positioned in the covered part of the pit. The instruments who generally play less loud (violins, celli and double basses) may be positioned in the open part of the pit. As a result, the sound of the different instrumental sections is projected differently towards the audience in the auditorium and the soloists and choir on stage. Also, the ensemble playing of the musicians is
different in an orchestra pit compared to a fully open stage setting in a concert hall, partly due to the difference in the acoustic environment. To investigate this difference, stage acoustic parameters have been measured in an orchestra pit, while varying its size. The results are compared to measurements of stage acoustics in concert halls.

Figure 1a shows a plan of a typical orchestra setup in the normal size orchestra pit of Het Muziektheater Amsterdam, which was investigated in this research. The transition between the open and covered parts is indicated by a dashed line. In an attempt to reduce the sound exposure of the musicians in this pit, and to improve ensemble conditions, the impact of increasing the pit size was studied. This was done by taking out several rows of seats, lowering the floor and moving the whole orchestra towards the audience, placing as many musicians in the open part of the pit as possible, see figure 1b. In section 2, the measurement method is explained. The results are presented in section 3 and discussed in section 4 and 5.

![Figure 1](image_url)

**Figure 1.** (a) Orchestra setup in the normal size orchestra pit. (b) Orchestra setup in the large size orchestra pit.
2. METHOD

2.1. Parameters

The most common objective room acoustic parameters to investigate stage acoustics are the ST early and ST late, based on research by Gade\(^1,2\) and described in ISO 3382-1\(^3\). These parameters are typically derived from impulse responses, measured at 1 meter distance from an omnidirectional sound source. Recently, Wenmaekers et al.\(^4\) proposed to modify and extend the commonly used ST parameters so they can be measured at various source to receiver (S-R) distances, denoted ST\(_{\text{early,d}}\) and ST\(_{\text{late,d}}\). This is done by introducing a variable time point ‘103-delay’ that takes into account the delay of direct sound by increased distance, see equation (1) and (2), where the ‘delay’ is the S-R distance divided by the speed of sound (see Wenmaekers et al.\(^4\) for more background information and literature). This way, the parameters can be measured at S-R distances up to 25 m, considering a time interval width of 30 ms as an acceptable minimum. The time interval of early reflected sound starts at 10 ms instead of 20 ms to be able to measure closer to the stage boundaries up to 2 m. The reference level at 1 meter distance is measured separately at only one position free from reflective walls are ceilings.

\[
\begin{align*}
\text{ST}_{\text{early,d}} &= 10 \lg \left( \frac{\int_{10}^{103-\text{delay}} p_d^2 \, dt}{\int_{0}^{10} p_{1m}^2 \, dt} \right) \\
\text{ST}_{\text{late,d}} &= 10 \lg \left( \frac{\int_{103-\text{delay}}^{\infty} p_d^2 \, dt}{\int_{0}^{10} p_{1m}^2 \, dt} \right)
\end{align*}
\]

where, \(p_d\) is the sound pressure measured at distance \(d\); \(p_{1m}\) is the sound pressure measured at 1 m distance; and delay is the S-R distance divided by the speed of sound; time to infinity is defined as the time of the cross point between the decay curve and the noise floor of the impulse response.

An important finding from previous research on 11 concert hall stages is that ST\(_{\text{early,d}}\) decays over distance and that this decay correlates well with a logarithmic trend line. In contrast, ST\(_{\text{late,d}}\) does not depend on distance and an average value over all positions can be considered. In this research, for the first time, the modified and extended ST parameters have been used to investigate the stage acoustics of an orchestra pit.

2.2. Measurement method

Figure 2 shows the plan of the orchestra pit in the normal size configuration. Three source positions have been selected, where S1 is at 1 m distance from the back wall. S2 is in the middle of the open area on the right-side and S3 is at 1 m from the stage edge in the covered part. The source positions are also used as receiver positions. In a similar
way, receiver positions R4 to R7 are selected. Position Rc represents the conductor position. In the larger size configuration, the position 2, 4 and 6 are moved towards the audience to stay in the middle of the larger open area, while the positions under the covered part remain unchanged. At all source positions S1 to S3, additional measurements were performed at 1 m distance at the front and right side of the loudspeaker (viewing direction towards the audience). It should be noted that the ST parameters should normally not be measured while placing the transducers closer than 2 m from any room boundary. This is particularly important to avoid exclusion of early reflections in the measurement interval 10 to 103-delay, in other words: to avoid early reflections arriving before 10 ms. However, in case of an orchestra pit, it is impossible to fulfill this condition because of the close proximity of the ceiling and back wall. This exclusion may result in an underestimation of the amount of early reflected sound energy. The reference level at 1 m distance (the denominator in equations 1 and 2) was determined at a position with all boundaries beyond 4 m distance. During the measurements, the orchestra pit was empty, except for in the larger size condition where seats and percussion instruments were stored along the back wall of the pit that may have caused additional absorption or scattering. Also, during both the measurement session, different stage sceneries for opera were present.

Impulse response measurements have been performed using an omnidirectional sound source AE type Pyrite, an amplifier AE type Amphion and B&K type 4189-A-021 microphones. The measurements in the normal size orchestra pit were performed in 2010 using Dirac 4 measurement software and in the larger size orchestra pit in 2012 using Dirac 5 measurement software. For each combination of source and receiver, multiple measurements were taken while rotating the sound source stepwise: 4 steps in 2010 and 5 steps in 2012 (recent research by Hak et al.6 in 2011 has shown that the uncertainty in source directivity is reduced only when using 5, 7 or 8 stepwise rotations). To further reduce measurement uncertainty, all impulse responses have a

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**Figure 2.** Plan of the normal size orchestra pit with source positions S1-S3 and receiver positions R1-R3 (equal to S1-R1) and receiver positions R4-R7 and Rc.5
decay range INR$^7$ of at least 45 dB. The source height was 1.35 m and the receiver height was 1.20 m. All parameters results for $ST_{\text{early,d}}$ and $ST_{\text{late,d}}$ were calculated using Dirac 5, averaged over the 250 to 2000 Hz octave bands.

3. RESULTS

Figure 3 shows the measurement results for $ST_{\text{early,d}}$ and $ST_{\text{late,d}}$ as a function of distance for the normal and large size orchestra pit of Het Muziektheater Amsterdam. In every graph, results are divided into three groups: both positions in the covered part of the pit; just one of both positions in the open or covered part of the pit; both positions in the open part of the pit. In both the normal and large size pit, the individual values for $ST_{\text{early,d}}$ of each group show a strong correlation to a distinctive trend line. For the $ST_{\text{late,d}}$ no clear distinction is found for the three groups and no correlation exists for the values as a function of the distance.

For both pit sizes, at a distance close to the source, the $ST_{\text{early,d}}$ is only a few dB below the direct sound level at 1 m distance in the covered part of the pit, while in the open part $ST_{\text{early,d}}$ is approximately 10 dB lower. The trend lines of $ST_{\text{early,d}}$ over distance seem to run more or less parallel for the groups ‘covered-covered’ and ‘open-open’. The trend

![Graphs showing early and late support over distance for normal and large size orchestra pits.](image-url)

**Figure 3.** Early Support (upper graphs) and Late Support (lower graphs) over distance for the normal size orchestra pit (left graphs) and large size orchestra pit (right graphs).
lines ‘open-covered’ are close to the group ‘covered-covered’ at short distance and close to the group ‘open-open’ at larger distance. Furthermore, we can conclude that, due to the enlargement of the orchestra pit, the trend lines have tilted, and ST_{early,d} is almost unchanged close to the source, but decreased by 3 to 5 dB at distances beyond 10 m. The average ST_{late,d} is 2.8 dB lower in the larger orchestra pit configuration.

4. COMPARISON TO CONCERT HALL STAGES
To investigate the possible meaning of the measurement results in the orchestra pit, a comparison is made by measurements on 11 different concert hall stages. In table 1, the coefficient ‘a’ and ‘b’ of the logarithmic trend lines ‘a lg(d) + b’ for ST_{early,d} and the average values for ST_{late,d} are given for each concert hall stage. More information can be found in reference 4.

In the left graph in figure 4, the results for the orchestra pit are compared to reference values from the concert halls. When comparing ST_{early,d} for the orchestra pit to a concert hall stage with a good and poor reputation, it can be seen that the amount of early reflected sound in the open part of the pit is more or less similar to a concert hall stage with a good reputation. However, when the source, receiver or both are in the covered part of the pit, the amount of early reflected sound level is considerably higher, especially at a shorter S-R distance. Also, the ST_{early,d} for the stage having a good reputation is almost independent from the distance, while the ST_{early,d} for the stage having a poor reputation and the investigated orchestra pit shows a much larger variation per distance.

In the right graph in figure 4, the average ST_{late,d} for both orchestra pit configuration are compared to the average value and for the different concert hall stages. It can be seen that, in general, less late reflected sound arrives in the orchestra pit than on typical

<table>
<thead>
<tr>
<th>Hall</th>
<th>ST_{early,d} = a lg(d) + b [dB]</th>
<th>ST_{late,d} [dB]</th>
<th>average</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>−10.8</td>
<td>−9.8</td>
<td>−14.5</td>
</tr>
<tr>
<td>B</td>
<td>−3.4</td>
<td>−9.8</td>
<td>−12.5</td>
</tr>
<tr>
<td>C</td>
<td>−1.6</td>
<td>−11.0</td>
<td>−15.2</td>
</tr>
<tr>
<td>C−</td>
<td>−1.5</td>
<td>−11.0</td>
<td>−12.1</td>
</tr>
<tr>
<td>D</td>
<td>−2.8</td>
<td>−12.4</td>
<td>−15.2</td>
</tr>
<tr>
<td>E</td>
<td>−5.4</td>
<td>−11.6</td>
<td>−16.0</td>
</tr>
<tr>
<td>E+</td>
<td>−4.6</td>
<td>−13.0</td>
<td>−16.3</td>
</tr>
<tr>
<td>F</td>
<td>−4.3</td>
<td>−12.2</td>
<td>−14.0</td>
</tr>
<tr>
<td>G</td>
<td>−5.5</td>
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<td>−13.6</td>
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<tr>
<td>H+</td>
<td>−3.9</td>
<td>−10.9</td>
<td>−15.0</td>
</tr>
</tbody>
</table>
concert hall stages. This can be explained by the lower reverberation time in the opera house of 1.3 seconds compared to the concert halls with an average reverberation time of 2 seconds. It is striking that, when the orchestra pit is enlarged, the average Late Support decreases by 2.8 dB. Actually, it might be expected that, when the pit has a larger opening, more sound could be reflected back into the pit. On the other hand, the higher Late Support in the normal size orchestra pit might be explained by the ‘late reverberation’ that may build up in the more closed volume of the pit, extra influenced by the fact that no musicians, chairs and stands were positioned in the orchestra pit during the measurements.

It is unknown to what extent the measured differences might have been caused by a different scenery on the stage (although no change in reverberation time was observed) or by the instruments stored against the back wall of the pit while performing the measurements in the large size orchestra pit.

5. DISCUSSION
The measured stage acoustic parameters can be used to study the noise exposure of musicians. A first concept of a calculation model to be able to do so was presented at Forum Acusticum 2011 [8] and an updated version was presented at ISRA 2013 [9]. Also, a first attempt was made in judging the sound exposure of musicians on different stages using the calculation model [10]. So far, the stage acoustic parameters as presented in current paper were not used to investigate the sound exposure of the musicians. However, the measurement results for $ST_{early,d}$ do show a high early
reflected sound level close to the sound source in the covered part of the pit. On concert hall stages, the early reflected sound level close to the sound source is often at least 10 dB lower than the direct sound at 1 m distance. For this orchestra pit, however, the early reflected sound level is in the same order of magnitude as the direct sound at 1 m distance. So, it can be expected that the sound exposure due to instruments in close proximity will be higher, up to 2 to 3 dB. When the pit is enlarged, the $ST_{early,d}$ close to the sound source appears to be almost unchanged. So, it can be expected that, only when more musicians take place in the open part of the pit (where $ST_{early,d}$ is much lower) the average sound exposure can be reduced by enlarging the orchestra pit.

While this study has provided several new insights, it is also important to mention the limitations of this study. The results for only one orchestra pit were presented in this paper. The three different sound paths trends have been observed in measurements in other orchestra pits, but the impact of enlarging the orchestra pit was not tested in other pits. Furthermore, for practical reasons the measurements were performed in an empty unoccupied orchestra pit, while in general it is recommended to perform measurements when seats and stands are present [4]. Future work should focus on exploring the influence of chairs, risers, stands, screens and persons on stage on the parameter results. Also, the results for the stage acoustic parameters when using actual instrument directivity should be compared to results for omnidirectional sound source directivity. This might be specifically important when performing measurements in orchestra pits as the highly directive (wind) instruments are often positioned in the covered part.

6. CONCLUSIONS

In this paper, the modified and extended Early and Late Support parameters have been used to investigate the ‘stage acoustics’ of an orchestra pit. By doing so, for the first time, it has been shown that three distinct groups of sound paths can be discriminated: both positions in the open part; both positions in the covered part; and just one of both positions in the open or covered part. The measurements of $ST_{early,d}$ and $ST_{late,d}$ confirm the common experience that musicians in an partly covered orchestra pit often lack a certain amount of late reflected sound, while the early reflected sound is too loud.

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