Analysis of Onstage Acoustics Preference of Musicians of Traditional Performance of Javanese Gamelan Based on Normalized Autocorrelation Function

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Abstract. On-stage sound field analysis of a traditional performance of the Javanese gamelan at Pendopo ISI Surakarta, Indonesia was conducted by analyzing the effective decay time of a normalized autocorrelation function called tau-e, τ_e, during a performance of the *Gambyong Pare Anom* dance. The parameter tau-e is used to describe the richness of the frequency content, tempo, and types of gamelan instruments being played at a certain time and position on stage. The tau-e parameter is important for musicians in order to maintain communication between each other such that they can keep the performance in harmony. In order to determine the acoustic parameters heard by gamelan musicians on stage, sound measurements were conducted at 4 points on stage during a performance. Each position represents a specific group of gamelan instruments, which have different characteristics of loudness and frequency, different functions and different ways the instruments are played. The analysis showed that each of the four positions had a different value of τ_e, which fluctuated throughout the performance. Overall, the dominant τ_e at position 1 was 20 ms; at position 2 it was 50 ms; at position 3 it was 20 ms; and at position 4 it was 40 ms. The distribution of τ_e on the stage shows that positions 1 and 3 had more frequency richness compared to positions 2 and 4.

Keywords: *frequency content; instrument layout; Javanese gamelan; normalized autocorrelation function; on-stage performance; performance harmonization.*

1 Introduction

In a performance a Javanese gamelan is composed of up to 40 gamelan instruments, called *ricikan*. As a kind of music ensemble, unlike classical music ensembles, Javanese gamelan is performed traditionally without a conductor to

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lead the players. Instead, who leads the performance at any instant changes dynamically among the musicians along the performance. Consequently, harmonization and consistency of performance are maintained by all musicians together through perception of the distinct characteristics of the sound produced by each gamelan instrument. In a recital, the role of performance leader changes between the musicians dynamically along the performance depending on the type of song or composition being played and the objectives of the performance. Therefore, the acoustic parameters of a performance may quickly change without any special command as usually given by a conductor. This is very common; changes in the acoustic parameters during a Javanese gamelan performance are part of the performance's exploration and the communication between the musicians or even with dancers and Javanese traditional vocalists called *sinden*. In order to maintain this communication and the consistency of the performance, each musician needs acoustic parameters such that he/she can play his/her role in the performance well[1].

The acoustic parameters that are important for the musicians in a Javanese gamelan are sound level, frequency, tempo and direction of arrival of the sound of the *ricikans* being played during the performance. These parameters are actually strongly affected by the acoustic properties of each *ricikan*, the position of the musician with respect to the *ricikans* being played, the layout of the *ricikans* on the stage and the acoustic properties of the room and stage where the ensemble of *ricikans* is being played.

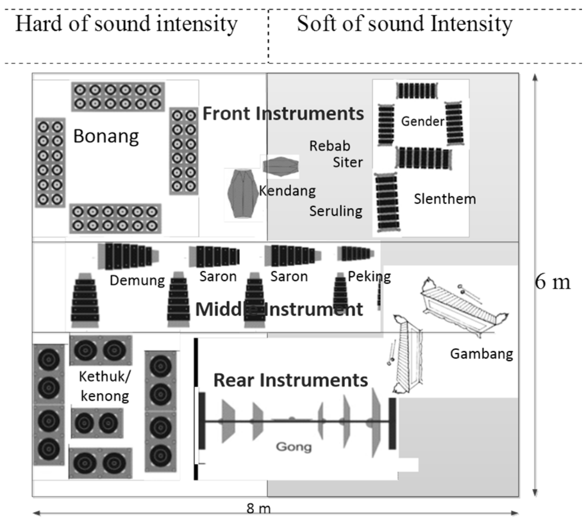

Figure 1 Typical layout of instruments of the Javanese gamelan instruments (*ricikans*) on stage.

In our previous research, acoustic characteristics of *ricikans* have been identified [2-4], i.e. fundamental frequency, sound envelope, and timbre. Figure 1 show how *ricikans* are grouped by hard sound intensity on the left side of the stage and by soft sound intensity on the right side of the stage. *Ricikans* may also be positioned in the front position (Javanese: *ngajeng*), middle position (Javanese: *tengah*) or rear position (Javanese: *wingking*) [5,6].

The combination of acoustic characteristics of the *ricikans* and their layout on stage causes each musician of the gamelan orchestra to receive a sound with different acoustic parameters. Gamelan musicians have to be able to identify and recognize properly the types of *ricikans* according to their own role in the performance. Identification and recognition of sound sources can be obtained by the parameters of LL and richness of frequency of the sound field at the musician's position. Parameter LL can be measured directly, while richness of frequency can be estimated from the τ_e parameter [7].

By definition, τ_e represents the time needed of a sound to decay by 10 dB calculated by an autocorrelation function. This is equivalent to the time taken by the energy of the sound to decrease to 10% of its original value [7]. Parameter τ_e is defined from the decay time envelope of a normalized autocorrelation function of a measured sound. Therefore, actually, τ_e describes the frequency content of a sound. Based on parameter τ_e , the tempo and reverberation time of the sound may be interpreted as well. Kato et al. conducted research on different kinds of sounds using the tau-e parameter to determine the effect of the vibration of the source for performing musicians and singers. In this research, the smaller the value of tau-e min, the greater (the longer) the vibration generated by the source as perceived by both musicians and singers [8]. The greater the value of τ_e , the narrower the frequency bandwidth, which means there is less frequency content and a lower performance tempo, and vice versa [7-9]. Considering sound pressure $p(t)$, the autocorrelation function of the sound is given by Eq. (1):

$$\varphi_p(\tau) = \lim_{\tau \to \infty} \frac{1}{2T} \int_{-T}^{+T} p(t)\,p(t+\tau)\,dt \tag{1}$$

and its normalization is given by Eq. (2):

$$\varphi(\tau) = \frac{\varphi_p(\tau)}{\varphi_p(0)} \tag{2}$$

Figure 2 is an ilustration of how to obtain the parameter τ_e from a normalized autocorrelation function graphic.

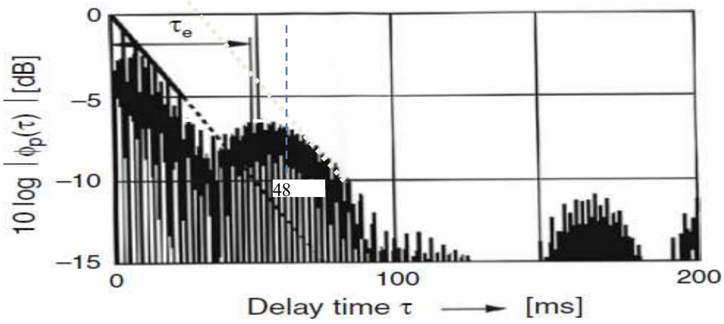

Figure 2 Illustration of parameter τ_e [6].

Hence, parameter τ_e explicitly shows the frequency content or frequency richness of a sound given by $p(t)$. The normalized autocorrelation function shown in Figure 2 was calculated by Equation (2) in the dB scale. The value of τ_e in Figure 2 is 48 ms.

In this paper, temporal and spectral acoustic parameters that govern harmonization and consistency of a Javanese gamelan performance were determined in order to understand how gamelan musicians perceive different types of sounds during the performance. One of the acoustic parameters used by musicians as a means to identify a *ricikan* is sound color. The acoustic parameters perceived by a musician at a certain position can be obtained from the frequencies of the sound measured at that position.

Section 2 of this paper will explain a method to obtain parameter τ_e and to determine the measurement points' positions on the stage. Section 3 will discuss other acoustic parameters, particularly sound frequency as perceived by the gamelan musicians in certain areas of the stage. Finally, the conclusions will be given in the last section of this paper.

2 Sound Measurement

Since there is no a particular leader to conduct a performance, gamelan musicians keep harmony in a traditional performance basically by analyzing the sound they hear. Therefore, the clearness of the sound perceived is an important factor for musicians. One way to have clearness of sound perception is through the arrangement and layout of the gamelan instruments on stage. The arrangement of the gamelan, i.e. the layout of the *ricikans*, determines the acoustic parameters as they are perceived by the musicians and so influences the effectiveness of communication between the musicians during a performance.

Considering the layout of a gamelan as shown in Figure 1, the temporal and spectral acoustic parameters on stage were measured at four different positions, namely position 1, position 2, position 3, and position 4. These positions were determined based on the roles of the *ricikans* and the composition being played. Figure 3 shows the positions of the measuring points on stage.

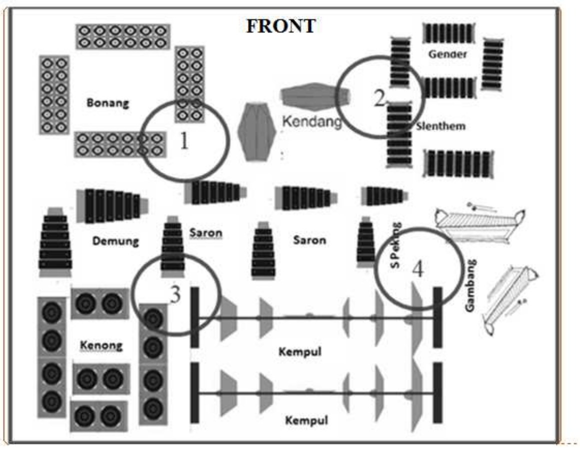

Figure 3 Positions of measurement on stage.

As can be seen in Figure 3, position 1 is located at the front of the stage and represents the group of *ricikans* that produce hard sound characteristics at high sound pressure levels, namely *bonang*, *kendang*, *demung*, and *saron*. These *ricikans* produce a sound with low to medium frequencies, except for *kendang* (drum). *Kendang* is a unique *ricikan* whose sound characteristics depend on an intuitive sense of the musician who is playing it during the performance. However, *kendang* has no a specific frequency characteristics. The sound characteristics of *kendang* are mostly expressed by loudness and tempo in relation to its role during a performance [4,5].

Position 2 is also located at the front of the stage, representing *ricikans* with soft sound characteristics (low sound pressure levels). Such *ricikans* include *gender*, *slenthem*, and *kendang*. They have sounds with overlapping frequencies (low to high frequencies). Positions 3 and 4 are located at the rear of the stage. Position 3 is surrounded by *ricikans* that produce hard sounds with low to medium frequencies. Meanwhile, position 4 is surrounded by *ricikans* that produce soft sounds with low to high frequencies. Position 3 represents the group containing *demung*, *saron*, *kethuk*/*kenong*, *gong*/*kempul*, while position 4 represents the group containing *peking*, *gambang*, *gong*/*kempul*. The instruments in the group containing *peking*, *gambang* and *gong*/*kempul* are played in a different manner compared to the other *ricikans*. The *peking* and the *gambang* are knocked twice for each note, while the *gong* is played only at certain times randomly, i.e. the *gong* is the only *ricikan* that is not played at a determined tempo during a performance.

The object of this research was the sound produced by a traditional Javanese gamelan during a performance at Pendopo ISI Surakarta. Pendopo ISI Surakarta is a semi-open performance hall where Javanese gamelan is usually performed. Sound measurements were conducted during a traditional performance of Javanese gamelan that was playing a *garap* (interpretation) of the intro of the *Gambyong Pare Anom* dance. During the sound recording, the dominant note being played was 6 (--6 5 6 2 6 5 6 1--), and the sound was dominated by the *ricikan* group composed of *saron*, *demung*, and *bonang*.

Sound measurements were conducted simultaneously at the four positions shown in Figure 3. Measurement was performed by BSWA™ audio interface, recorded at a sampling rate of 44100 Hz and then stored to a computer as a digital signal. To obtain parameter τ_e, the recorded sounds were analyzed using a Yoshimasa sound analyzer[10], version 5, using an integration interval window of 0.5 s and a running step of 0.1 s. Based on the obtained acoustic parameter τ_e, the temporal and spectral parameters of each *ricikan* at its position was then determined.

In addition, through the obtained values of tau-e, the richness of frequency of the sound was determined with a spectrogram using an FFT analyzer at the four measurement positions simultaneously. The FFT analyzer used a Hamming window and the Welch method with 512 points and 256 points overlap. The Obtained parameter was tau-e.

As mentioned before, the acoustic characteristics of the sound produced by the *ricikans* are used by the musicians to keep the performance of the Javanese gamelan in harmony. Therefore, the musicians have to be able to properly identify the sound of the other *ricikans* in relation to their own role. All acoustic parameters allow the musicians to communicate with each other during a gamelan performance and serve as a guide for each musician to determine the next note to be played.

To keep the performance in harmony, in order to play a note the gamelan musicians have to wait and analyze the sounds from other *ricikans* being played. In turn, this results in a small random time delay among the *ricikans* being played, even if they play the same note. Therefore, a Javanese gamelan performance randomly flows as a result of this small time delay (short/fast). As a result, the sound will resonate relatively long in the room where the performance is being conducted. Figure 4 shows 10-second samples of simultaneous recordings from a performance of a *garap* of *Gambyong Pare Anom* recital at four measurement positions.

As can be seen in Figure 4, loudness at position 3 was the highest, while at position 2 it was the lowest. The differences in loudness are caused by the difference in acoustic characteristics of the *ricikans* around each position.

As mentioned previously, the frequency characteristics of the sound perceived by the musicians guides them during the performance. The richness of frequency (temporal) can be obtained from the τ_e parameter [6,7]. Figure 5 shows values of τ_e that were estimated from sound recorded at the four measurement positions as a function of time.

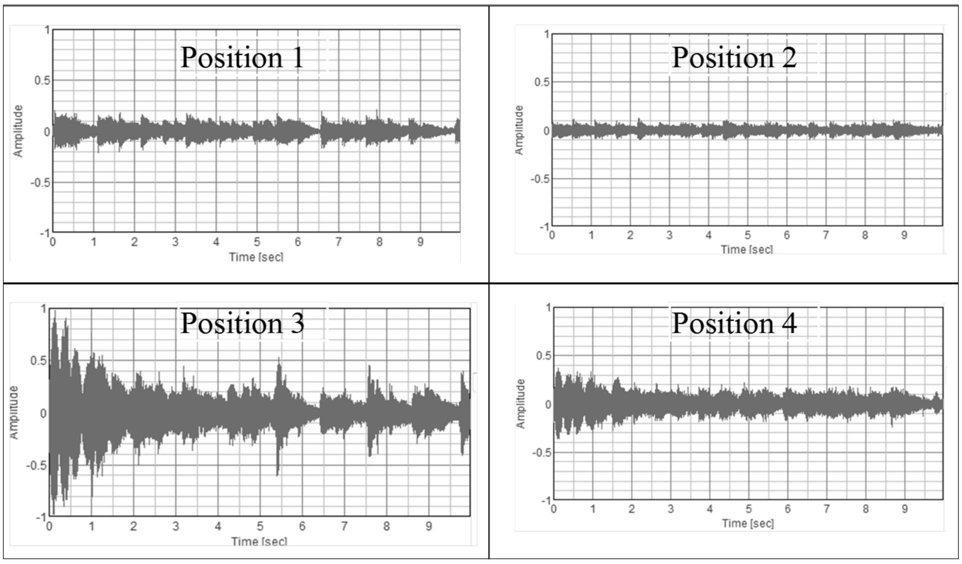

Figure 4 The signal for the 4th position of measurement.

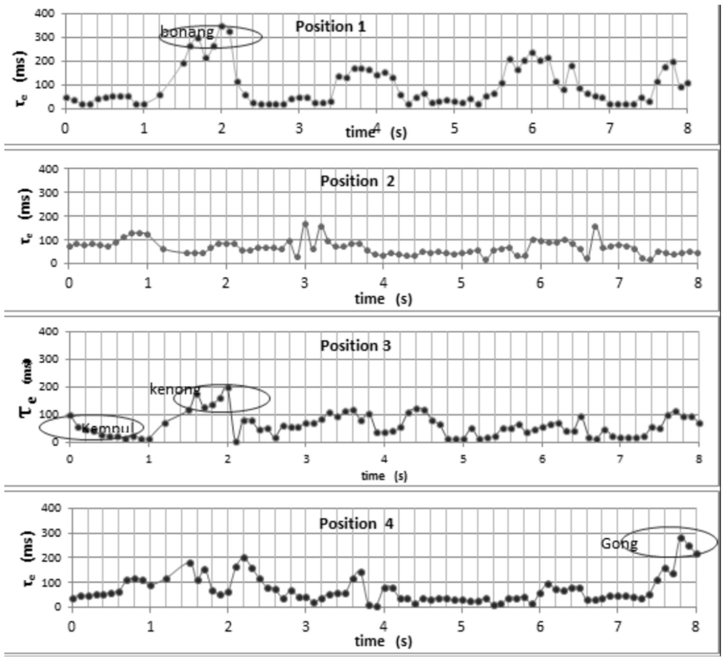

Figure 5 Values of τ_e parameter for this performance.

Referring to Figure 5, throughout the performance, the value of τ_e at positions 1 and 3 fluctuated more dynamically compared to those at positions 2 and 4. The fluctuation shows the difference in notes being played on the different *ricikans* and frequency content at the measuring position. Fluctuation of τ_e throughout the performance occurs because the sounds generated by the *demung*, the *bonang*, and the *saron* at these two positions are more dominant, with large changes in amplitude and frequency. Meanwhile, the *ricikans* at positions 2 and 4 are played in a more stable manner and produce overlapping frequencies. For example, in the period of 1 to 2 seconds, the value of τ_e at positions 1 and 3 were higher than at any other period of time because the frequencies of the *demung* and the *bonang* are noticeably more dominant than that of any other *ricikan* (see Figure 5).

Overall, the changes in τ_e value at positions 1, 3, and 4 were more fluctuating. This is because more *ricikans* are played at a different octave at positions 1, 3, and 4. Especially at position 3 there is higher intensity. In contrast, the value of τ_e at position 2 is the most stable due to the way the *ricikans* are played (in this case the *slenthem* and the *gender*). To determine the τ_e value of the dominant sound during the performance, distributions of τ_e were created as shown in Figure 6.

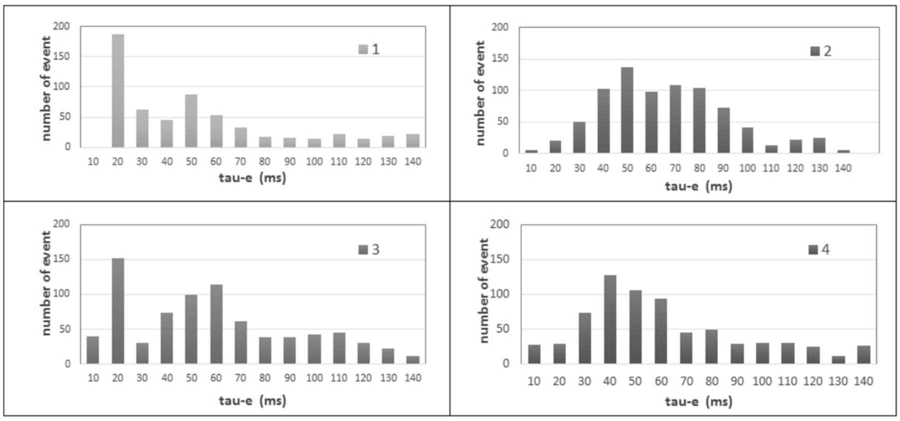

Figure 6 Distribution of τ_e for 4th position.

3 Discussion

Referring to Figure 6, position 1 and 3 were dominated by sound with a τ_e of 20 ms, while positions 2 and 4 were dominated by sound with a τ_e of 50 and 40 ms, respectively. This means that the sound at positions 1 and 3 contained a larger variety of frequencies than at positions 2 and 4. Further, Figure 7 shows that more *ricikans* were played at positions 1 and 3 with different frequencies than those played at positions 2 and 4.

Actually, position 1 was surrounded by a group of *ricikans* consisting of *bonang*, *kendang*, *demung*, and *saron*. *Ricikans* of this group are played quite loudly, while each *ricikan* has a different fundametal frequency. Position 2 was surrounded by a group of *ricikans* consisting of *kendang*, *peking*, *gendher* and *slenthem*. This group of *ricikans* produces sounds with an overlapping fundamental frequency and low intensity, except for the *peking*. Position 3 was surrounded by a group of *ricikans* consisting of *kenong*, *gong*/*kempul*, *demung* and *saron*. *Ricikans* from this group are only played at certain times. This group produces sounds with high loudness, where each *ricikan* has a different fundamental frequency. Meanwhile, position 4 was surrounded by a group of *ricikans* consisting of *gambang*, *peking* and *gong*/*kempul*. Each *ricikan* in this group produces a sound with a different fundamental frequency and is played in a different manner. For an example, *gambang* and *peking* are each played by striking twice for each tone, so that their sound resonates longer at the same tone or frequency. Figure 7 shows the frequency content of the sound at each measuring position.

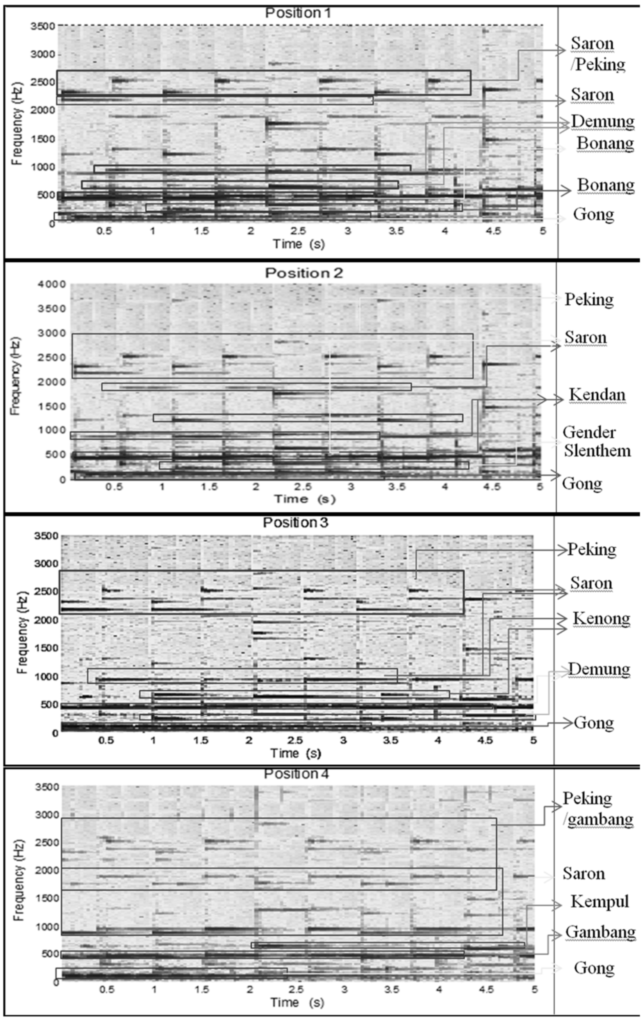

Figure 7 Spectrograms of sound obtained at four measurement positions.

Figure 7 clearly shows that the dominant sound frequencies at all four of the measuring positions were close to 500 Hz but with different intensities. This is due to the sound envelopes of certain *ricikans*, especially the *kempul*/*gong* and the *demung*. These *ricikans* have sound envelopes of more than 5 seconds [2,3], which is relatively longer than the time elapsed between tones (around 0.3 seconds). In effect, this results in sound masking due to the *ricikan*(*s*) being struck again before the sound passes its fade-away time. Therefore, in some performances, especially those with a fast tempo, a *ricikan* can be damped immediately after being struck (a technique called *pithèt*) to allow the sound to fade quickly and to prevent sound overlap that might mask the next tone.

At position 1, the sounds of *bonang*, *kendang*, *demung*, and *saron* were more dominant with medium frequencies and higher intensity with respect to the other *ricikans*. At position 2, medium and high frequencies were dominant, with lower intensity. At this position, the sounds came from *slenthem*, *gender*, and *kendang*. They produce medium and high-frequency sounds, as well as overlapping frequencies. At position 3, the sounds in the medium frequencies were dominant with higher intensity compared to the other positions. The sounds come from *demung*, *saron*, and *kenong*, which are more dominant and produce the highest sound intensity at different octave frequencies. Unlike at the other positions, the sounds produced at position 4 were dominated by higher frequencies and intensities, especially coming from the *peking*. On the other hand, the *gambang* produced a sound at medium frequency and low intensity. The *peking* and the *gambang* are played in a different way compared to the other *ricikans*: they are struck twice for each note, which results in an extended duration of the sound.

Figure 7 shows that the richness of frequency at position 4 was relatively poor. However, during some periods, the values of τ_e at this position increased due to the emergence of sounds from the *gong*/*kempul*. As a result, frequencies and levels of *gong* and *kempul* were more dominant and tended to be more stable and more obvious than those of other *ricikans*. This result is represented by peaks around 8 seconds in the graph of τ_e shown in Figure 6.

Referring to Figure 7, the acoustic parameters needed by each musician to maintain communication and harmony are often not only generated by *ricikans* nearby but also by *ricikans* located relatively far away from the musician. Therefore, each gamelan musician has to have the ability to identify the color of the sound (timbre) produced by each *ricikan* around him/her.

In this research, the dimensions of the stage of the object of measurement were 6 m x 8 m, leaving only a small distance between the *ricikans* arranged on stage. In this situation, at one position a gamelan musician may hear sound not only from *ricikans* very near to his/her position. This situation can be verified from the frequency content at each position, as shown in Figure 5. For example, in position 2, close to the *slenthem* and the *gendher*, the frequency of the *saron*, which was located at a greater distance, was received as well. The same thing happened at position 1: not only the sound of the *bonang* and the *demung* but also the sound of the *peking* and the *kempul* were clearly audible from position 1.

As mentioned before, in order to maintain the harmony of a performance, each musician frequently needs not only acoustic characteristics of the *ricikans* close by, but also from those that are further away. Beside the parameters of LL and frequency, harmonization and communication between musicians are influenced by the reverberation time. Based on the value of τ_e, the subsequent reverberation time can be determined in Eq. (4) [6,7]:

$$T_{sub} \cong 23\tau_e \tag{4}$$

Using Eq. (4), the values of T_{sub} for the Javanese gamelan performance at the four measurement points are shown in Table 1.

Table 1 Values of T_{sub} on the stage.

Position	τ_e **(ms)**	T_{sub} **(ms)**
1	20	460
2	40	1150
3	20	460
4	50	920

Reverberation time influences the clarity of the sound heard by each musician. The reverberation perceived by the musicians is actually influenced by the richness of frequency of the sound produced at different fundamental frequencies and overtones of the *ricikans* as well as by the way each *ricikan* is being played. Therefore, the value of τ_e can be used to design acoustics parameters of stage (and room) of a performance and the *ricikan* layout onstage.

4 Conclusions

As a kind of music ensemble, a Javanese gamelan consists of a number of *ricikans* arranged on a stage in a specific manner to accommodate communication between the musicians in order to keep the performance in harmony. The number of *ricikans* around each musician and their acoustic characteristics are also crucial for maintaining communication during a performance. Frequently, a musician not only needs sound parameters from *ricikans* that are nearby but also from *ricikans* that are further away. One of the acoustic parameters that are needed by Javanese gamelan musicians is sound color (timbre). The richness of the audible frequencies can be identified by the τ_e parameter. The recording and analysis of the intro of the *Gambyong Pare*

Anom dance played by a traditional Javanese gamelan showed that measurement position 1 on stage had a τ_e of 20 ms, position 2 had a τ_e of 50 ms, position 3 had a τ_e of 20 ms, and position 4 had a τ_e of 40 ms. The difference in τ_e represents the difference in frequency richness and the dominant sound of the *ricikans* around the musicians, including the sound reverb and sound level around their positions.

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