PRESENTS

A Model for the prediction of Sound Levels within a Symphonic Orchestra based on measured Sound Strength

by R. H. C. Wenmaekers, C. C. J. M. Hak and L. C. J. van Luxemburg

Summary

Members and directors of symphonic orchestras are concerned about the noise levels musicians are exposed to and their ease of playing ensemble. The results of many research has shown that the noise levels within an orchestra can be high. Also, research has shown that the sound level will vary between different musicians playing different instruments and musical pieces or musicians being positioned differently on various stages. Aspects of influence on sound levels can be musically based: the piece and its interpretation by the orchestra; or acoustically: the impact of the stage and hall acoustics. However, the contribution of each instrument and each acoustical aspect on the total sound level cannot be determined from sound level measurements. Therefore, a sound level prediction model is proposed based on the sound strength G and the early to late reflection ratio LQ7-40. For every combination of two orchestra instruments, the direct, early reflected and late reflected sound energy transfer is calculated. In the direct sound transfer, the directivity and sound power of the instrument and the attenuation of the orchestra are taken into account. The early and late reflected sound energy is based on the sound power and on measured values of G and LQ7-40. From the individual sound level contributions, the total sound level and balance between different instruments and different acoustical aspects can be calculated. First results show that the model gives insight in the sound levels within a symphonic orchestra from a health as well as a musical point of view.

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Remy H.C. Wenmaekers
Level Acoustics & Eindhoven University of Technology, Eindhoven, The Netherlands.
Constant C.J.M. Hak
Eindhoven University of Technology, Eindhoven, The Netherlands.
L.(Renz) C.J. van Luxemburg
Level Acoustics & Eindhoven University of Technology, Eindhoven, The Netherlands.

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Members and directors of symphonic orchestras are concerned about the noise levels musicians are exposed to and their ease of playing ensemble. The results of many research has shown that the noise levels within an orchestra can be high. Also, research has shown that the sound level will vary between different musicians playing different instruments and musical pieces or musicians being positioned differently on various stages. Aspects of influence on sound levels can be musically based: the piece and its interpretation by the orchestra; or acoustically: the impact of the stage and hall acoustics. However, the contribution of each instrument and each acoustical aspect on the total sound level cannot be determined from sound level measurements.
Therefore, a sound level prediction model is proposed based on the sound strength G and the early to late reflection ratio $LQ_{7\text{-}40}$. For every combination of two orchestra instruments, the direct, early reflected and late reflected sound energy transfer is calculated. In the direct sound transfer, the directivity and sound power of the instrument and the attenuation of the orchestra are taken into account. The early and late reflected sound energy is based on the sound power and on measured values of G and $LQ_{7\text{-}40}$. From the individual sound level contributions, the total sound level and balance between different instruments and different acoustical aspects can be calculated. First results show that the model gives insight in the sound levels within a symphonic orchestra from a health as well as a musical point of view.

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1. Introduction

Members and directors of symphonic orchestras are concerned about the noise levels musicians are exposed to and their ease of playing ensemble [1]. The result of earlier investigations has shown that the noise levels within an orchestra can cause hearing loss [2]. Also, research has shown that the sound level will vary between different musicians playing different instruments and musical pieces or musicians being positioned differently on various stages [3]. Aspects of influence on sound levels can be musically based: the piece and its interpretation by the orchestra; or acoustically: the impact of the stage and hall acoustics. However, the contribution of each instrument and each acoustical aspect on the total sound level cannot be determined from sound level measurements.

Therefore, a sound level prediction model is proposed where the direct, early reflected and late reflected sound energy transfer is calculated based on measured data and a geometric model of a generic symphonic orchestra. From the individual sound level contributions, the total sound level and balance between different instruments and different acoustical aspects can be estimated. In this paper, the proposed method will be described and an example of the necessary input data will be presented. Also, the possible output of the model using different presenting styles will be discussed. Finally, suggestions are made for further development of the model.

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2. Method

The receiving sound levels of different musicians in a symphonic orchestra at a musicians' or conductors' position depend on many aspects. For every receiver the energy as well as frequency balance of the sound levels is different. When only considering acoustical aspects, and discarding musical aspects, the sound level of a single sound source at a receiver position can be described using the properties of the sound source, the sound path and the receiver. The model which is proposed hereafter is summarized in figure 1.

2.1. Sound source

In general a sound source can be described by the sound intensity $L_I(f,\varphi,\theta,d)$ which is frequency (f), orientation (elevation φ and azimuth θ) and distance (d) dependant. However, a musical instrument can not easily be defined by these parameters, because the spectrum and directivity may change per note and playing style. When assessing sound levels, one is often interested in an average value over time. It may then be legitimate to use average values. In this model, measured average values of sound intensity $L_I(f,\varphi,\theta)$ for common orchestral instruments at a single fixed distance are used from Pätynen & Lokki [4]. To asses spectral and loudness differences between instruments the sound power L_w is needed, which is derived from calibrated anechoic recordings by Pätynen et al. [5].

2.2. Sound path

The transfer of sound from a sound source to a receiver in a room can be fully described by the room impulse response, which can either be measured or predicted. However, in case of a musical instrument this implies that the impulse response should be determined using a sound source with the average directivity properties for every musical instrument. Also, the impulse response must be determined under the same conditions of a concert or rehearsal, which implies that the orchestra and/or audience must be taken into account.

In this model, the impulse response is divided in three typical room acoustical aspects to study the balance between them: the direct sound, the early reflected sound and the late reflected sound. The direct sound path is of interest to study the influence of available space and screens. The early reflected sound is generally considered to be meaningful for ensemble playing on stage while the late reflected sound may contribute to a sense of feedback from the hall [6].

The direct sound is calculated analytically so that the influence of directivity of the sound source and the obstruction of the orchestra can be integrated. The early and late reflected sound energy is estimated from measured room impulse responses using an omnidirectional sound source on an empty stage. At the moment, there is no method available to translate these values so that source directivity and orchestra attenuation can be integrated.

2.2.1. Direct sound

The direct sound path depends on the source-receiver distance and orientation of the source relative to the receiver, assuming that the source musician is looking into the conductors' direction. Besides that, the attenuation of the orchestra is included from measured values of $\Delta L(f)$ by Dammerud [7].

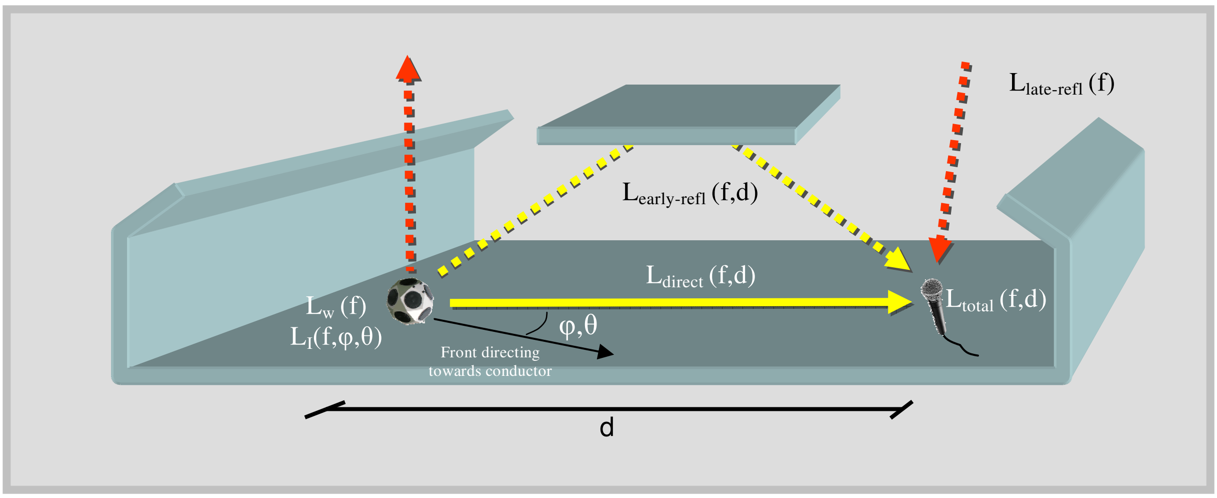

Figure 1: summary of the source – receiver model

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L_{direct} is then determined from equation 1 and 2:

$$L_{direct}(f,d) = L_{eq;1m}(f,\varphi,\theta) - 20\lg(d) + \Delta L(f,d) \quad (1)$$

$$\Delta L(f,d) = a(f)\cdot d + c(f) \quad (2)$$

Where,

- $L_{eq;1m}$(f,φ,θ) is the sound level in dB at 1 meter distance per frequency band in Hz at elevation φ and azimuth θ in degrees estimated from measured values of sound intensity L_I(f,φ,θ) and $L_{eq;1m;front}$ (f) derived from the frontal anechoic recordings of every instrument. This input data will be treated in section 3.2 and 3.3;
- d is the source receiver distance in meters;
- ΔL(f) is the attenuation by the orchestra in dB estimated from measurements by Dammerud [7] using an attenuation factor 'a' in dB loss per meter through the orchestra and a constant 'c' in dB for the overall shift of attenuation due to the effect of the floor and orchestra reflections, see table II in [7].

2.2.2. Early reflected sound

The early reflected sound level $L_{early\text{-}refl}$ is estimated from the sound power L_w of the instrument and the measured sound strength for the time interval 7 to 40 ms denoted $G_{7\text{-}40}$ [8], based on an estimated transition time point of 40 ms between early and late sound [9]. The $G_{7\text{-}40}$ can be determined from a measured impulse response using equation 3.

$$G_{7-40}(f) = 10\lg\left[\frac{10^{\frac{G(f)}{10}}}{1+10^{\frac{C_{40}(f)-LQ_{7-40}(f)}{10}}}\right] \quad (3)$$

Where,

- G(f) is the sound strength in dB per frequency band in Hz [10];
- C_{40}(f) is the clarity in dB per frequency band in Hz [10] based on an estimated transition time point of 40 ms between early and late sound;
- $LQ_{7\text{-}40}$(f) is the early to late reflection ratio in dB per frequency band in Hz based on an estimated transition time point of 40 ms between early and late sound [11].

The $G_{7\text{-}40}$ depends on the distance between the source and receiver and is stage and hall dependant. In this research, the $G_{7\text{-}40}$ is estimated based on a logarithmic regression of 32 measured values at various distances for 7 different concert hall stages [8]. The measured results of $G_{7\text{-}40}$ will be treated in section 3.5.

The early reflected sound level $L_{early\text{-}refl}$ is than determined using equation 4 and 5.

$$L_{early-refl}(f,d) = L_w(f) + G_{7-40}(f,d) - 31 \quad (4)$$

$$G_{7-40}(f,d) = A(f)\cdot\lg[d] + C(f) \quad (5)$$

Where,

- L_w(f) is the sound power in dB per frequency band in Hz estimated from measured values for every instrument derived from anechoic recordings by Pätynen et al. [5]. This input data will be treated in section 3.3;
- $G_{7\text{-}40}$(f,d) is the early reflected sound strength in dB per frequency band in Hz and distance in meters. Following Dammerud's approach a variable factor 'A' in dB/m and a constant 'C' in dB is used, see section 3.5;
- d is the source receiver distance in meters.

2.2.3. Late reflected sound

The late reflected sound level $L_{late\text{-}refl}$ is determined from the sound power L_w of the instrument and the measured sound strength for the time interval 40 ms to infinity denoted $G_{40\text{-}inf}$ [8] using equation 6 and 7. The $G_{40\text{-}inf}$ is not dependant on the source to receiver distance, so a fixed value per stage is used, see section 3.4.

$$G_{40-\inf}(f) = 10\lg\left[\frac{10^{\frac{G(f)}{10}}}{1+10^{\frac{C_{40}(f)}{10}}}\right] \quad (6)$$

$$L_{late-refl}(f) = L_w(f) + G_{40-\inf}(f) - 31 \quad (7)$$

Where,

- G(f) is the sound strength in dB per frequency band in Hz [10];
- C_{40}(f) is the clarity in dB per frequency band in Hz [10] based on an estimated transition time point of 40 ms between early and late sound;
- L_w(f) is the sound power in dB per frequency band in Hz.

2.3. Receiver

The ears are highly sophisticated sound receivers, with varying sensitivity to frequency and directionality towards the viewing direction. The varying sensitivity is introduced in this model by A or C weighting the sound level. However, the model can also be used to consider separate frequency bands. So far, the directional hearing is not taken into account by the model.

3. Input parameters

3.1. A generic orchestra setup

Different types of orchestra setups are interesting to study [4]. An example of a possible setup is shown in figure 2. The different musicians and conductor are numbered 1 to 100 and placed on a 2D rectangular grid with a variable musician distance in x and y direction. The rectangular grid may not always represent the orchestra setup at best, but gives the advantage that the influence of available space and stage size can be studied easily by changing the musician distance in x and y direction. To study differences in height, the distance z of each instrument is also defined.

					clr		perc	timp	bso	trb				tba	
	59	60	61	62	flu	81	82	80	obo	75	76	77	78	79	
hrns	56	57	58	63	64	65	66	67	68	69	70	71	72	73	74
	23	24	25	48	49	50	51	52	53	54	55		trp		
vi2	17	18	19	20	21	22	30	31	32	33	vla				
	11	12	13	14	15	16	26	27	28	29		cel	46	47	dbl
	6	7	8	9	10				38	39	40	41	44	45	
vi1	1	2	3	4	5		100	cond	34	35	36	37	42	43	

Figure 2: example of an orchestra on a rectangular grid

3.2. Directivity

For every type of instrument, the directivity is estimated from measured values by Pätynen & Lokki [4]. The relative sound intensity $L_I(f,\varphi,\theta)$ of the instrument is made available trough a Matlab GUI for the octave bands 125 Hz to 16 kHz in accordance with the common loudspeaker format (CLF) with steps of 10 degrees. This results in 8 x 614 = 4,912 data points per musical instrument.

The CLF format is defined by 36 arcs running from the front to the back of the sound source. This results in a finer grid where the sound source directivity is usually the highest. In this model the CLF output is calculated without rotating the base of the original coordinate system 90 degrees downwards on the transverse axis [14]. This way, the angle between a source and receiver is easily defined by elevation φ and azimuth θ. The front orientation of the directivity is defined as the frontal viewing direction of the musician.

3.3. Sound power

The sound power $L_w(f)$ is obtained from anechoic recordings of four different pieces made available by Pätynen et al. [4]. The equivalent sound pressure level $L_{eq;front}(f)$ in dB is determined for every recording of the frontal microphone no. 6 per instrument and musical piece using the software Dirac 5.0. The silent parts in the recordings have not been removed, so results can be interpreted as a sound exposure level for the particular piece of music. An absolute sound level calibration was made available by Pätynen.

The sound power $L_w(f)$ is calculated using equation 8.

$$L_w(f) = L_{eq;front} + 20\lg(d) + 10\lg\left(\sum_{n=1}^{N} S_i 10^{\frac{L_I(f,\varphi,\theta)}{10}}\right) \quad (8)$$

Where,

- $L_{eq;front}(f)$ is the equivalent sound pressure level in dB per frequency band in Hz at the front of the musician at microphone no. 6;
- S_i is the partial surface in m^2 per angle of the directivity data on a sphere of 1 m radius (N=614);
- $L_I(f,\varphi,\theta)$ is the relative sound intensity at elevation φ and azimuth θ in degrees (N=614), the musicians viewing direction is defined as 0 dB;
- d is the microphone distance in meters, d = 2,3.

To be able to compare L_{direct} to $L_{early\text{-}refl}$ and $L_{late\text{-}refl}$ the sound level at 1 m distance $L_{eq;1m}(f)$ has been determined.

3.4. Direct sound level own instrument

The direct sound level of the own instrument is modelled by using a fixed source receiver distance per instrument. For most instruments this distance is estimated to be 0.5 meter, except violins where the estimated distance is 0.3 m. An angle of 180 degrees from the musicians viewing direction is used when calculating the directivity, except for the horns where 0 degree is used. Further research is needed to optimise these distances and angles.

3.5. Measured values of $G_{7\text{-}40}$ and $G_{40\text{-}inf}$

As an example, average mid-frequencies values (500 and 1000 Hz) of $G_{7\text{-}40}$ and $G_{40\text{-}inf}$ have been calculated for 36 combinations of 4 source (S) and 9 receiver (R) positions for 7 different stages A to G [12] using software Dirac 5.0. For every source and receiver combination, 4 impulse responses have been measured while rotating the omnidirectional sound source in equal steps of 90 degrees. The average and maximum standard deviation of 4 rotations at one position is $\sigma_{average} \leq$ 0.4 dB and $\sigma_{max} \leq$ 1.2 dB for the mid-frequency range of 2,016 data points. (Recent research has shown that 5 equal-step rotations may result in a considerable reduction of uncertainty [13]). The mutual distance between S and R positions varies

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between 2 and 10.6 meters and is on average 5.3 meters.

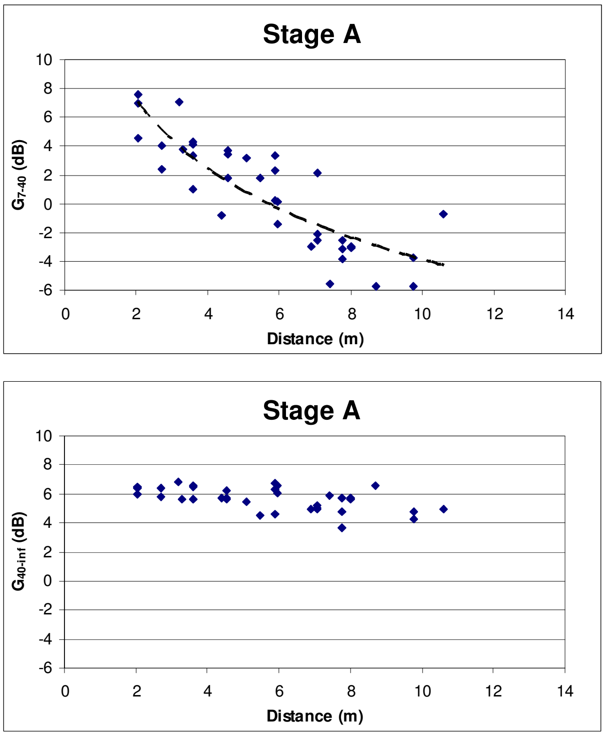

Figure 3: measured $G_{7\text{-}40}$ and $G_{40\text{-}inf}$ on stage A

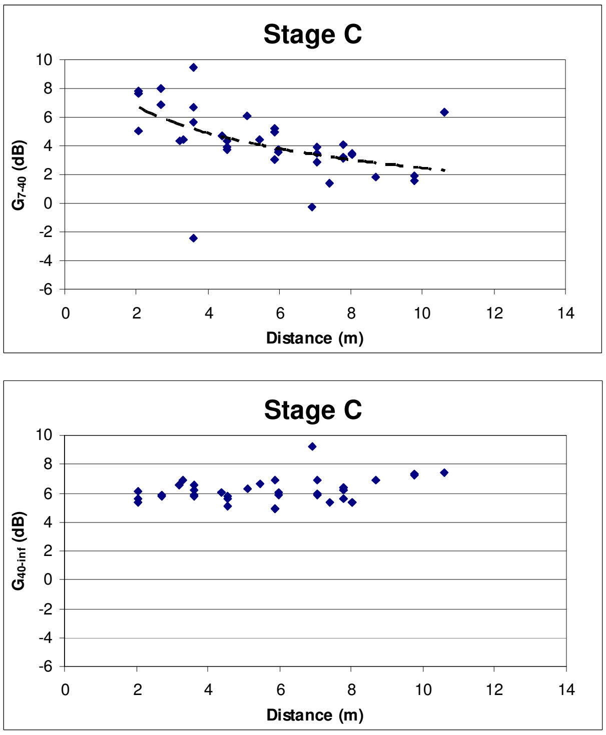

Figure 4: measured $G_{7\text{-}40}$ and $G_{40\text{-}inf}$ on stage C

Figure 3 and figure 4 shows the results from measured $G_{7\text{-}40}$ and $G_{40\text{-}inf}$ per source-receiver distance for stage A with a disputable reputation and stage C with a good reputation in terms of stage acoustics. Results from both stages show a clear dependency of distance for $G_{7\text{-}40}$ with a spread from the dashed logarithmic regression line of approximately 2 dB. The results for $G_{40\text{-}inf}$ show no clear dependency of distance for both stages and also have a spread of approximately 2 dB.

Table 1: mid frequency input for $G_{7\text{-}40}$ in dB from a variable factor 'A' in dB/m and a constant 'C' in dB see equation 5 and $G_{40\text{-}inf}$ in dB

	$G_{7-40} = A \cdot \lg[d] + C$		$G_{40\text{-}inf}$
Stage	A [dB/m]	C [dB]	[dB]
A	-15,7	11,9	5,7
B	-5,3	6,4	8,6
C	-6,2	8,6	6,1
D	-3,0	3,3	6,4
E	-7,6	6,0	5,3
F	-8,5	5,0	7,8
G	-8,3	6,8	7,0

More research is needed to validate and improve this method. Among other things, the transition time point of 40 ms needs further investigation [6, 8]. Also, the measurement uncertainty increases at frequencies above 1000 Hz [13] and results over distance show a considerable spread. Finally, more research is needed to develop a method that takes into account instrument directivity and orchestra attenuation on $G_{7\text{-}40}$ and $G_{40\text{-}inf}$ [6, 8].

4. Output processing and presentation

The output of the model is values for $L_{direct}(f)$, $L_{early\text{-}refl}(f)$ and $L_{late\text{-}refl}(f)$ for every combination of source and receiver position. Also, values for $L_{total}(f)$ can be determined. For a symphonic orchestra of 100 musicians this results in 10,000 values for every parameter and frequency band. The sound energy of sound sources with equal instrument and musical parts can be summed to study grouping effects. The values can be generated for different pieces of music.

The model can give insight in the sound exposure per receiver per room acoustical aspect or in total. The results can be presented in a mapping for the whole orchestra. In this way, an assessment can be made of the contribution of the orchestra setup, the different instruments and the acoustics of the stage and hall to the sound exposure on stage.

Secondly, the contributions of different musicians to the sound exposure at a single receiver can be studied per room acoustical aspect or in total. These results can also be presented in a mapping per receiver position to visualise where most of the sound is coming from.

Thirdly, the contributions of room acoustic aspects on the sound exposure per source group can be determined for every receiver. This can give insight in de balance between different instrument groups and what room acoustics aspects are causing this balance. For instance, it can be assessed when early reflected sound is contributing to the playing ensemble or when masking may occur by late reflected sound.

5. Further research

The proposed model for the prediction of sound levels within a symphonic orchestra based on measured sound strength seems promising. However, many different input parameters are required of which some are uncertain. Also, the calculations are extensive. More results will follow after succeeding research.

So far, the sound strength parameters can not be determined from measurements using the real directivity of the musical instruments. More research is needed to investigate which uncertainties are introduced by using an ominidirectional sound source. This could be studied using image source and raytracing models.

Besides that, the influence of the attenuation by the orchestra on the sound strength is not taken into account. The deviations by measuring on an empty stage can be high. Further research is necessary to develop a method to translate values measured on an empty stage.

6. Acknowledgements

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