Measurement of Stage to Pit Balance in Four Proscenium Arch Theatres

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Introduction

In terms of acoustics, proscenium arch theatres are fundamentally different from concert halls. Concert halls, in the classical sense, have a single distributed sound source at one end of a room and group of listeners at the other end. A theatre has two sound sources in acoustically dissimilar rooms and an audience in a third equally dissimilar room. In a concert hall, the musicians are in the same acoustical space as their associates and their audience. In a theatre the singers and instrumentalists are in two very different spaces - the stage and the orchestra pit. The audience, of course, is in yet another space. The differences between a theatre and a concert hall are deceptive: subtle at first glance and formidable upon further examination.

Despite this, the acoustical study of theatres is, in many ways, borrowed technology, either from concert halls or telephony. One unique aspect of theatre acoustics is the balance that must be struck between singers on stage and the instrumentalists in the orchestra pit. In the acoustical sense, measured Balance is a simple logarithmic ratio of sound emanating from the stage to sound from the pit. Values greater than zero indicate that the sound from the stage predominates. To date, Balance has received little attention in the literature.

Barron measured Balance in three English proscenium arch theatres[1]. He published broadband data indicating average values of approximately +2 dB with a range of 4 dB in each room. He noted that areas of poor balance were localized and specific to the particular house. Unpublished broadband data from the Opera Bastille in Paris also shows an average value of -2 dB[2]. The covered pit at the Princess of Wales Theatre in Toronto Canada led to Balance levels much higher than other rooms with open pits, in the range of 7 to 10 dB[3]. Measurements in the Queen Elizabeth Theatre in Vancouver, Canada suggested that the frequency characteristics of Balance may be important[3].

The Basics of Balance

Singers in a theatre or opera house are often at a disadvantage because they are out numbered by instrumentalists in the orchestra pit. Two things help to mitigate this, the geometry of the room and nature of a singer’s voice.

Singers trained in the western operatic tradition develop a fifth formant, one more than a typical speaker[4,5]. The formant is centred around 2500 to 3000 Hz and is the principle mechanism by which a single singer is able to project over the much stronger forces of an orchestra. The fact that the orchestra is located underneath the stage, in a room that is often poorly coupled to the audience chamber, also works to the singer’s benefit.

From a listener’s perspective there are two distinct scenarios in a proscenium arch theatre: Balance on the orchestra level (stalls) and Balance on the balcony. On the orchestra level, the orchestra pit is all but invisible. Direct sound from the pit is thus subject to barrier effects caused by the pit rail and the first few rows of seats. Sound from the stage propagates towards the orchestra level listener at grazing incidence and is subject to related phenomena: the well known seat dip effect[6,7] and the less familiar "head dip".

Listeners on the balcony generally have a clear view of most of the orchestra pit and the stage. As such, barrier effects are of little concern. Balcony seats are also more likely to receive early reflections from the ceiling that will help mitigate problems like seat dip. In a proscenium arch theatre, the best sounding seats are often on the balcony.

The seat dip effect results in selective low frequency attenuation of sound propagating across theatre seating at grazing incidence. Attenuation can be as much as 20 dB. Seat dip frequencies range from 80 to 200 Hz, covering the fundamentals of voices and musical instruments from the musical notes approximately E2 to G3. Davies et al.[8] recently established thresholds of perception for seat dip at 3.8 ± 0.2 dB for an 80 ms time window and 5.7 ± 0.4 dB for a shorter 40 ms window.

Recent work by Mommertz[9] has substantiated early studies by Meyer, Kuttruff and Schulte[10] suggesting a high frequency "head dip" effect. Head dip is caused by the scattering of sound by audience members' heads and, like seat dip, can result in losses as much as 20 dB. The frequency of maximum attenuation increases with the distance between the source and the receiver, peaking in the range of 4000 Hz. Like seat dip, the head dip phenomenon decreases rapidly when the sound path is raised above grazing incidence. Head dip frequencies coincide with the singers formant, for source receiver distances greater than approximately 10 m.

Measurement Techniques

Measurements were performed in four unoccupied theatres, listed below:

Table 1

THEATRE	CITY	SEATS	BALCONIES	DESCRIPTION
McPherson Theatre	Victoria, B.C.	700	1	Vaudeville, long balcony
Royal Theatre	Victoria, B.C.	1,500	1	Vaudeville, long balcony
Centennial Auditorium	Saskatoon	2,000	3	1960s "opera house" format
O'Keefe Centre	Toronto	3,200	1	Fan-shaped

The four rooms provide a good representative sample of proscenium arch theatre styles. The two rooms in Victoria are vaudeville houses, typical of most of the early twentieth century theatre stock in Europe and North America. Both include the ubiquitous long balcony overhang. There is no orchestra pit to speak of in either theatre, merely a small 300 mm depression in audience floor at the foot of the stage.

The Centennial Auditorium in Saskatoon is a three tiered multi-purpose auditorium built in the late 1960s. Its layout is similar to an Italian opera house. For those familiar with Ottawa's National Arts Centre, it was designed by the same people at the same time. The two buildings are similar in many ways.

The O'Keefe Centre (recently renamed the Hummingbird Centre) is a classic example of a large post war fan shaped theatre. It is known for its poor acoustics and is currently undergoing renovation.

Directional and omni-directional sound sources were used on stage and in the pit, respectively. The omni-directional source was a dodecahedron with twelve 75 mm loudspeakers. The directional source was fashioned from the dodecahedron by sealing eleven of the speakers with 1.5 mm thick steel plates. The source locations are similar to those employed by Barron[1]; Central and Lateral directional sources on stage, and omni-directional sources in the 1st violin and Bass locations in the orchestra pit.

The excitation signal was a 15th order Maximum Length Sequence and the receiver was an omni-directional microphone. Measurements were performed at ten different seating locations for a total of forty measurements, yielding twenty Balance ratios per theatre. The seating locations were all on the same side of the auditorium, the rooms being symmetrical around the centre-line.

The McPherson Theatre and Centennial Auditorium were measured on empty stages with the upstage and wing curtains lowered in place. The Royal Theatre and O'Keefe Centre were measured with sets on stage. Both sets were rather spartan but included large reflecting surfaces.

Three of the four rooms had open pits. In the only exception, O'Keefe Centre, the two pit sources were located in the open part of the pit.

Balance ratios were calculated in 1/3 octave bands according to:

$$B_t = \frac{10\log\left(\int_0^t p_{stage}^2(f,\tau)d\tau\right)}{10\log\left(\int_0^t p_{pit}^2(f,\tau)d\tau\right)} + K(f) \qquad (1)$$

where: *t* is the temporal threshold between early and late sound

K(f) is the frequency dependant difference (in dB) between the directional and omni-directional sound sources on the stage and in the pit respectively.

Two early to late thresholds were employed: 10 ms and 50 ms. These were intended to quantify direct and early reflected sound respectively and are referred to as B10 and B50. Steady state ratios are simply referred to as B.

Typical Results

Broadband, steady state Balance values for all four rooms are shown in Table 1. These values are in general agreement with Barron's measurements of three British theatres, in the range of +2 dB. Ironically, the lowest B comes from the room that is closest in shape to a traditional opera house, The Saskatoon Centennial Auditorium. Differences between broad band steady state Balance on the balcony and the orchestra level (stalls) are small.

Table 2

Theatre	B (dB)	
	Orchestra	Balcony
McPherson	-0.9	-0.2
Royal	2.0	1.5
Saskatoon	-2.6	-2.1
O'Keefe	2.8	3.7

Figure 1 shows some typical results, in this case from The McPherson Theatre in Victoria. The graph includes some rough indicators of the salient frequency ranges for singers as well as the suggested criterion for Balance. For listeners on the orchestra level (stalls), low frequency Balance favours the instrumentalists in the orchestra pit, by as much as 13 dB. This is more than twice the seat dip threshold of perceptibility established by Davies et al.[8], suggesting that the measured difference is audible. On the balcony, this effect is less pronounced in The McPherson as well as the three remaining theatres.

Note that Balance dips towards the pit's advantage in the range the singer's formant. All the measurements in this survey displayed a similar dip, although in each case the measurements were performed in an unoccupied room. One would expect this situation to be exacerbated by head dip in an occupied room. In this frequency range three of the four rooms show little or no difference between results on the balcony or orchestra levels.

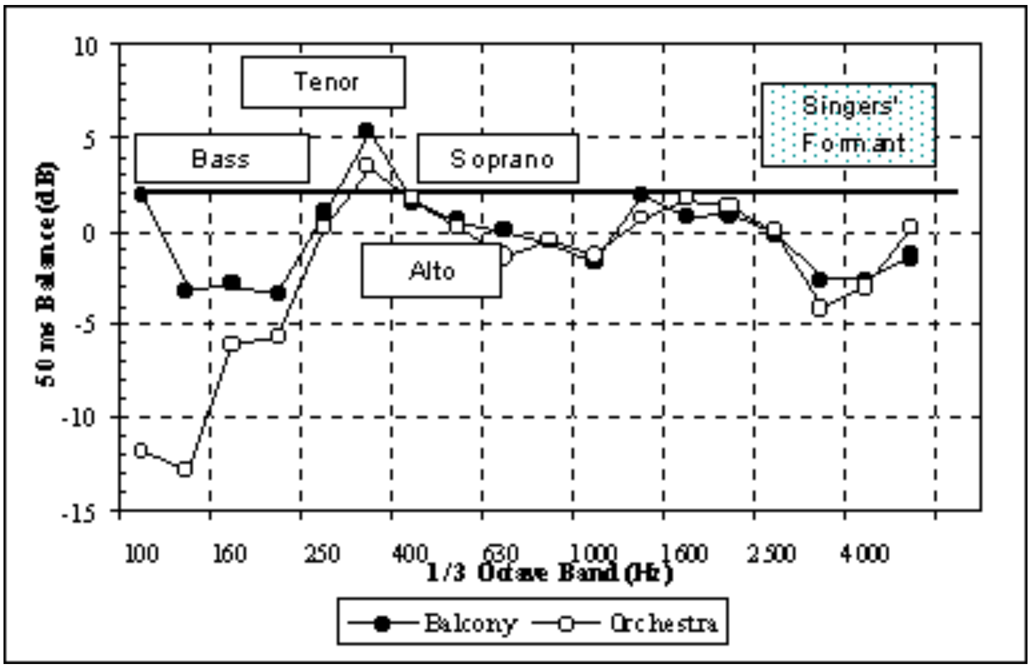

Figure 1 *50 ms Balance (B50) measured in The McPherson Theatre. Also shown in the graph are the approximate ranges of the four singing groups and the range of the singers' formant. The thick line indicates a (possible) optimum Balance. Above this line Balance favours the singers on stage, values less than this indicate a Balance in favour of the instrumentalists in the pit.*

Figure 2 and Figure 3 show the influence of source orientation on B50 at high frequencies. These measurements come from the Saskatoon Centennial Auditorium. As one might expect, when the directional source on stage is pointed towards the wings (Lateral), high frequency balance decreases significantly. On both the orchestra level (stalls) and the balcony, lateral high frequency Balance decreases by as much as 10 dB. In other theatres the difference was moderated somewhat, in the range of 4 or 5 dB. There are two possible reasons for this; one of the three rooms, The McPherson, was much narrower, the other two were measured with sets on the stage. The room cited in Figure 2 and Figure 3 was wide and measured with an empty stage.

For the middle frequency range, in three of the four rooms, the central source B50 is less than the lateral source B50. The reason for this is not immediately apparent. The Saskatoon Centennial Auditorium was the only room that did not demonstrate the middle frequency cross-over.

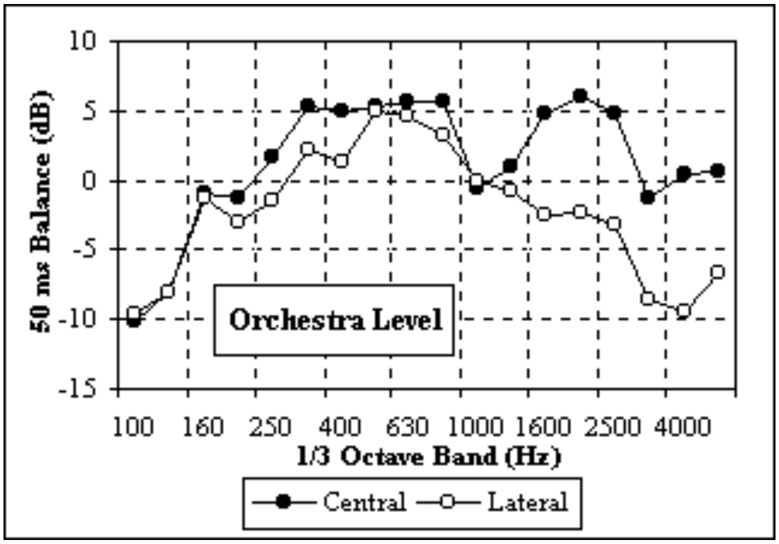

Figure 2 B50 measured on the orchestra level (stalls) in The Centennial Auditorium, Saskatoon. At high frequencies Balance varies significantly with source direction.

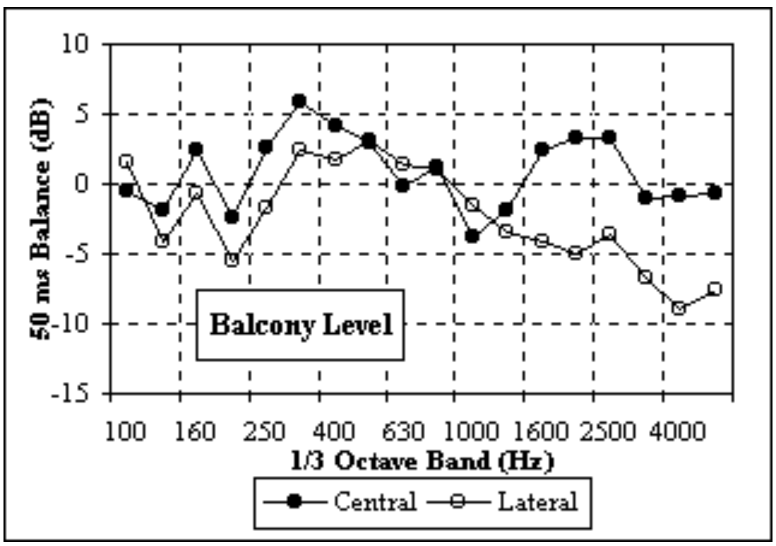

Figure 3 Measurements on the balcony of the same room as Figure 2. High frequency Balance varies with source direction as before although the degradation is less pronounced.

To summarize this section: in each of the four rooms reported here, three regions of the Balance graph can be identified. At low frequencies, B50 on the orchestra level (stalls) is much less than on the balcony. At middle frequencies, the central source Balance dips below the lateral source and there is little difference between the orchestra level and the balcony. At high frequencies, central source B50 is significantly higher than lateral source B50 and it appears that audience chamber and stage set geometry effect the extent of the difference.

The Effect of Orchestra Pit Level

The McPherson and Royal Theatres in Victoria are somewhat unique to North America in that they have very shallow orchestra pits, only 300 mm deep. There are, of course, many Baroque houses in Europe with similarly shallow pits. The other two pits in this study have hydraulic pit lifts that are now standard in most houses. Thus, these four theatres present a good opportunity to study the influence of the orchestra pit depth on Balance.

Intuitively, it should be expected that pit height has a greater influence for listeners on the orchestra level than for those on the balcony. Listeners on the balcony often have clear sight (and sound) lines to the pit regardless of its height. For listeners on the orchestra level however, the height of the pit should greatly influence the barrier like attenuation imparted by the pit rail or the first few rows of seats. Deeper pits should demonstrate greater high frequency barrier attenuation and thus tip the Balance in favour of the singers on stage.

Figure 4, below, shows B50 at the ten locations measured in the McPherson Theatre. As found in most of the theatres in this study, low frequency B50 favours the orchestra pit on all five of the measurement locations on the orchestra level (stalls). B50 increases on the balcony to more appropriate levels. However, a comparison with the 2 m deep pit in Saskatoon, shown in Figure 5, demonstrates very little consistent difference. A similar comparison at high frequencies was equally inconclusive. Steady state Balance ratios (B) were also insensitive to orchestra pit depth.

The problem with using B or B50 to quantify the effects of the pit depth is that they include the influence of reflected sound. It appears that pit depth effects direct sound much more than reflected sound. A demonstration of this was available through the two sets of measurements performed in Saskatoon, employing its hydraulic pit lift.

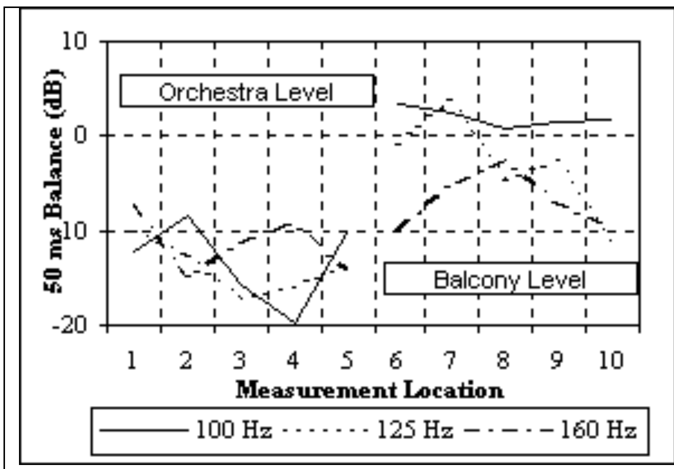

Figure 4 *B50 in The McPherson Theatre, Victoria B.C*

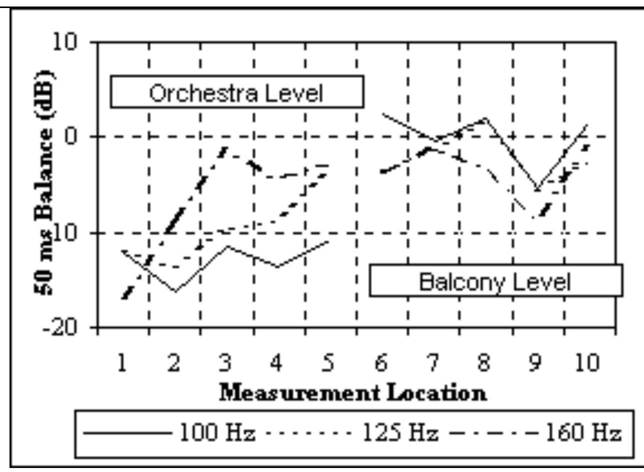

Figure 5 *B50 measured in Saskatoon Centennial Auditorium*

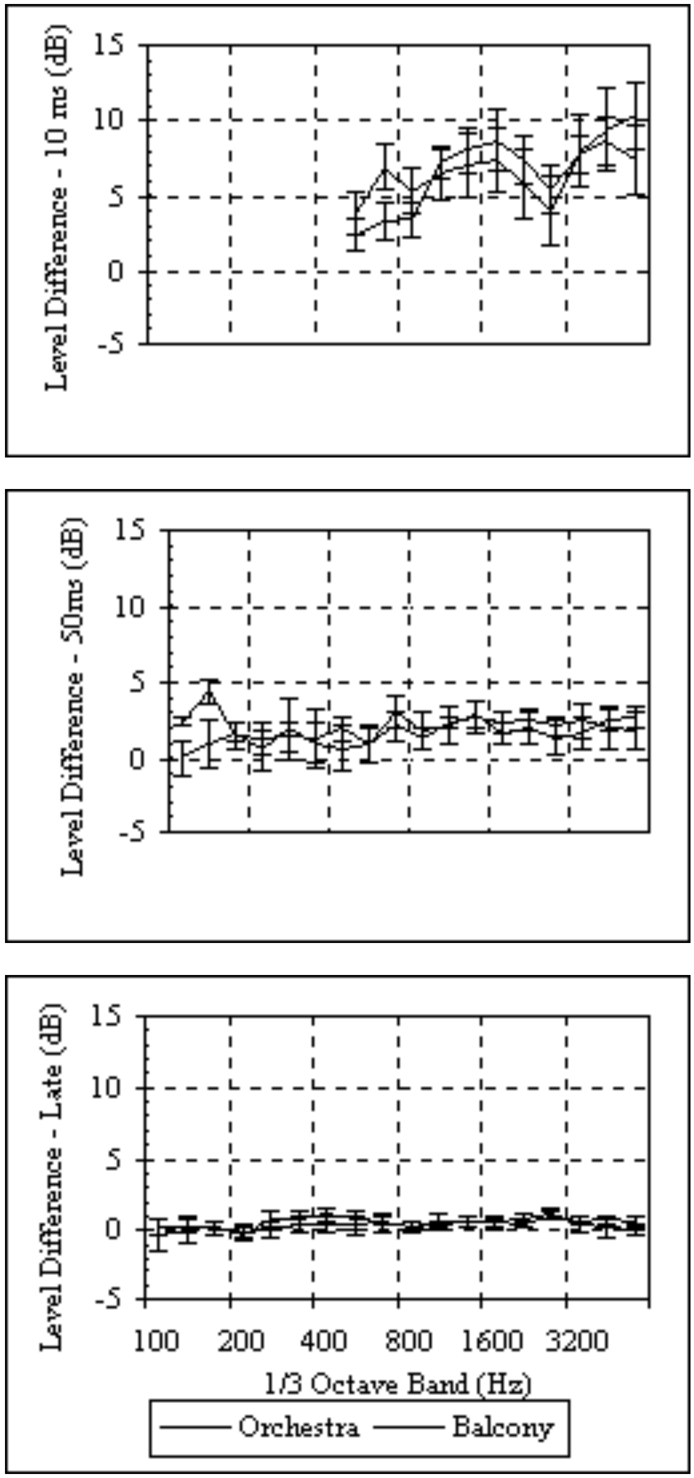

Figure 6 *Level difference between omni-directional sources at two different orchestra pit depths (2 m and 3 m). High frequency barrier effects are evident in the direct component (10 ms) but not in the early (50 ms) or late reflected sound.*

In the experiment, measurements were performed on the orchestra (stalls) and balcony levels using the two omni-directional source locations in the pit. Two full sets of these measurements were recorded, at pit depths of 2 and 3 m. Energy level differences (i.e. $L_{2m\ depth} - L_{3m\ depth}$) were calculated for direct sound (0 to 10ms), early (0 to 50ms) and late reflected sound (50ms to ¥). Results are shown in Figure 6 and Table 3.

Table 3

	Level Difference (dB)			
	Direct	Early	Late	Total
Orchestra	6.3	2.1	0.5	0.9
Balcony	6.8	1.7	0.3	0.8

At the top of Figure 6, Level Difference is in the range of 5 to 10 dB and increases with frequency. This agrees with Meyer's suggestion[11] that orchestra pit sources are subject to barrier effect and the frequency dependent attenuation that it implies. However, the remaining curves in Figure 6 and the averaged level difference in Table 3 indicate that barrier effect does not have as great an influence on early, late reflected sound or the total sound level. The conclusion to be drawn from this exercise is that the depth of the orchestra pit affects direct sound only and not reflected sound. As such, one cannot expect to see big changes in steady state Balance (B) as the pit is moved up or down. B50 includes only direct and early reflected and may therefore be more sensitive to pit depth than steady state Balance (B).

Interestingly, level differences measured on the balcony and on the orchestra level (stalls) are virtually the same. Because a listener on the balcony generally has a clear view of the pit, regardless of its depth, one would expect a smaller level difference on the balcony than that experienced below on the orchestra level. This does not appear to be the case, at least for the room examined here.

Conclusions

Measurements of stage to pit balance have been performed in four different proscenium arch theatres. The measurements suggest the following trends: (i) low frequency balance favours the pit for listeners on the orchestra level (stalls); (ii) for listeners on the balcony level, low frequency balance is about even and, in some cases, favours the stage; (iii) at high frequencies, in the range of the singers' formant, the balance curve dips again in favour of the orchestra pit, the orientation of the stage source influences high frequency balance and there was no significant difference between the balcony and the orchestra level; (iv) lowering an orchestra pit effects direct sound much more than early or late reflected sound. As a consequence, steady state Balance is not very sensitive to the movement of an orchestra pit. Low frequency balance is most likely influenced by the seat dip effect. High frequency reduction of balance is likely to be exacerbated in occupied rooms by the head dip phenomenon.

Several questions remain, the most significant of which is the subjective significance of the measurements. Although significant differences have been noted, for example between the balcony and the orchestra level (stalls), difference limens for Balance are as yet unknown.

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