RELATIONSHIPS BETWEEN WALL TILT AND SOUND FIELD GROWTH AND DECAY

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1 INTRODUCTION

Two recent concert hall design competitions involved radically tilted walls. While tilting in section, as rotation in plan, can be used to effect lateralisation of the sound form the stage, it has been shown in analysis and design that tilting the walls inward reduces the duration of the reverberation, as it directs sound more quickly into the sound absorbing audience.

In 1980 Kuttruff and Straßen published work including the effect of room shape on decay rates, for very simple room shapes[1]. Essert studied the effect of geometry on auditorium parameters and subjective listening, considering gross variation in plan and section of a performance space[2], and also used fig-8 microphones and Soundfield microphones to measure and visualise 3D impulse responses in auditoria[3]. This paper connects the Soundfield work to the parametric modelling.

The work outlined here quantifies the lateralization of sound promoted by wall tilt and the effects on overall decay rate using a computer model to analyse parametric variations in the model.

2 PARAMETRIC MODEL

The simple shoebox concert hall model was created in CATT9.0c and analysed with TUCT 1.1a2.
Dimensions: 20m W x 40L x 18H. 2 wrap-around balconies.
Flat, horizontal, somewhat diffusing ceiling.
Volume:13,500m^3 approx.
Number of planes: 102

Surface absorption and scattering properties were chosen typical for a generic concert hall: hard materials for room boundaries and occupied audience absorption for audience areas. The front wall "organ zone" was slightly absorbing and scattering.

The walls were constructed in 3 separate levels, so that the walls at stalls (level A), 1st balcony (level B) and 2nd balcony level (level C) could be varied independently. The area and height of the low and middle walls A&B are equal respectively to the area and height of the upper walls C. CATT geometry files were set up to allow variation in side wall tilt inward in 5 degree increments: 90 degrees (vertical), 85, 80, 75, 70), in such a way that volume, surface area and audience area remained constant.

TUCT does not account for audience grazing, which is an important aspect of auditorium acoustics, so this paper focuses on mid-frequency propagation.

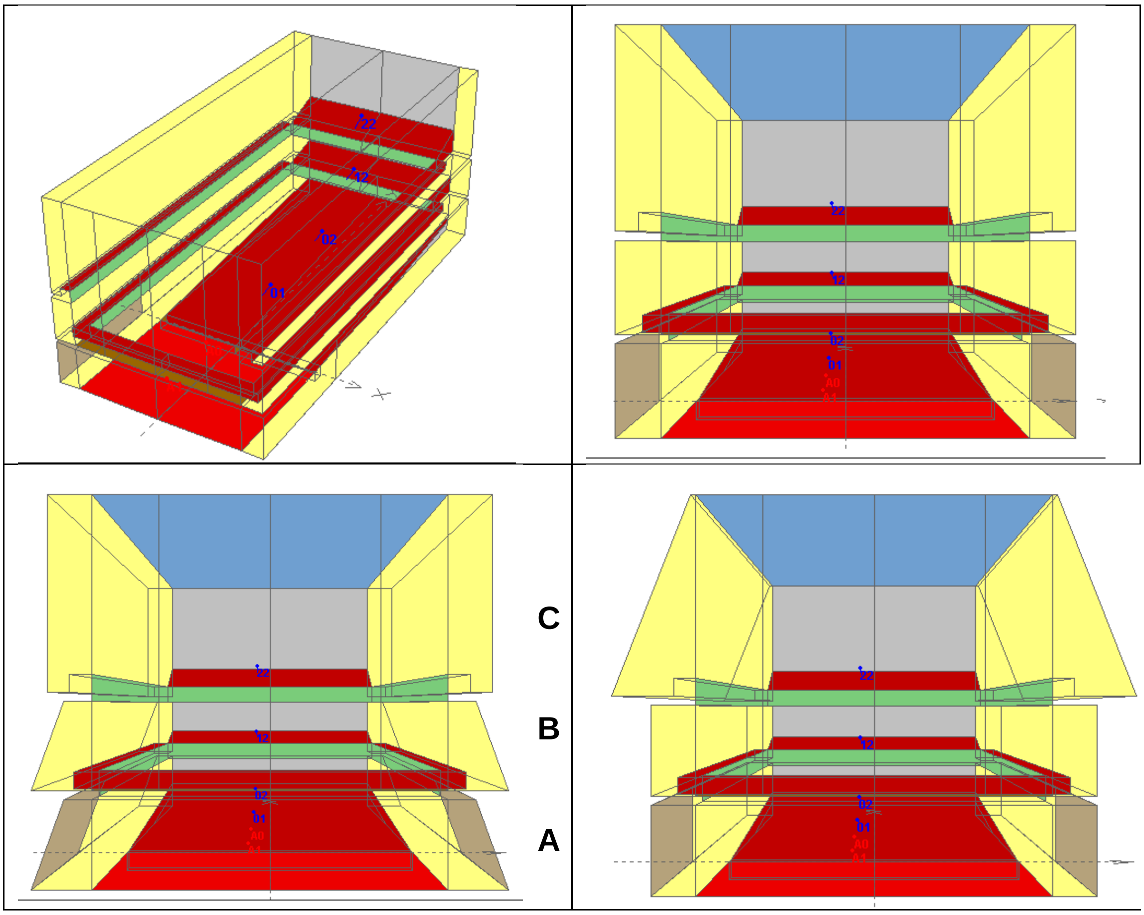

Figure 1. 3D model. Side walls tilt through 20 degrees from 90 (vertical) to 70. Sources downstage and upstage near center line. Receivers front stalls (1/3 back), rear stalls (2/3 back), balcony 1, balcony 2. Lower images show maximum extent (20 degrees) of tilt for lower walls A&B and upper walls C.

3 EXPERIMENT

The side wall angle was varied through the 5 angles in four groups:
Run A: Stalls (A) walls tilted
Run B: Balcony 1 (B) walls tilted
Run C: Balcony 2 (C) walls tilted
Run AB: Both A and B walls tilted

For the TUCT analysis Algorithm 1 was used with 1,000,000 rays. Diffuse reflections up to order 2 were split for scattering.

Acoustical parameters and impulse responses were generated from each of the room configurations. Impulse responses were generated for Binaural and B-format output.

Impulse responses were further analysed with Matlab to study decay curves, growth curves, directional fractions for the X, Y and Z B-format components and evolution of the lateral energy over time.

4 RESULTS

4.1 Decays and related parameters

Basic mono parameters, were computed from the W channel and also from summed binaural, with little difference between them. These are summarised in Figure 2.

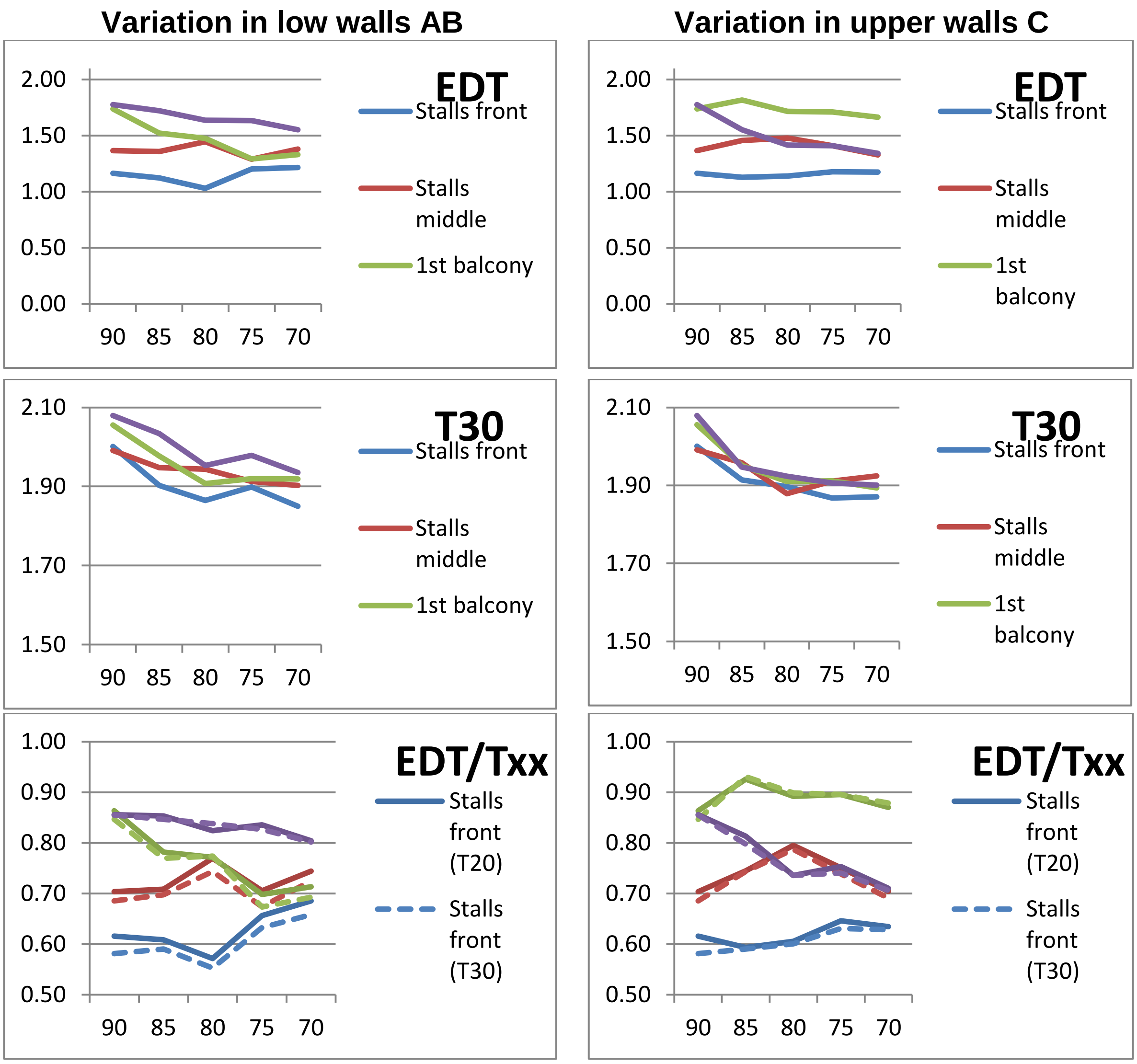

Figure 2. Reverberation times EDT and T30 and ratio of EDT to T20 and T30 for different room geometries and in different receiver locations, averaged for the two source positions. Left column shows variation with tilt of lower walls A and B by the same amount, with upper walls C vertical. Right column shows variation of tilt of upper walls C , with lower walls A and B fixed at vertical.

For receivers in the balconies EDT is reduced with increasing wall tilt; they are not the receivers of this energy, as early energy directed into the audience increases the early decay rate.

For all receivers T30 decreases with increasing wall tilt, although from 70 – 80 degrees there is little change. Stalls decays are double sloped in all configurations, and T30 is 30-40% longer than EDT.

In the balconies, the double sloped nature increases with wall tilt (EDT/T30 decreases), particularly for the 1st balcony where 2nd-order reflections are influenced by the wall tilt.

In the stalls there is no overall trend in the EDT. As the stalls receives early energy directly from the tilted walls the changes in delay and level of reflections in the first 10dB can serve to create a plateau decay or a cliff type decay (or something in between).

For the balcony, the double sloped nature increases (EDT/T decreases) with tilt of the lower walls. This is particularly true for the 1st balcony where 2nd-order reflections are influenced by the wall tilt.

4.2 Decay of lateral energy

The late lateral decay rate is generally fairly close to the late omni decay rate. Double slope decay is evident, more pronounced in the stalls than in the upper levels of the room. Figure 3 shows decays from the basic shoebox (all walls 90 degrees), and the room with lower walls tilted to 70deg, upper walls vertical: A=70 B=70 C=90.

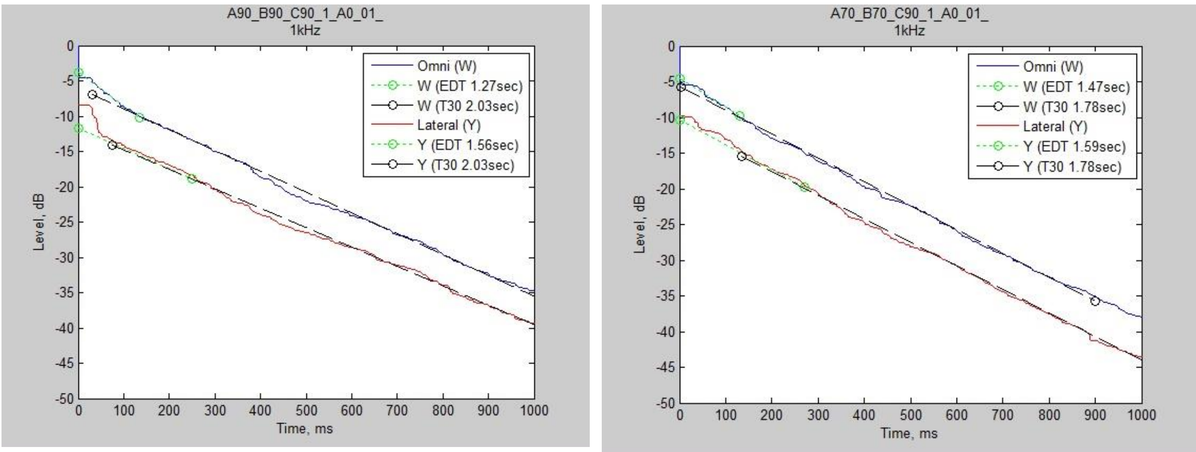

Figure 3. Lateral (Y) and omni (W) decay curves, normalised to total energy in W.
Left: A = B = C = 90, stalls receiver
Right: A = B = 70; C = 90, stalls receiver. Both for 1kHz octave..

4.3 Growth of directional fractions over time

Growth of total and directional energy over time were tracked by forward integrating the X, Y Z and W channels. As an example two locations in two rooms are plotted in Figure 4. (Note that all channels include the energy between 0-5ms, which is normally excluded from standard measurements of LF.)

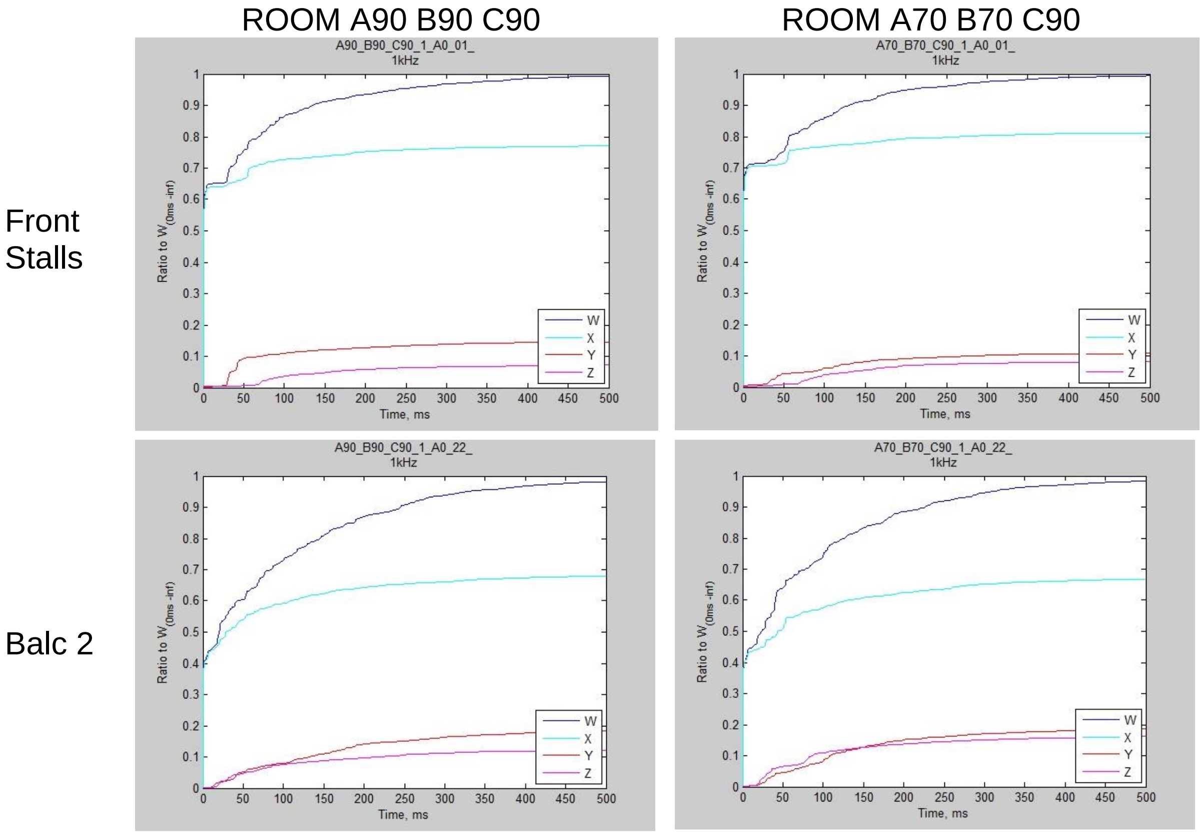

Figure 4. Growth of directional fractions X, Y, Z normalised to total energy (W). Room A90 B90 C90 has all walls vertical. Room A70 B70 C90 has lower walls tilted 20deg, upper walls vertical. 30ms integration window, 2ms step. 1kHz octave band. Data normalised to total energy in W.

The lateral fraction rises more quickly in the stalls than in the balcony.

The total lateral level is roughly the same in the balcony for the two rooms, but in the stalls, the vertical walls provide greater total lateral energy than the tilted walls.

4.4 Running lateral fraction

Some years ago one of the authors developed an approach to analyse and project 3D impulse responses recorded in B-format. Using sliding-window cross-correlation of each of the XYZ channels with the W channel we constructed the X, Y, Z components to establish the general direction of the sound in that time window[3].

$$F_x(\tau) = \frac{\sum_{t=\tau-\delta/2}^{t=\tau+\delta/2} x(t)w(t)}{\sum_{t=\tau-\delta/2}^{t=\tau+\delta/2} w(t)w(t)}$$

In this situation the level of the W channel is increased by 3dB to account for the B-format level convention.

The X, Y and Z fractions were computed with various widths of integration window. For the purpose of viewing general traits in direction a window width of 30ms, with 2ms sliding offset were chosen for this paper. Examples from the same pair of rooms are shown in Figure 5.

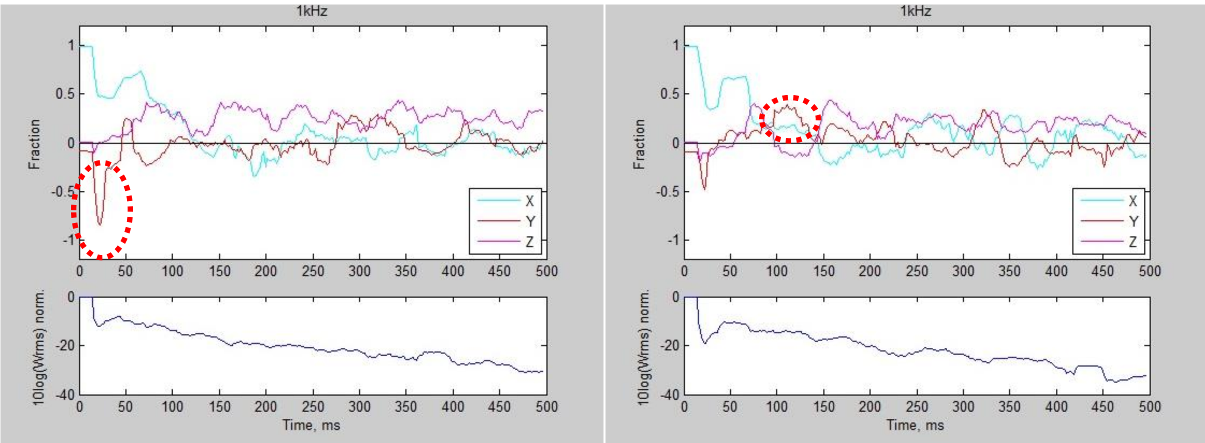

Figure 5. Directional fractions X, Y, Z normalised to total energy (W). Left image: A90 B90 C90. Right image: A70 B70 C90. 30msec smoothing window, 2ms offset. Source A0 downstage, Receiver 01 front stalls. Lower plot is smoothed W_{rms}.

Basically a smoothed echogram in 3 dimensions, this plot enables evaluation of the general direction at different times in the impulse response. The general flow of energy back and forth through the length of the room takes about 115ms, and this is visible in the X channel.

In the left image (vertical walls) the lateral channel Y shows stronger early reflection(s) before 50ms. In the right image (tilted walls A & B) there is a stronger lump of lateral energy between 100 and 130ms (highlighted).

Similar observations were made from plots like this for each room configuration and source/receiver.

This fractional plot technique has been used as a basis for display of energy in 3D over time.

4.5 Trends across rooms

Growth of the lateral energy over time depends on the room shape. In Figure 6 lateral energy growth over time is plotted for 5 hall geometries in 3 listener positions.

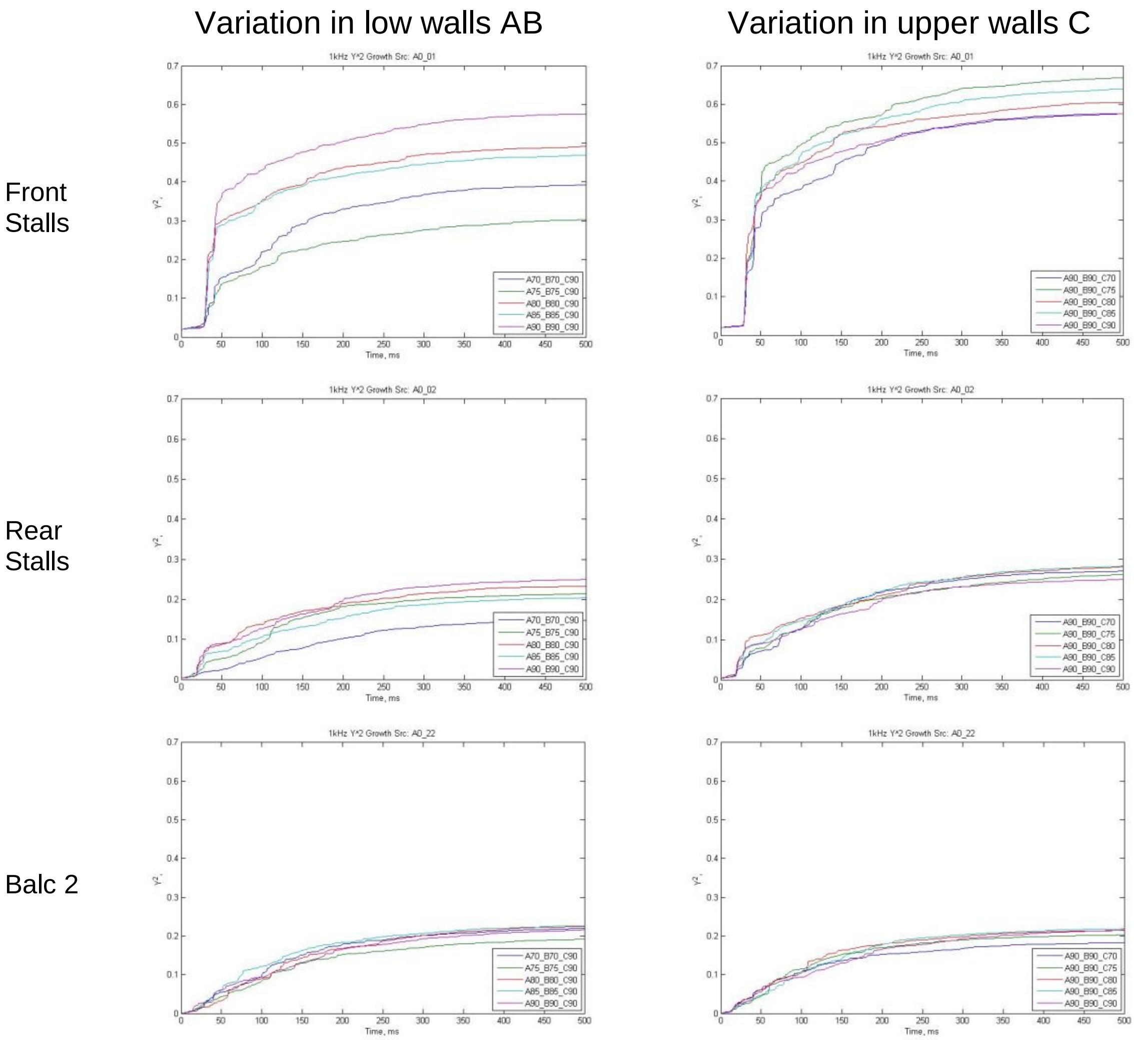

Figure 6. Growth of lateral energy Y across different room geometries. 30msec window, 2ms step. 1kHz octave band. Vertical scale is arbitrary, but equal across all figures, not normalised to W.

Lateral energy is greater in the front stalls than in the other areas. This is mostly due to early lateral reflections from the lower side walls.

Typically on the order of 50% of the lateral energy arrives after 100ms, and 25% after 150ms.

Variation in lateral energy with wall angle is greatest in the stalls.

In front stalls (01), the vertical side walls produce greater lateral energy starting early in time than any of the tilted walls.

In the rear stalls (02) the 80 degree walls deliver the most early lateral energy, but by 200ms the vertical walls have provided more. The most strongly tilted (70 deg) walls provide the least lateral energy over all time periods; we can suggest that the sound is being grounded out into the audience without a specular first order path to the listener.

Variation in the upper wall tilt has a greater effect on the lateral energy in the stalls than in the upper tiers.

The rise over time of both total and lateral energy is more gradual in the 2nd balcony than it is lower in the room.

5 DISCUSSION

The computed Lateral Fraction Y/W curves in this study indicate a range on the order of 0.1 to 0.2 for total Lateral Energy / Total Omni energy.

Though there is yet much to learn, one accepted difference limen for measured Early Lateral Fraction LF is 0.05, as ensconced in ISO 3382[5]. Though the integrations plotted here do include the first 5 ms in the Y fraction, there is not generally significant lateral energy in the 0-5ms time window, especially with the “perfect soundfield microphone” implied in TUCT; so we suggest that the LF difference limen can be considered at least roughly relevant for the fractional plots.

In the balcony the variation of Lateral Energy Y(t) with this range of upper (C) wall tilt is generally on the order of 0.25 before 100ms, or half a difference limen, and increases to 0.5 between 100 and 200ms. This holds for tilting of upper or lower walls.

In the stalls the variation of Lateral Energy is considerably greater – 0.1 to 0.3, or 5 to 6 difference limen. This depends on specific location and first and second order reflections from the side walls.

Lateral energy is connected to key perceptual qualities in concert halls, such as Apparent Source Width and Listener Envelopment. Further work should incorporate the relationships between low frequency response and surface size, and this will require different modelling algorithms. Effects of audience grazing should be accounted for as well, not least because the early lateral reflections in the stalls are often highly attenuated at low frequencies by grazing.

Evaluation of lateral energy over time, and indeed all the fractional components of the 3D impulse response, with new visualisation and auralisation tools will shed further light on the relationships between room geometry, directional energy flow and perception.

6 REFERENCES

1. H. Kuttruff & T. Straßen, ‘Zur Abhängigkeit des Raumnachhalls von der Wanddiffusität und von der Raumform,’ Acustica 45 p. 246-255 (1980).
2. R. Essert, ‘Links between concert hall geometry, objective parameters and sound quality,’ J. Acoust Soc Am. 105(2) p. 986 (1999).
3. R. Essert, Measurement of Spatial Impulse Responses with a Soundfield Microphone,’ J. Acoust. Soc. Am 100 5pAA3 (1996).
4. ISO 3382-1:2009 Part 1, ‘Measurement of room acoustic parameters’.