QUALITY OF LOW FREQUENCY AUDIO REPRODUCTION IN CRITICAL LISTENING SPACES

Dr. Bruno Fazenda
University of Salford
b.m.fazenda@salford.ac.uk

NB: This has been presented at the 10th Meeting of the Audio Engineering Society, Portuguese Section, 12th and 13th December 2008

Outline

- Background
- Motivation - Why investigate perception of room modes?
- Methods
  - Modal factors under study
  - Low Frequency Models and Auralisation
  - Subjective test methods
    - ABX
    - PEST
- Results
  - Modal Q and modal decay
  - Measuring the Subjective Transition Frequency
  - Room aspect ratios and modal distribution
  - Optimal Modal Spacing
  - The MTF as a descriptor of Low Frequency Quality
- Implications for Room Design

Why investigate perception of room modes?

- The room is **an integral part** of the reproduction system
- It will superimpose its own characteristics (acoustic response) into what the listener hears
- In Studio Monitoring Design most acousticians have been trying to define a 'standard' room
  - To ensure compatibility between studios
  - To ensure compatibility between studio monitoring rooms and the user's listening environment
    - Living room
    - Cars
    - iPods
    - etc

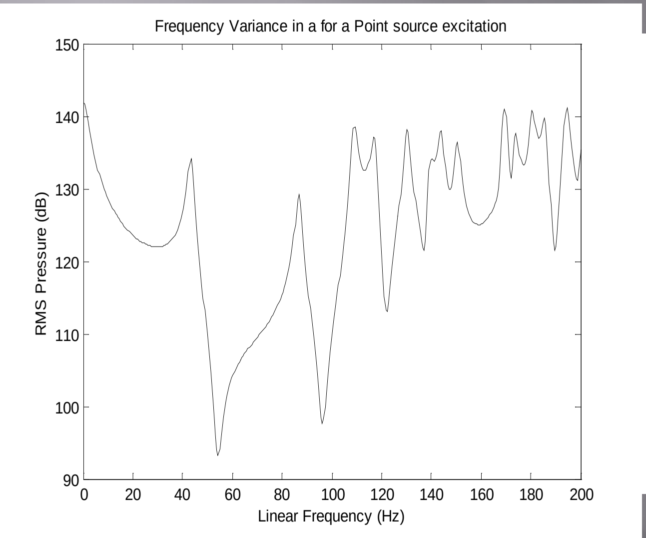
Why investigate perception of room modes?

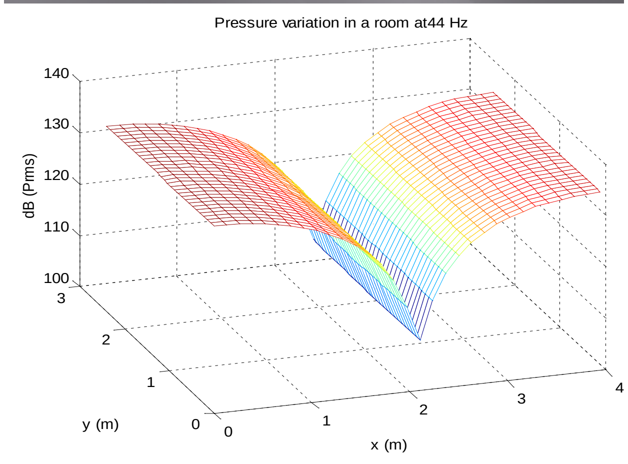
- Room modes
  - This could be thought of as the 'low frequency reverberation' – all rooms have some
  - Proven to be one of the main problems when trying to listen accurately
  - Changes perception of reproduced sound quite dramatically
  - One of the main reasons for room related problems in the final production

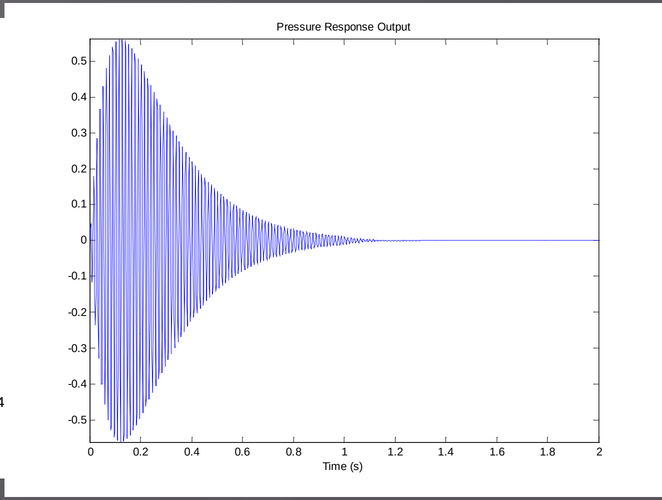
What are Room Modes?

- Modes are standing waves that exist at specific frequencies associated with the room dimensions and existing damping
- Objectively, room modes cause:

1. Frequency variance – Peaks and valleys in the frequency response
2. Spatial variance – Quiet and loud zones for individual frequencies
3. Resonant behaviour – Changes in attack and decay of sound



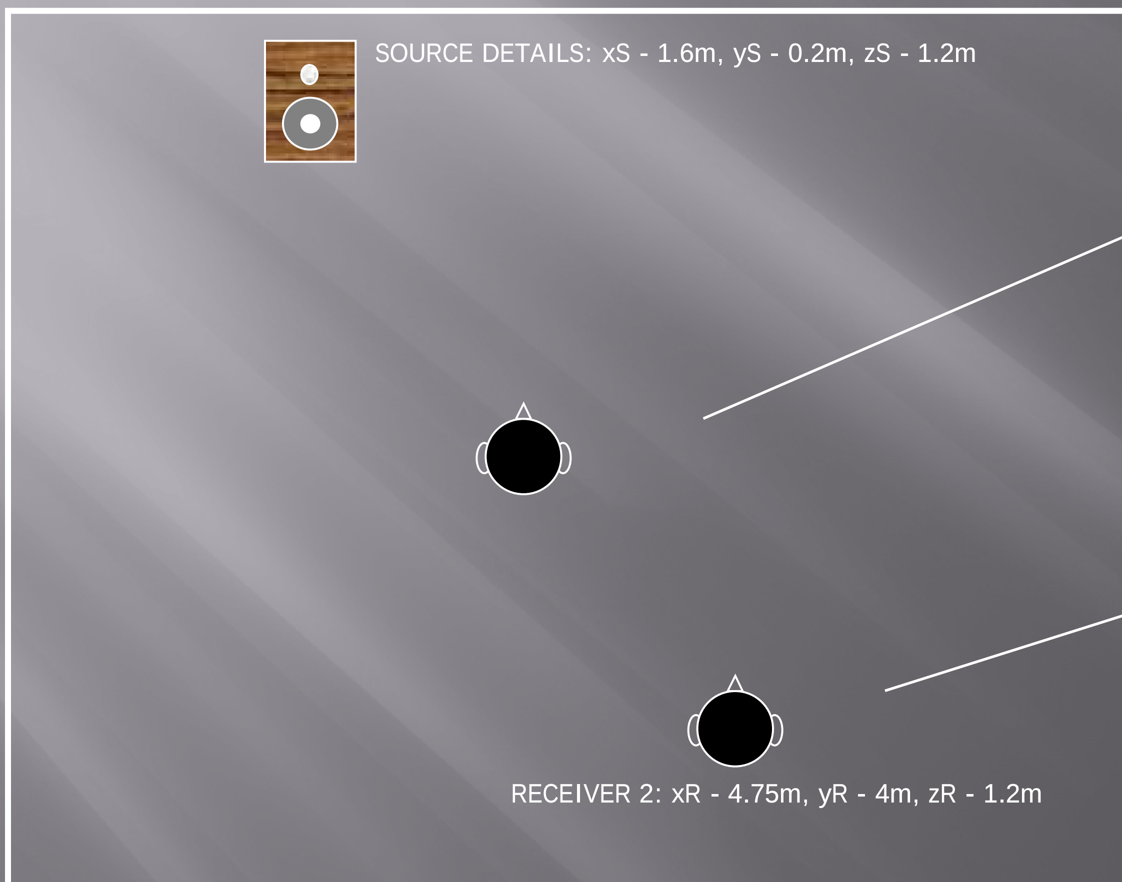


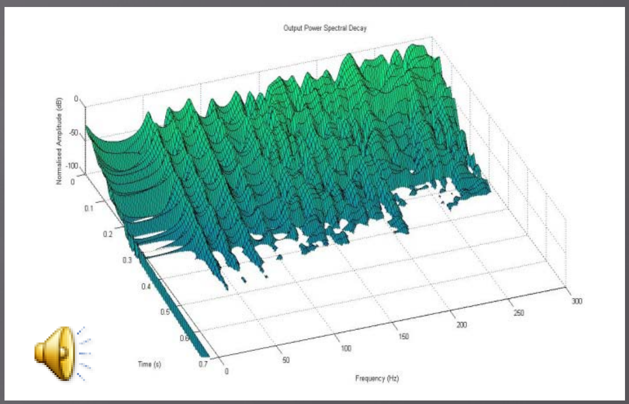


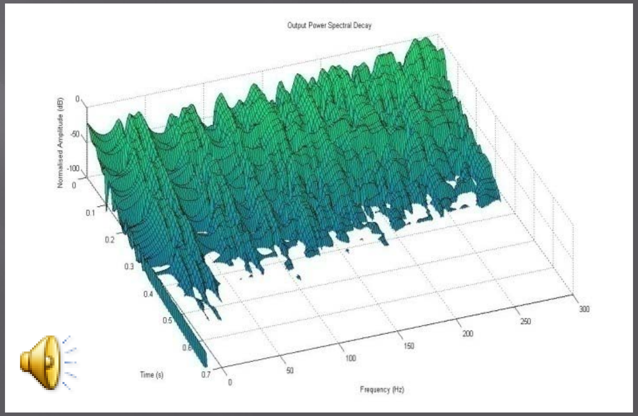
Audible Modal Effects

- Subjectively, the effects of room modes are well known:

ROOM DETAILS: 75m3 – 6.33 x 4.83 x 2.45 (m)







Why investigate perception of room modes?

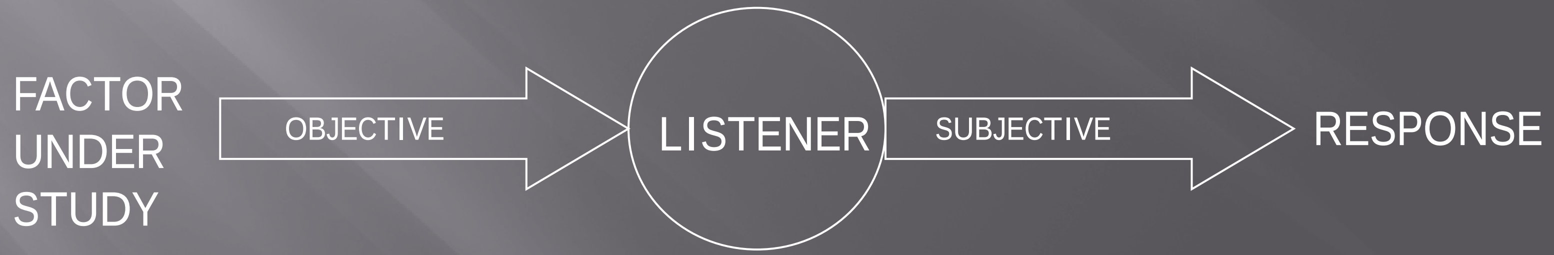
- To support Control Techniques
  - Room acoustic design/treatment requires guidance in terms of required performance
  - Active control solutions require targets
- Which have mainly been based on objective measures of the modal sound-field

Factors under study

Methods

Psychoacoustic Methods

- A sensory evaluation where Human is the measurement instrument
- Quantify the perception of a given aspect by:
  - Varying parametric factors that make up that aspect
  - Identifying Human response to it
    - detection
    - mood
    - Preference
- So, for a given study we need to:
  - Identify the factor under study
  - Appropriately present a different number of cases to a panel of listeners – modelling and auditions
  - Obtain a meaningful response from each listener
  - Analyse if there are any significant results from the panel – statistical analysis



Modal Factors

- In psychoacoustic we are interested in the response of listeners to the manipulation of a single factor
- For each resonant mode there are 3 main factors that can be described or measured:
  - **Amplitude**
    - This depends on coupling to modeshapes in the room and the source content around that particular frequency
  - **Centre frequency**
    - This depends on the physical dimensions of the room
    - And to some lesser extent on damping
  - **Q-factor** (related to modal decay time)
    - This depends on the acoustic conditions existent in the room (rigidity of walls; absorption; active control)
- In a given modal soundfield there is an additional factor that potentially affects the correct perception of sound
  - **Modal distribution and modal density** (more on this later)

Modal Factors

- All room conditions in the modal sound-field are associated with one or more of the above factors, Eg:
  - The amplitude of a particular frequency depends on source and receiver positions and how loud the source is at that frequency
  - Modal distribution refers to the ‘lining up’ of the modal centre frequencies and is associated with the room aspect ratios
  - The frequency response at a given position depends greatly on how much absorption is efficient at low frequencies

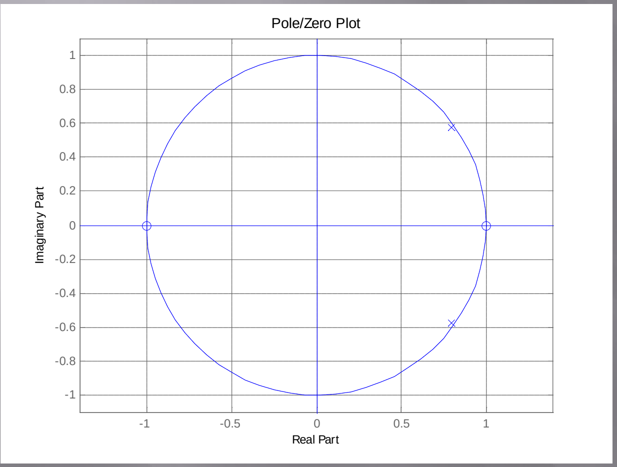
Modelling the room

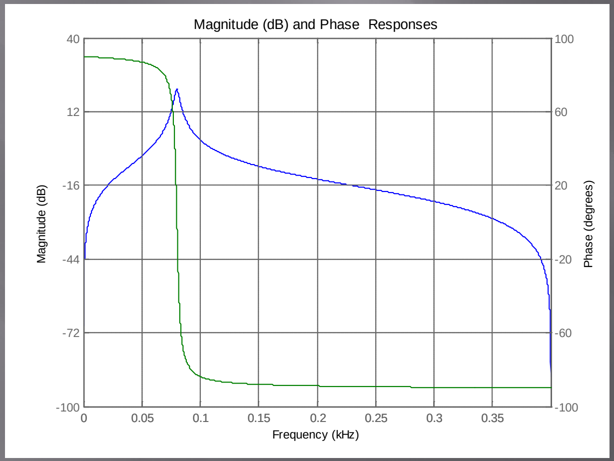
Methods

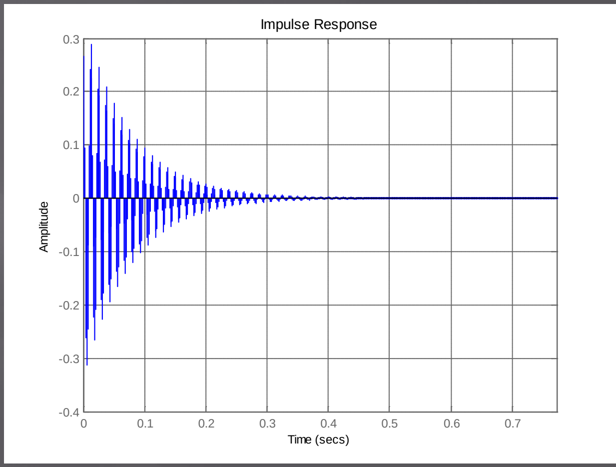
Low Frequency Models

- Bi-quad IIR bandpass filters
  - Allows control over centre frequency, amplitude and Q-factor
  - An addition of bi-quads can effectively model the response of a generic room (Morjopoulos, 1991)

$$y(k) = 2R_p Cos\theta y(k-1) + R_p^2 y(k-2) + Kx(k) - Kx(k-2)$$

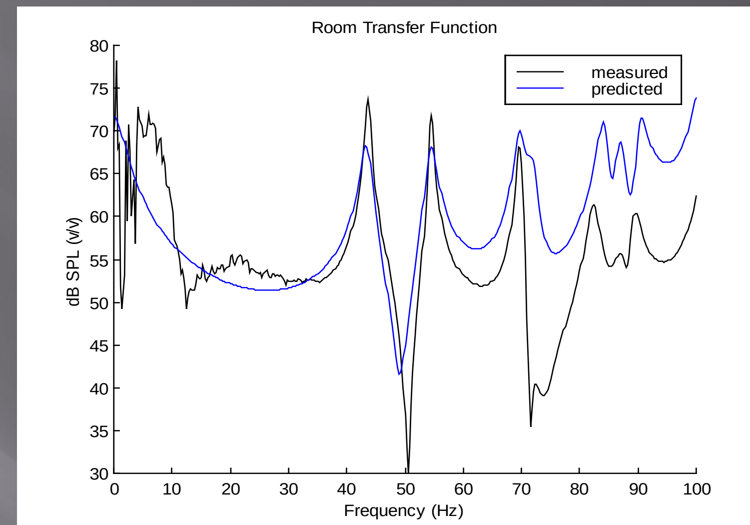






Low Frequency Models

- Green's function for a rectangular room (eg: Kuttruff, 2000)
  - Limitations:
    - Assumes relatively low damping
    - Assumes modes and modeshapes are orthogonal
    - Easier for rectangular rooms
  - Advantages:
    - Allows adequate control over various room aspects
      - Aspect ratios
      - Dimensions, volume
      - Damping
      - Source and receiver position

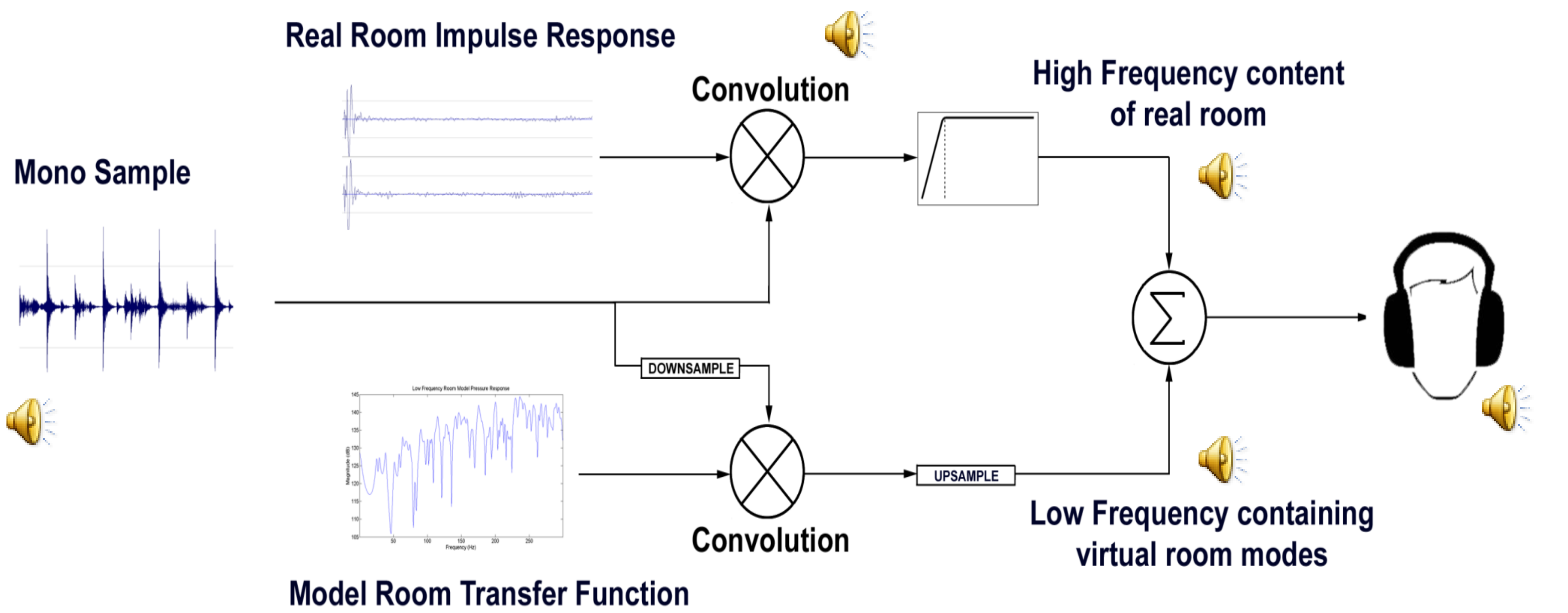


$$Cos(k_{nx}x)Cos(k_{ny}y)Cos(k_{nz}z)$$

$$Cos(k_{nx}x_0)Cos(k_{ny}y_0)Cos(k_{nz}z_0)$$

$$p_\omega(r,r_0) = j\omega\rho_0 cQ\sum_n^{(3)} \frac{\psi_{r_0}\psi_r}{\mathrm{X}_n\left(\omega^2 - \omega_n^2 - 2j\delta_n\omega_n\right)}$$

Creating an Audition Sample

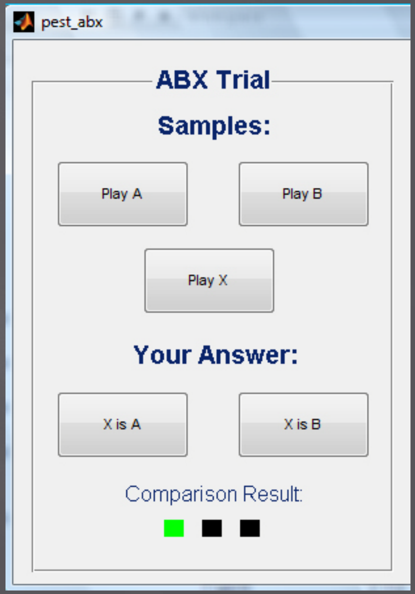


Subjective testing methods

Methods

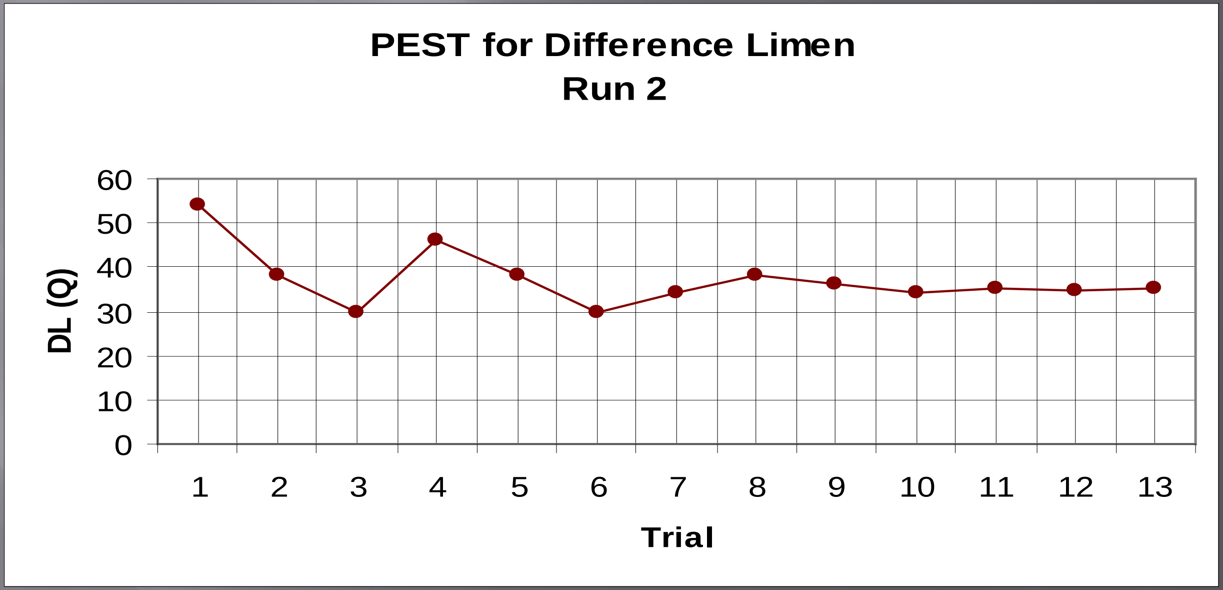
Subjective Testing

- ABX testing:
  - Tests if listener is able to detect differences between samples A and B
  - Listener is presented 3 test samples (A, B and an unknown X which is either A or B)
  - Listener has to answer which is X
  - Repeat with random X (at least 10 times)
  - Chi Square statistical analysis reveals likelihood of guessing
    - Eg: 8/10 correct is considered true detection



Subjective Testing

- Parameter Estimation by Sequential Testing (PEST)
  - Identifies difference limen in a minimum number of auditions (Trials)
  - Subject is asked to detect a difference between 2 samples
  - Test rules are automated to reach a final figure

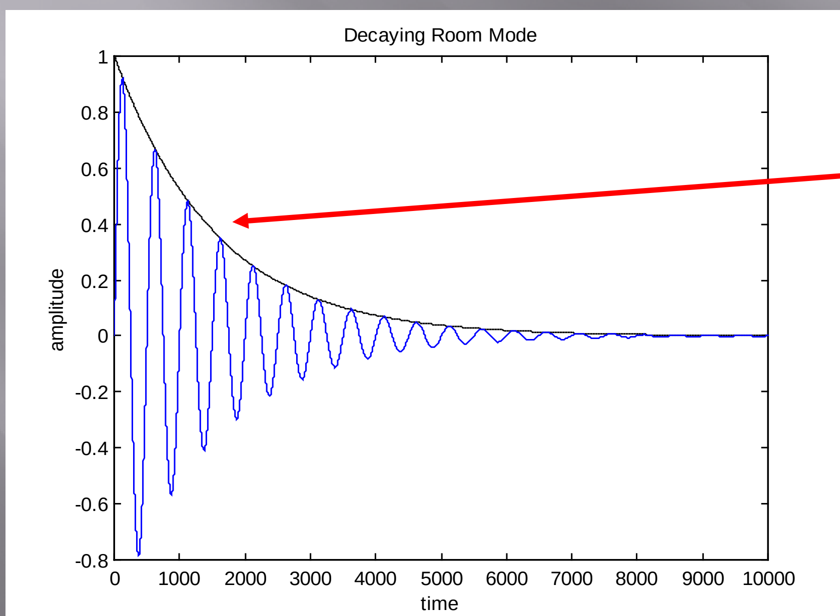


Q-factor detection thresholds

Results

Q–factor Detection Thresholds

- Some of our previous work was based on the determination of thresholds for the detection of changes to Q-factor
- Modal Q-factor and decay time are inversely proportional
- Modal Q-factor is associated with the amount of effective damping in the room
  - A change in modal Q-factor may be obtained by altering the damping (absorption) in the room



$$e^{-\beta t}$$

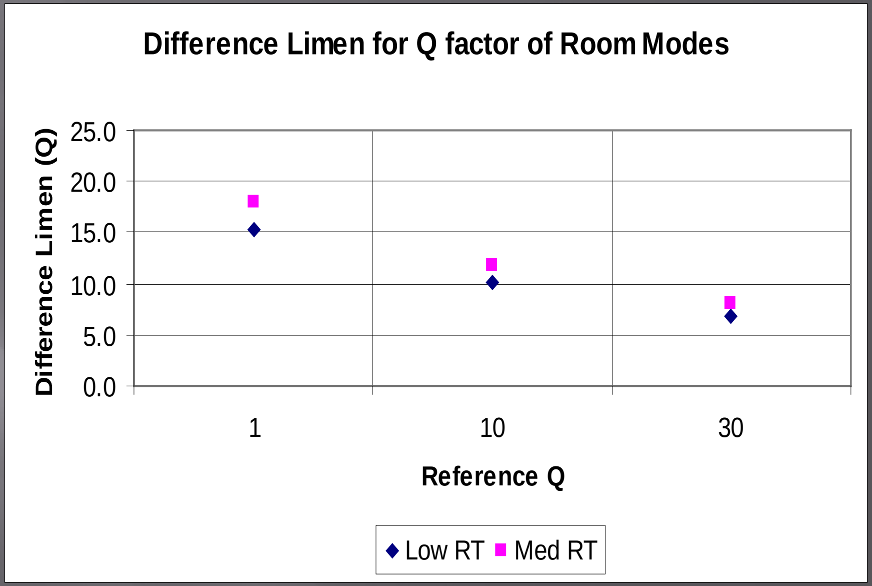
$$Q = \frac{f_{res}}{\beta} \qquad T_{60} = -\ln\left(\frac{10^{-3}}{\beta}\right)$$

Q-factor Detection Thresholds

- Thresholds of detection for Q-factor changes are useful in determining the necessary damping required to render modes inaudible
- As we will see this is one of the most important aspects when controlling the effects of room modes
  - Just like mid and high frequency absorption is effective at controlling reflections and reverberation
- This is also one of the most difficult to achieve
  - Low frequency modes have long wavelengths and much energy

Q-factor Detection Thresholds

- Subjective experiment results show:
- Thresholds increase for lower Qs
  - More difficult to detect changes in shorter decays
  - More difficult to detect changes in Q-factor as the room tends towards more absorptive conditions
- On average, a modal Q of a least 16 is necessary to detect modal behaviour
  - This corresponds to a decay of 0.5 seconds at 65Hz
- Higher RT increases the thresholds
  - Mid-frequency reverberation may help to mask modal activity

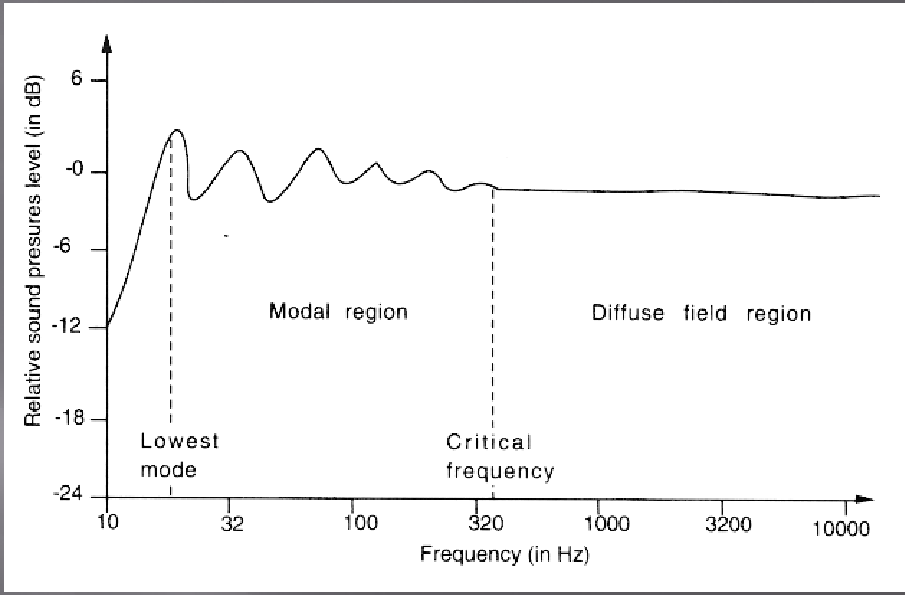


Measuring the subjective transition frequency

Results

Measuring the Subjective Transition Frequency

- The **Schroeder frequency** refers to the **transition** between the modal region and diffuse field conditions
- It states that at least 3 modes 'share' the same bandwidth
  - A desirable minimum modal density
- It is commonly stated that due to the higher modal density above this transition frequency the effects of modes are no longer detectable
- Hence larger rooms (with high modal density even at low frequencies) do not suffer from the problems of room modes



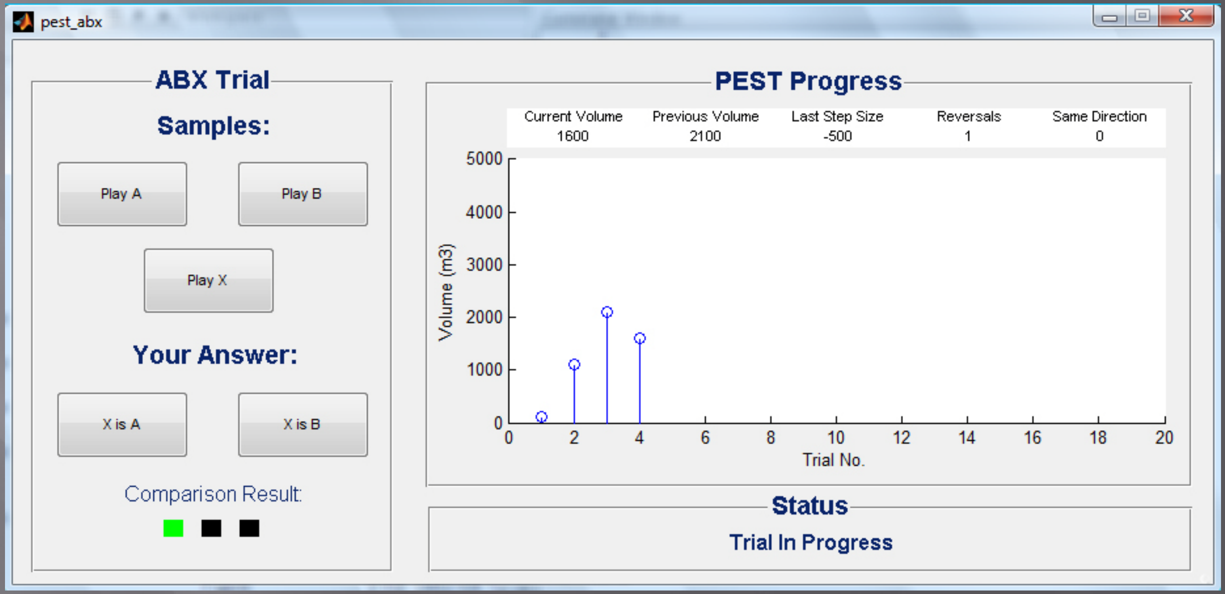
$$f_s = 2000\sqrt{\frac{T}{V}}$$

T ← REVERBERATION TIME

V ← VOLUME

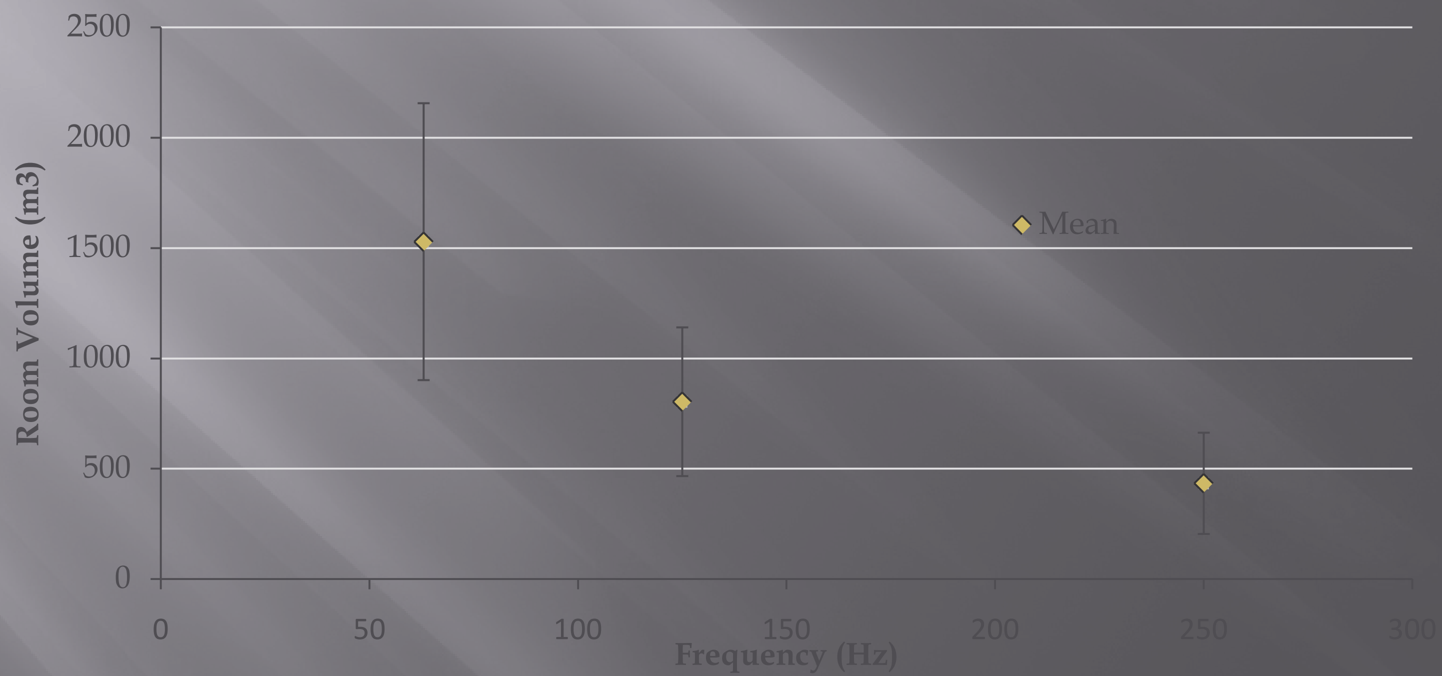
Measuring the Subjective Transition Frequency

- Increasing room volume appears to flatten the response
  - See demonstration
- Using an Hybrid ABX/PEST method we attempted to define a room volume where the difference between a sample room and a (smooth) 100,000m^3 room was not detectable
  - At 63Hz, 125Hz and 250 Hz
  - 8 subjects



Measuring the Subjective Transition Frequency

- Results:
- To get a subjectively acceptable modal density at lower frequencies we need larger room volumes
  - Nothing new here!
  - But how do we define a ‘subjective’ modal density across frequency?



Measuring the Subjective Transition Frequency

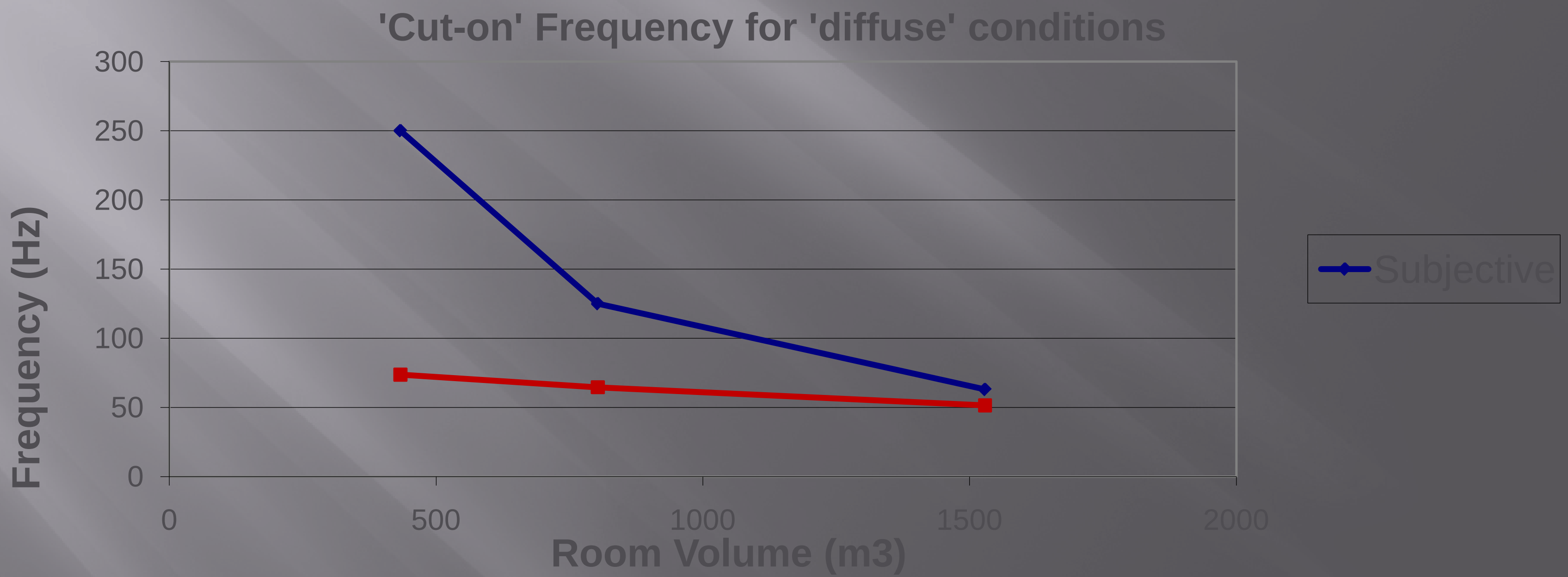
- Modal bandwidth and density for each frequency can be obtained from the results
  - Note that at 63Hz a modal bandwidth of 4 is obtained which is very close to the Schroeder's definition
  - However, this density needs to increase considerably with frequency for the effects of modes to be rendered inaudible

$$\frac{\delta N}{BW_{modal}} = \frac{4\pi F^2 V}{c^3}$$

Frequency (Hz)	**63**	**125**	**250**
Modal Bandwidth	2.17	2.63	3.75
Subjective Volume Threshold	1529	803	433
'Subjective' Modal Density	4.1	10.3	31.6

Measuring the Subjective Transition Frequency

- So how does this compare with Schroeder's method?
  - The Schroeder frequency predicts diffuse conditions at much lower critical frequencies, particularly for smaller rooms
  - According to our subjects, the effects of modes are still detectable up to much higher frequencies



Measuring the Subjective Transition Frequency

- Discussion:
- There appears to be no specific ‘ideal modal density’ across frequency
- Subjectively optimal density appears to be frequency dependent
- This contradicts the basis for the Schroeder frequency which guarantees that modal effects are inaudible once there are at least 3 modes in one bandwidth
  - regardless of frequency
- But are we telling the whole story?
- NO!

Measuring the Subjective Transition Frequency

- So far, the models used have not taken into account the specific coupling of source and receiver positions to the mode shapes in the room
  - In line with the use of the Schroeder frequency definition
  - Also an issue when defining room aspect ratios (more on this later)
- When the shape functions are included, the smoothing of the frequency response is not obtained
  - See demonstration

$$p_{\omega}(r,r_0) = j\omega\rho_0 cQ\sum_{n}^{(3)} \frac{\psi_{r_0}\psi_r}{X_n\left(\omega^2 - \omega_n^2 - 2j\delta_n\omega_n\right)}$$

Measuring the Subjective Transition Frequency

- PEST results would never converge if mode shapes are included
- A new test was devised
- A set of fixed room volumes were compared to a ‘reference’
  - ‘Reference’ represented large and small rooms

Small Room	Reference Volume	500	500	500	500	500
	Test volume	100	250	400	450	490
Large Room	Reference Volume	10000	10000	10000	10000	10000
	Test volume	1000	5000	9000	9500	9990

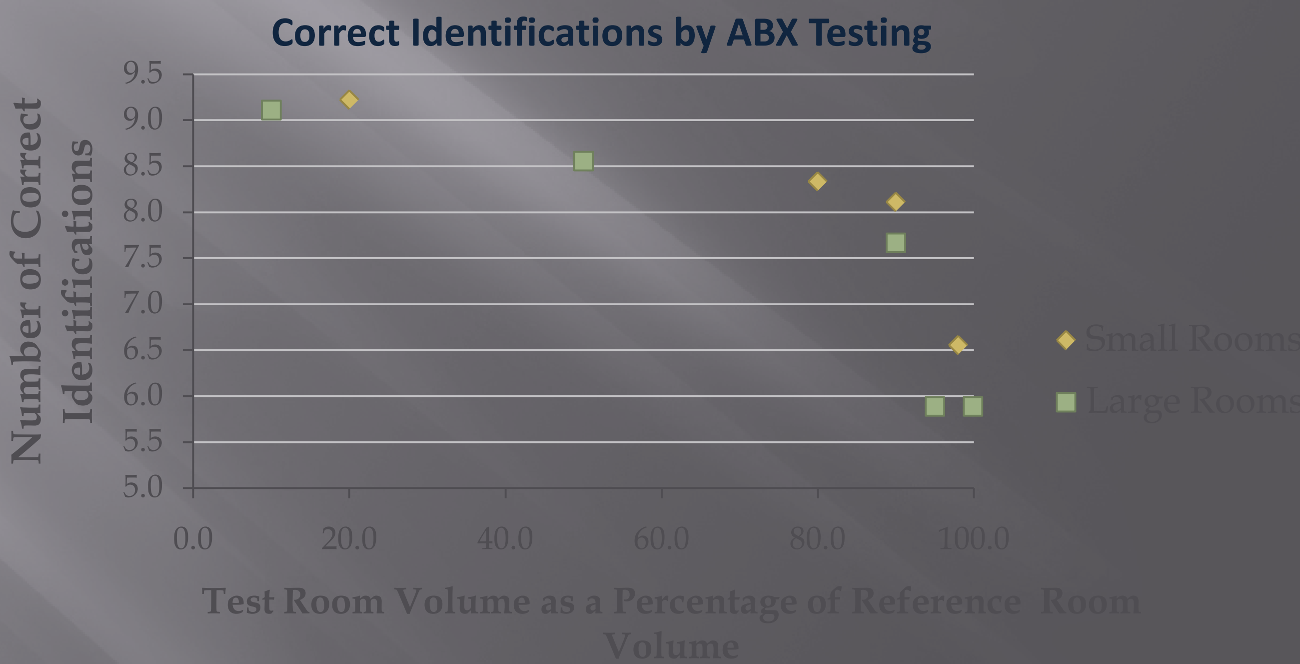
- Hypothesis:
  - Differences caused by modal effects in **small rooms** should be detected since transition frequency in these cases is high
  - Differences between large rooms should not be detected since the transition frequency in such cases is typically low

Measuring the Subjective Transition Frequency

- Used ABX Test to determine if difference was detectable
  - 10 trials for each pair
  - Used musical samples
  - Eight subjects tested

Measuring the Subjective Transition Frequency

- Results:
- No apparent difference between large and small room volumes
- Differences between rooms are detectable until test is within 10% of ‘reference’ volume



Measuring the Subjective Transition Frequency

- Discussion:
  - Coupling and Mode interaction are highly important
  - A high modal density does not appear to be beneficial in removing the modal behaviour
  - Even if the sound-field can be described as diffuse, our perception does not appear to follow these conditions
- So why do large rooms sound less ‘resonant’ than smaller rooms?
  - Indeed the density is higher but the energy is spread out over many modes instead of a few as happens in small rooms
  - If the decay at low frequencies is too long then it will still sound ‘resonant’
    - Since the energy is ‘returned’ from the modes during the natural response
    - Like a reverberant room

Room aspect ratios

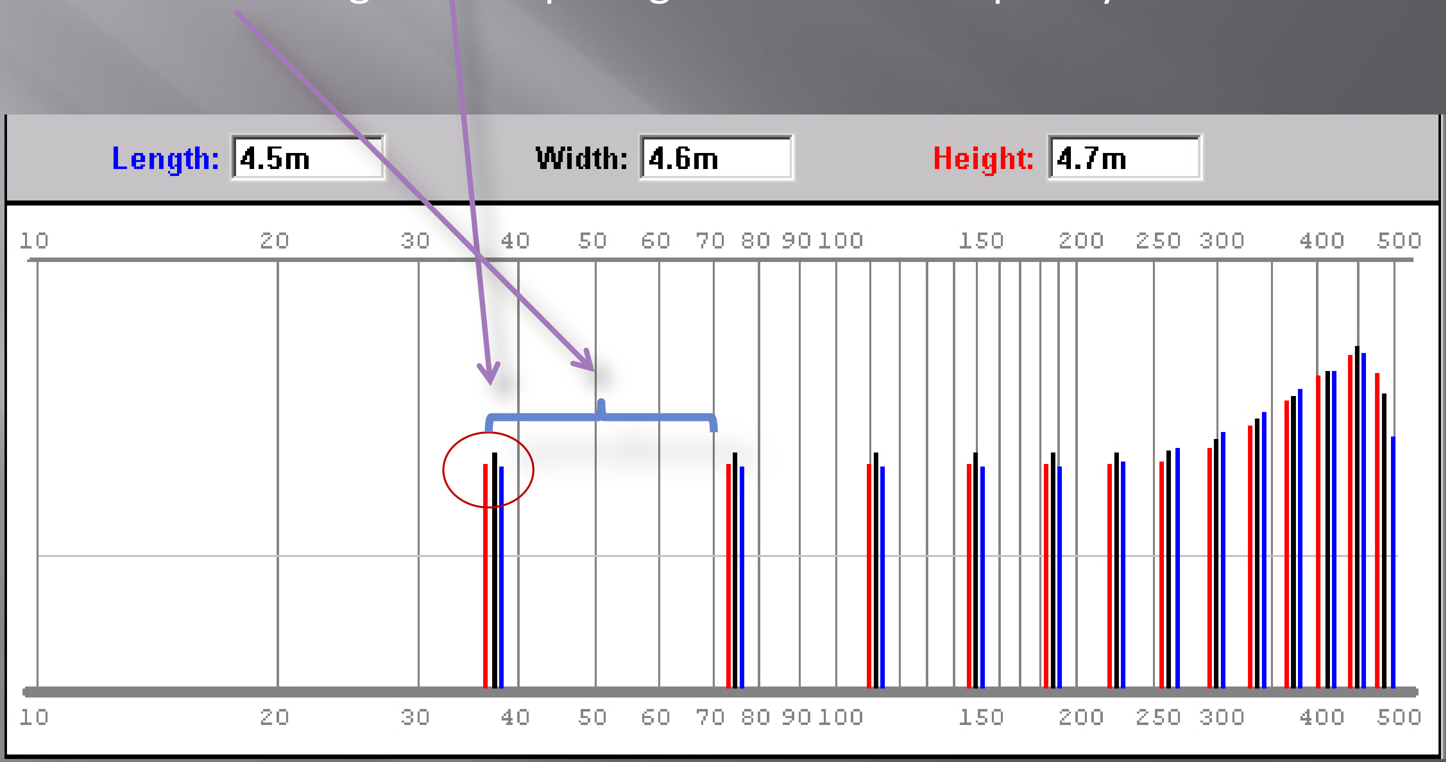
Results

Room Aspect Ratios

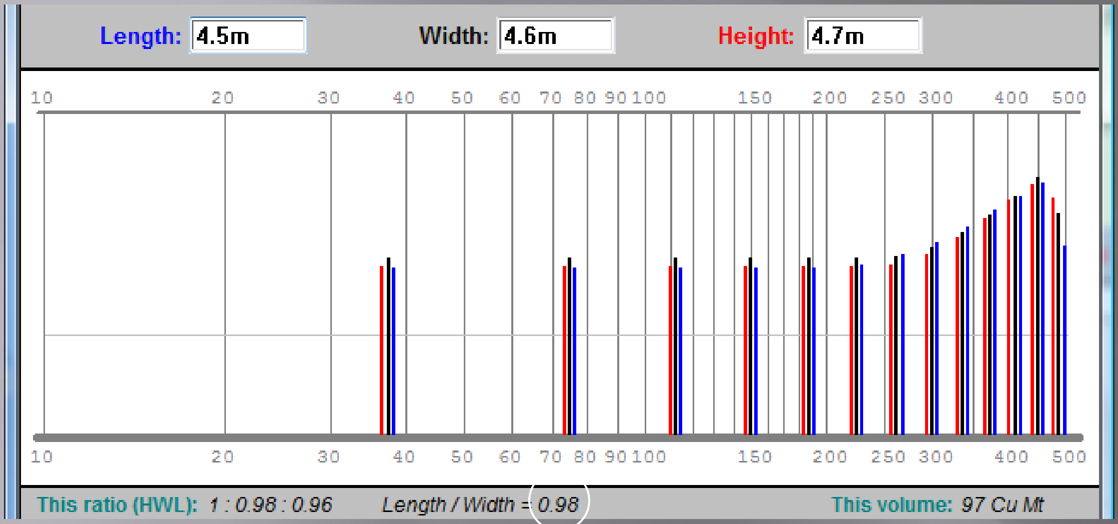
- It is common to associate a ‘flat’ frequency response to good audio quality
- In rooms this is very difficult at low frequencies due to modal activity
- Solutions have been investigated that attempt to achieve a ‘flatter’ frequency response by ‘arranging’ the modes optimally
- This is physically possible by changing the dimensions and aspect ratios of the room

Room Aspect Ratios

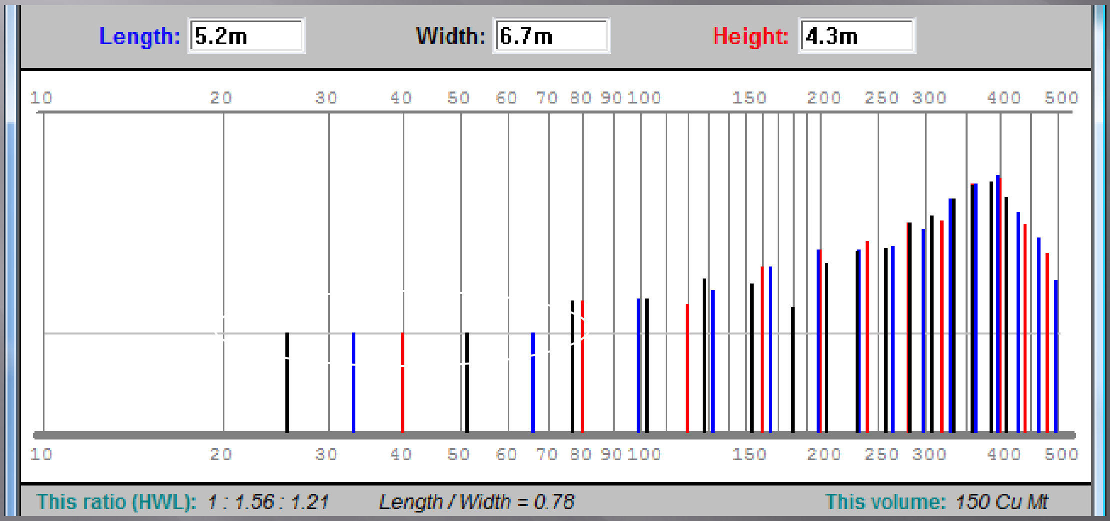
- Early researchers set optimization targets for aspect ratio optimization
  - Avoid modal degeneracy – two or more modes very close together
  - Achieve homogeneous spacing of modes in frequency



Room Aspect Ratios

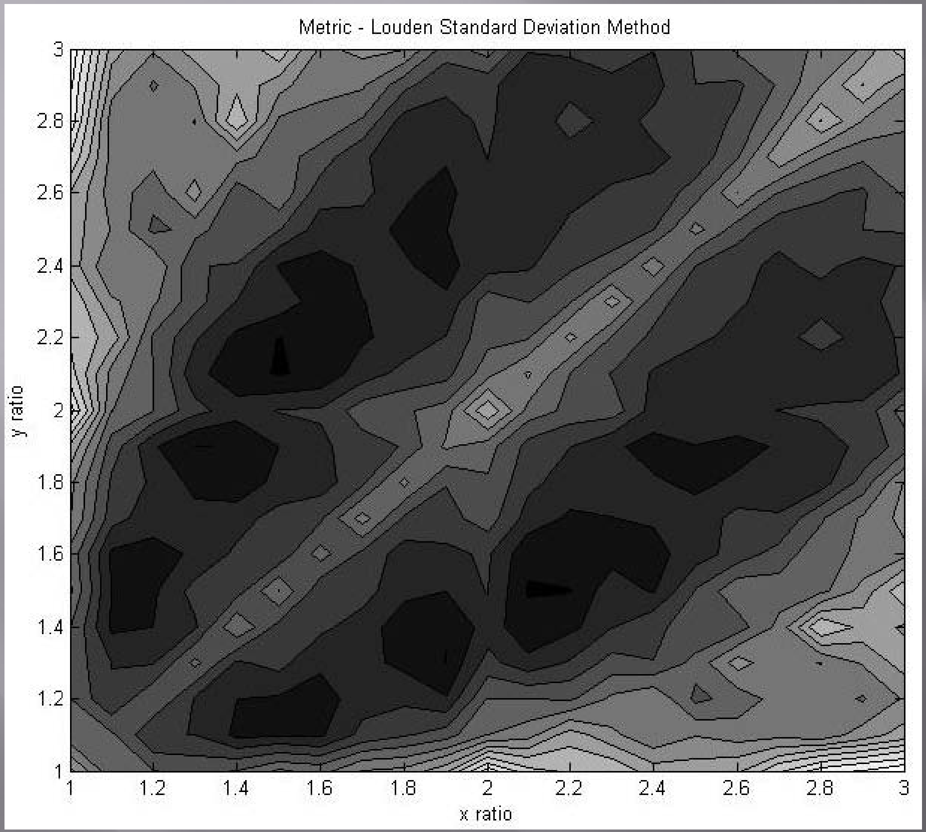


IN THIS EXAMPLE MODES 'BUNCH UP' BECAUSE ASPECT RATIOS ARE VERY CLOSE TO AN INTEGER



THIS MODAL DISTRIBUTION IS MORE HOMOGENEOUS WITH MODES 'SPREADING OUT'

Room Aspect Ratios



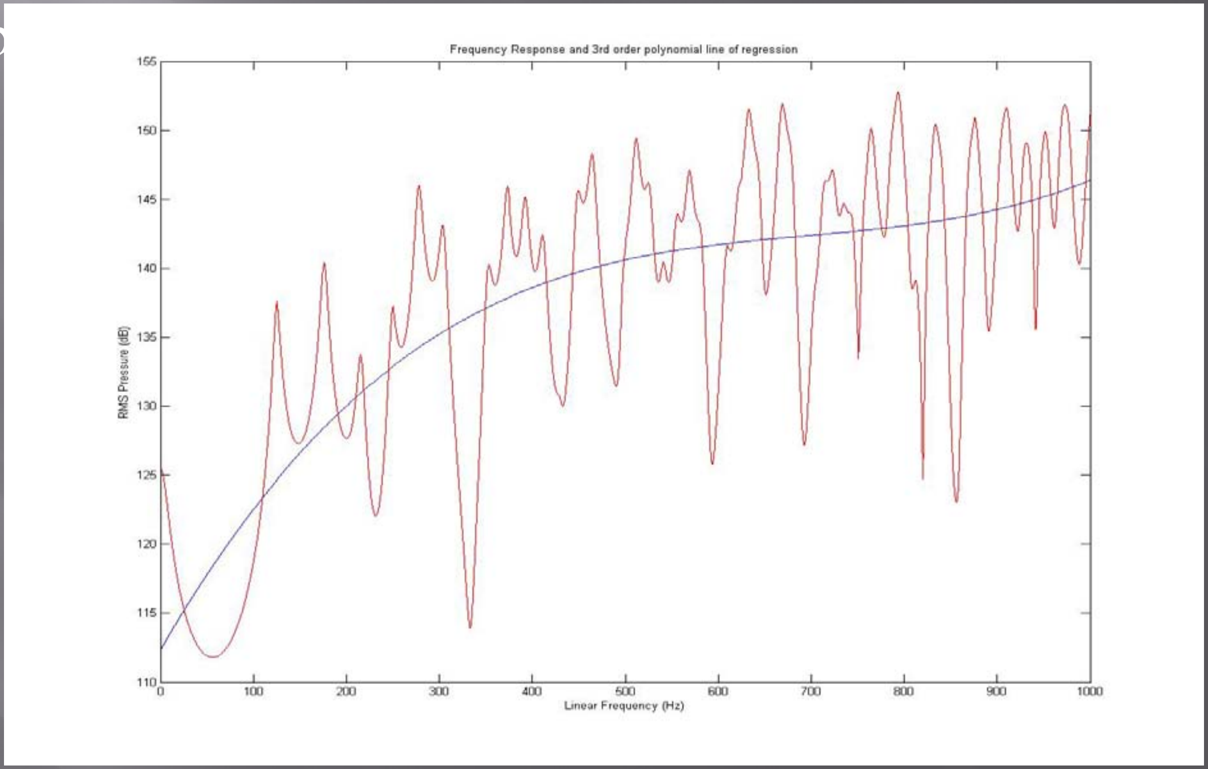
- Metrics have been defined to indicate the reproduction quality of the room
  - In this case (Louden, 1971) it is based on the spacing between modes
  - Other have used similar metrics (Bolt,Walker,...)
  - Darker areas in the map are best
- This seems to make good sense
  - Where dimensions are equal or integer multiples, degeneracy occurs, so the room is classified as bad

Room Aspect Ratios

- These methods are based upon assumptions of modal behaviour
  - All modal frequencies are of equal magnitude
  - All possible modal frequencies are excited
- But this is not possible in a real application
  - Modal magnitude and number of modes excited are all dependent on...
- Source and Receiver coupling
  - The frequency response is then affected by the phase of each mode
  - Different source and receiver positions in the room give different responses for the same room!
  - So the performance of a given room is highly dependent on source and receiver positions

Room Aspect Ratios

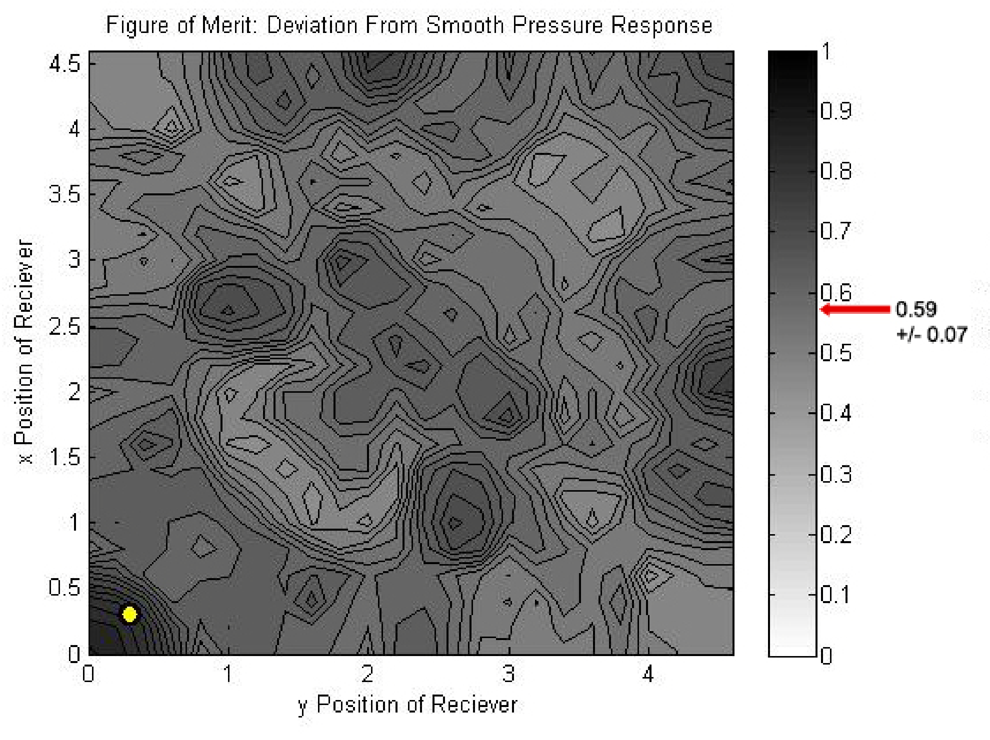
- A new metric is needed that takes into account source and receiver positions and their coupling to the room mode shapes
- How about the deviation from a smooth response?
- Room aspect ratios can now be evaluated from their predicted resp



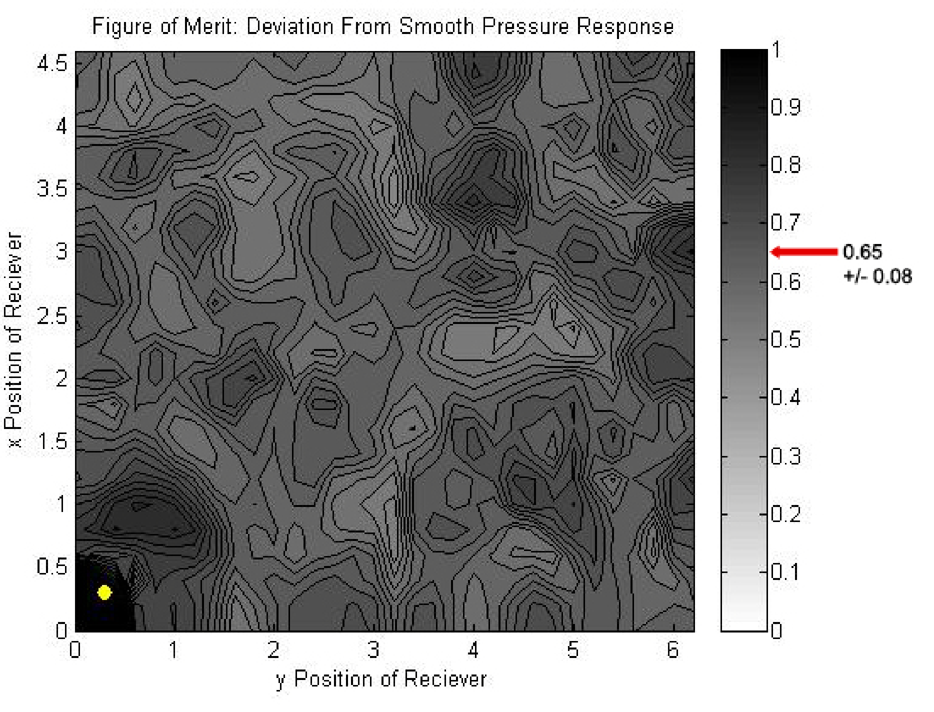
Room Aspect Ratios

Maps indicate 'good' and 'bad' listening positions within the room
A 'good' room should have a higher mean score and a smaller variance

- A 'bad' room ratio:

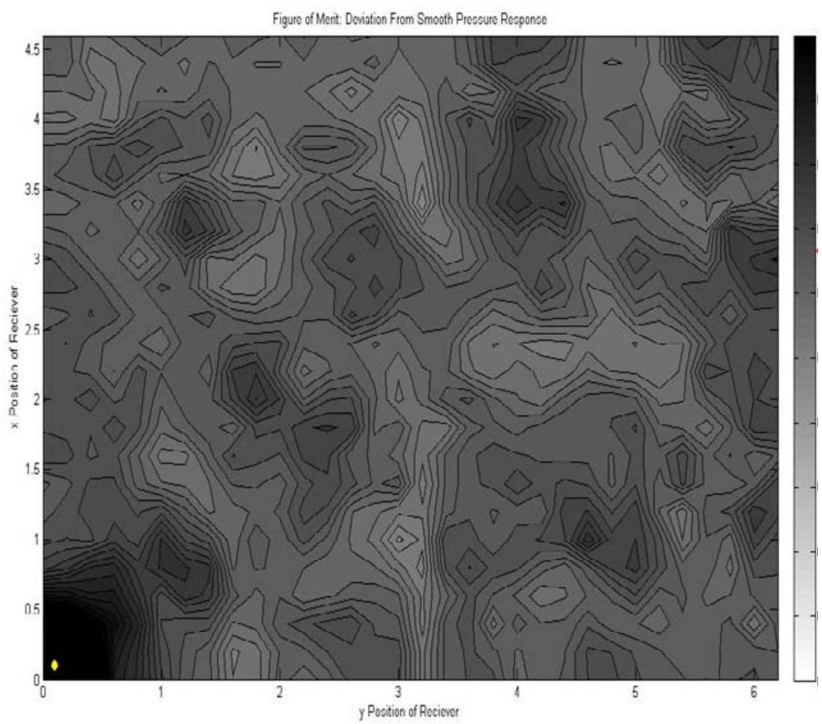


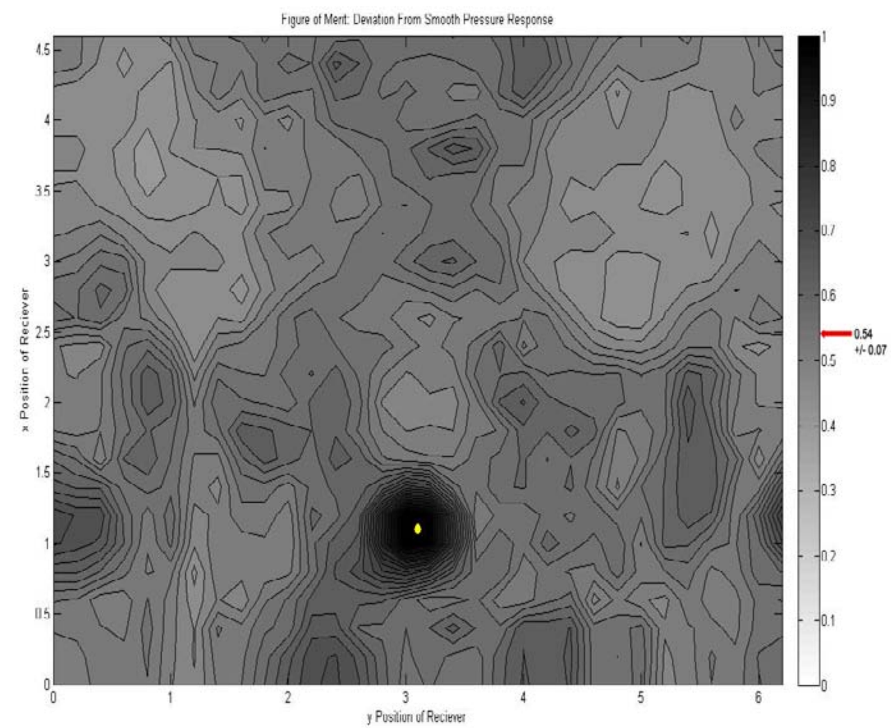
- A 'good' room ratio:



Room Aspect Ratios

- Source position significantly affects the response in the room
  - ‘Good’ room ratio:



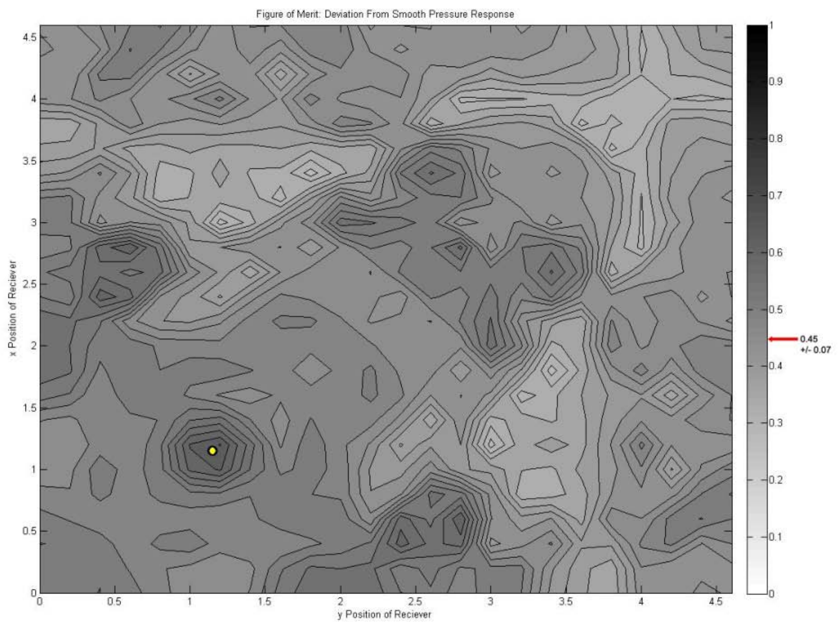


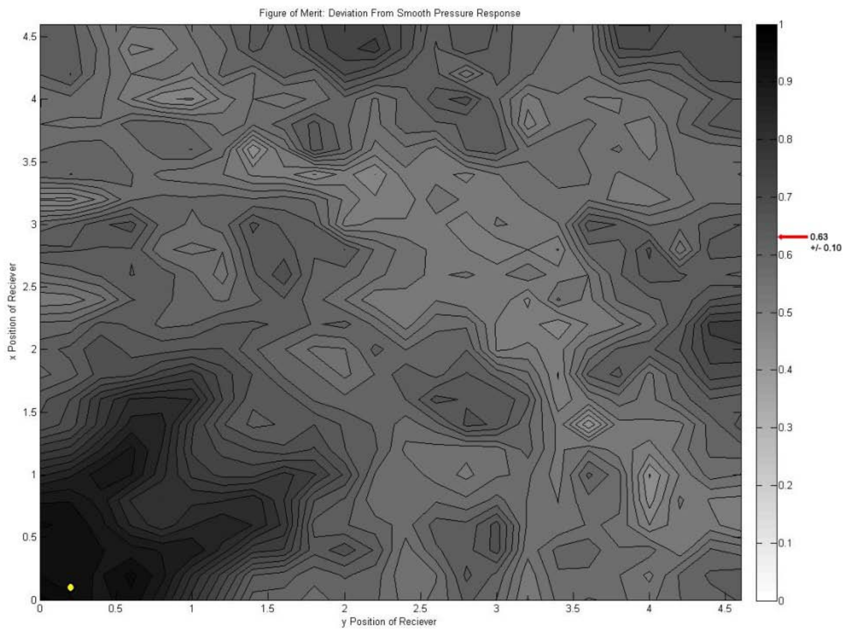
0.67 ± 0.11

0.54 ± 0.07

Room Aspect Ratios

- And it is possible to improve the response even in a 'bad' room





$$0.45 \pm 0.07$$

$$0.63 \pm 0.10$$

Room Aspect Ratios

- Discussion:
  - Defining low frequency reproduction quality from aspect ratios is only meaningful if source is in the corner
  - A more appropriate metric needs to take into account source and receiver position and its coupling to mode shapes
  - Good rooms are those that achieve a more homogeneous high score
    - Across a desirable listening area
    - For many typical source positions
  - Preliminary testing is showing some correlation between this metric and the perceived response in the room

Optimal modal spacing

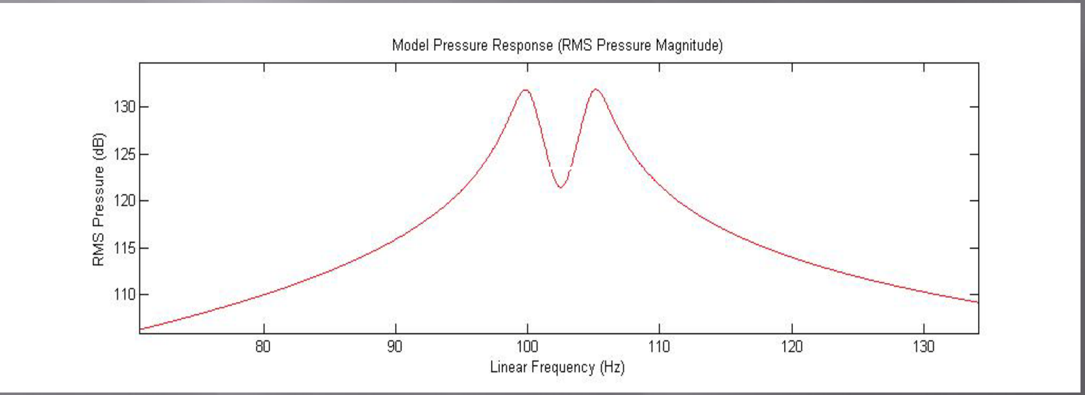
Results

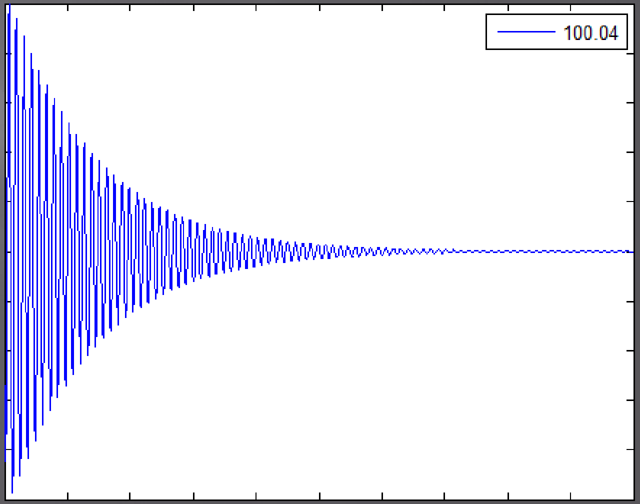
Optimal Modal Spacing

- One of the problems with room modes is that they are isolated in frequency
  - Creating a natural response of the room that is very dependent on the modal frequency
- Another important aspect (as seen before) is that they exhibit long decays
- Increasing damping and reducing decay seems to be one of the best ways of controlling modal energy
  - But this is quite difficult with passive methods (i.e. Absoprtion)
- Can the decay be reduced in other ways?

Optimal Modal Spacing

- In any system
  - a flat response gives an impulse in time
  - Any deviation from this flat response produces a time decay – room modes being an ubiquitous example
- A single mode has a long decay
- Two modes with a given spacing produce a smoother response
  - And a shorter decay
  - And an associated beating effect!
- So what is the optimal spacing?
  - Objectively and Subjectively

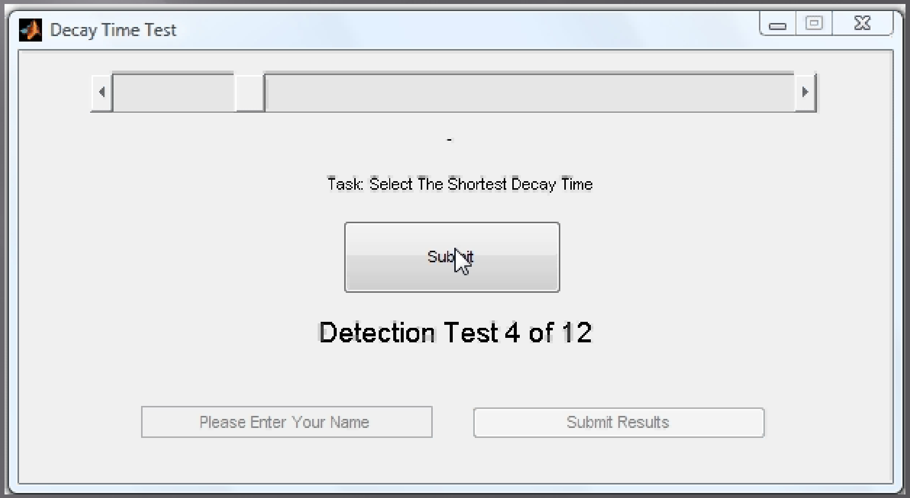




Optimal Modal Spacing

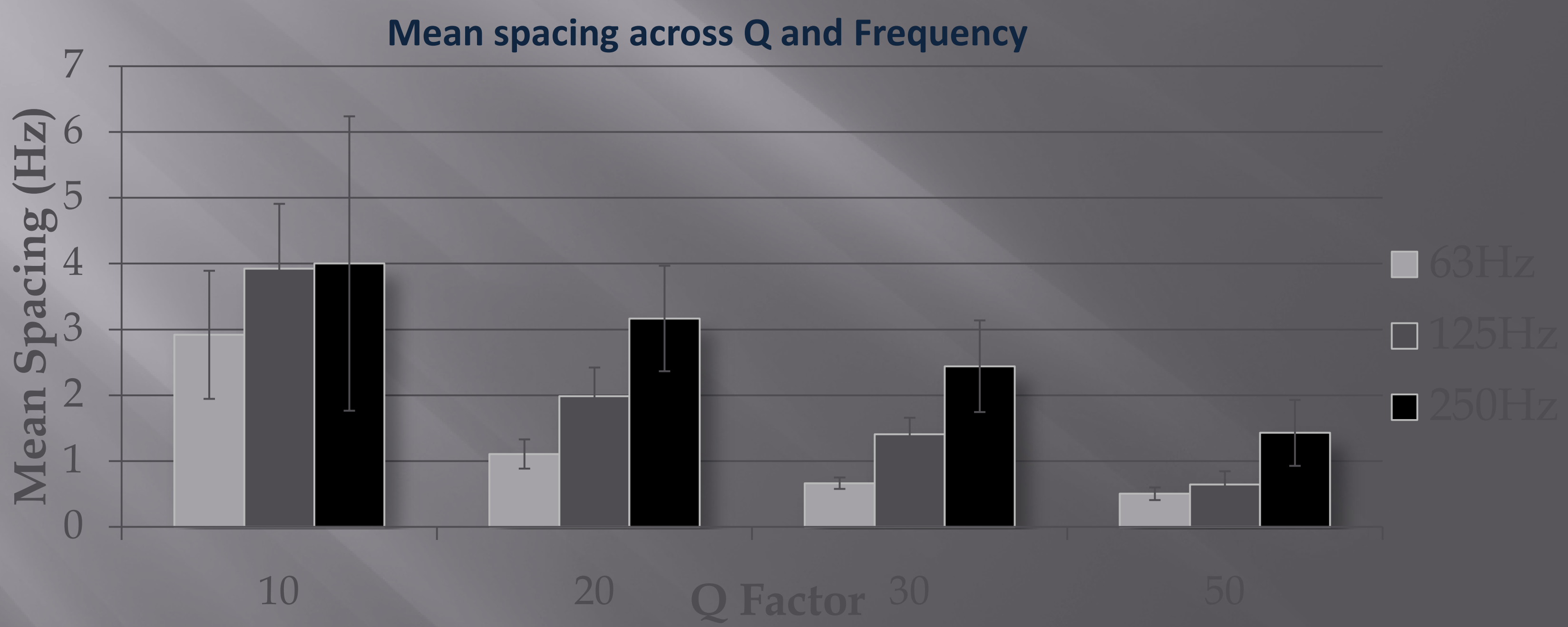
- To test this we used an adapted Green Function model of two resonances
- Frequencies tested
  - 1st (fixed frequency) 63Hz, 125Hz, 250Hz
  - 2nd (adjustable frequency)
- Q Factors tested
  - 10, 20, 30, 50
- 11 Subjects

Task – to adjust slider until overall shortest decay is perceived



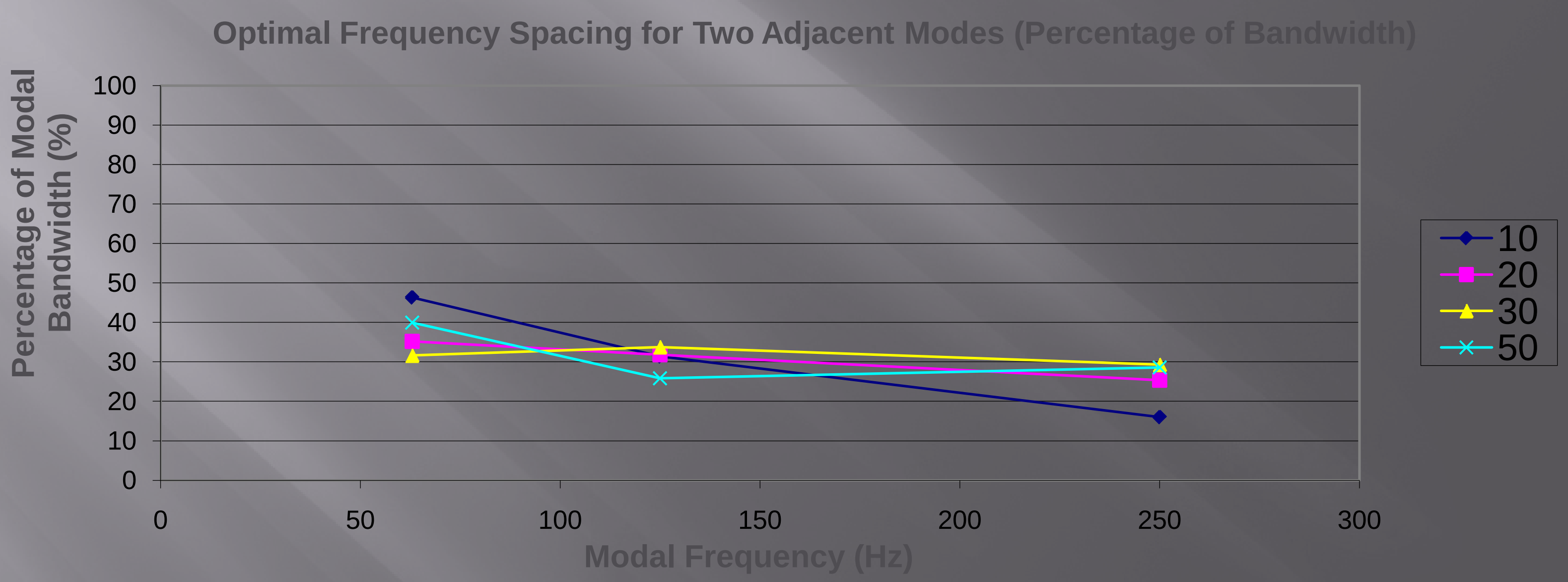
Optimal Modal Spacing

- Results:
  - Optimal spacing increases with frequency
  - Optimal spacing decreases with Q-factor
  - At high damping cases (Q=10) variation of results indicates little difference between frequencies tested



Optimal Modal Spacing

- Display the optimal modal spacing as a percentage of the bandwidth
  - $Bw = f_c/Q$
- Optimal spacing is fairly constant across frequency for all Q-factor levels
  - Except for low Q factor cases



Optimal Modal Spacing

- Discussion:

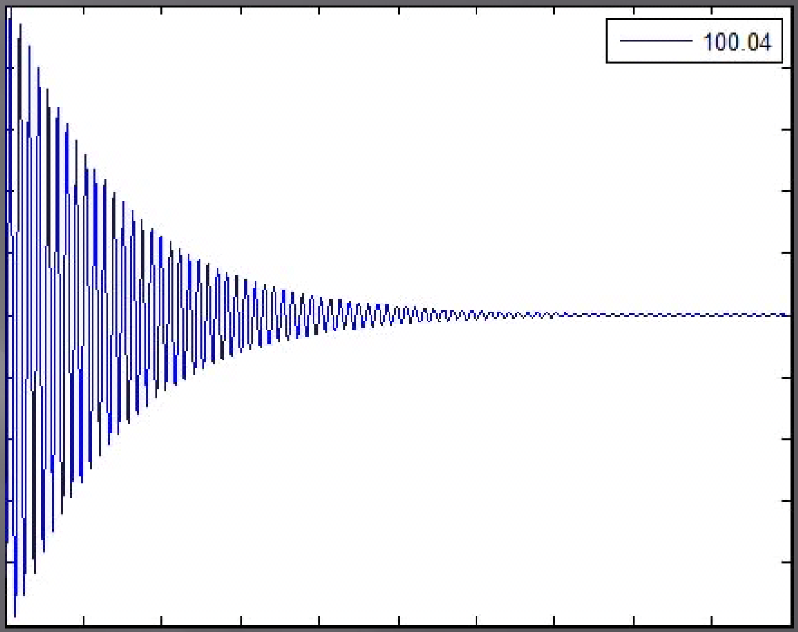
1. Optimal spacing is between 25% - 40% of the bandwidth of one mode
    1. Note again the optimal 4 modes per bandwidth

2. This is closer than often occurs in real rooms

3. It seems to be more important to focus on the lower frequencies
    1. Less homogeneous response

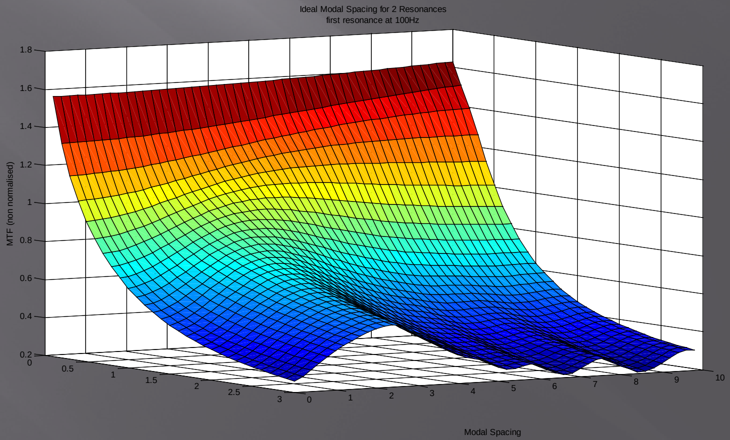
Modal Spacing

- This animation shows the effect of increasing the spacing between two resonances in the time domain
  - Original is fixed at f=100Hz
  - The frequency spacing of the second resonance is varied from 0Hz to 10Hz
  - No alteration of the Q-factor
- It is interesting to see:
  - The point at which the time response is shorter
  - The appearance of 'beat' effects as the two resonances *share* the same frequency region



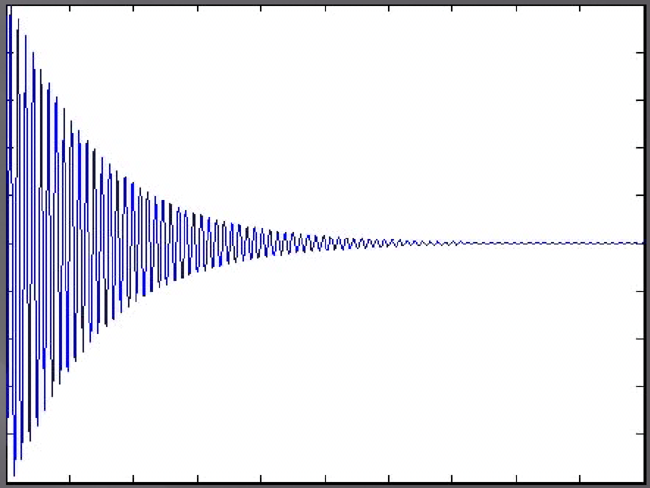
Modal Spacing

- Using the Modulation Transfer Function as a metric, the optimal modal spacing between two resonances is investigated
  - The MTF measures the loss of modulation in a signal
  - It combines temporal and frequency response in one metric
- The effect of damping is visible:
  - The optimal spacing becomes less 'important' as the room tends towards lower decays
  - Q-factors are much lower
  - Modal overlap is greater



Modal Density

- The Schroeder frequency associates with the number of modes per frequency bandwidth
  - Modal density
- The animation shows the effect of increasing modal density
  - Original frequency is f=100Hz
  - The temporal response is shown to change as more resonances are added
    - Fixed spacing – 0.1Hz
    - Up to 120Hz
- Note:
  - Reduction in the temporal response
  - 'beats' appear at lower relative amplitude compared to frequency spacing case



Modulation Transfer Function

Results

Modulation Transfer Function

- Originally developed in the field of optics as a quantifier of lens image resolution
- Measures preservation of modulation
  - Using various modulation frequencies - 3.15Hz to 12.5Hz
  - At different audio frequencies
- Provides a measure of temporal performance at each audio frequency
- Scores are bound between 1(no loss of modulation) and 0 (no modulation preserved)
  - Can be averaged to a single figure
  - Rating scale

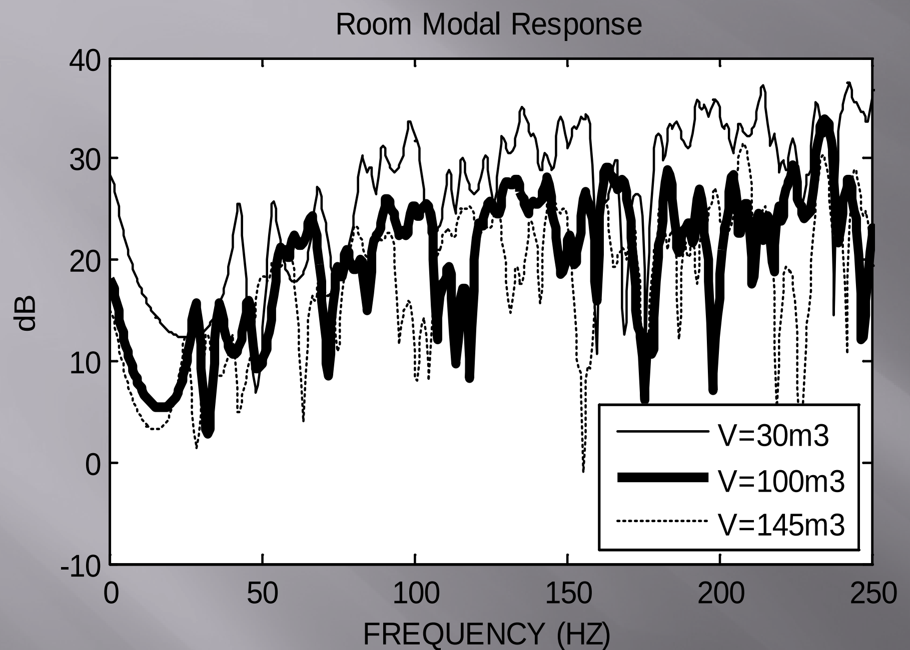
- May be determined from impulse response/spectra measurements

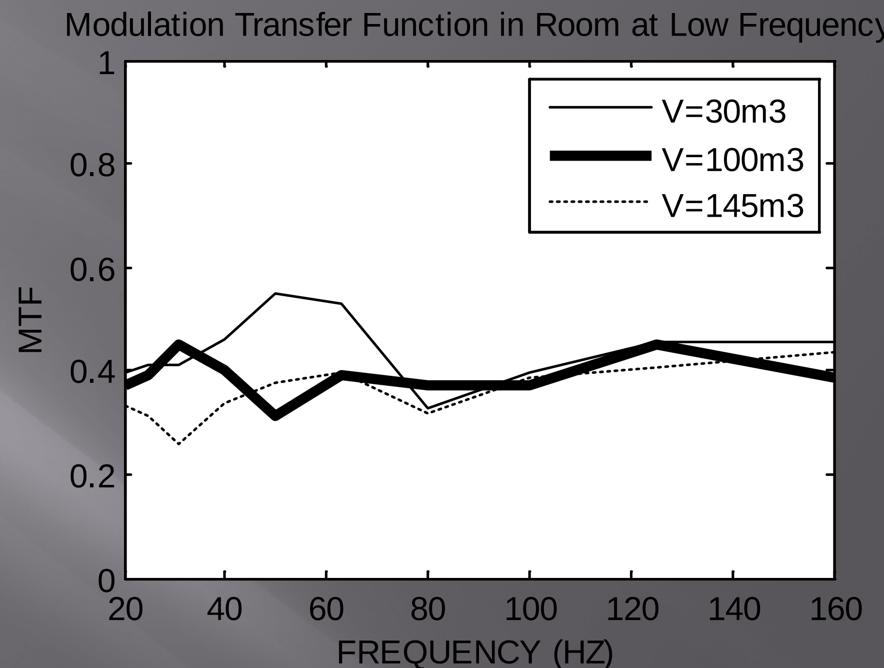
Modulation Transfer Function

- This work used the MTF to investigate the effect of various factors known to affect low frequency room response:
  - Volume
    - Modal density
  - Room aspect ratio
    - Modal distribution
  - Absorption (Damping)
    - Decay time

  using MTF ratings
- A number of room responses were modelled
- Compare to existing data on subjective perception of modal activity

Effects of Room Volume

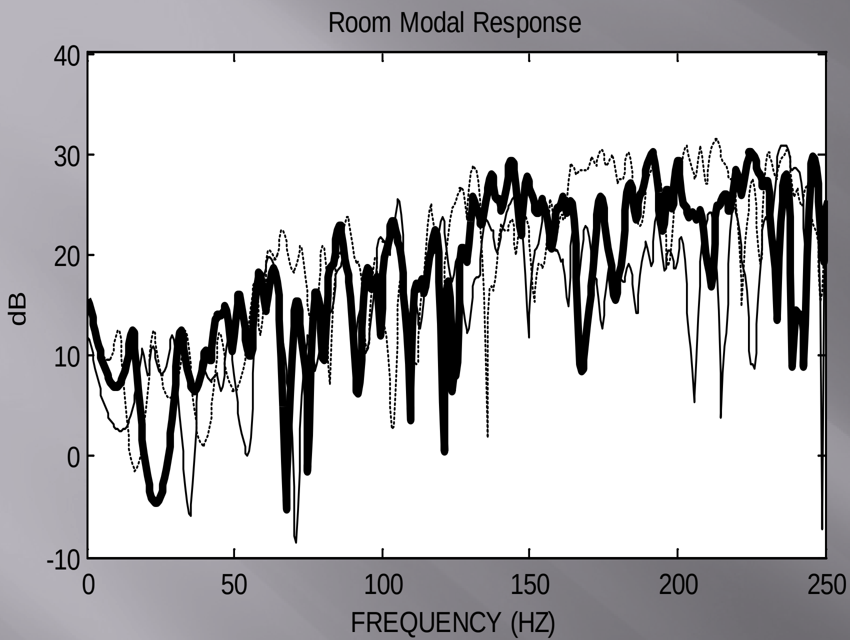


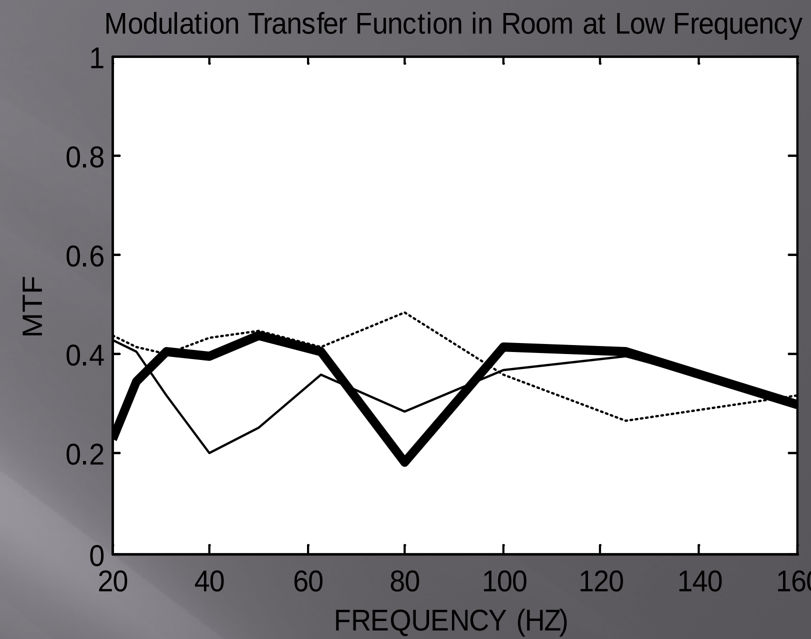


Room Volume (m^3)	MTF (avg. over all frequency bands)	Rating
30	0.44	Poor/Fair
100	0.39	Poor
145	0.36	Poor

Bruno Fazenda - 2008

Effects of Room Aspect Ratio

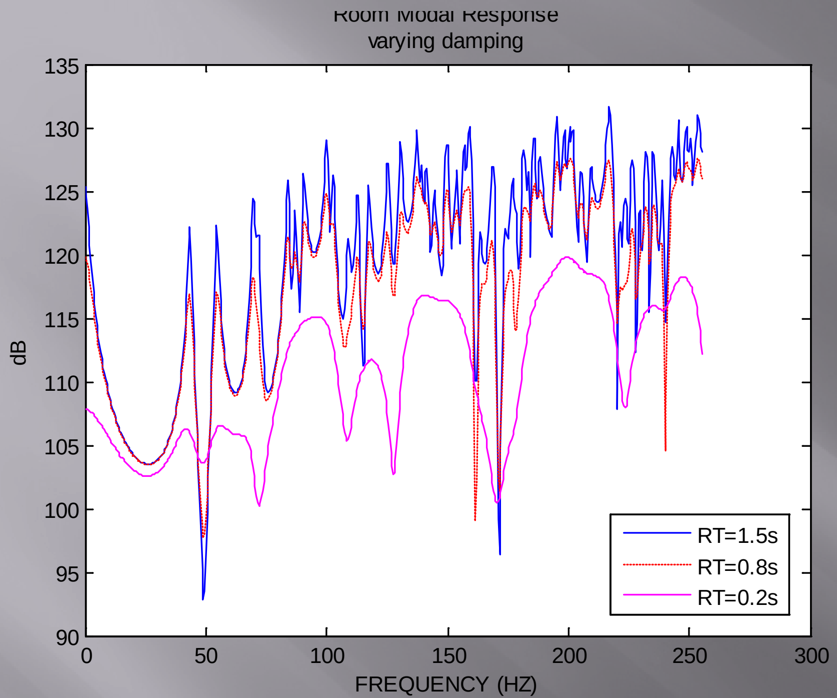


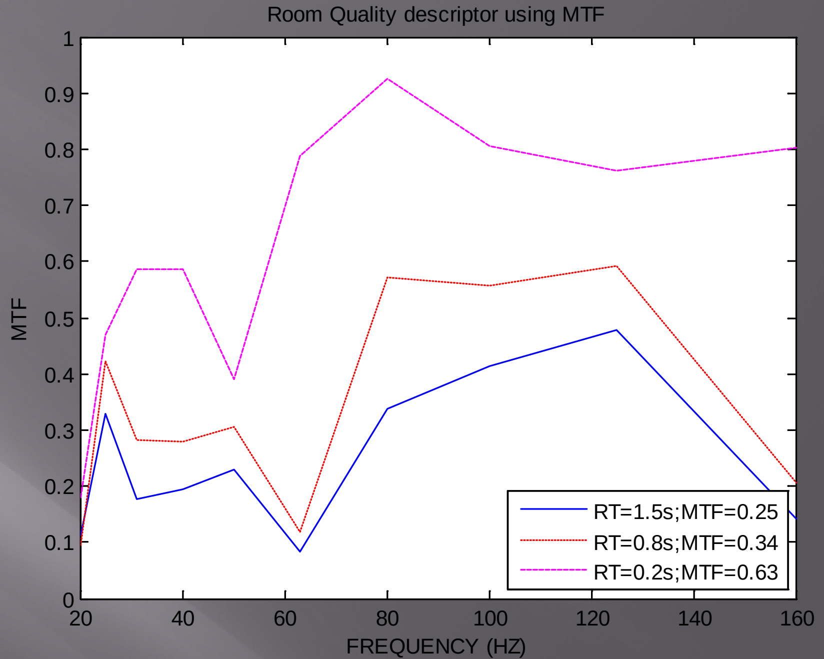


Aspect Ratio	MTF (avg. over all frequency bands)	Rating
1:2.58:2.97	0.33	Poor
1:1.41:3.6	0.35	Poor
1:1:5.08	0.40	Fair

Bruno Fazenda - 2008

Effects of Damping





Average Decay Time (s)	MTF (avg. over all frequency bands)	Rating
1.5	0.25	Bad
0.8	0.34	Poor
0.2	0.63	Good

Contrast with other research

- Fazenda, Avis and Davies, 2003
  - Detection of modal activity (40Hz-200Hz) using music stimuli
  - Q-factor of the modes used as variable under measurement

Q factor of modes (40Hz-200Hz)	MTF score	Rating
19	0.6	fair/good
(Measured Threshold) 16	**0.65**	**good**
11	0.76	excellent

- Karjalainen et al., 2004
  - Detection of a single mode when in the presence of other modes
- Goldberg, 2005
  - Determined thresholds of audibility for single resonant decays using upwards log sweep

Source	**Measured Threshold (frequency range)**	MTF	**Rating**
Karjalainen et al.	2s (<100 Hz) 0.2s (100Hz-800Hz)	<0.25 0.63	Bad Good
Goldberg	0.2s (20Hz-1KHZ)	0.63	Good

Conclusions on MTF

- MTF appears to be a useful measure of LF room performance and correlates well with previous results on subjective perception
- MTF frequency plots indicate
  - Overall performance across frequency range
  - Problematic frequencies
- Factors such as volume and modal distribution appear to have a 'peripheral' effect on room performance and corresponding MTF scores when compared to damping
- Combined effects such as loudspeaker performance and position-related coupling effects can be taken into account if present in measurement/simulation

Implications for room design

Conclusions

Implications for Room Design

- The transition frequency between modal and diffuse regions in a room seems to be higher than considered hitherto
  - Particularly in the case of small rooms
- A modal density of at least four appears to be ideal at the lower frequencies but this figure should increase for the higher modal range to about 30
  - Rather than a ‘magical’ constant bandwidth
- A higher modal density may alleviate modal problems only if the source and receiver coupling result in a smooth overall response
  - Dips in the magnitude frequency response appear to be as (or more) problematic as peaks

Implications for Room Design

- Adjusting for ‘correct’ modal spacing may afford a smoother frequency response and in turn a shorter modal decay
  - Although the effects of beats may become a problem
- Optimal modal spacing is defined between 25% and 40% of modal bandwidth
  - This could be achievable in the lower modal range with careful room dimensioning and/or low frequency diffusion
  - Not so relevant at higher modal range or in rooms with large damping

Implications for Room Design

- Definition of room aspect ratios as a measure to improve reproduction quality is only meaningful if source and receiver positions as well as their coupling to modeshapes are taken into account
- In this case, a metric that measures the deviation from a smooth frequency response appears more promising than what has currently been used
- In most applications, the response in the room may be improved by optimising source (and receiver) position even in a supposedly ‘bad’ room ratio

Implications for Room Design

- A reduction of the decay of modes still appears to be the most effective method of reducing their unwanted effects
  - Using passive or active methods
- However, other methods currently available have been shown to be effective if used correctly and guided by subjective metrics

References

- Fazenda, B.M. “Perception of Room Modes in Critical Listening Spaces”, PhD Thesis, University of Salford, UK, December 2004
- Fazenda B.M., Avis M.R., and Davies W.J. “Perception of Modal Distribution metrics in Critical Listening Spaces – Dependence on Room Aspect Ratios”, Journal of the Audio Engineering Society, Vol. 53, No. 12, December 2005
- Fazenda B.M., Avis M.R., and Davies W.J., Comments on “perception of modal distribution metrics in critical listening spaces—dependence on room aspect ratios”* - Letters to the Editor, Journal of the Audio Engineering Society., Vol. 54, no. 5, May 2006
- Avis, M.R., Fazenda, B.M., Davies, W.J. “Thresholds of detection for changes to the Q-factor of low frequency modes in listening environments”, Journal of the Audio Engineering Society, Vol. 55, No. 7/8, July/August 2007
- Fazenda, B.M., Davies, W.J. “The views of control room users”, Proceedings of the Institute of Acoustics, Vol 23, Pt 8, 2001
- Fazenda, B.M., Avis, M.R., Davies, W.J., Jacobsen, F “Perception of modal distribution in critical listening spaces”, Proceedings of the 11th International Conference on Sound and Vibration, July 2004, St. Petersburg, Russia
- Fazenda, B.M., Avis, M.R. “Perception of low frequencies in small rooms”, Proceedings of the European Acoustics Symposium, September 2004, Guimarães, Portugal
- Fazenda, B.M., Holland, K., Newell, P. “The measurement of sound quality for critical listening”, Proceedings of the 12th International Conference on Sound and Vibration, Lisbon, July, 2005
- Fazenda, B., Holland, K., Newell, P., Castro, S., “The time domain performance of standard listening rooms: an assessment of current rooms and recommendations for achieving improved compatibility”, Proceedings of the Institute of Acoustics, Vol 27, Pt 5, Oxford, 2005
- Fazenda, B., Holland, K., Newell, P., Castro, S., “Modulation Transfer Function as a Measure of Room Low Frequency Performance”, Proceedings of the Institute of Acoustics, Vol 28, Pt 8, Oxford, 2006
- Fazenda, B., Wankling, M., “Optimal Modal Spacing and Density for Critical Listening”, to be presented at the 125th Audio Engineering Society Convention (October 3 - 5), San Francisco, USA, 2008