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OPTIMUM DIMENSION RATIOS FOR STUDIOS, CONTROL ROOMS AND LISTENING ROOMS

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Summary

Most control rooms, listening rooms and small studios have dimensions that become comparable with the wavelength of the sound within the normally accepted audio range. Standing waves, where one of the room dimensions is an integer multiple of half the wavelength of the sound energy, result in irregular frequency responses. The response will also be a strong function of position of both the listener and the sound source because of the changing coupling to the spatial distribution of the modes. This behaviour is fundamental to sound in enclosed spaces and is accentuated if the room proportions cause clustering of the modes.

For practical purposes, it is necessary to define a range of acceptable room proportions from which selections may be made to suit particular cases. This requires the derivation of some form of criterion identifying regions of 'good' and 'poor' room proportions.

This Report describes the development of a computer program to produce plots of the distribution of an index of room 'quality' for rectangular rooms with different proportions. From these plots, regions of 'good' and 'poor' rooms were identified. A general design criterion was derived to restrict room proportions to those giving rooms with more even distributions of low-frequency modes.

Issued under the Authority of

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1. INTRODUCTION

Most control rooms, listening rooms and small studios* have dimensions that will become comparable with the wavelength of the sound at some frequency within the normally accepted audio range. The effects on the perceived frequency response of the modal behaviour of the sound within the room are well documented[1 - 6].

At some frequencies, one of the room dimensions will be an integer multiple of half the wavelength of the sound energy. A standing wave will be established because the total path length allows coherent addition of the energy reflected from the room boundaries. This will occur not only for every multiple of the principal dimensions of the room (length, width and height), involving two opposing parallel surfaces, but also for reflection paths involving four or six room surfaces. These modes are known respectively as axial, tangential and oblique.

For example, a room of dimensions $8 \times 5 \times 3.5$ m will have three axial fundamental modes of about 22 Hz, 34 Hz and 49 Hz. The lowest tangential and oblique modes will be about 40 Hz and 64 Hz respectively. In the frequency region up to about 200 Hz[5], the response will be characterised by large peaks at frequencies close to the modal frequencies, with significant dips between. The total range of response levels will be of the order of 20 dB. Fig. 1 shows typical theoretical and measured results for a small listening room (97 m^3).

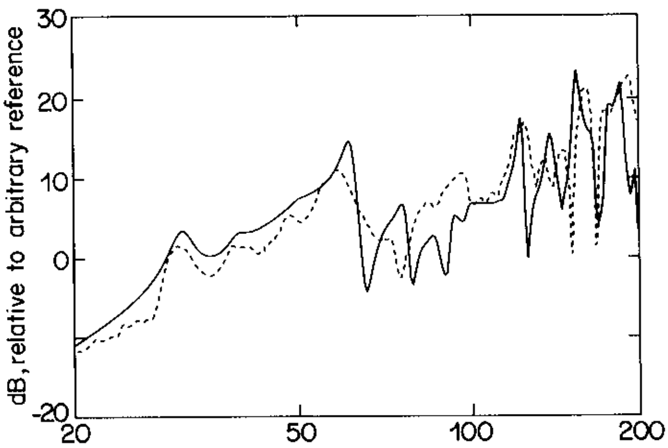
The response will also be a strong function of position of both the listener and the sound source; both the coupling of the source to the room modes and the magnitude of the listener's perception of the mode will depend on the positions relative to the standing wave pressure distribution. This behaviour is fundamental to sound in enclosed spaces and is essentially unaffected by room shape or any other parameters apart from the volume, although increasing the acoustic absorption has the effect of smoothing the responses by damping the resonances.

A non-rectangular enclosure exhibits similar modal behaviour — it is just more difficult to calculate the eigentones.

The problems caused by isolated or sparse mode distributions are increased if the room proportions tend to cause the modes to cluster together. Rooms with the three principal dimensions related by simple integers are especially poor. It is, therefore, desirable to find room shapes that minimise any such groupings. Several so-called 'optimum' dimension ratios have been suggested in the past and are in fairly common use. In general, however, it is not possible to constrain room designs to a small set of preferred proportions because they are almost always unsuitable in other respects; for example, in having insufficient floor area for the given height.

For practical purposes, it is necessary to define a range of acceptable room proportions from which selections may be made to suit particular cases. This requires the derivation of some form of criterion identifying regions of 'good' and 'poor' room proportions.

Based on the work described in Ref. 7, a computer program was developed to produce plots of the distribution of an index of room 'quality' for rectangular rooms with different proportions.



——— (a) calculated response, using summation of room modes

-------- (b) measured response

Fig. 1 - Low-frequency response in listening room.

2. CALCULATION OF ROOM 'QUALITY' INDEX

2.1 General

In general, a rectangular room has four principal characteristic dimensional parameters — length, width, height and volume (any three of which are independent). A fully general plot of the quality

* For simplicity, this group of room types will be referred to simply as 'listening rooms' in the remainder of this Report.

would therefore be four-dimensional and difficult to portray on paper. By fixing one or more of these four parameters, the number of independent axes can be reduced. For example, if the volume is fixed, the independent parameters are reduced to two — the length/height and width/height ratios. The quality index can then be portrayed as a contour map with two independent axes.

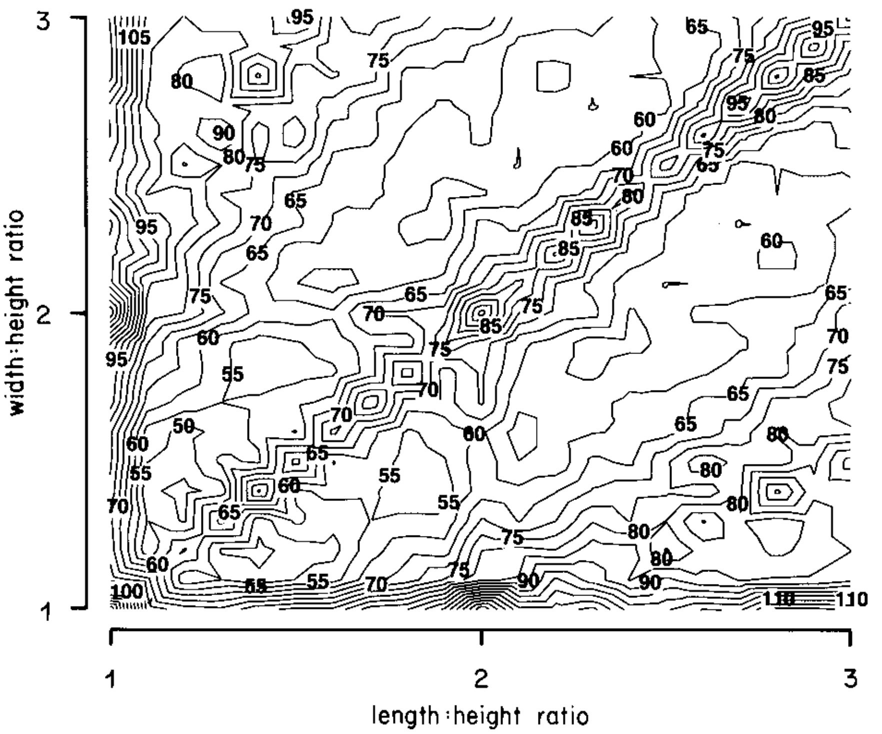
Each set of room proportions required the derivation and sorting of all mode centre frequencies (up to the limit set for consideration). These were then processed as required for the quality index. The resulting values were then used as an input array to a contour-plotting routine, to produce 'maps' showing the quality index as a function of room proportions. The contour-plotting routine used in this work was based on that described in Ref. 8.

2.2 Mean-square room quality index

Several different room quality indices were investigated. The one most immediately obvious was the mean-square spacing of the mode frequencies. This gives greater weight to more widely spaced pairs and is a common statistical measure of differences between sets of parameters. After derivation and sorting of the mode frequencies, the frequency differences between every pair of modes was squared and summed. The total was then divided by the number of modes included.

The example of this procedure shown in Fig. 2 is for a fixed room volume of 200 m^3 and axes of length/height and width/height ratios, with a range of 1 to 3 for both. The upper frequency limit for the inclusion of modes into the summation was set at 120 Hz. This involved the processing of about 60 modes for each value of room proportion. To avoid fractions, the numerical values shown in Fig. 2 indicate 10 times the quality index and are smaller for 'better' rooms. The array of points used for the contour plotting was 20×20. In this example, because the room volume was fixed, the height varied with floor proportions.

By inspection of the contour map, areas of particularly good or poor rooms could be identified and local minima identified. The 'optimum' aspect ratios predicted by this means were 1.40:1.19:1 for nearly cubic rooms and 2.2:1.75:1 for rooms of which the width and length are both about twice the height. The height of 4.9 m for the nearly cubic room is, perhaps, unrealistic for a room of 200 m^3. The proportions of about $8.2 \times 6.5 \times 3.7$ m for the second room are more reasonable and fairly representative of practical rooms, at least the somewhat larger ones. The results also show the inferior quality of room proportions along the diagonal, corresponding to rooms with square floor plans. This is especially so close to the integer multiples of the height (at the points 1/1, 2/2 and 3/3). Rooms with proportions close to one axis (i.e. with one floor dimension nearly the same as the height) are also inferior. The 'better' rooms form a somewhat-curved, diagonal line, roughly parallel to the main diagonal but displaced from it,



Numbers are 10 times the mean square mode spacing, lower values = 'better' quality.

Fig. 2 - Contour map of room 'quality', for 200 m^3 room, using mean square mode spacing for modes up to 120 Hz.

extending from about 1.2/1.4, through 1.75/2.2 and 2.2/2.8.

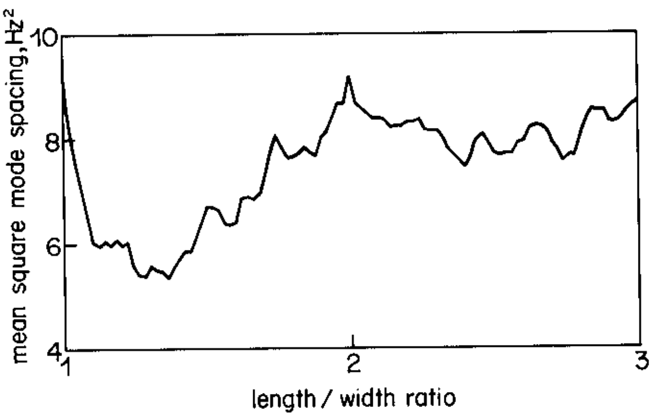
2.3 Other room quality indices

It could be argued that the spacings of the lowest modal frequencies are the most important factor and that the index should be weighted in that direction. However, the naturally more widely spaced low frequency modes are implicitly weighted in that way by the mean square function.

Other possible criteria are the magnitude of the largest spacing between any two adjacent modes and other powers of the mean mode spacing. In none of these cases did the optimum room proportions change much from their mean-square index values. The general appearances of the maps and conclusions about areas of higher and lower quality also remained the same.

2.4 Other bases for plotting the distributions of room quality index

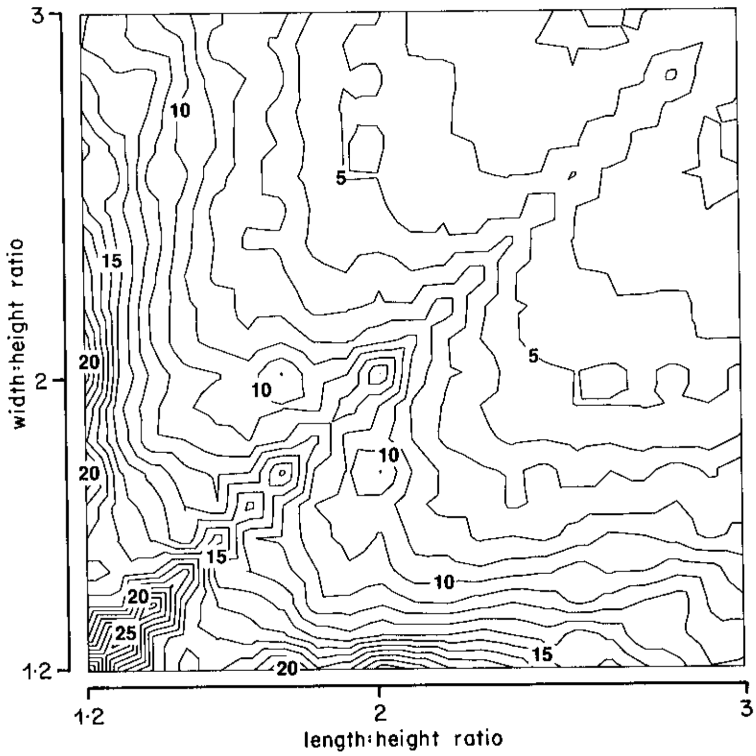
Fig. 3 shows a plot of the mean-square quality index for rooms of fixed height, fixed volume and variable ratio of length to width. Thus, two of the three independent parameters have been fixed and the resulting plot is a one-dimensional function of the floor shape, length/height. For this example, the height was 3 m and the volume 100 m^3. The vertical axis shows values of the quality index (smaller for 'better' rooms). The region around 1.3 shows the lowest values, with two local minima at about 1.27 and 1.36. The local maximum at 2 and the extended region of higher values over the whole range from about 1.7 upwards are also evident. The minimum at 1.36 represents a room 6.73 × 4.95 × 3 m, the size of which is consistent with typical control rooms.



Vertical axis is the mean square mode spacing.

Fig. 3 - Plot of room 'quality', for 100 m^3 room of 3 m height, using mean square mode spacing for modes up to 120 Hz.

Finally, the beneficial effects of larger rooms are illustrated in Fig. 4 which shows a map of the mean-square quality index for rooms of fixed height (3.5 m) and variable volume. The numerical values shown are the mean-square quality index. The same general structure as in Fig. 2 is evident but overlaid with a strong bias towards larger rooms (towards the 3,3 corner). The corner at 3,3 represents a room of



Numbers are the mean square mode spacing

Fig. 4 - Contour map of room 'quality', for fixed height of 3.5 m and variable volume.

386 m^3. In this case, both axes begin at 1.2 × room height to avoid the dense contour distribution around the point 1,1 and to a lesser extent along both axes, caused not only by the poor room proportions but also the small sizes of the rooms (43 m^3 at 1,1).

2.5 Other room heights

The plot of room quality described in Section 2.4 was for a fixed room height of 3.5 m. Plots for heights of 2.5 m, 3 m, and 4 m were also made for comparison. The general shape and character of the contours and the areas of 'good' and 'poor' rooms were essentially identical, although of course, the numerical values of the 'quality' index were significantly different.

2.6 Summary

It is clearly impossible to set specific room shapes as a standard. The purpose of this work was to derive a relatively simple criterion for room proportions, to encompass the majority of the area of 'good quality' rooms and exclude all of the 'poor' rooms and to be accepted as a uniform standard for high-quality listening environments. For this purpose, the type of plot shown in Fig. 5 is most useful. It recognises the common property of listening rooms of different shapes and sizes in having a more or less fixed height.

For the purposes of the derivation of a criterion for room proportions, the plots for 2.5 m, 3 m, 3.5 m and 4 m height were analysed in detail. The resulting criteria for these different heights were essentially indistinguishable. The plots for 3.5 m height only are used throughout the remainder of this Report.

3. EXISTING STANDARDS

Most broadcasting and recording organisations have some guides to preferred room shape, either expressed formally or as an informal design procedure.

As an example, Fig. 5 shows a typical existing criterion[9], overlaid on the plot of the room quality for a 3.5 m high room as described above. The shaded areas represent admissible room proportions. This criterion sets $l/h < 1.9$ or > 2.1, w/h in the range 1.1-1.9 and l/w in the range 1.25-1.45.

It is clear from Fig. 5 that the criterion is unfavourably biased towards greater values of l/h, especially for smaller rooms. There also appears to be little benefit from omitting the area on either side of $l/h = 2$. The largest room that could be built with a 3 m height according to this criterion is about 140 m^3. It would have the dimensions 8.27 × 5.7 × 3 m. For 3.5 m height, the largest room would be 224 m^3. These are restrictive limitations, especially for the 3 m height, which is a common maximum available internal height in typical buildings.

This type of criterion is constrained by effectively 'going through the origin', that is the limits on length and width are both simple multipliers of height. The whole region of reasonably satisfactory rooms with w/h ratios around 1.8 and rather greater l/h ratios (between about 2.4 and 3) are excluded.

4. A PROPOSAL FOR A NEW CRITERION

The criterion described in Section 3 could be improved by shifting the permissible l/w ratios from 1.25-1.45 towards about 1.1-1.35. This would permit better smaller rooms, particularly around 50 m^3 for a height of 3 m. However, the main area of rather greater l/h ratios would be excluded even more.

Fig. 6 shows a much better basis for a criterion. The lower limit for l/w is of the same form as previously, that is, a simple multiplier. In this example, it has a value of 1.1. This is indicated by the line '*a—a*'. The upper limit for l/h has been altered to the line marked '*b—b*'. It clearly includes much more of the usable range of 'better' rooms.

On the axes of l/h and w/h, the equation of line *b-b* is:

$$l/h = 4.5\ w/h - 4$$

(The exact position of the line '*b—b*' has been chosen to make the coefficients numerically relatively simple.)

As stated above, the equations for the criterion had similar values for different room heights. Thus, the recommended room proportion criterion can be taken to apply to rooms of any reasonable height, certainly over the range 2.5 to 4 m. It should be noted that the criterion does not exclude the region around $l/h = 2$.

One slight limitation may be the size of the smallest room that could be constructed to meet this criterion. In rare cases this may be problematical. This would be particularly true for rooms with high ceilings for their volumes. The smallest room satisfying this new criterion has proportions 1.294 : 1.176 : 1. This gives minimum volumes of 41 m^3 for 3 m height, 65 m^3 for 3.5 m height and 97 m^3 for 4 m height.

For rooms with heights above about 4.5 m the room volumes are generally so large that the problems

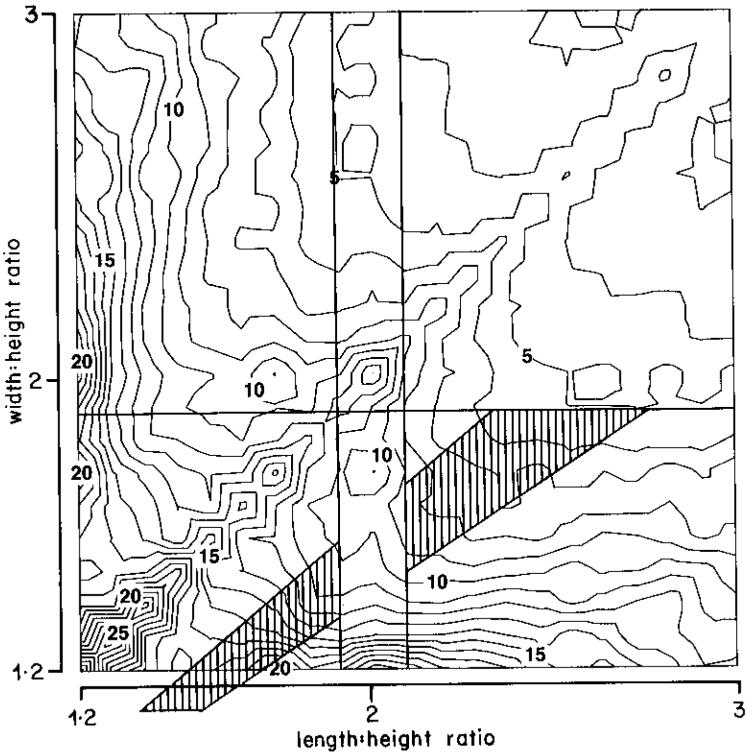


Fig. 5 - Contour map of room 'quality', for fixed height of 3.5 m and variable volume, overlaid with room proportion design criteria from Ref. 9.

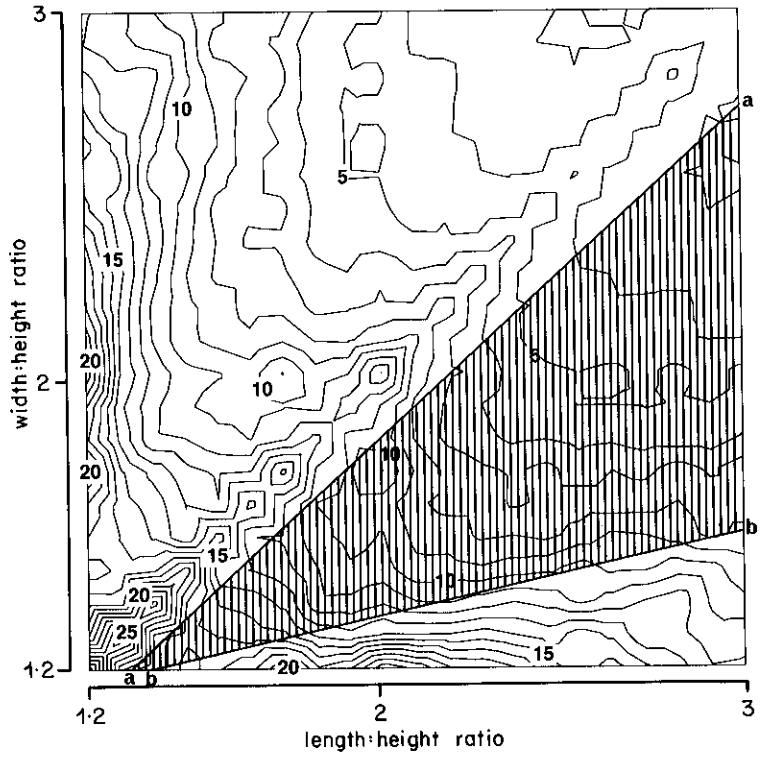


Fig. 6 - Contour map of room 'quality', for fixed height of 3.5 m and variable volume with proposed new room proportion design criteria.

of uneven mode distribution become less important in the usual audio frequency range. They may still be of some significance if frequencies much lower than about 50 Hz have to be recorded or reproduced with reasonable fidelity. It is possible that the criterion described here would not be applicable to those designs.

5. USE OF THE CRITERION IN ROOM DESIGN

Given such a criterion with its interdependencies, it is not immediately obvious how acceptable room dimensions can be selected. However, the use of a simple spreadsheet or table (either by computer or manually) can be used to find ranges of suitable room proportions to fit a particular location and requirement.

Generally, the required room volume, V, and height, h, are already known, the former from the site (or from the budget) and the latter from the available building floor-floor clearance or the desired total height of the finished room.

Given the volume and the height, the product, P, of l/h and w/h must be given by

$$P = V/h^3$$

Then, for a range of values of l/h, the corresponding values of w/h and l/w can be calculated. The lower limit of l/w (1.1) and the upper limit of l/h ($l/h = 4.5\ w/h - 4$) are given by the criterion. It is a simple matter to find which of the table of values for l/h lead to possible rooms.

Table 1 shows a spreadsheet calculation illustrating the method. The Appendix contains the spreadsheet cell values and functions required to reproduce Table 1.

Table 1: Calculation of possible room shapes.

Volume = 100.00 Length/width ratio product = 3.70
Height = 3.00

l/h	w/h	l/w	low limit l/w	high limit l/h	length	width
2.00	1.85	1.08	1.10	4.33		
2.10	1.76	1.19	1.10	3.94	6.30	5.29
2.20	1.68	1.31	1.10	3.58	6.60	5.05
2.30	1.61	1.43	1.10	3.25	6.90	4.83
2.40	1.54	1.56	1.10	2.94	7.20	4.63
2.50	1.48	1.69	1.10	2.67	7.50	4.44
2.60	1.42	1.83	1.10	2.41		
2.70	1.37	1.97	1.10	2.17		
2.80	1.32	2.12	1.10	1.95		
2.90	1.28	2.27	1.10	1.75		

In general, possible rooms only exist for a restricted range of values of l/h. In the limit, only one room is possible. The volume of that room is the smallest that can be constructed, for that height, which will still meet the criterion.

Clearly, other bases of calculations are possible; for example, in some cases it may be more convenient to use a fixed floor area as one of the determining factors.

6. DISCUSSIONS AND RECOMMENDATIONS

It has been shown that the use of a quality index for the calculation of a single figure, representing the uniformity of low-frequency mode spacings, results in distribution patterns from which rooms of 'better' and 'worse' quality can be identified.

Because of the number of degrees of freedom, the presentation of the data has to be constrained, so that the resulting plot is presentable on paper. Plots for rooms of fixed height, fixed volume and fixed height and volume have been described.

The general characteristics of these patterns and the zones of 'better' and 'worse' quality are independent of room size (although the absolute values of the quality index are better for larger rooms). They are also reasonably independent of the exact nature of the quality index.

Existing simple criteria for acceptable room proportions tend to exclude large zones of 'good' rooms, without any valid acoustic justification.

A new criterion for acceptable room proportions has been derived. It permits a much wider range of room proportions without unjustified exclusion zones. This criterion was based on the essentially practical limitation of rooms of fixed height and variable volume. The optimum numerical values of the criterion are only weakly dependent on room height and the criterion can, therefore, be used for all (reasonable) room heights.

The proposed new criterion for acceptable room proportions are:

$$1.1w/h <= l/h <= 4.5w/h - 4$$

7. FOOTNOTE

This work was originally carried out in preparation for EBU and BR (formerly CCIR) groups discussing Recommendations for the design of listening rooms. At the time of writing, the design criterion derived in this work has been adopted by BR TG10/3 and is included in the latest draft of the BR Recommendations for the design of Listening Rooms for the assessment of small impairments in audio systems.

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APPENDIX

Spreadsheet Formulae

```
Cell : Contents

A1  : “Volume =”
B1  : 100
D1  : “Length width ratio product =”
G1  : B1/B2/B2/B2

A2  : “Height =”
B2  : 3

A5  : “l/h”
B5  : “w/h”
C5  : “l/w”
D5  : “low limit”
E5  : “high limit”
F5  : “Length”
G5  : “Width”

D6  : “l/w”
E6  : “l/h”

A8  : 2
B8  : @G@1/A8
C8  : A8/B8
D8  : 1.1
E8  : B8*4.5-4
F8  : if(C8>=D8 & A8<=E8,A8*@B@2,“”)
G8  : if(C8>=D8 & A8<=E8,B8*@B@2,“”)

A9  : A8+1
B9  : @G@1/A9
C9  : A9/B9
D9  : 1.1
E9  : B9*4.5-4
F9  : if(C9>=D9 & A9<=E9,A9*@B@2,“”)
G9  : if(C9>=D9 & A9<=E9,B9*@B@2,“”)

A10 : A9+1
B10 : @G@1/A10
C10 : A10/B10
D10 : 1.1
E10 : B10*4.5-4
F10 : if(C10>=D10 & A10<=E10,A10*@B@2,“”)
G10 : if(C10>=D10 & A10<=E10,B10*@B@2,“”)
                    .
                    .
                    .
                    .
                    .
```

The cells A9-G9 can be replicated to A10-G10, A11-G11, ..., ...

Note: This format should be compatible with most common computer spreadsheets. The notation “@B@2” denotes an absolute cell reference.

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