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LETTERS TO THE EDITOR

THE REVERBERATION TIME OF TALL SPACES

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1. INTRODUCTION

The poor acoustics of some high-ceilinged rooms can make designers cautious about providing such designs. This is unfortunate, as there is much pressure to adopt such designs for new public and commercial buildings. This work demonstrates that this caution is not justified, in that, the reverberation time of a high-ceilinged space need not be greater than that of a lower room as long as appropriate care is taken with the specification of the upper walls.

For several reasons there is a growing requirement for high-ceilinged spaces. Tall spaces can be a way of providing daylight to the rear of deep rooms via high-level windows; providing halls that can be used for sports as well as assemblies; providing adequate air volume in workshops and for multipurpose designs where use may change over time. Because the floor plan area is defined by other constraints, and because certain materials and designs have become commonplace, these new spaces are often relatively simple adaptations of standard designs with the addition of higher ceilings. Unfortunately, just raising the height of a ceiling can have serious consequences for the acoustics of the space and potentially leaves the design team open to criticism.

The room parameter most commonly used by architects is the mid-frequency reverberation time of the space. In part, this is because it is this parameter that is given in guidance notes, for example reference [1], and can, therefore, form part of the design brief. Design teams know whether current designs pass reverberation time guidance, but cannot be sure that they will once the ceiling height is increased.

Although it would seem relatively simple for acoustic practitioners to determine, on a design-by-design basis, whether guidance will be met, such modelling usually occurs rather late in the design process. Design teams would benefit from a rule of thumb that says whether increasing the height of a design will make the environment unacceptable or not; or at least whether, if some of the additional wall area had acoustic treatment applied, compliance could always be met.

In practice, and as reported in reference [2], unless the space is for specialist use, low reverberation times are rarely a problem. It is excessive reverberation that must be avoided because communication can become very difficult in such a space.

In the following it is shown that for any cuboid design, increasing the height of the space will not increase the mid-frequency reverberation time if the average absorption coefficient of the additional walls is greater than the average absorption coefficient of the pre-existing design. In practice, this caveat can be easily met by the inclusion of acoustic treatment on some of the additional surfaces if required.

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2. ANALYSIS OF THE PROBLEM

The Sabine formula [3] gives the reverberation time (s), R_T of a space as

$$R_T = \frac{0{\cdot}16V}{\alpha A}, \tag{1}$$

where V is the volume of the space (m^3), α the average absorption coefficient of the surfaces and A the surface area of the room (m^2). (Air absorption need not be considered in the following, as it is of marginal significance at the most important frequencies for most rooms.)

If V_1 is the volume of the original design of surface area A_1 with average absorption coefficient α_1, then extending the height of the space gives an additional volume of V_2 with additional surface area A_2 and average absorption coefficient α_2. The reverberation time R_T of the new space is then given by

$$R_T = \frac{0{\cdot}16(V_1 + V_2)}{\alpha_1 A_1 + \alpha_2 A_2}. \tag{2}$$

If the additional height is not to risk the reverberation time of the space rising above the upper limit of guidance, then the reverberation time of the new space must not be greater than the reverberation time, r, of the original space, i.e.,

$$r \geqslant R_T. \tag{3}$$

That this will always be so is not obvious. When the average absorption coefficient of the additional walls is the same, or less than, the previous room average, then the opposite will always hold, i.e.,

$$r < R_T. \tag{4}$$

This is because as additional height is added to a cuboid, the volume of the space will grow faster than the surface area. Thus, the numerator in equation (1) will grow faster than the denominator and the reverberation time will increase.

This argument fails in the more complex case, where the absorption coefficients of the additional walls are not the same as that of pre-existing space, because it is not clear that the numerator in equation (2) will always out-climb the denominator, particularly if α_2 is large. So, in general, is equation (3) true or is it equation (4) that is true? Or is there no general case and each design needs to be treated separately? If we cannot show that there is a general case, then we cannot guarantee to architects that taller spaces will not have reverberation times above guidance. Writing equation (3) out in full, we have

$$\frac{0{\cdot}16V_1}{\alpha_1 A_1} \geqslant \frac{0{\cdot}16(V_1 + V_2)}{\alpha_1 A_1 + \alpha_2 A_2}, \tag{5}$$

for *all possible* combinations of V_1, V_2, A_1, A_2, α_1, α_2.

Equation (5) can be expanded as

$$\frac{0{\cdot}16h_1 lw}{\alpha_1(2(l + w)h_1 + 2lw)} \geqslant \frac{0{\cdot}16(h_1 lw + h_2 lw)}{\alpha_1(2(l + w)h_1 + 2lw) + 2\alpha_2 h_2(l + w)}, \tag{6}$$

where h_1 is the height of the original design, h_2 is the additional height added, and l and w the length and width, respectively, of both designs.

Cancelling common terms

$$\frac{h_1}{\alpha_1((l+w)h_1+lw)} \geqslant \frac{h_1+h_2}{\alpha_1((l+w)h_1+lw)+\alpha_2 h_2(l+w)}.$$

Multiplying both sides by both denominators

$$h_1(\alpha_1((l+w)h_1+lw)+\alpha_2 h_2(l+w)) \geqslant \alpha_1((l+w)h_1+lw)(h_1+h_2)$$

or

$$h_1(\alpha_1(dh_1+D)+\alpha_2 dh_2) \geqslant \alpha_1(dh_1+D)(h_1+h_2),$$

where $D = lw$ and $d = l + w$.

Expanding

$$h_1^2\alpha_1 d + h_1 D\alpha_1 + h_1 h_2 d\alpha_2 \geqslant h_1^2 D\alpha_1 d + h_1 D^2\alpha_1 + h_1 h_2 dD\alpha_1 + h_2 D^2\alpha_1.$$

Cancelling common terms once more

$$h_1 d\alpha_2 \geqslant h_1 d\alpha_1 + D\alpha_1. \tag{7}$$

Note: h_2, the additional height added, no longer appears in equation (7), which is of the form:

$$a \geqslant b + c$$

and must be true if (but not only if) a > 2b and a > 2c simultaneously. Thus, equation (7) is true if

$$h_1 d\alpha_2 \geqslant 2h_1 d\alpha_1$$

and

$$h_1 d\alpha_2 \geqslant 2D\alpha_1,$$

i.e., if

$$\alpha_2 > 2\alpha_1 \quad \text{and} \quad h_1(l+w)\alpha_2 \geqslant 2lw\alpha_1. \tag{8a, b}$$

Equation (8a), which simply requires the upper walls to be constructed of materials that have on average at least twice the absorption coefficient of the other parts of the design, is definitely true as the upper walls will include acoustic treatment.

Equation (8b), which connects the size of the space with the absorption coefficients, can be simplified if we use realistic, but cautious, values for the absorption coefficients and for the height of the original design.

In practice, h_1 is likely to be greater than 3 m, α_1 less than 0·3 and the room not square. With a height of 3·5 m, $\alpha_1 = 0{\cdot}2$, $\alpha_2 = 0{\cdot}7$ and a major/minor axis ratio of 1·75, equation (8b) implies that guidance cannot then be breached for any design with a major axis less than or equal to 26·4 m—a substantial room for such a low ceiling height. Similar results are obtained for other realistic values.

3. CONCLUSION

In order to keep the design process fluid, building designers can benefit from simple rules of thumb that they can use during the early stages of the design process. For high-ceilinged buildings this means giving them the confidence that acoustically suitable spaces can still be created without major adjustments to built form or materials used.

It has been shown that for any practical cuboid design, increasing the height of the space will not increase the reverberation time if the average absorption coefficient of the additional walls is greater than twice the average sound absorption coefficient of the pre-existing design. In practice, this requirement can easily be met by the inclusion of acoustic treatment on some of the additional surfaces.

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