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Spatial sampling of sound pressure in rooms using manual scanning paths

Carl Hopkins
Acoustics Research Unit, School of Architecture, University of Liverpool, Liverpool L69 7ZN, UK

ABSTRACT

In building acoustics and environmental noise, measurements are often needed to determine the spatial average sound pressure level inside a room. This is usually carried out by using mechanical or manual scanning methods, or fixed microphone positions. In comparison with mechanical scanning devices, the human body allows quite complex paths to be traced out in three-dimensional space. This paper assesses the efficacy of some different averaging paths that can be carried out with manual scanning. It is assumed that the sound field is a three-dimensional diffuse field for which the spatial correlation coefficient can be used to determine the variance and the equivalent number of discrete, uncorrelated samples. Numerical simulations indicate the advantages and disadvantages of various manual scanning paths in terms of their equivalent number of discrete, uncorrelated samples.

1. INTRODUCTION

In the assessment of sound insulation, environmental noise, and building services noise it is necessary to quantify the room average sound pressure level using spatial and temporal averaging. For broad-band noise signals used in sound insulation measurements, temporal averaging is rarely problematic because the standard deviation due to spatial variation is significantly larger than that due to temporal variation[1]. The spatial average is determined using either fixed microphone positions with a tripod, mechanized continuously-moving microphones, or manual scanning by a human operator with a sound level meter. For continuously-moving microphones the process is often automated with a mechanical device that moves the microphone along a pre-defined path. A well-established system involves a rotating boom which traces out a circular path. However, in small furnished rooms it can be awkward to use tripods and rotating booms and it is often desirable to minimize both the amount of equipment and the measurement time on site. For these reasons, manual scanning with a hand-held sound level meter has advantages if the effects of unwanted noise and absorption from the human operator are negligible. The main issue then becomes the traceability of the measurement, particularly for the purposes of accreditation. The reason for this is that unlike the mechanized continuously-moving microphone there is no pre-defined path for the operator to trace, and unlike fixed microphone positions it is not possible to calculate a standard deviation to describe the spatial variation in the sound pressure level. This means that there is no traceability in the measurement to give any confidence that a good estimate has been made of the spatial average sound pressure level. To address this issue, this paper compares the efficacy of different manual scanning paths in rooms where the sound field can be assumed to be diffuse in three-dimensions.

2. ANTHROPOMETRIC CONSIDERATIONS FOR MANUAL SCANNING PATHS

In comparison with mechanical scanning devices, the human body allows quite complex paths to be traced out in three-dimensional space, although it is equally possible to mimic the simple paths of mechanical devices such as the circular path of a rotating boom. In general, two types of manual scanning path can be considered: those for which the path length depends primarily on the room dimensions and the source position, and those which depend on the combination of anthropometric dimensions, room dimensions and source position. The former includes straight line paths across the room where the operator simply walks across the room, whereas the latter includes curved paths traced out by rotation of the arm and body.

The ability of the human body to trace out curved paths allows spatial sampling over a large portion of an irregular volume whilst maintaining a relatively uniform scanning speed. The first step is to establish the average length of an outstretched arm as this minimizes the effect of reflections from the body on the measured signal. Based on anthropometric data for the average lateral reach of adult males[2] and a typical sound level meter it can be assumed that the average distance from the shoulder joint to microphone for an outstretched arm holding a sound level meter is approximately 0.7 m. This arm length might be slightly shorter for the average adult female, but due to the variety of sound level meter sizes it is reasonable to base the calculations on a single value. In fact, 0.7 m forms a useful benchmark because it fortuitously corresponds to the minimum radius required for circular paths with a rotating boom in International Standards for field sound insulation measurements[3]. The next step is to consider the physical limitations of the arm when rotating about the vertical axis. If an outstretched arm is rotated without moving the body it is only possible to comfortably trace out a 135° arc in a horizontal plane in front of the body. However, in the same horizontal plane it is possible to trace out a semi-circle by moving the outstretched arm from an angle -45° relative to the sagittal plane of the human body (an imaginary plane that runs from the head to the feet, dividing the body into equal left and right portions) to +135° (i.e. behind the body). To trace out the path of a full circle, helix or spiral it is necessary to rotate the body by pivoting around the right foot with the right hand outstretched (or left foot and left hand).

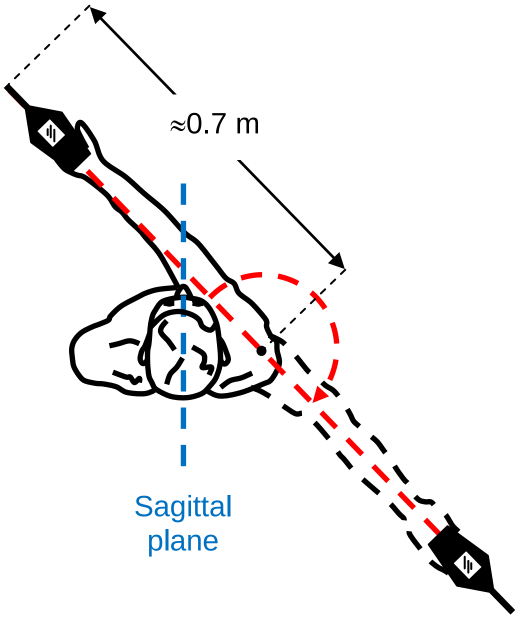

Figure 1: Plan view of head and torso with outstretched arm holding a sound level meter.

3. SPATIAL SAMPLING IN A THREE-DIMENSIONAL DIFFUSE FIELD

In the field, measurements are taken in the central zone of rooms with a variety of different sound fields. However, a three-dimensional diffuse field model is a reasonable approximation for the majority of rooms in the mid- and high-frequency ranges (typically covering 250 – 5000 Hz). In the low-frequency range (50 – 200 Hz), measurements taken in the central zone of small rooms with fewer than five modes in a frequency band are prone to underestimate the sound pressure level with a repeatability that is unsatisfactorily high. For sound insulation measurements in the low-frequency range, the average sound pressure level from the central zone determined with fixed or scanning measurements can be supplemented with additional fixed corner positions to improve the repeatability and the relevance to occupants[4].

Use of the diffuse field model makes it possible to draw general conclusions based on well-defined features of a diffuse field; primarily the relation between the pressure at two arbitrary points in the sound field. Early investigations into spatial correlation between two points in a diffuse field were carried out by Cook *et al*[5]. From later work by Lubman[6], the spatial correlation coefficient, $R(kd)$, for mean-square pressure with pure tones in a three-dimensional diffuse field is given by

$$R(kd) = [\mathrm{sinc}(kd)]^2 \quad (1)$$

where k is the wavenumber (rads/m) and d is the distance between the two points (m). Chu[7] has subsequently demonstrated that there is insignificant change to the result for pure tones when considering broad-band noise in one-third-octave or octave bands.

A. Fixed microphone positions

In order to assess the efficacy of continuous scanning paths it is instructive to first consider spatial sampling using fixed microphone positions. For mean-square pressure in a three-dimensional diffuse field, the spatial correlation coefficient varies as shown in Figure 2. The spatial correlation coefficient has its first zero-crossing at $kd = \pi$ and it is common to use this first zero-crossing to define the minimum kd required for uncorrelated samples; this corresponds to $d = 0.5\lambda$. Hence if the distance between all fixed microphone positions is 0.5λ then each position yields a discrete, uncorrelated sample.

For measurements that use parallel filter analysis it is both practical and convenient to prescribe inter-microphone spacing using a minimum distance between fixed microphone positions in metres, rather than a minimum fraction of a wavelength. The requirement on fixed microphone positions for field sound insulation measurements[3] is given as a minimum separating distance of 0.7 m between microphone positions; this corresponds to $d = 0.5\lambda$ at 250 Hz.

The nature of the squared sinc function means that the use of a minimum distance of 0.7 m will result in samples that are significantly correlated in the low-frequency range, 50 – 200 Hz, with only a small degree of correlation in the mid- and high frequency ranges that cover 250 – 5000 Hz.

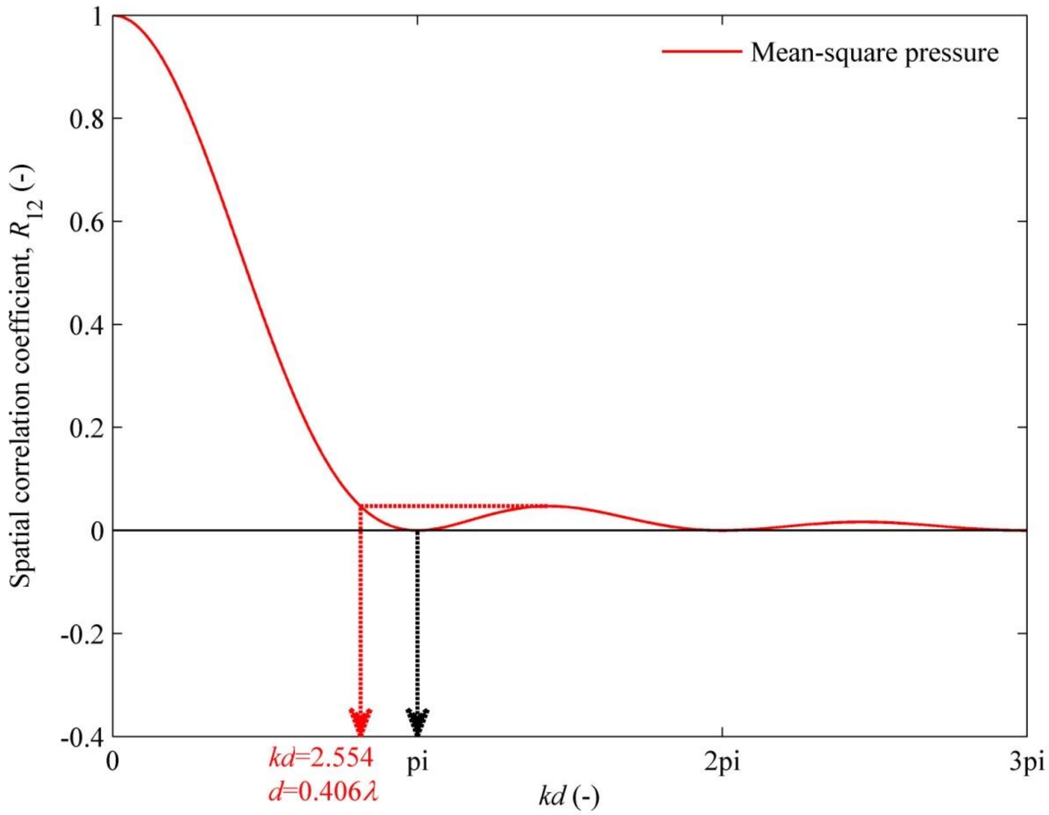

Figure 2: Spatial correlation coefficient for mean-square pressure in a 3D diffuse field

To assess the effect of correlated samples on the estimate of the spatial average, mean-square pressure, we consider N samples of mean-square pressure, for which the average mean-square pressure (time-averaged), X, is given by

$$X = \frac{1}{N}\sum_{i=1}^{N} p_i^2 \tag{2}$$

Following the approach of Lubman[6] a normalized variance, V_s^2, can be defined for this average mean-square pressure using

$$V_s^2 = \frac{\mathrm{Var}[X]}{(\mathrm{E}[X])^2} \tag{3}$$

The true, spatial average, mean-square pressure, E[X] is

$$E[X] = \sqrt{\sigma_{p_i^2}\sigma_{p_j^2}} \tag{4}$$

where σ is the standard deviation for the mean-square pressure at a point i or j.

For N samples of mean-square pressure which are correlated to some degree, the variance is calculated from the covariance using

$$\mathrm{Var}[X] = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} \mathrm{cov}\left(p_i^2, p_j^2\right) \tag{5}$$

Hence the normalized variance is dependent upon the spatial correlation coefficient, $R(kd_{ij})$, and is given by

$$V_s^2 = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{\mathrm{cov}(p_i^2,p_j^2)}{\sigma_{p_i^2}\sigma_{p_j^2}} = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}R(kd_{ij}) \quad (6)$$

where d_{ij} is the distance (magnitude) between points i and j.

The equivalent number of discrete, uncorrelated samples, N_{eq}, can then be calculated from

$$N_{eq} = \frac{1}{V_s^2} \quad (7)$$

Hence when all samples are uncorrelated, $V_s^2 = N^{-1}$ and $N_{eq} = N$.

Equations (1), (6) and (7) can now be used to compare the normalized variance and the equivalent number of discrete, uncorrelated samples for values of d that are either a fixed distance, or a fixed fraction of a wavelength. We shall assume $N = 5$ which is of particular interest because it equals the minimum number of fixed microphone positions that are used in field sound insulation measurements[3].

To choose fixed fractions of a wavelength for the comparison, it is noted from Figure 2 that $R(kd)$ still has non-zero values when $kd > \pi$. The largest non-zero value occurs when $kd = 4.496$, where $R(4.496) = 0.047$. Therefore to assess the effect of including more correlated samples, the smallest kd value is chosen at which $R(kd) = 0.047$. This occurs at $kd = 2.554$ and equates to $d = 0.406\lambda$. In addition it is useful to include $d = 0.5\lambda$ because this gives the lowest possible value for the normalized variance.

To choose fixed distances for the comparison, it is useful to consider the requirements on microphone positions for field sound insulation measurements. These are typically given by three minimum separating distances: 0.7 m between microphone positions, 0.5 m between any microphone position and the room boundaries, and 1.0 m between any microphone position and the sound source. For fixed microphone positions with a single source position in a box-shaped room, the smallest room volume in which these criteria can be satisfied for five microphone positions is $\approx$8 m^3. If the requirement for 0.7 m between microphone positions was altered so it was based on a fraction of a wavelength at 100 Hz (which is often the lowest frequency considered in field measurements), then the minimum distance would be 1.7 m for $d = 0.5\lambda$, and 1.4 m for $d = 0.406\lambda$. The smallest source room volume that would satisfy the three requirements for five microphone positions would then be $\approx$30 and $\approx$20 m^3 respectively. To cover these different possibilities, three distances will be considered: 0.35, 0.7, and 1.4 m.

Figure 3 allows comparison of the normalized variance and the equivalent number of discrete, uncorrelated samples for the different separation distances described above with $N = 5$ microphone positions. From these results it is concluded that for any manual scanning path to be similar or better than five fixed microphone positions, it should have $N_{eq} \geq 4.2$ at frequencies above 200 Hz. Another benefit of basing decisions on frequencies above 200 Hz is that below this frequency there are relatively few rooms in dwellings that have sound fields which can be considered to be diffuse in three dimensions.

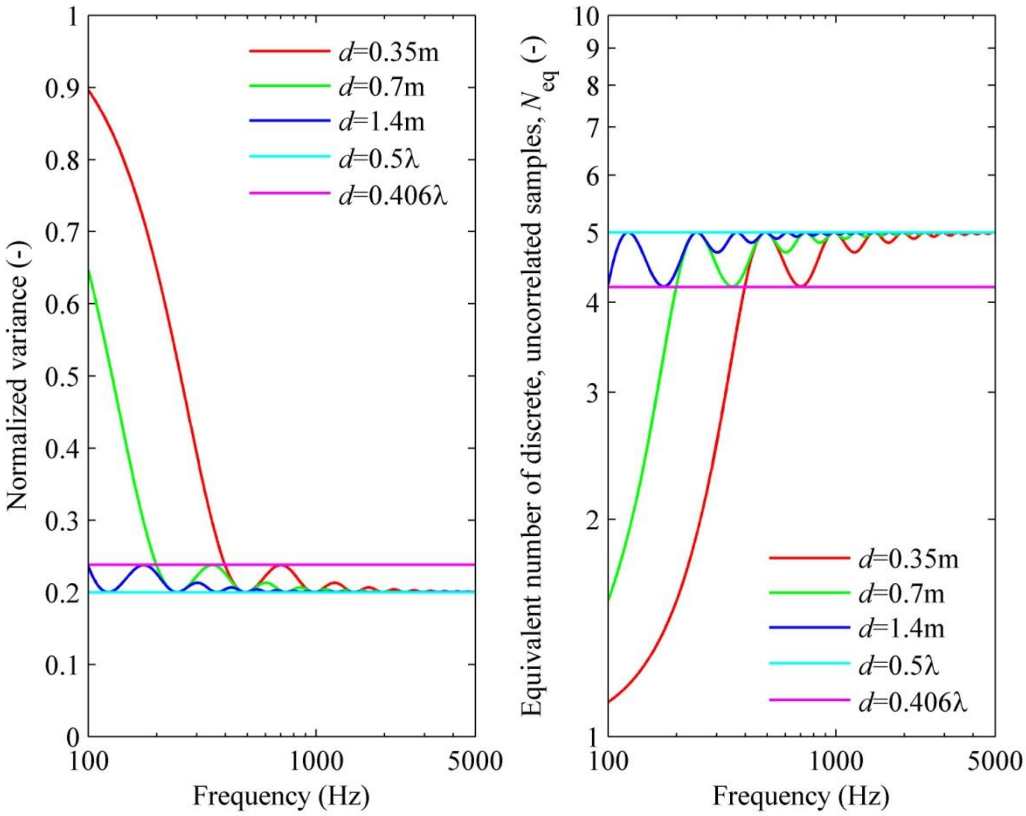

Figure 3: Normalized variance and the equivalent number of discrete, uncorrelated samples for different separation distances, *d*, for with N = 5 fixed microphone positions.

B. Continuously-moving microphones

For a continuously-moving microphone that traces out a specified path it is possible to quantify the equivalent number of discrete, uncorrelated samples by consideration of the sound pressure at discrete positions along the path. It is therefore assumed that continuous sampling of mean-square pressure is carried out sufficiently slowly to ensure adequate time-averaging, and at a uniform speed so that equal weighting is given to all points along the path. For continuous averaging, the summations in equation (6) become integrals as $N \rightarrow \infty$ for which solutions have been derived for simple averaging paths such as a continuous straight line[6] as well as a closed circular path and the surface of a disk[8]. In this paper, equation (6) is solved numerically as this allows any path geometry to be tackled with any sound field for which the spatial correlation coefficient is known, and for which the discrete sample points are uniformly spaced along a defined averaging path. This is ideal for investigating more complicated manual scanning paths such as a random walk, a helix or a conical spiral.

For manual scanning it will be assumed here that the presence of the human body and the sound level meter do not significantly affect the sound field. Manual scanning paths can then be considered in three categories: (a) paths that require walking across the room, (b) paths which can be carried out from a fixed standing position in the room without rotation of the trunk of the body, and (c) paths which can be carried out by rotating the body about a fixed point. The following geometrical paths have been considered as potential candidates for manual scanning: straight line (type a), sinusoid (type b), lissajous (type b), lemniscate (type b), semi-circle(s) (type b), circle (type c), helix (types a,c), conical spiral (types a,c).

4. RESULTS AND DISCUSSION

For straight line scanning paths the longest path length lies between the upper and lower corners of the room that lie diagonally opposite each other. This path is possible in any unfurnished box-shaped room, and in some furnished rooms. The start and end points of this line must satisfy the minimum distance between any microphone position and the room boundaries; this is commonly 0.5 m in Standards for the field measurement of sound insulation. The line lengths shown in Figure 4 correspond to 5.22 m for a 50 m^3 room (5 x 4 x 2.5 m), and 3.91 m for a 30 m^3 room (4 x 3 x 2.5 m). At high frequencies the results illustrate the advantage of scanning compared to fixed positions because of the large numbers of uncorrelated samples that are produced. In rooms with volumes $\geq$ 30 m^3 this approach is significantly more efficient than five fixed positions because N_{eq} > 5 above 200 Hz and $N_{eq} \approx 100$ at the highest frequencies of interest. The only problem with this method is that it is prone to operator noise during the walk across the floor.

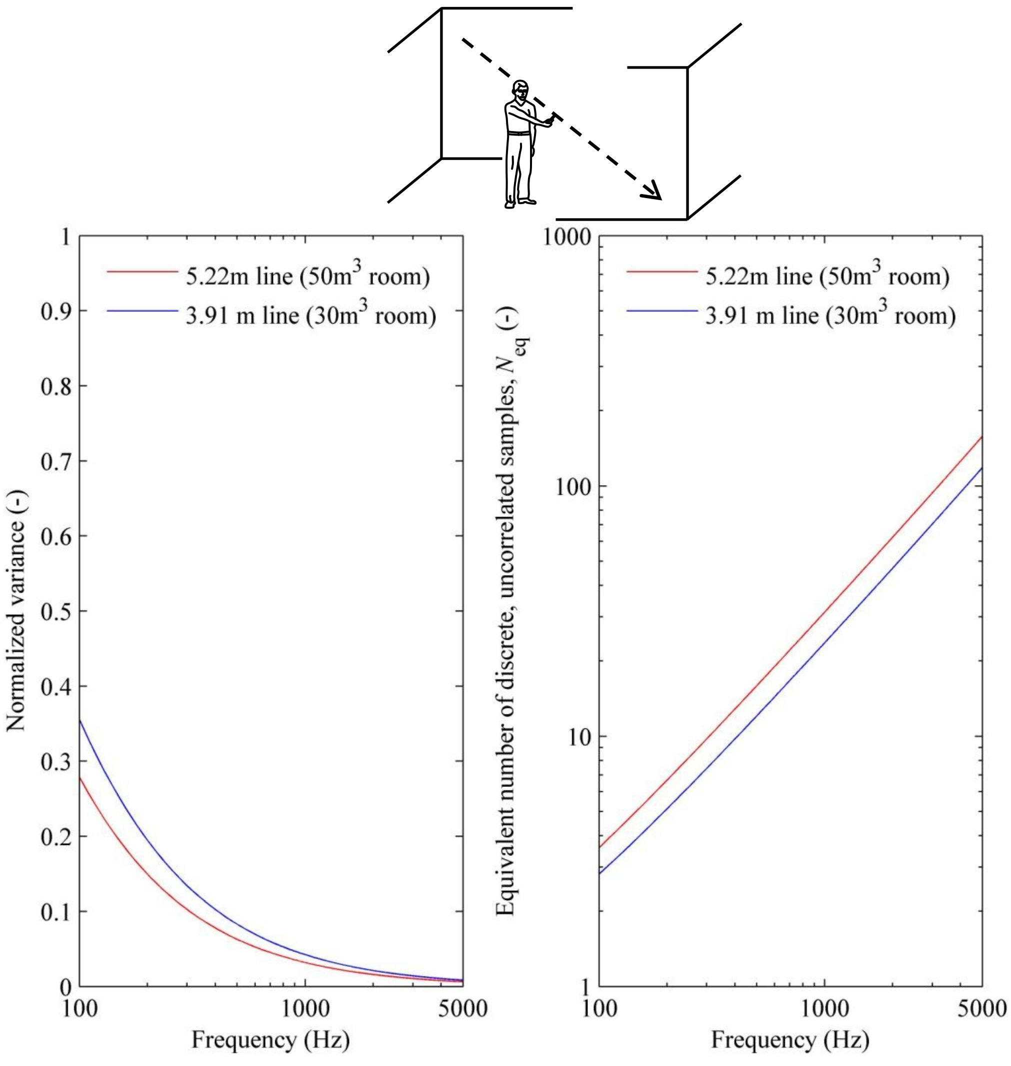

Figure 4: Straight line scanning paths – normalized variance and N_{eq}.

Paths which can be carried out whilst stationary at a fixed point are shown in Figure 5. These paths are advantageous in that minimal body movement is needed, hence they should minimize operator noise. In addition they can be carried out in small, furnished rooms where the room volume available for measurement is limited. Each path length is determined by anthropometric limitations where the furthest point on each path is defined by an average length of 0.7 m for an outstretched arm holding a sound level meter.

Figure 5 indicates that simple, short paths such as a lissajous, sinusoid or semi-circle are less efficient than straight lines (refer back to Figure 4) in the low- and mid-frequency ranges that cover 50 – 1000 Hz. However, when three semi-circles are traced out in one continuous motion with a 45° separation between the planes in which each consecutive semi-circle lies, it is possible to produce N_{eq} values that are similar to the approach using straight lines. Note that whilst it is also possible for the body to trace out three semi-circles with separations up to 60°, there is negligible increase in N_{eq}.

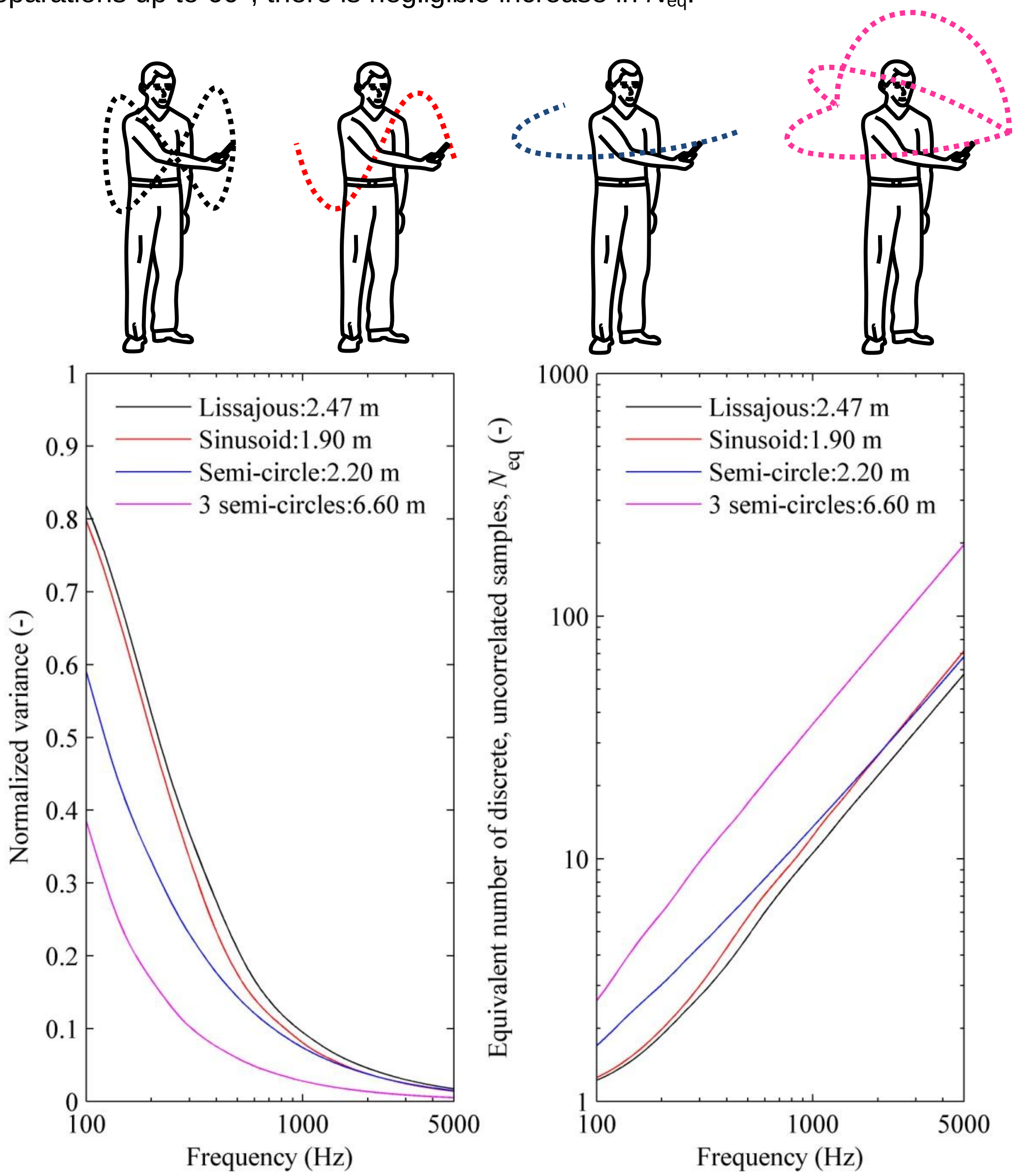

Figure 5: Manual scanning paths carried out from a fixed standing position – normalized variance and N_{eq}.

Three paths are now considered that can be carried out by rotating the body about a fixed point; these are a circle, helix and a conical spiral as shown in Figure 6. The advantage of rotating the body is that operator noise can be minimized whilst scanning over long path lengths. For each path it is assumed that it is possible to rotate the body through 360° whilst pivoting around one foot. The hand on the same side of the body as this foot is used to hold the meter with outstretched arm. A circular path with a radius of ≈0.7 m effectively simulates a rotating boom, whilst the helix offers the possibility of achieving significantly more uncorrelated points due to the vertical separation in the path. In small rooms that are filled with furniture around the sides of the room, a conical spiral could be positioned with its apex at the narrowest part of the volume; this might be near the middle of the ceiling when there are wall-hung cupboards, or near the middle of the floor when there are sofas, beds, or tables positioned against the walls. All three paths are efficient. The circle and the conical spiral both give N_{eq} > 5 above 200 Hz, but the helix is significantly more efficient with N_{eq} > 10 above 200 Hz as well as being more feasible than a conical spiral.

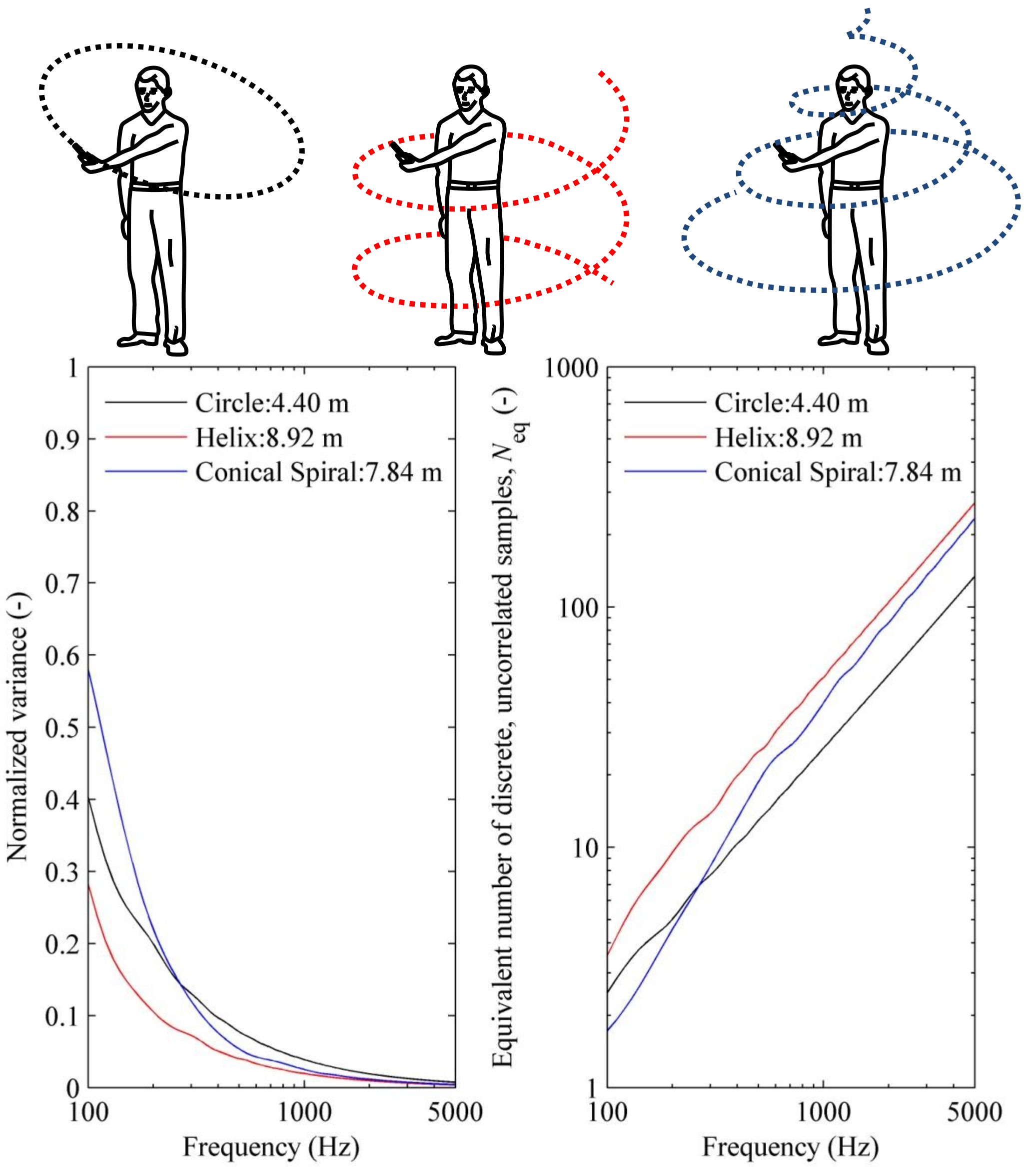

Figure 6: Manual scanning paths that involve rotation of the body around a fixed point – normalized variance and N_{eq}.

The path of the helix is described by

$$x = r\cos t \quad y = r\sin t \quad z = ct \tag{8}$$

where r is the radius, and $2\pi c$ is the separation between the loops of the helix. Assuming that a typical room height is 2.5 m, and that the minimum distance between any microphone position and the room boundaries is 0.5 m, the maximum height for the helix is 1.5 m. For an outstretched arm holding a sound level meter the radius of the helix is taken as r = 0.7 m for which two periods with $c = 1.5/(4\pi)$ gives the helical path sketched above Figure 6 which has a length of 8.92 m.

Problems with oversampling that were previously noted by Lubman *et al*[8] for sampling on the surface of a disk can be observed when comparing the circle and the conical spiral below 200 Hz. Despite the longer path length for the conical spiral, the closely-packed curves cause more correlated samples which results in a lower variance than with the circle.

5. CONCLUSIONS

Numerical simulations have been used to assess the efficacy of various manual scanning paths in a three-dimensional diffuse field. The results indicate that it is possible to achieve equivalence to at least five uncorrelated, fixed position samples at frequencies above 200 Hz using the following manual scanning paths: straight lines between diagonally opposite room corners, a continuous path formed from three semi-circles, or a helix.

The straight line is perhaps the most straightforward method but it is prone to problems with operator noise whilst walking across the room. Operator noise due to movement can be minimized using either a continuous path formed from three semi-circles, or a helix. In comparison with a circular path of the same radius, these two paths produce significantly more discrete, uncorrelated samples.

The intention with future work is to extend the simulations to non-diffuse fields and to investigate scanning paths that simulate a walk through fully-furnished rooms.

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