On the efficacy of spatial sampling using manual scanning paths to determine the spatial average sound pressure level in rooms

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ABSTRACT

In architectural acoustics, noise control and environmental noise, there are often steady-state signals for which it is necessary to measure the spatial average, sound pressure level inside rooms. This requires using fixed microphone positions, mechanical scanning devices, or manual scanning. In comparison with mechanical scanning devices, the human body allows manual scanning to trace out complex geometrical paths in three-dimensional space. To determine the efficacy of manual scanning paths in terms of an equivalent number of uncorrelated samples, an analytical approach is solved numerically. The benchmark used to assess these paths is a minimum of five uncorrelated, fixed microphone positions at frequencies above 200Hz. For paths involving an operator walking across the room, potential problems exist with walking noise and non-uniform scanning speeds. Hence paths are considered that are based on a fixed standing position, or rotation of the body about a fixed point. In empty rooms, it is shown that a circle, helix or cylindrical-type path satisfy the benchmark requirement with the latter two paths being highly efficient at generating large numbers of uncorrelated samples. In furnished rooms where there is limited space for the operator to move, an efficient path comprises three semicircles with 45° to 60° separations.

I. INTRODUCTION

For steady-state signals, the spatial and temporal average sound pressure level in a room is a fundamental measurement in architectural acoustics, noise control and environmental noise. For engineering-grade measurements in the field, the spatial average in the central zone of a room is usually determined using fixed microphone positions with a tripod, or a mechanized continuously-moving microphone such as a rotating boom that traces out a circular path. This allows the operator to be outside the room during the measurement so that they do not increase the background noise level, or affect the sound field in the room. However, it can be convenient for a human operator to manually scan the space inside a room with a hand-held sound level meter. This is particularly relevant with environmental noise measurements where it is often essential for the operator to give a subjective assessment of the noise, and with sound insulation measurements where there is ongoing and intermittent construction work that affects the receiving room. Another advantage of manual scanning is that it reduces the amount of equipment that is needed on site, as well as reducing the overall measurement time. However, in some situations the disadvantages related to the effect of the operator on background noise level and the sound absorption in the room may outweigh the advantages.

When the effects of unwanted noise and absorption from the operator are negligible, the main issue becomes the efficacy and traceability of the manual scanning measurement. Unlike the mechanized continuously-moving microphone there is no pre-defined path for an operator to trace, and unlike fixed microphone positions it is not possible to calculate a standard deviation to quantify the spatial variation in the sound pressure level. Therefore, there is no traceability in the measurement to give any confidence that a satisfactory estimate has been made of the spatial average sound pressure level. This provides the impetus in this paper to determine the effectiveness of manual scanning paths through numerical simulation.

Different manual scanning paths are assessed to identify paths that are equivalent or better than a set of five fixed microphone positions.

II. NUMERICAL SIMULATION

In the 1950s, research by Cook *et al*[1] investigated spatial correlation between the sound pressure at positions in a diffuse sound field. However, it was limited in its practical application because many measurements require a spatial average of the mean-square sound pressure. The latter is crucial in the determination of sound power from laboratory measurements in reverberant rooms. This was extensively investigated by Lubman[2,3,4] who introduced a spatial correlation coefficient for mean-square pressure in a diffuse field, and the concept of discrete, uncorrelated samples from which it was possible to assess continuous spatial averaging over a straight line or a circular traverse. This approach has been adopted in this paper to investigate manual scanning paths which can have significantly more complex geometries.

The primary frequency range of interest is taken to be 100–5000Hz. Below 100Hz, a spatial average sound pressure level that is determined in the central zone of a small room (away from the room boundaries) is rarely useful without additional measurements. This is primarily due to the lack of modes, and the requirement to avoid sampling in the interference patterns near the room boundaries. To address this problem, the spatial average sound pressure level in the central zone of the room can be combined with sound pressure level measurements in the room corners[5,6].

A. Equivalent number of uncorrelated samples

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 as a time-averaged value, X, is given by

$$X = \frac{1}{N}\sum_{i=1}^{N}\overline{p_i^2} \quad (1)$$

Following the approach of Lubman[2] a normalized variance, V_s^2, can be defined for N samples of mean-square pressure which are correlated to some degree according to

$$V_s^2 = \frac{\mathrm{Var}[X]}{(\mathrm{E}[X])^2} = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{\mathrm{cov}\left(\overline{p_i^2},\overline{p_j^2}\right)}{\sigma_{\overline{p_i^2}}\sigma_{\overline{p_j^2}}} = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}R\left(kd_{ij}\right) \quad (2)$$

where Var[X] is the variance of the spatial average, mean-square pressure, E[X] is the true, spatial average, mean-square pressure, cov indicates the covariance, σ is the standard deviation, R is the spatial correlation coefficient, k is the wavenumber (rad/m), and d_{ij} is the magnitude of the distance between points i and j (m).

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

$$N_{\mathrm{eq}} = \frac{1}{V_s^2} \quad (3)$$

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

For a continuously-moving microphone that traces out a specified path it is possible to quantify the equivalent number of uncorrelated samples by considering the sound pressure at discrete positions along the path[2]. It is 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 that are spaced 0.002m apart. For continuous averaging, the summations in Eq. (2) become integrals as $N\rightarrow\infty$ for which solutions have been derived for simple averaging paths such as a continuous straight line[2], as well as for a closed circular path and the surface of a disk[3]. To investigate more complicated path geometries that are used with manual scanning, the approach used in this paper is to solve Eq. (2) numerically. 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.

B. Spatial correlation for mean-square pressure in typical rooms

Calculation of the normalized variance from Eq. (2) requires the spatial correlation coefficient for the sound field of interest in typical rooms. The theoretical formulations for the spatial correlation coefficient were developed for diffuse fields because there were applications to laboratory reverberation rooms used for sound power measurements as well as some concert halls. From Lubman[2], the spatial correlation coefficient, $R(kd)$, for mean-square pressure with pure tones in a three-dimensional diffuse field is given by

$$R(kd) = [\mathrm{sinc}(kd)]^2 \tag{4}$$

where k is the wavenumber (rad/m) and d is the distance (m) between two sampling points in the sound field. In all calculations of the wavenumber, the speed of sound is taken as 343m/s.

In architectural acoustics, noise control and environmental noise it is common to take measurements using constant-percentage filter bands and to measure broad-band noise rather than pure tones. However, Chu[7] has shown that Eq. (4) which applies to pure tones is also valid for broad-band noise measured in one-third-octave or octave bands.

Manual scanning measurements are primarily intended for dwellings where room volumes are typically less than 80m^3. This is in contrast to the large reverberation rooms commonly found in laboratories for sound power measurements. For this reason it is necessary to investigate whether the spatial correlation coefficient for mean-square sound pressure in a three-dimensional diffuse field is adequate for smaller reverberant spaces.

Cook *et al*[1] proposed that sound fields in rooms could potentially be assessed by measuring the spatial correlation coefficient for sound pressure (not mean-square pressure) along three mutually perpendicular straight lines and comparing it against diffuse field theory. The approach of Cook *et al* is used here for mean-square pressure. However, instead of using measurements, ray-tracing and normal mode models are used to determine complex pressures at specified positions in a box-shaped room containing a harmonic point source. Idealised diffusing surfaces are assessed with ray tracing using LMS Raynoise software with the Triangular Beam Method. A diffusion coefficient of unity is assigned to all surfaces so that all reflected sound power occurs in non-specular directions; this approach will therefore provide a fair comparison with diffuse field theory. As these idealised surfaces are not commonly found in typical rooms, a more realistic approach is used to assess a modal sound field with the normal mode approach[8] based on specularly reflecting surfaces. In this calculation the mean-square sound pressure at a receiver positioned at $\mathbf{r}$=(x,y,z) from a point source positioned at $\mathbf{r}_s=(x_s,y_s,z_s)$ is determined according to

$$\overline{p^2}(\mathbf{r}|\mathbf{r}_s) = \frac{\omega^2\rho_0^2\hat{Q}^2}{2V^2}\sum_{m=0}^{\infty}\left|\frac{\psi_m(\mathbf{r})\psi_m(\mathbf{r_s})}{\Lambda_m(k_m^2-k^2+2ik\delta_m)}\right|^2 \tag{5}$$

where ω is the angular frequency, $\hat{Q}$ is the peak volume velocity of the point source, V is the room volume, ψ_m is the eigenfunction of the normal modes for rigid boundaries with the wavenumber and associated constants for mode m (corresponding to $f_{p,q,r}$) given by

$$k_m^2 = k_\mathrm{x}^2 + k_\mathrm{y}^2 + k_\mathrm{z}^2 \quad \text{where} \quad k_\mathrm{x} = \frac{p\pi}{L_\mathrm{x}} \quad k_\mathrm{y} = \frac{q\pi}{L_\mathrm{y}} \quad k_\mathrm{z} = \frac{r\pi}{L_\mathrm{z}} \tag{6}$$

It is assumed that all boundaries have the same specific acoustic admittance; hence the damping constant, δ_m, is

$$\delta_m = \beta_{\mathrm{a,s}}\left(\frac{\varepsilon_p}{L_{\mathrm{x}}} + \frac{\varepsilon_q}{L_{\mathrm{y}}} + \frac{\varepsilon_r}{L_{\mathrm{z}}}\right) \tag{7}$$

where $\beta_{\mathrm{a,s}}$ is the specific acoustic admittance, and ε_p, ε_q and ε_r correspond to mode $f_{p,q,r}$ (if p=0, then ε_p=1 else ε_p=2; if q=0, then ε_q=1 else ε_q=2; if r=0 then ε_r=1 else ε_r=2).

The term, Λ_m, is calculated using

$$\Lambda_m = \frac{1}{\varepsilon_p \varepsilon_q \varepsilon_r} \tag{8}$$

The spatial correlation coefficient for mean-square pressure between two points, i and j, is calculated from the complex pressures, p_i and p_j, according to

$$R(kd_{ij}) = \frac{\langle p_i^2 p_j^2 \rangle_t}{\sqrt{\langle p_i^4 \rangle_t \langle p_j^4 \rangle_t}} \tag{9}$$

where

$$\begin{aligned}\langle p_i^2 p_j^2 \rangle_t &= \frac{1}{2}\mathrm{Re}\{p_i^2 (p_j^2)^*\} \\ &= \tfrac{1}{2}\left[(\mathrm{Re}\{p_i\}^2 - \mathrm{Im}\{p_i\}^2)\left(\mathrm{Re}\{p_j\}^2 - \mathrm{Im}\{p_j\}^2\right) + 4\mathrm{Re}\{p_i\}\mathrm{Im}\{p_i\}\mathrm{Re}\{p_j\}\mathrm{Im}\{p_j\}\right]\end{aligned} \tag{10}$$

and

$$\langle p_i^4 \rangle_t = \frac{1}{2}[(\mathrm{Re}\{p_i\}^2 - \mathrm{Im}\{p_i\}^2)^2 + (2\mathrm{Re}\{p_i\}\mathrm{Im}\{p_i\})^2] \tag{11}$$

An example using ray-tracing and the normal mode approach is now considered for a 50m^3 room (5 x 4 x 2.5m) with a point source positioned near one corner. The absorption is uniformly distributed over the entire surface area to give a reverberation time of 1s based on the Sabine equation, and a Schroeder frequency of 283Hz. For each of the *x*, *y* and *z* directions the mean-square pressure is determined at 0.1m intervals along ten randomly positioned lines that run parallel to each axis. The use of multiple lines allows a 95% confidence interval to be calculated for $R(kd)$ at each value of kd along each of the *x*, *y* and *z* axes. For sound insulation measurements, the sound pressure level is always sampled with specified minimum distances to the boundaries and the source[9]. To avoid biasing the result with mean-square pressure sampled close to reflecting boundaries where interference patterns exist, a minimum distance of 0.5m is used between grid points and the room boundaries. In addition there is a minimum distance of 1m between grid points and the point source to avoid its direct field. However, the use of these minimum distances does not significantly change the majority of the average values; the largest change in the average value of the spatial correlation coefficient being 0.08.

The spatial correlation coefficients are plotted against the Helmholtz number (kd) in Fig. 1. When $kd \geq \pi$ the spatial correlation is negligible and there is good agreement between ray tracing and the normal mode approach with diffuse field theory for lines along all three perpendicular dimensions. When $kd < \pi$ the spatial correlation is generally high, yet the diffuse field theory fortuitously provides a reasonable estimate of the upper limit for $R(kd)$ that can be expected along the three perpendicular dimensions for both ray tracing and the normal mode approach. For this reason it is considered preferable to use the spatial correlation coefficient for a three-dimensional diffuse field given by Eq. (4) to evaluate different manual scanning paths instead of calculated values for individual rooms with modal sound fields. This ensures a clearer and more concise comparison of different scanning paths. The results will apply to many rooms in dwellings above 200Hz in which the Schroeder frequency commonly falls between the 200Hz and 315Hz one-third-octave bands.

III. 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, there are two types of manual scanning path that 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 human body is able to trace out curved paths that allow spatial sampling over a large portion of an irregular room volume whilst maintaining a relatively uniform scanning speed. In order to calculate the geometrical data that is needed to define manual scanning paths, it is necessary to establish the average length of an outstretched arm. The arm must be outstretched to minimize the effect of reflections from the body on the measured signal. Based on anthropometric data for the average lateral reach of adult males[10] and a typical sound level meter it can be assumed that the average distance from the shoulder joint to the microphone for an outstretched arm holding a sound level meter is approximately 0.7m. 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, 0.7m forms a useful benchmark because it fortuitously corresponds to the minimum radius that is required for circular paths with a mechanized rotating boom required in International Standards for field sound insulation measurements[11]. One must also consider the physical limitations of the arm when rotating about a vertical axis passing through the shoulder as indicated in Fig. 2. 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 semicircle 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 or helix it is necessary to rotate the body by pivoting around the right foot with the right hand outstretched (or left foot and left hand). Based on existing Standards using rotating boom microphones[11], the angular velocity in any manual scan should be uniform and $\leq 2\pi/15$ rad/s.

IV. EFFICACY OF MANUAL SCANNING PATHS

Manual scanning paths can be considered in the following categories: paths that require walking across the room, paths which can be carried out from a fixed standing position and paths which can be carried out by rotating about a fixed point. Their efficacy is considered by using fixed microphone positions as a benchmark.

A. Fixed microphone positions

To assess the efficacy of manual scanning it is necessary to identify the minimum number of fixed microphone positions that are commonly used in practice, for use as a benchmark. Based on the requirements in the ISO Standards for field sound insulation measurements[11], this minimum number is five positions; although it is noted that the equivalent ANSI Standard[12] requires a minimum of six positions.

From Eq. (4), $R(kd)$ varies with Helmholtz number as shown in Fig. 3. The lowest frequency at which $R(kd)=0$ occurs at $kd=\pi$. Hence a minimum microphone spacing that corresponds to $d=0.5\lambda$ can be used as a requirement to ensure uncorrelated samples with fixed microphone positions. However, $R(kd)$ still has non-zero values when $kd>\pi$. The largest non-zero value occurs when $kd=4.496$ where $R(kd) = 0.047$. 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 $d=0.406\lambda$. Instead of using a minimum fraction of a wavelength it is more practical and convenient to prescribe inter-microphone spacing as a minimum distance in metres, particularly as modern analysers use parallel filter analysis. The minimum separating distance between microphone positions used for field sound insulation measurements[11] is 0.7m which corresponds to $d=0.5\lambda$ at 250Hz. This results in samples that are correlated in the frequency range up to 200Hz, with only a small degree of correlation in the frequency range 250–5000Hz.

The normalized variance and the equivalent number of discrete, uncorrelated samples for five, fixed microphone positions with different inter-microphone spacing are shown on Fig. 4. The inter-microphone spacings are chosen in terms of distance, as well as fractions of a wavelength. In small furnished rooms it is not always possible to find five microphone positions which result in five uncorrelated samples; hence it is appropriate to assess a range of possible requirements on minimum distances between microphone positions. Values of 0.35, 0.7 and 1.4m are chosen where 0.7m corresponds to the minimum distance required between microphone positions for field sound insulation measurements[11]. Ideally, the five fixed positions would result in five uncorrelated samples. However, Fig. 4 shows that inter-microphone spacings ≤0.7m give rise to between one and four uncorrelated samples in the low-frequency range. For sufficiently large room volumes, Fig. 4 indicates that it is beneficial to increase the inter-microphone spacing from 0.7m to 1.4m. In an attempt to aid operators who have to choose microphone positions that satisfy the spacing requirements in small rooms it is worth considering the effect of changing the basis for the requirement from 0.5λ to 0.406λ. Fig. 4 shows that this is inappropriate as it causes a significant reduction in the number of uncorrelated samples from five to approximately four which will adversely affect the estimate of the spatial average mean-square pressure.

In ISO Standards for field sound insulation measurements[11], the requirements on microphone positions are given by three minimum separating distances: 0.7m between microphone positions, 0.5m between any microphone position and the room boundaries, and 1m 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 $\approx 8\text{m}^3$ although these positions may not be easy to find without using simple computer code to determine and check each position. If the minimum requirement for 0.7m between microphone positions is changed so that it is based upon a fraction of a wavelength at 100 Hz (which is often the lowest frequency considered in field measurements), then the minimum distance is 1.7m for d=0.5λ, and 1.4m for d=0.406λ. Then, the smallest source room volume that would satisfy the three requirements for five microphone positions would be $\approx 30\text{m}^3$ and $\approx 20\text{m}^3$ respectively.

It is concluded that it is reasonable to assess the efficacy of manual scanning paths based upon the use of five, fixed microphone positions. Hence from Section IV.A, any manual scanning path with $N_{eq} \geq 5$ at frequencies above the 200Hz one-third-octave band will be equivalent, or more efficient than five, fixed microphone positions in typical rooms in dwellings. Below 200Hz it is necessary to make a direct comparison with the calculation for five, fixed microphone positions and to consider the deviations from the spatial correlation coefficient for a three-dimensional diffuse sound field that were noted in Section II.B.

B. Paths involving walking

In furnished rooms it is reasonable to consider walking around the obstacles in a room whilst slowly sweeping the arm that holds the sound level meter. To do this it is feasible for the operator to walk with a constant velocity (e.g. at 0.3m/s) whilst rotating the arm at a constant angular velocity (e.g. at $\pi/9$ rad/s). Fig. 5 shows calculated speed profiles along two possible scanning paths which vary significantly from the constant walking velocity of 0.3m/s. This illustrates the fact that rotation of the arm parallel to the transverse plane of the body results in non-uniform scanning speeds along the scanning path.

To minimize this problem with non-uniform scanning speeds the sound level meter can be held parallel to the sagittal plane of the body whilst slowly reducing its height at a constant speed and walking across the room with a constant velocity. This is possible in any unfurnished box-shaped room, and in some furnished rooms. However, there are distinct practical problems due to operator noise during the walk across the floor, and the existence of reflections or shielding when holding the sound level meter so close to the human body. Despite these disadvantages it is informative to investigate the potential of this manual scanning path using the longest possible path length across a room as it provides a comparator for other manual scanning paths. The longest straight line path lies between the upper and lower corners of a room that are diagonally opposite each other. The start and end points of this line must satisfy the minimum distance between any microphone position and the room boundaries; this is commonly 0.5m in ISO Standards for the field measurement of sound insulation[11]. For a typical room height of 2.5m the drop in height from corner to corner is therefore 1.5m.

Fig. 6 shows N_{eq} for three straight line paths between diagonally opposite room corners with line lengths indicated in the legend that correspond to 50, 30 and 15m^3 rooms. At high frequencies the results illustrate the advantage of scanning compared to fixed positions because it produces large numbers of uncorrelated samples. In rooms with volumes ≥30m^3 this approach is significantly more efficient than five fixed positions because N_{eq}>5 above 200Hz and N_{eq}>100 at 5000Hz.

C. Paths which can be carried out from a fixed standing position

Paths which can be carried out from a standing position are advantageous in that minimal movement is needed; hence they reduce noise from the operator. In addition they can be carried out in small, furnished rooms where the room volume available for measurement is limited. For a furnished room such as a dining room where the table usually occupies most of the central floor area of the room, such a manual scanning path is feasible whereas a straight line path between diagonally opposite room corners is not.

Fig. 7 indicates that short paths such as a sinusoid, lissajous, or semicircle are less efficient than straight diagonal lines across the room in the range 100–1000Hz. It should be noted that a lemniscate is also feasible but it is not plotted here because it gives very similar results to the lissajous. In contrast, when three semicircles are traced out with a 45° separation between planes containing the adjacent semicircles, it is possible to produce N_{eq} values that are similar to the approach using straight diagonal lines. Ideally, the individual semicircles should not lie in the same plane as the room surfaces to avoid biased sampling in modal sound fields.

Therefore in box-shaped rooms the first semicircle should be displaced by ≈15° from the horizontal or vertical plane. Alternatively three semicircles can be traced out with a larger separation than 45° because anthropometric limitations will allow the separation to be increased from 45° up to 60°. However, there is negligible increase in N_{eq} compared to a 45° separation; hence there is no advantage in using 60° other than avoiding semicircles that lay in the same plane as room surfaces. In contrast to paths involving walking and scanning, there are negligible difficulties in achieving uniform scanning speeds for the path using three semicircles.

Swedish Standard SS 25267[13] defines a manual scanning path which can be described as a cylindrical-type path. This requires the use of a 0.3–0.9m extension rod for the microphone as indicated in Fig. 8. To satisfy the minimum distance between the microphone and the room boundaries this approach requires relatively large rooms, often unfurnished. For a right handed sweep, the path starts 0.5m above the floor from a position 90° to the left side, the rod is then swept in an arc parallel to the ground to cover an angle of 225°. The sweep continues vertically upwards along a straight line until 1.9m above the floor, after which another circular sweep covers 225° in the opposite direction, before descending to the starting point along a vertical straight line. Fig. 8 shows N_{eq} for this scanning path with and without extension rods of various lengths. It is concluded that the extension rod significantly increases N_{eq} compared to the hand-held sound level meter, although both are highly efficient methods of generating large numbers of uncorrelated samples.

D. Paths which can be carried out by rotating the body about a fixed point

The advantage of rotating the body is that operator noise can be minimized whilst scanning long paths to try and increase the number of uncorrelated samples. It is assumed that it is feasible to rotate the body through 360° whilst pivoting around a point on the floor. The hand on the same side of the body as the pivot point is used to hold the sound level meter with outstretched arm. A circular path with a radius of ≈0.7m effectively simulates a rotating boom and it is notable that ANSI Standard E336-05[12] currently allows manual scanning with such a circular path. However, a helix offers the possibility of achieving significantly more uncorrelated points due to the vertical separation along the path.

In small rooms that are filled with furniture, a conical spiral can be positioned with its apex at the narrowest part of the volume. An example for a conical spiral with its axis aligned along the vertical dimension of the room and its apex near the centre of the ceiling is sketched in Fig. 9. This could be considered for a room with wall-hung cupboards at head-height. Alternatively, in rooms with furniture at one end of a small room, one could envisage tracing out a conical spiral with its axis aligned horizontally whilst walking with constant velocity across the room. For both the circle and the helix it is feasible to achieve a uniform scanning speed with practice; this is expected to be very difficult for a conical spiral.

Fig. 9 shows N_{eq} for three paths that can be carried out by rotating the body about a fixed point; these are a circle, helix and a conical spiral. All three paths are efficient. The circle and the conical spiral both give $N_{eq}>5$ above 200Hz. However, the helix is significantly more efficient with $N_{eq}>10$ above 200Hz as well as it being feasible to achieve a uniform scanning speed compared to a conical spiral. Despite the longer path length for the conical spiral, the closely-packed curves near the apex cause more correlated samples as can be seen by comparing the circle and the conical spiral below 200Hz. This important issue of oversampling was identified by Lubman *et al*[3] for sampling on the surface of a disk in laboratory sound power measurements. For the conical spiral, oversampling results in a lower

N_{eq} than with the circle which adversely affects the estimate of the spatial average mean-square sound pressure level below 200Hz.

For the circle and the helix there are no significant problems in achieving a uniform scanning speed although this is not true for the conical spiral. Therefore, it is only the circle and the helix that are worthy of consideration as efficient manual scanning paths that are carried out by rotating the body about a fixed point. The helix geometry is described by

$$x = r\cos t \qquad y = r\sin t \qquad z = ct \tag{12}$$

where r is the radius, and $2\pi c$ is the separation between the loops of the helix.

One possible technique to scan a helical path is to rotate the body 360° from a crouched position to standing whilst pivoting on one heel and using the hand on the same side of the body to hold the sound level meter with outstretched arm. Assuming a typical room height of 2.5m, and a requirement for the minimum distance between any microphone position and room boundaries to be 0.5m, the maximum height of the helix is 1.5m. Hence, for the helical pattern shown in the sketch on Fig. 9 the path length is 8.92m when r=0.7m, and c=3/(8π).

V. CONCLUSIONS

The effectiveness of different manual scanning paths with complex geometries has been assessed using an analytical approach which is solved numerically. Although the sound fields in typical rooms do not always approximate to a three-dimensional diffuse field over the frequency range 100-5000Hz it is shown that the spatial correlation coefficient for such an idealised situation is a reasonable basis upon which to compare the efficacy of different paths.

For manual scanning paths involving walking it is not possible to achieve a constant scanning speed when walking with constant velocity whilst rotating the arm parallel to the transverse plane of the body with a constant angular velocity. However constant speed is possible with a straight line path by holding the sound level meter parallel to the sagittal plane, walking with constant velocity in a straight line between diagonally opposite room corners and slowly reducing the height of the meter at a constant speed in this vertical plane. Although this scanning path provides relatively large numbers of uncorrelated samples, this is outweighed by the disadvantages of noise from the operator walking across the room and having to hold the sound level meter close to the human body. These issues can be avoided by scanning from a fixed standing position or rotating about a fixed point with an outstretched arm. It is shown that it is possible to achieve a minimum of five uncorrelated, fixed position samples at frequencies above 200Hz using the following paths: a continuous path formed from three semicircles, a circle, a helix, or a cylindrical-type path from Swedish Standard SS 25267. For rooms filled with furniture it is advantageous to adopt the most efficient manual scanning path that can be carried out whilst stationary; namely three semicircles with 45° to 60° separations. For empty rooms the simplest option is a circle, although a helix or cylindrical-type path is significantly more efficient at generating large numbers of uncorrelated samples.

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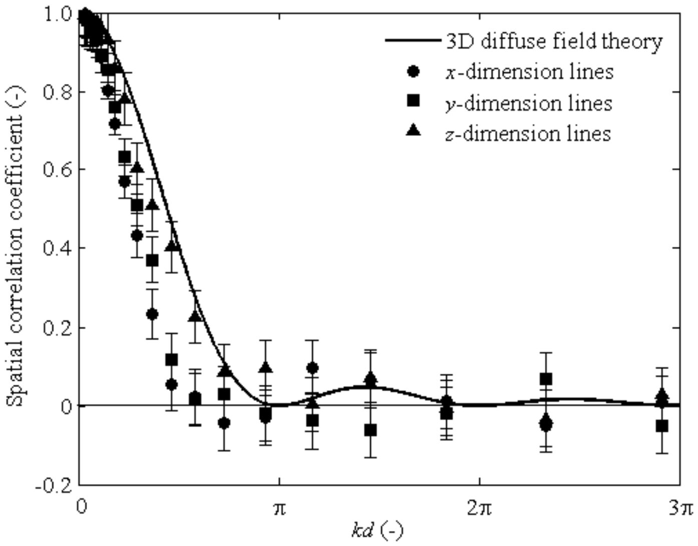
[13]SS 25267:2004 Acoustics - Sound classification of spaces in buildings – Dwellings. Swedish Standards Institute.

Figures

a)



b)

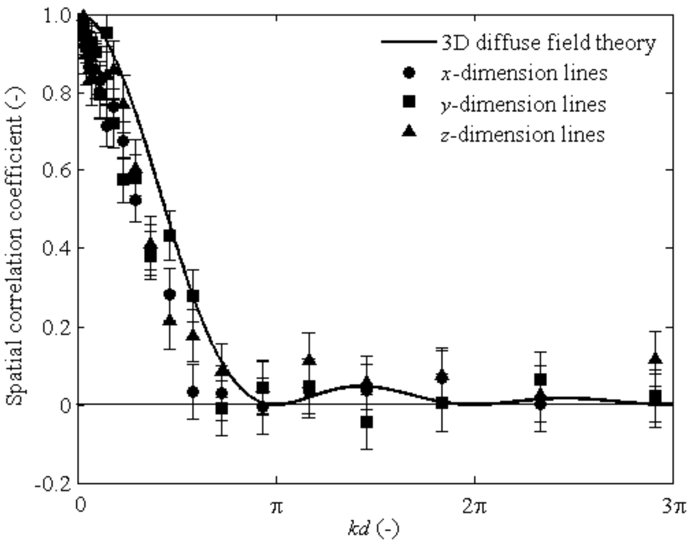


Figure 1.

Comparison of the spatial correlation coefficient for a three-dimensional diffuse field with that determined in a 50m^3 room along lines parallel to the *x*, *y* and *z* axes. The error bars indicate the 95% confidence intervals.

a) Ray-tracing (diffusion coefficient is unity for all surfaces)

b) Normal-mode approach

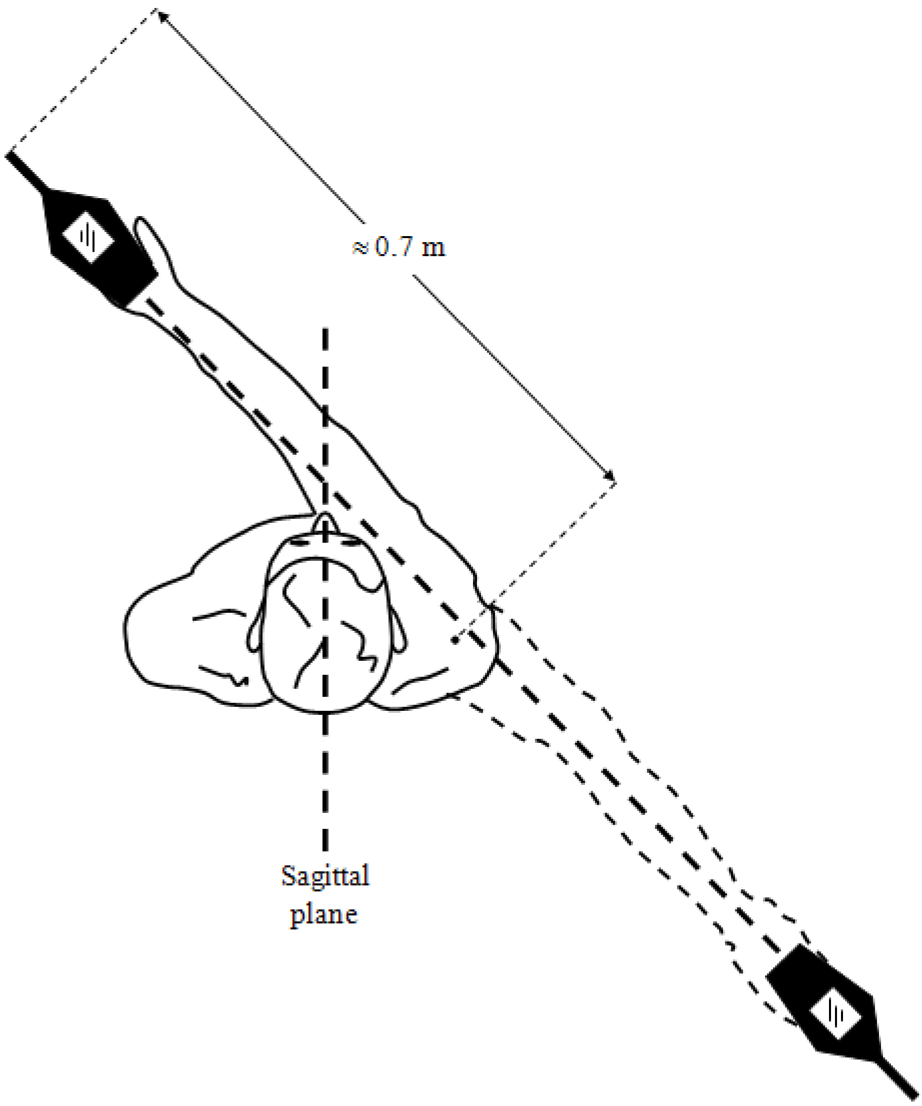


Figure 2.

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

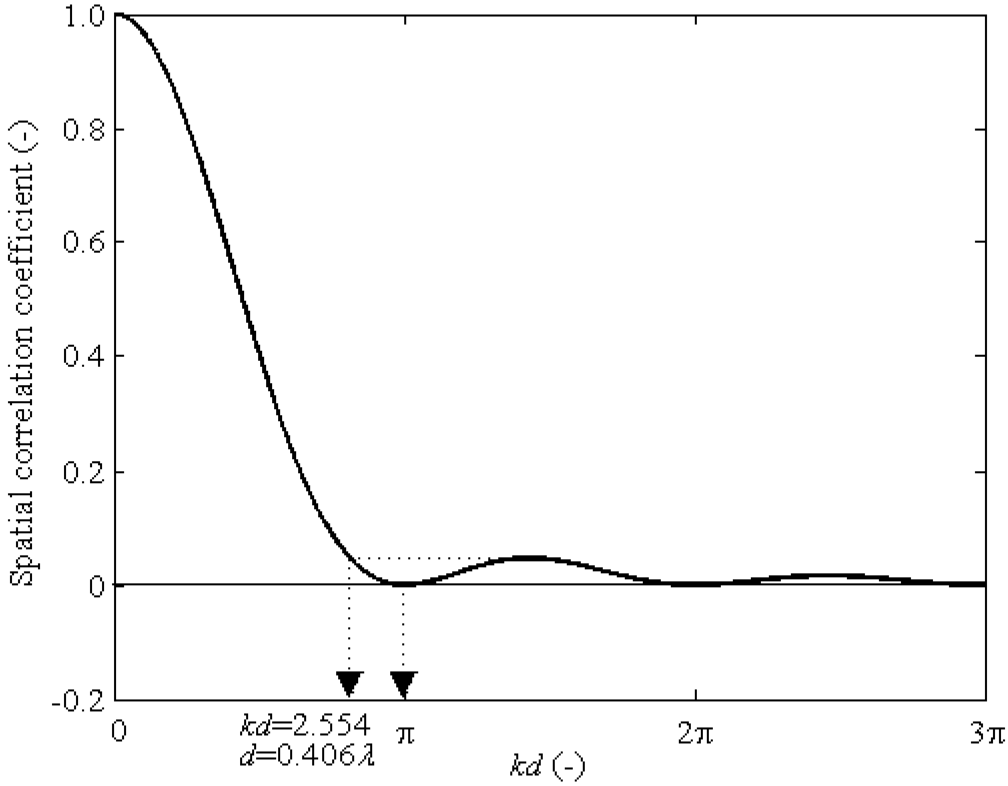


Figure 3.

Spatial correlation coefficient for mean-square pressure in a three-dimensional diffuse field.

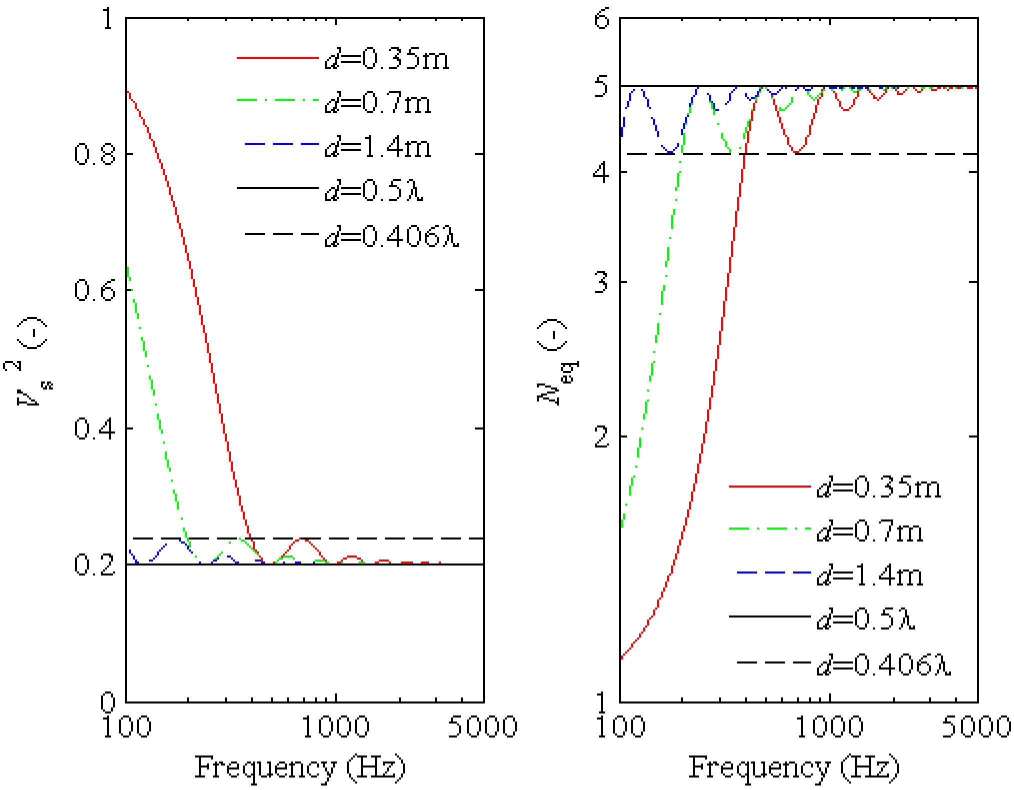
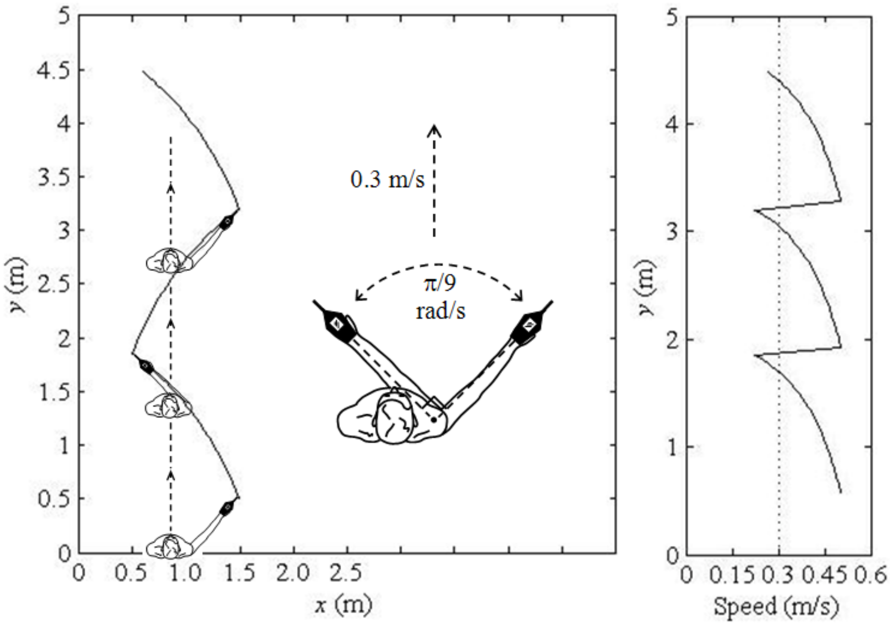


Figure 4.

Normalized variance and the equivalent number of discrete, uncorrelated samples for five, fixed microphone positions at different separation distances in a three-dimensional diffuse field.

a)



b)

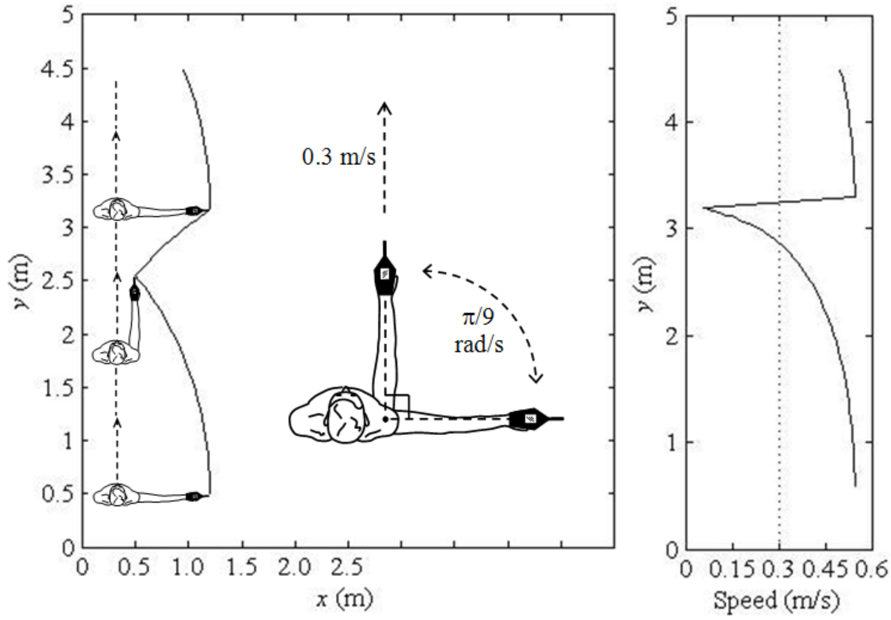


Figure 5.

Microphone path and scanning speed for two different manual scanning paths (a) and (b) that are carried out with an outstretched arm rotating parallel to the transverse plane of the body with a constant angular velocity ($\pi/9$ rad/s) whilst walking forward with a constant velocity (0.3 m/s).

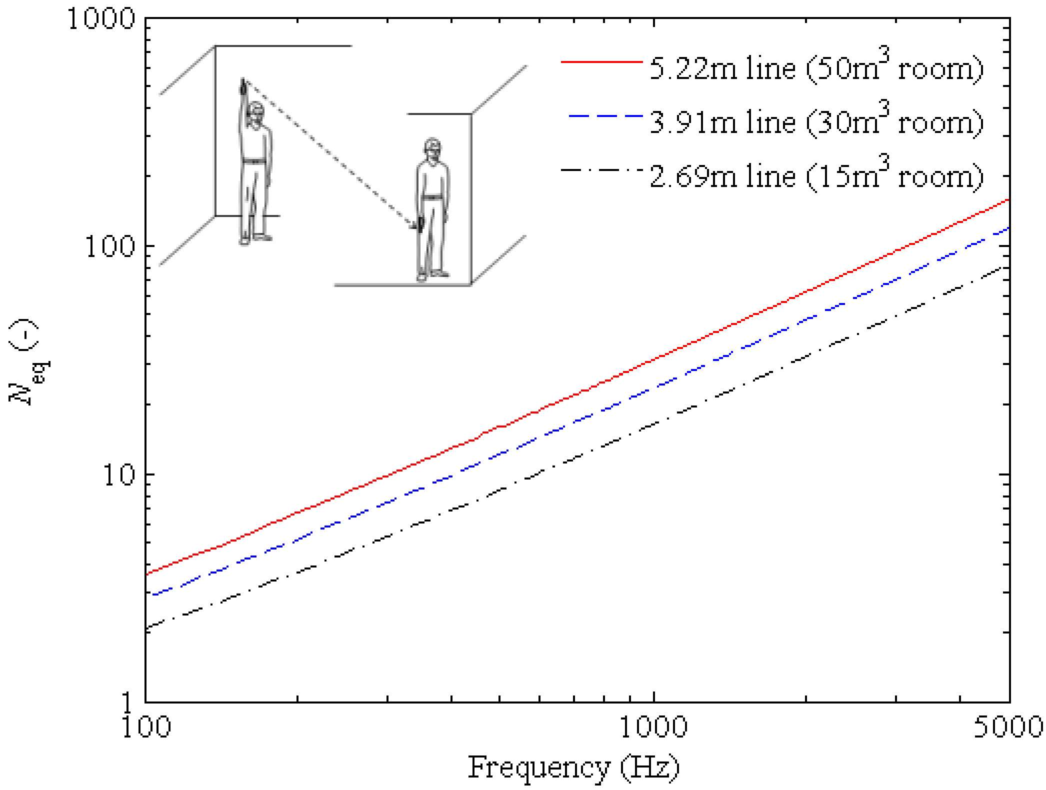


Figure 6.

Equivalent number of discrete, uncorrelated samples for straight line scanning paths involving walking across the room.

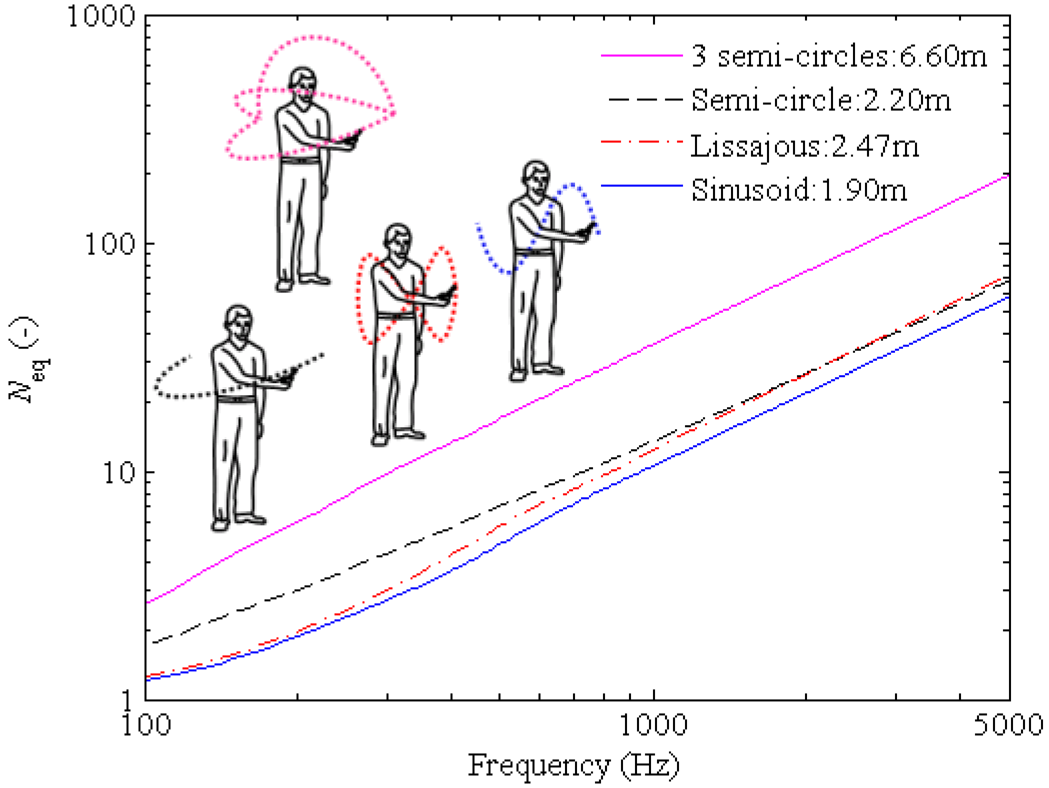


Figure 7.

Equivalent number of discrete, uncorrelated samples for four different paths carried out from a fixed standing position.

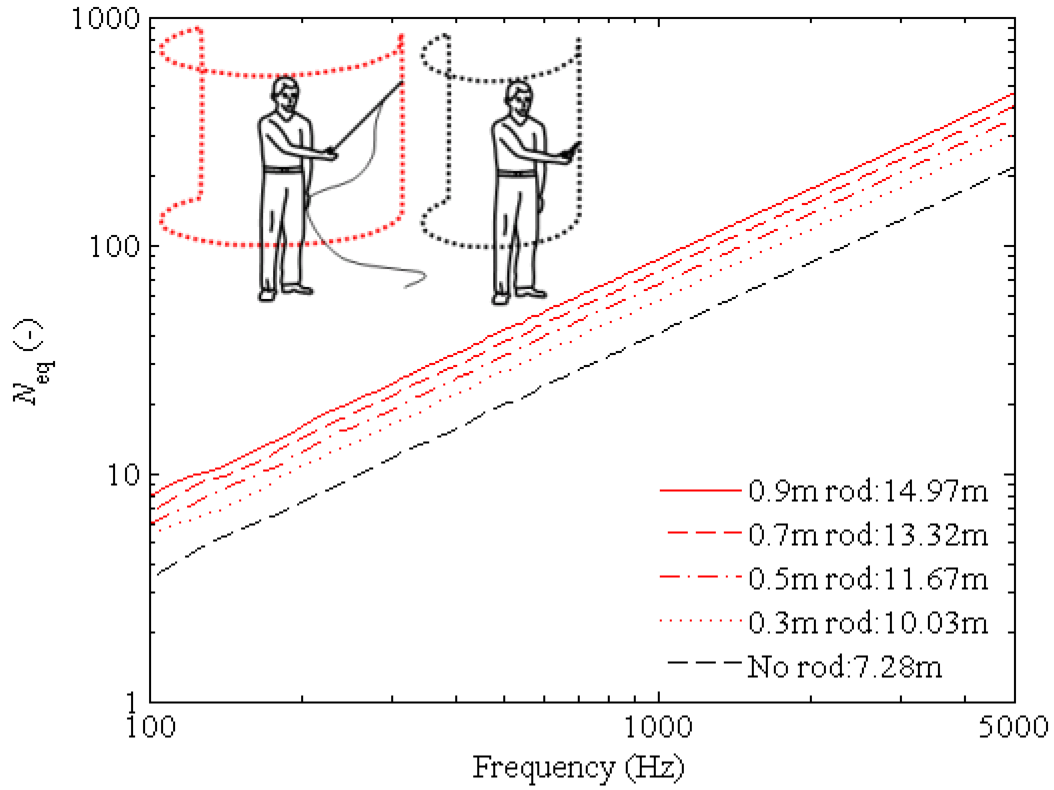


Figure 8.

Equivalent number of discrete, uncorrelated samples for a cylindrical-type path carried out from a fixed standing position.

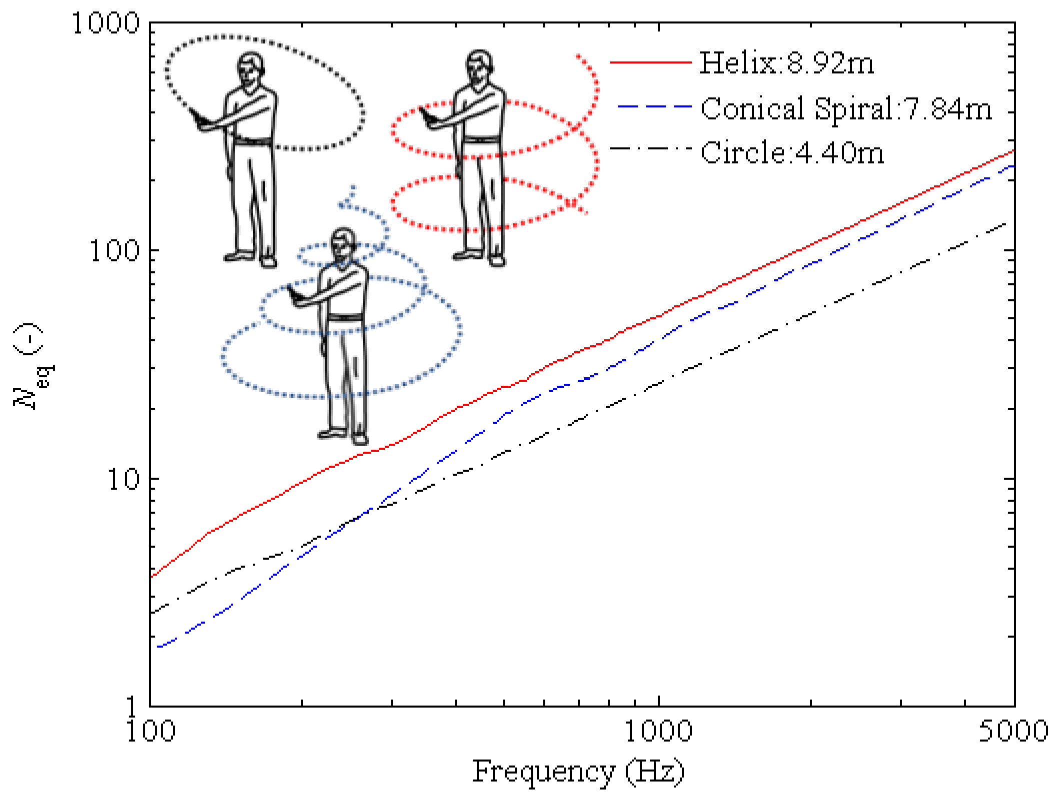


Figure 9.

Equivalent number of discrete, uncorrelated samples for three different paths carried out by rotating the body about a fixed point.