Optimisation of Stirrer Designs in a Reverberation Chamber

Janet Clegg, Andrew C. Marvin, *Member, IEEE*, John F. Dawson, *Member, IEEE,* and Stuart J. Porter, *Member, IEEE*

***Abstract*— This paper describes an investigation into the key factors, which contribute towards an effective mode stirrer. The work concentrates around the lower frequency range, since all stirrers have poorer performance at low frequencies. The stirrer's shape and size have been investigated together with an optimisation of the finer details in the stirrer's shape. The modelling of the mode stirred chamber has been performed using the Transmission Line Matrix method. Software has been developed which, for each position of the stirrer as it rotates, builds the shape of the stirrer using thin perfectly conducting boundaries. Results indicate that the design of the stirrer's basic shape has a small but significant impact on its performance. A genetic algorithm has been used to optimise certain parameters in the shape of the stirrer and a fitness factor based on a free space model of the stirrer has been used. The free space model runs 1500 times faster than the model in the chamber. The optimisation is shown to improve the stirrer's performance in three different sized chambers. Computer modelling has been verified by measurements performed in the chamber at the University of York.**

***Index Terms*—Mode Stirring, Reverberation Chamber, Genetic Algorithms, Transmission Line Matrix Methods, Measurement, Modeling.**

I. Introduction

A mode stirred chamber is a cavity whose fields are perturbed by a rotating scatterer or stirrer in order to produce fields that are statistically uniform and isotropic. By statistically uniform and isotropic it is meant that equal energy is arriving from all aspect angles and at all polarizations, when averaged over a number of stirrer positions. Although mode stirrers have been used for many years, there has been little research into modelling or optimising the design of the stirrer. In this paper a method is described which models the rotation of the stirrer within the Transmission Line Matrix (TLM) software. The effect on the stirrer's performance of its size and shape are investigated and a genetic algorithm (GA) is used to optimise parameters defining the shape of the stirrer. The paper begins with a short description of the requirements for an acceptable reverberation chamber performance, as set out by IEC Standard 6100-4-21 [1] and a measure is defined, which indicates how well a chamber with a stirrer satisfies this IEC criteria. The modelling of the stirrer using TLM is discussed in section III and this is followed by a description of the optimisation method in section IV. Results from the computer modelling are reported in section V, followed by measurement results in Section VI.

Manuscript received December 9, 2003. This work has been funded by the Platform Grant in EMC awarded to the University of York by the U.K Engineering and Physical Science Research Council.

J. Clegg, A.C.Marvin, J.F.Dawson and S.J. Porter are with the Department of Electronics at the University of York, England. (phone: +44 (0)1904 432406; e-mail: jc@ ohm.york.ac.uk).

II. Requirements for Acceptable Mode Stirring

The lowest frequency, f_s, for which a mode stirred chamber can be used is determined by the size of the chamber (since this determines the modal structure [2], [3]) and the effectiveness of the stirrer. IEC Standard 6100-4-21 [1] sets out a procedure for calibrating a mode stirred chamber. This calibration is carried out in order to determine the frequency range over which mode stirring is satisfactory. For the calibration, the following procedure must be carried out. The fields must be recorded at eight positions within the working volume and uniformity must be tested at 45 logarithmically spaced frequencies over the first decade, after which only 20 frequencies per decade are required. Depending on the desired lowest frequency of use, it may be necessary to use up to fifty tuner positions for the lower frequencies. At each of the eight positions within the working volume the maximum field (maximum over stirrer positions) is recorded and the standard deviation (deviation between the eight positions in space) is calculated for the three orthogonal field directions (E_x, E_y and E_z) separately, and also for all the data together, E_{total} (i.e. 24 field values consisting of 8 positions for each of E_x, E_y and E_z). For acceptable mode stirring these four standard deviations plotted against frequency should lie below the specified IEC Standard 6100-4-21 tolerance level [1], although the standard states that three frequencies per octave may exceed the tolerance by no more than 1dB. The Standard also suggests that the stirrer should satisfy a tuner efficiency test, which ensures that the stirrer is capable of providing the required number of independent positions.

In order to compare the quality of various stirrers discussed in this paper, the measures D_x, D_y, D_z, D_{total} are defined. They represent the average difference (in dB) over frequencies 200-1200 MHz that the standard deviation curves (of E_x, E_y, E_z and E_{total} respectively) fall below the tolerance level. Note that if the standard deviation exceeds the tolerance level at any frequency, this difference becomes negative, reducing the measure. The larger these measures are, the better the stirrer's performance in terms of satisfying the IEC criteria. A single quality measure assigned to each stirrer could be defined by letting $D = D_x + D_y + D_z + D_{total}$. Again the larger D is the better the stirrer is at satisfying the IEC criteria for acceptable mode stirring, accounting also for the three frequencies per octave excursions.

III. The TLM Model of the Stirrer

Most of the modelling has been carried out using the TLM method for a room size of 4.7m x 3m x 2.37m (although other room sizes have been modelled using optimal designs of stirrer). The computer model of the chamber has a long run time and, since IEC Standard 6100-4-21 suggests that fifty angle positions may be required for the lower frequencies, the model needs to run fifty separate times for each stirrer investigated. The run time is determined mainly by the grid size and the losses in the chamber. A grid size of 5cm has been chosen, which enables the model to be reliable up to a frequency of 600 MHz (based on ten grid units per wavelength). Although the figures in this paper show results for frequencies up to 1.2GHz, it should be noted that these results become progressively less accurate for frequencies greater than 600 MHz. In this work, we are most interested in the performance of the stirrer at the lower frequencies since the stirrer has poor performance at these lower frequencies. In order to allow the simulation to be performed in a reasonable time scale, a reduction of the chamber Q-factor was required by setting the chamber wall reflection coefficients to -0.99. This produces a Q factor that varies between 800 and 2000 in the frequency range 200-600 MHz and is representative of a chamber with equipment. Using these values, the model takes approximately fifty minutes (Athlon 2100XP) for each angle position of the stirrer, and therefore a full turn of the stirrer takes 42 hours to run. A finer mesh size or a reflection coefficient magnitude closer to unity would have meant a prohibitively long time for the model to run.

The mode stirrers considered within this paper consist of a set of perfectly conducting (PEC) planes placed inside the chamber. PEC boundaries in TLM can only align with the three orthogonal axes therefore planes at arbitrary angles in the room have been modelled using a stepped approximation (see Fig. 1-3). It was found that there was less than 1dB peak difference between the radiation pattern from a perfect "flat" scatterer (i.e. aligned with the computational grid) and the stepped approximation for frequencies in the range 200-600 MHz (i.e. between f_s and 3 x f_s for this room) and a peak difference of 3dB at the higher frequencies [4], [5]. This work addresses the stirrer performance in the lower frequency range and therefore the possible 3dB difference at the higher frequencies is not a concern, since the stirrer performance is adequate in this range.

Software has been developed which automates the process of repeatedly choosing the stepped boundaries, running the TLM model and rotating the stirrer. The software starts by reading information on the original location of the planes which make up the stirrer, their sizes and the axis of rotation. It then calculates the stepped boundaries required in order to model the stirrer as closely as possible at this angle position, produces the TLM input file and runs the model, rotates the entire stirrer through the appropriate angle step and repeats this process until the stirrer has rotated through a full turn.

This paper concentrates on four different designs of mode stirrer. One of these designs is simplistic and was used mainly in an initial investigation into how large the stirrer should be. Two of the designs are realistic (feasible to build) whereas the fourth design would be impractical to build in reality. The fourth design was an attempt to allow the optimiser more freedom in choosing the shape of the stirrer, although this freedom also allows more complexity in its shape.

The "simple" stirrer consists of four rectangular plates that meet along the vertical axis, which is the axis of rotation. All plates are at right angles to each other such that a birds-eye view of the stirrer forms a cross-shape (see Fig. 1). The "complex" stirrer is a design obtained from the simple stirrer by bending each of the four plates at the midpoint through a horizontal line, so that each plate forms a 'V' shape (see Fig. 2 and Fig. 12). The third design of stirrer is referred to as a "z shape" stirrer and consists of three plates joined together to form a 'Z' shape (see Fig. 3). The fourth and final stirrer design is depicted in Fig. 4 and will be referred to as the "random plate" stirrer. A pre-determined volume is split into all possible plates of size 0.2mx0.2m that lie on the three orthogonal axes. Optimisation involves finding the best set of these plates within the volume.

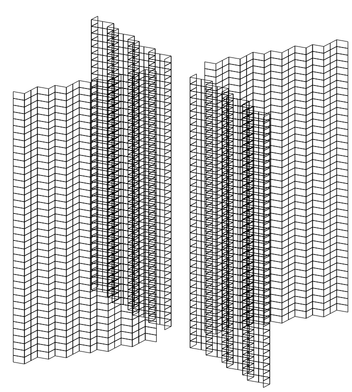

Fig. 1. 3-D representation of TLM model of simple stirrer

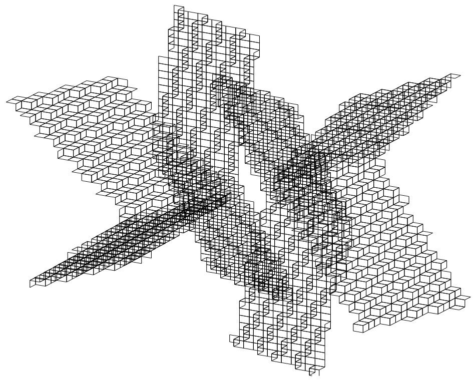

Fig. 2. 3-D representation of TLM model of complex stirrer

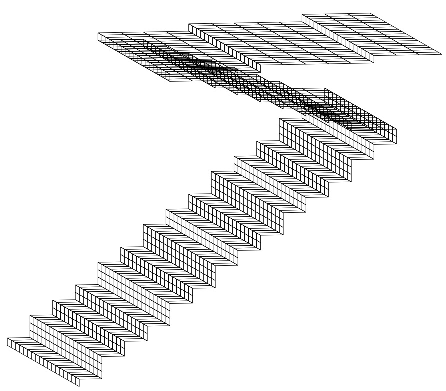

Fig. 3. 3-D representation of TLM model of z shape stirrer

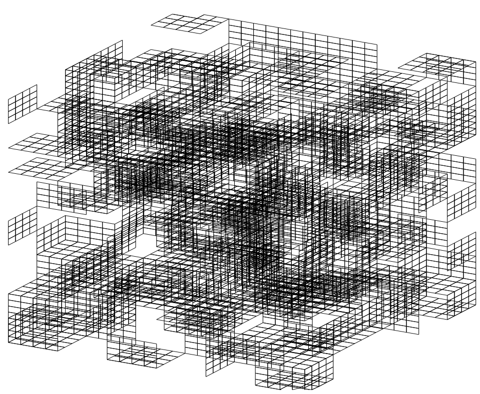

Fig. 4. 3-D representation of TLM model of random plate stirrer

IV. Optimisation using a Genetic Algorithm

A genetic algorithm (GA) was developed to optimise the stirrer designs. A steady state algorithm using tournament selection was used, based on reports of fast convergence in the literature [6]. Since each model of the mode stirrer in the chamber takes 42 hours to run, it would be impossible to use this model within the GA to evaluate the fitness of the members of its population. The fitness has therefore been evaluated by deriving a fitness factor from a "free space" model. The viability of the method is shown in Fig 5 where the free-space scattering performance and the modelled chamber performance are correlated, based on 11 samples (with a correlation coefficient of -0.8).

The stirrer is placed inside a TLM space that is 4m x 4m x 4m with free-space (absorbing) boundary conditions. The stirrer's performance must be considered due to fields that could be incident from any direction. After looking at the possibility of plane waves incident on the stirrer from various directions, it was found that a better representation of randomly incident fields could be achieved by placing sources of excitation (elemental dipoles) in a sphere around the stirrer (see Fig. 6), where no adjacent excitations are of the same polarisation. This produces fields within the volume of the sphere that are close to uniform, i.e. having a standard deviation of 1.7dB relative to the mean. The reflected fields are examined at points also positioned on a sphere around the stirrer (see Fig 6).

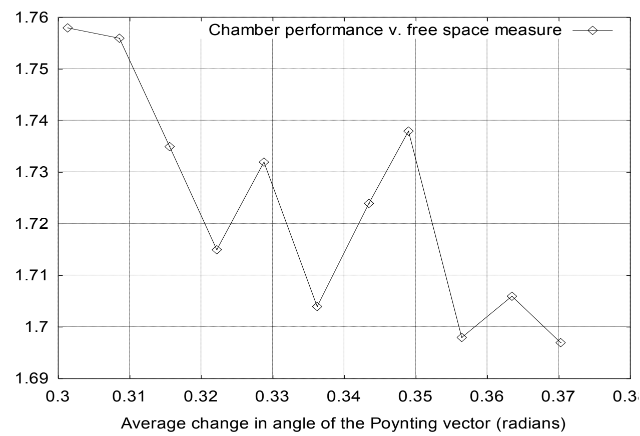

Fig. 5 Chamber performance versus free space measure

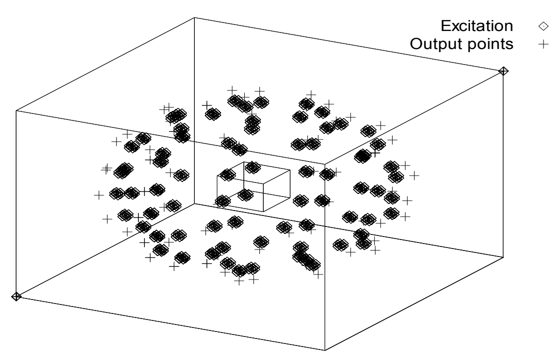

Fig. 6. The "free space" model to evaluate each stirrer in the GA

Deriving a measure of the stirrer's performance in free space involves deciding what qualities the stirrer ought to have when static (i.e. not rotating). Intuitively, a good stirrer might be expected to "change" the fields significantly, but it is not clear whether this should be a change in magnitude, in direction, or in both and whether these changes would be in either the E and H fields or in the Poynting vector. Another consideration in designing the free space measure is deciding from where these changes in fields should be measured. The change due to the stirrer's presence could be compared to no stirrer occupying the same volume or compared to some "poor scatterer" being present; and, if a "poor scatterer" is chosen as the comparison case, then its shape needs to be decided.

Much work has been done in choosing the best options for the free space measure, out of the possibilities listed above. Each possible measure's suitability has been assessed based on the knowledge that increasing the size of the stirrer should improve the measure, together with the fact that there should be a significant difference in quality between the simple stirrer and a complex stirrer of the same size (since it is known from models run inside the chamber that the complex stirrer is much "better" than a simple stirrer of the same size). It was found that the quantity that followed this progression of improvement the best was the change in angle of the Poynting vector due to the stirrer's presence compared to a simple cube (see Fig. 6) occupying the same volume. At each output point two Poynting vectors are found, one when the cube is present and the other when the stirrer is present. The angle between these two vectors is calculated in radians (the maximum angle change possible being π). Fig. 7 displays this change (averaged over all output points) for various sizes of simple stirrer together with a complex stirrer.

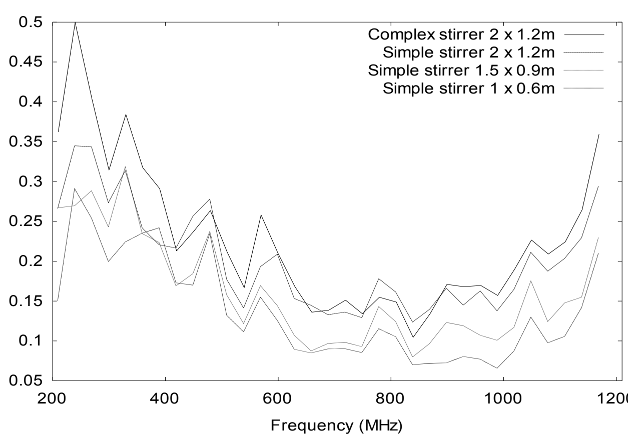

Fig. 7. The change in angle of the Poynting vector for several stirrers, cube present.

Based on these results, the cost function in the GA has been chosen to be the change in the angle of the Poynting vector due to the stirrer's presence compared to the presence of a cube, where this change is added over all output points and frequencies. The run time for evaluating each stirrer in the free space model is approximately 1.6 minutes, so that to evaluate fifty offspring at each generation takes 83 minutes.

In optimizing the various stirrer designs using the GA, the overall sizes of the stirrers have been kept as similar as possible to each other so that comparisons are related mainly to the shape of the stirrer rather than its size. The simple stirrer is 2m high with diameter 1.2m. The plates in the complex stirrer are the same size as those of the simple stirrer, but are bent at angles. Therefore the surface area remains the same in both cases but, by changing the bend angle, the radius and height of the volume of revolution changes. The random plate stirrer has been allowed to fill a slightly larger volume of space that is 2m high and 1.2m square and the z shape stirrer is restricted to a maximum volume of revolution 2m high and 1.2m in diameter.

The parameters allowed to vary in optimizing the complex stirrer are the angles which each of the eight plates makes with the vertical axis. In the case of the z shape stirrer the angles of the plates to the horizontal have been allowed to vary together with the lengths of each plate, whilst the width of the plates are chosen such that the volume of the cylinder shape produced as the stirrer rotates remains the same for each stirrer. For the random plate stirrer, the pre-determined volume is split into all possible positions for plates of size 0.2m x 0.2m that lie on the three orthogonal axes. Each of these positions can have either value 0 (no plate present) or 1 (plate present) and optimisation involves finding the best configuration of these plates.

The GA takes approximately 25-30 generations to converge to its optimal value and Fig. 8 displays a typical example of how the fitness in the GA converges to this optimum over generation number. Since a population size of 64 was used with 50 offspring produced at each generation, it means the GA had searched through a total of 1564 models. There is no guarantee that the GA has actually reached the global optimum rather than some local optimum; but this is the case for most complex problem of optimisation.

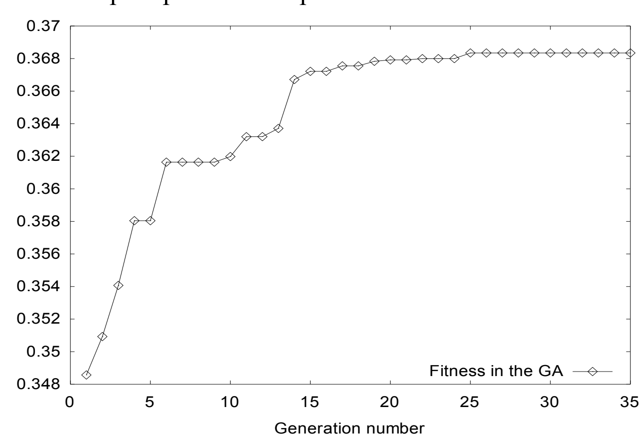

Fig. 8. Average change in angle of the Poynting vector plotted against generation number in the GA.

V. Modelling Results

The stirrer that performed the best out of the four designs, in terms of the IEC criteria, is the random plate stirrer and the optimal configuration is depicted in Fig. 4. The modelled standard deviation curves along with the IEC tolerance level when this stirrer is placed inside the York chamber are displayed in Fig. 9. Although the individual curves are not distinguishable in Fig. 9, the envelope of the curves gives some indication of how well below the tolerance level they lie. Note that the standard deviations in Fig. 9 are plotted for *all* frequencies computed, i.e. 1667 values, rather than simply those frequency values specified by IEC Standard 6100-4-21. It is these standard deviation curves from which the measures D have been calculated (i.e. the difference between the standard deviation curves and tolerance level averaged over *all* frequencies), and Table 1 contains the values of the measures D for the optimal random plate stirrer. The measures D are much easier to use to compare the quality of various different stirrers, since comparing several sets of graphs such as those depicted in Fig. 9 by eye is very difficult.

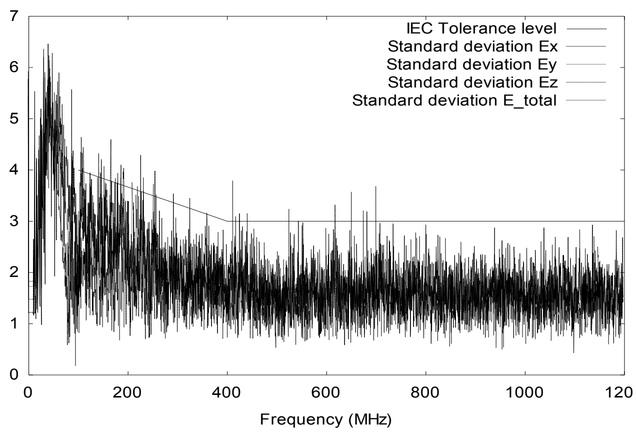

Fig. 9. Modelled standard deviation and IEC tolerance level for the best random plate stirrer

Table 1 also contains the measures D for the optimal complex stirrer together with the worst performing (in terms of its free space fitness factor) complex stirrer; the optimal z stirrer with the worst z stirrer; and finally the simple stirrer. The simple stirrer's lack of performance is to be expected due to the symmetry in its shape and the fact that there will be little conversion of energy between polarisation states. From Table 1 it can be seen that the complex stirrer performs considerably better than the z shape stirrer.

TABLE I
THE MEASURES D FOR VARIOUS STIRRERS

	D_x	D_y	D_z	D_{total}	D
Optimal random plate stirrer	1.366	1.360	1.382	1.296	5.404
Optimal complex	1.335	1.320	1.332	1.221	5.208
Worst complex	1.347	1.346	1.134	1.093	4.920
Optimal z shape	1.230	1.257	1.121	0.802	4.410
Worst z shape	1.199	1.240	0.944	0.670	4.053
Simple stirrer	0.983	0.994	0.961	0.627	3.565

It has been reported by Wu et al. [7] that increasing the size of the stirrer will improve its performance. This concept has been verified in this work using both the simple stirrer and the optimal complex stirrer placed in the 4.7m x 3m x 2.37m chamber. Three sizes of each of the two designs have been placed in the chamber and evaluated, according to the measures D. Note that both the height and the diameter of the stirrers are increased in equal proportions. Table 2 contains the measures D, where dimensions are displayed in the order height x diameter. It can be seen that, by doubling the dimensions of the stirrer, the measure D increases by 1.133 in the case of the simple stirrer and by 1.091 for the complex stirrer.

TABLE 2
QUALITY MEASURES FOR THE SIMPLE /COMPLEX STIRRER OF DIFFERENT SIZES

h x d	D_x	D_y	D_z	D_{total}	D
2x1.2m simple	0.983	0.994	0.961	0.627	3.565
1.5x.9m simple	1.068	1.087	0.992	0.396	3.543
1x0.6m simple	0.936	0.968	0.668	-0.140	2.432
2x1.2m complex	1.335	1.320	1.332	1.221	5.208
1.5x.9mcomplex	1.307	1.267	1.220	1.089	4.883
1x0.6m complex	1.175	1.156	0.980	0.806	4.117

The results in Table 1 verify that optimising using the free space model does improve the stirrer's performance when tested inside the particular chamber whose dimensions are 4.7m x 3m x 2.37m. In order to verify that this improvement can be achieved for alternative chamber sizes, the optimal and worst stirrers (both z shape and complex stirrer) have been modelled in two other rooms. Table 3 contains the measures D for a chamber whose dimensions are 5.2m x 2.5m x 2.37m (referred to as R1) and for a chamber with dimensions 4.2m x 3.5m x 2.37m (referred to as R2). The results in Table 3 (together with those from Table 1 for the initial sized room) show that the optimal stirrers based on the free space fitness factor have produced improvements in three different sized chambers. The fact that this free space evaluation is applicable to different sized chambers is very valuable. This technique of using a free space model means a far faster evaluation of the stirrer; typically 1.6 minutes for the free space model as against 42 hours to evaluate a stirrer within the chamber itself.

TABLE 3
OPTIMAL AND WORST STIRRER'S PERFORMANCE IN 2 MORE CHAMBER SIZES

	D_x	D_y	D_z	D_{total}	D
opt complex R1	1.353	1.310	1.326	1.217	5.206
bad complex R1	1.327	1.268	1.287	1.133	5.015
opt z shape R1	1.254	1.172	1.222	0.829	4.477
bad z shape R1	1.223	1.158	0.960	0.679	4.020
opt complex R2	1.356	1.385	1.365	1.246	5.352
bad complex R2	1.331	1.361	1.302	1.222	5.216
opt z shape R2	1.221	1.306	1.116	0.838	4.481
bad z shape R2	1.179	1.278	0.970	0.685	4.112

Although it has been shown that the shape of the complex stirrer performs better than the z shape stirrer, the question still remains as to what it is in the shape of the stirrer that makes it perform well. Lunden [8], [9], [10] reported some results which implied that the size of the diameter of a stirrer affected its performance more than its height. To evaluate each stirrer, Lunden used the smallest frequency for which the stirrer had 200 independent samples. To test his theory, four stirrers of linearly increasing diameter have been evaluated in the model of the chamber, where the height of each stirrer has been determined by insisting that the swept volume is the same in all four cases. The smallest diameter was 1.2m and the largest 2.6m with respective heights of 1.5m and 0.3m. Each stirrer was first optimised within the GA, but only four angles were allowed to vary. This means that the shape of the stirrer was as the complex stirrer apart from the fact that only angles at the top of the stirrer were allowed to vary, the bottom angles were chosen to equal the top angles so that instead of a V shape, each blade was flat. By restricting the swept volume, the tall stirrer with small diameter could have only very small angles in the GA. In the case of the largest diameter, the GA optimisation produced angles as large as possible for all four blades. By making these angles large, the GA was maximising the total surface area of each blade. This result introduces the question of how much the total surface area of the plates affects stirrer performance. Table 4 contains the resulting measures D when each of the four stirrers are tested inside the chamber (d=diameter, h=height).

TABLE 4
MEASURES D FOR STIRRERS OF VARYING DIAMETERS

	D_x	D_y	D_z	D_{total}	D
d=1.20 h=1.50	1.088	1.041	1.045	0.922	4.096
d=1.66 h=0.73	1.149	1.112	1.059	0.989	4.309
d=2.13 h=0.446	1.160	1.194	0.974	0.920	4.248
d=2.60 h=0.30	1.105	1.165	1.016	0.971	4.257

The stirrer with smallest diameter (d=1.2m) performs slightly worse than the three stirrers with larger diameter, but there is no significant difference between the performance of these other three stirrers. It is thought that the slightly worse performance of the stirrer with the smallest diameter is due to the size of angles (through restricting the swept volume) rather than its small diameter. The other three stirrers have at least one angle as large as 70 degrees, whereas the largest angle in the stirrer whose diameter is 1.2m is only 17 degrees. The results in Table 4 are evaluated based on D, which is a measure of field uniformity, whereas Lunden evaluates stirrer performance based on the smallest frequency for which the stirrer has 200 independent samples. The results in Table 4 imply that, keeping a constant swept volume, the proportions of height and diameter have little effect on field uniformity. Lunden has recently published additional work [11] on stirrer optimization, again concluding that stirrer diameter has a large effect on the smallest frequency for which the stirrer has 200 independent samples.

In order to gain more insight into what makes a good shape of stirrer, the free space measure has been evaluated for 10,500 "random" stirrers. The stirrers are "random" in that the number of plates making up each one is chosen to be a random integer between 1 and 12, and for each of these plates their size and positioning in space are randomly chosen (although they are restricted to lying within a predetermined volume). For each of these random stirrers their total surface area, swept volume, radius of swept volume and height of the swept volume are recorded together with their free space measure. The aim is to see any relationship between these quantities and the quality of the stirrer's performance. Figs. 10 and 11 are two of the resulting scatter plots. Fig. 10 displays the total surface area plotted against the free space measure and it can be seen that the rate of increase in performance with respect to surface area is greatest for the smallest surface area, but that this rate of increase reduces as surface area increases. The scatter plot of the swept volume plotted against the free space measure (not shown here) displays an approximate linear dependence between swept volume and performance, i.e. the rate of increase in performance remains approximately constant throughout the range of volumes considered. Fig. 11 displays the radius of the swept volume plotted against the free space measure and it can be seen that increasing the radius has little effect for very small radii; but, for radii larger than about 0.8m, increasing its size seems to improve performance quite steadily. A very similar shape of scatter plot to Fig. 11 is obtained for the height of the swept volume, although the rate of change in performance for heights greater than 0.8m is not as great as that of Fig. 11. This result confirms Lunden's conclusions that increasing the radius has a slightly larger effect on stirrer performance than increasing the height.

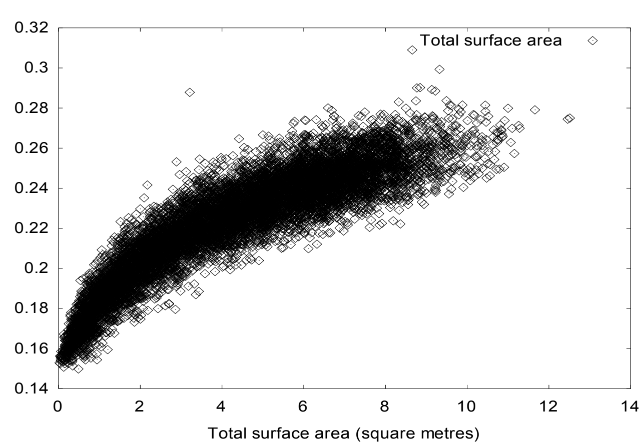

Fig. 10. Total surface area versus average change in Poynting vector

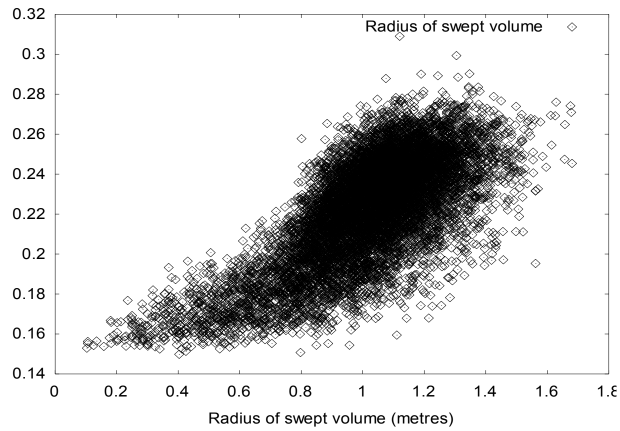

Fig. 11. Radius of swept volume versus average change in Poynting vector

The measure D can be used to compare the performance of the various stirrer designs. In order to gain some insight into the significance of an increase in the measure D, consider the following two unrealistic stirrers. A stirrer which just meets the IEC criteria (i.e. whose standard deviation curves lie exactly on the tolerance level) for all frequencies in the range 200MHz - 1200MHz will have a measure D=0. On the other hand a stirrer which is "perfect" will have zero standard deviation curves at all frequencies in the range and its measure would be D=12.27. Therefore the maximum increase possible in the measure D between a stirrer that only just satisfies the IEC criteria and one which is absolutely "perfect" (but unrealistic) is 12.27. The basic design of a stirrer has been shown to have a significant effect on its performance. Between the worst performing shape (the simple stirrer) and the best performing stirrer (the random plate stirrer) of a similar size an improvement in the measure D of 1.839 was obtained. Note also from Table 2, that a complex stirrer whose size is just 1m x 0.6m performs significantly better in terms of the measure D than the simple stirrer with double these dimensions. The simple stirrer is quite a poor performer, possibly because of the symmetry in its shape, but even between two stirrers whose shapes have little symmetry (i.e. the z shape stirrer and the random plate stirrer) an increase of 0.994 in the value of D has been achieved. The stirrer's performance has been shown to depend on its size and, from Table 2, an average increase of 1.112 in the measure D can be achieved by doubling the dimensions of the stirrer. Optimizing the parameters in each of the stirrer designs does improve the measure D, but only by a small amount. In the case of the complex stirrer an increase of 0.288 has been achieved by optimising the angles of the plates, and for the z shape stirrer an increase of 0.357 was achieved. Although these improvements through optimisation are not as large as those obtained by changing the basic design of the stirrer, they are improvements which can be achieved without causing difficulties in other respects. For instance, if the size of the stirrer is increased, the working volume becomes smaller and if the shape of the stirrer is changed to a more complex shape, fabrication becomes more difficult and expensive. By comparison, the optimisation can be performed quite easily using only computer time to evaluate the free space model, and the optimised stirrer is usually no more complex to build and does not take up more space than the basic shape originally chosen. Tables 1 and 3 also suggest that the optimisation is applicable to several chamber sizes. The value of having a free space model which can be evaluated at such speed and whose quality measure seems to be applicable to different sized chambers (see Section IV) is significant.

VI. Measurement Results

The complex stirrer was built for use in the screened room at the University of York. The York chamber has dimensions 4.7m x 3m x 2.37m and a photograph of the stirrer can be seen in Fig. 12. The stirrer was built in such a way that the angles of the plates could be adjusted, so that the optimal set of angles from the GA could be compared to the worst set of angles. The stirrer is rotated using a stepper motor that is controlled by computer software. Log-periodic antennas were used as transmit antenna (placed in the corner behind the stirrer) and also for recording the received power. A passive 12cm dipole with a 1:1 balun was used to measure the electric fields at the eight positions within the working volume. Since a reduction in the Q factor is necessary in the TLM model of the chamber (the reflection coefficient of the chamber walls was set at –0.99) in order for the run time to be reasonable, absorber is used in the York chamber to reduce the Q factor to the same level as that in the model. The Q factors were calculated using the method in [12] for both the TLM model and the actual chamber and absorber was added to the York chamber until the Q factor was comparable to that in the model. Both the worst and the best stirrer angle sets were tested, using the criteria from IEC Standard 6100-4-21.

Tuner efficiency was evaluated as specified in Appendix A of IEC Standard 6100-4-21. This involved recording the received power while the stirrer rotates through 0.8 degree angle steps (i.e. 450 positions through a full turn of the stirrer). If the 450 values of received power are $x_1, x_2, \ldots, x_{450}$ then the correlation coefficient

$$r_k = \frac{1}{450}\sum_{i=1}^{450}\frac{(x_i-\mu)(x_{i+k}-\mu)}{\sigma^2} \qquad (1)$$

is evaluated for $k=1,2,3,\ldots,k_r$ where k_r is the lowest value of k for which $r<0.37$ and where μ and σ are the mean and standard deviation of the 450 values. The number of independent samples is then given by the value of $450/k_r$. Fig. 13 displays the number of independent angle positions for both the optimal and worst complex stirrers, and it can be seen that there are at least 50 independent angle positions available at 200 MHz which means that tuner efficiency is acceptable from 200 MHz. Since 200 MHz is more than three times the first resonance of the chamber and below it there are at least sixty modes present [2], it means that 200 MHz could be set as the lowest usable frequency (LUF) of the chamber.

Table 5 contains the measures D that have been obtained from the measurement data for both the optimal stirrer and the worst stirrer. There is an improvement of 0.086 in the value of D between optimal and worst stirrers, whereas the modelled results predicted a slightly larger improvement of 0.288 (see Table 1). Although the optimisation does improve the stirrer's performance, the improvement is relatively small and a much greater improvement in performance can be achieved by changing the design of the stirrer rather than just changing the parameters of a single design. Fig. 14 shows the standard deviation curves for the optimal complex stirrer, together with the tolerance level, for the specific frequency values specified by IEC Standard 6100-4-21. It can be seen that the IEC criteria is in fact satisfied.

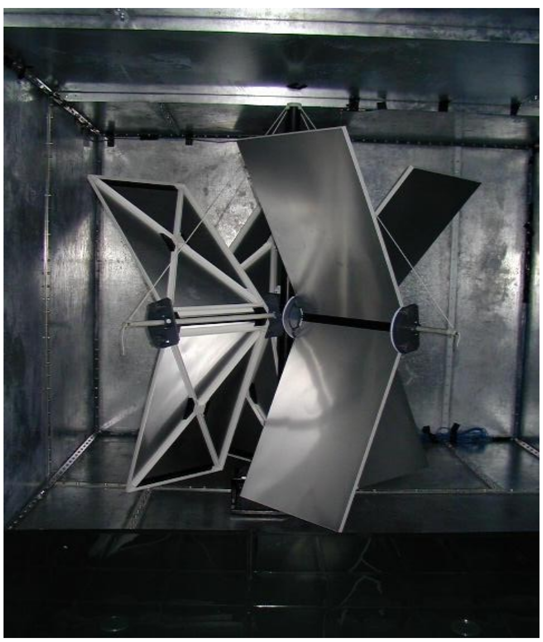

Fig. 12. The mode stirrer used in the York chamber

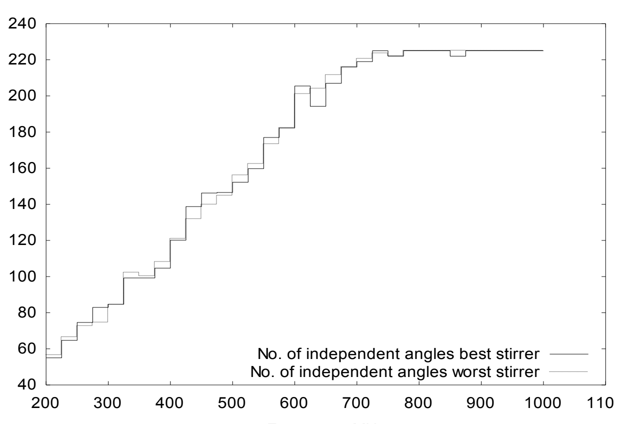

Fig. 13. The number of independent angle positions for the York stirrer

TABLE 5
OPTIMAL AND WORST COMPLEX STIRRERS MEASUREMENT RESULTS

	D_x	D_y	D_z	D_{total}	D
Optimal stirrer	1.097	1.150	1.163	1.066	4.476
Worst stirrer	1.136	1.073	1.127	1.054	4.390

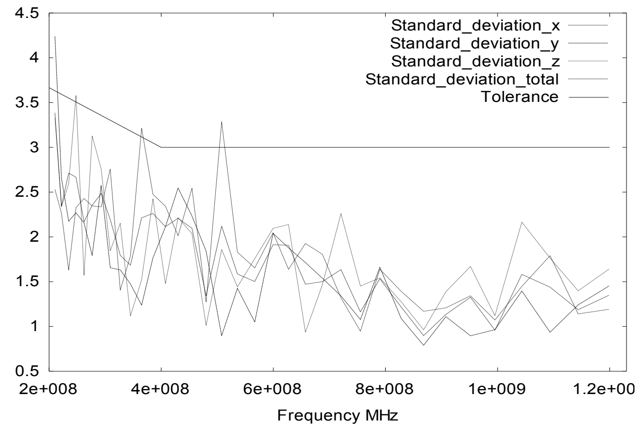

Fig. 14. Standard deviations and IEC tolerance for optimal stirrer in the York chamber

VII. CONCLUSION

This paper has described an investigation into the optimisation of a mode stirrer. The size and shape of the stirrer have been considered and a genetic algorithm has been used to optimise finer details in the stirrer designs. TLM software has been used for the computer modelling together with software which has been developed in order to automate the process of modelling the stirrer as it rotates. Measures have been defined whose sizes indicate how well the stirrers satisfy the criteria for suitable mode stirring as set out in IEC Standard 6100-4-21. It can be deduced from this work that one of the most important considerations in choosing a mode stirrer is in its basic shape, and the shape that performs the best (out of the shapes considered in this paper) is the complex stirrer. Once the shape has been chosen, the stirrer can be improved by increasing its size, although this is limited by the required amount of working volume. Improvements in the stirrer's performance can also be achieved by optimizing certain parameters within the basic design of the stirrer using a GA. Within the GA, the fitness factor is based on a free space model, and this means a far faster evaluation of the stirrer, typically 1.6 minutes as against 42 hours if the stirrer were evaluated in the chamber itself. It has been shown that a higher value of the fitness factor derived from the free space model does indicate improvements in the performance of the stirrer in three different sized chambers (see Table 3); that this free space evaluation is applicable to different sized chambers is extremely valuable. Although the optimisation does improve the stirrer's performance, the improvement is relatively small compared to that obtained by changing the design of the stirrer. A large number of random stirrers have been investigated to try and discover what aspects of the shape of the stirrer affect its performance the most. Increasing the radius was found to improve stirrer performance slightly more than increasing the height. Future work could involve further optimisation that would search through very different shapes of stirrer (shapes which are practical to build) rather than keeping the basic shape the same and searching for the best angles in the plates.

Measurements have been performed to verify that the optimisation within the GA does actually produce an improvement within a real chamber.

REFERENCES

[1] IEC 61000-4-21 Draft, "Electromagnetic Compatibility (EMC) Part 4: Testing and Measurement Techniques Section 21: Reverberation Chamber Test Methods," International Electrotechnical Commission, 2003.

[2] M.L. Crawford, G.H. Koepke, "Design, Evaluation and use of a Reverberation Chamber for Performing Electromagnetic Susceptibility/Vulnerability Measurements," Nat. Bur. Stand. (USA), NBS Tech Note 1092.

[3] D.A. Hill, "Electromagnetic Theory of Reverberation Chambers", National Institute of Standards and Technology, Technical Note 1506, 1998.

[4] J.Clegg, A.C.Marvin, J.F.Dawson, S.J.Porter, M. Brunger-Koch, "The use of the Transmission Line Matrix Method to Optimise a Mode Stirrer", Fourth International Workshop on Computational Electromagnetics in the time domain: TLM/FDTD and related techniques (CEM-TD), Nottingham, 17-19 September 2001, pp85-90, ISBN 0-9541146-0-4.

[5] J. Clegg, A. C. Marvin, J. F. Dawson, S. J. Porter, M. Brunger-Koch, "Optimization of stirrer designs in a mode stirred chamber using TLM", XXVIIth General Assembly of the International Union of Radio Science (URSI), Maastricht Exhibition and Congress Centre (MECC), Maastricht, the Netherlands.

[6] J.M. Johnson, Y. Rahmat-Samii, "Genetic Algorithms in Engineering Electromagnetics," IEEE Antennas and Propagation Magazine, Vol.39, No. 4, August 1997.

[7] D.I. Wu, D.C. Chang, "The Effect of an Electrically Large Stirrer in a Mode-Stirred Chamber," IEEE Transactions on Electromagnetic Compatibility, Vol. 31, No. 2, May 1989, pp164-169.

[8] O. Lunden, L. Jansson, M. Backstrom, "Measurements of Stirrer Efficiency in Mode-Stirred Reverberation Chambers", FOA-R-99-01139-612--SE, May 1999.

[9] O. Lunden, M. Backstrom, N. Wellander, "Evaluation of Stirrer Efficiency in FOI Mode-Stirred Reverberation Chambers", FOI-R--99-0250--SE, Nov. 2001.

[10] O Lunden, M Backstrom, "A factorial Designed Experiment for Evaluation of Mode-Stirrers in Reverberation Chambers", Proceedings of 2003 IEEE International Symposium on EMC, Istanbul, Turkey, May,2003.

[11] N. Wellander, O. Lunden, M. Backstrom,"Parameter estimates for the stirrer efficiency in reverberation chambers", EMC Zurich 2005, pp 35-38.

[12] M P Robinson, J Clegg. "Improved determination of Q-factor and resonant frequency by a quadratic curve-fitting method", IEEE Trans. EMC, Vol. 47, No. 2, May, 2005, pp 399-403.