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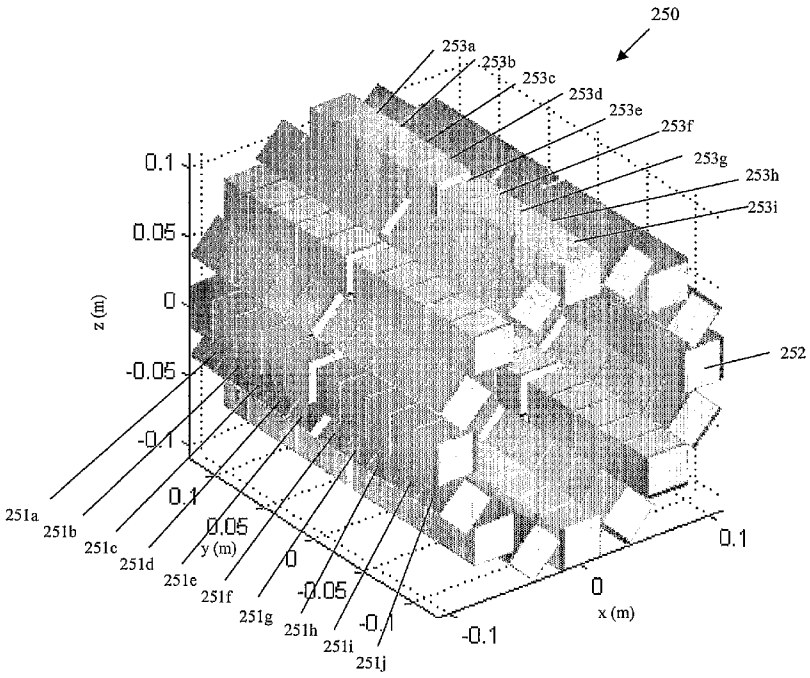
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(54) **Title:** MAGNETIC FIELD-GENERATING APPARATUS



(57) **Abstract:** An apparatus for generating a homogenous magnetic field has a plurality of sub-arrays (251a-251j), each having a plurality of permanent magnets disposed in an annular array about an axis. A separation (253e) is provided between two of the sub-arrays (251e, 251f) that are disposed at or toward the centre of the assembly along the longitudinal axis such that second order derivatives of the principal component of the magnetic field in an area within the assembly are substantially zero in three orthogonal directions.

WO 2007/120057 A1

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MAGNETIC FIELD-GENERATING APPARATUS

FIELD OF THE INVENTION

The present invention relates to a method and apparatus for generating a homogenous magnetic field. In particular, but not exclusively, the present invention relates to a method and apparatus for generating a homogenous magnetic field for use in Nuclear Magnetic Resonance (NMR) systems.

BACKGROUND TO THE INVENTION

NMR spectroscopy is an analytical and diagnostic technique that can be used for structural and quantitative analysis of a compound in a mixture. An NMR spectrometer generally comprises one or more magnets producing a strong magnetic field within a test region.

To generate the strong magnetic field, Halbach arrays may be used. Halbach arrays are a means of creating multiple magnetic fields from a ring of magnetised rare-earth material. The number and location of the magnetic dipoles can be varied by manipulating the orientation of the magnetisation around the ring. If a homogeneous magnetic field is required, Halbach (1979) has shown a successive magnetisation angle may be chosen such that a dipolar magnetic field is produced by the array. Figure 1 shows that, when the criterion for a dipolar Halbach array is met, the magnetic field produced by the array is transverse to the longitudinal axis of the array. The direction of the lines of magnetic flux under this condition will hereafter be known as the principal component of magnetic field.

NMR experiments require magnetic fields that are as strong and as homogenous as possible. For a dipolar Halbach array constructed from discrete magnets, the strength of the field is well understood, and is readily calculable. However, little research has been done on characterising and improving the homogeneity of the field produced by such an array. As noted earlier, homogeneity is a desired characteristic in NMR applications.

There has been research into improving other properties of the field produced by a Halbach array, for instance magnetic field parallelness. One example is US Patent No. 6,885,267 to Kuriyama et al., which describes a Halbach array-type magnetic field generating apparatus. The magnets in Kuriyama et al. are arranged such that the magnetic field generated in the Halbach array has improved magnetic field parallelness. The improved parallelness is beneficial in that the apparatus can accurately magnetise the orientation of magnetic films and like devices.

In this specification where reference has been made to patent specifications, other external documents, or other sources of information, this is generally for the purpose of providing a context for discussing the features of the invention. Unless specifically stated otherwise, reference to such external documents or such sources of information is not to be construed as an admission that such documents or such sources of information, in any jurisdiction, are prior art or form part of the common general knowledge in the art.

It is an object of the present invention to provide an assembly based on a Halbach array which provides an improved homogenous magnetic field within the assembly, or to at least to provide the public with a useful choice.

SUMMARY OF THE INVENTION

The term "comprising" as used in this specification means "consisting at least in part of". When interpreting each statement in this specification that includes the term "comprising", features other than that or those prefaced by the term may also be present. Related terms such as "comprise" and "comprises" are to be interpreted in the same manner.

The term 'homogeneous magnetic field' as used in this specification means a sufficiently homogeneous magnetic field so as to enable NMR excitation of a sufficient volume of sample and to provide an analysable NMR signal in that region.

In one aspect, the present invention broadly comprises an apparatus for generating a homogenous magnetic field, comprising an assembly having a plurality of sub-arrays, each

sub-array comprising a plurality of permanent magnets disposed in an annular array about an axis (hereafter "longitudinal axis"), wherein a separation is provided between two of the sub-arrays that are disposed at or toward the centre of the assembly along the longitudinal axis such that second order derivatives of the principal component of the magnetic field in an area within the assembly are substantially zero in three orthogonal directions.

The assembly may have only two sub-arrays. Alternatively, the assembly may have more than two sub-arrays.

Preferably, the assembly comprises an even number of sub-arrays, such as two, four, six, eight, ten, or more sub-arrays for example. In such a configuration, the separation is provided between the two central sub-arrays.

Alternatively, the assembly may comprise an odd number of sub-arrays, such as five, seven, nine, or more sub-arrays for example. In such a configuration, the separation is provided between two of the sub-arrays that are generally centrally disposed within the assembly. For example, in an assembly having seven sub-arrays, the separation is suitably provided between the third and fourth sub-arrays. For an assembly having an odd number of sub-arrays less than seven, at least some of the sub-arrays may have different sizes such that the separation is positioned generally centrally within the assembly. However, for an assembly having an odd number of sub-arrays of seven or more, satisfactory results can be achieved with sub-arrays having a substantially consistent size.

Preferably, separations are provided between at least some of the sub-arrays, with the separations disposed in such a way as to minimise fourth order derivatives of the principal component of magnetic field.

Preferably, the longitudinal dimension of each of the sub-arrays disposed in the assembly is arranged so as to minimise fourth order derivatives terms of the principal component of magnetic field.

The separation(s) may be occupied by air, another gas, or a vacuum. Preferably, the separation(s) is/are occupied by a substantially non-magnetic material.

Preferably, the size(s) of the separation(s) is/are less than the radius of the annular array of the permanent magnets.

Preferably, each sub-array has at least four permanent magnets. In some embodiments, the number of permanent magnets in each sub-array may be a multiple of four, such as four, eight, twelve, sixteen, or more permanent magnets.

Preferably, all of the permanent magnets in a sub-array have substantially the same length and width. More preferably, all of the permanent magnets in the assembly have substantially the same length and width.

Preferably, each sub-array comprises an annular plate having disposed thereon or therein the plurality of permanent magnets.

In a further aspect, the invention comprises an NMR apparatus comprising an apparatus as outlined in relation to the first aspect above arranged to create a zone of homogeneous magnetic field at some location within the assembly, and into a sample when provided.

In a further aspect, the invention comprises a method of generating a homogenous magnetic field using an assembly comprising a plurality of sub-arrays, each sub-array comprising a plurality of permanent magnets disposed in an annular array about an axis (hereafter 'longitudinal axis'), the method comprising the steps of:

arranging two sub-arrays that are disposed at or toward the centre of the assembly adjacent one another and along the longitudinal axis; and

providing a separation between the two sub-arrays that are disposed at or toward the centre of the assembly, such that second order derivatives of the principal component of the magnetic field in an area in the assembly are substantially zero in three orthogonal directions.

The assembly may comprise only two sub-arrays. Alternatively, the assembly may comprise more than two sub-arrays.

The assembly may comprise any one or more features outlined in respect of the first aspect above.

The method may comprise arranging one or more further sub-arrays adjacent each of said two sub-arrays that are disposed at or toward the centre of the assembly such that the magnetic assembly has more than two sub-arrays.

Preferably, the method further comprises: determining an optimal separation for the two sub-arrays that are disposed at or toward the centre of the assembly using some optimisation technique, for example root-finding.

Preferably, the method further comprises: determining an optimal radius for the two sub-arrays that are disposed at or toward the centre of the assembly using some optimisation technique, for example root finding. In one form, a Newton-Rhapson root-finding algorithm is used.

Preferably, the method further comprises: determining an optimal separation between each of the sub-arrays other than the two sub-arrays that are disposed at or toward the centre of the assembly using some optimisation technique, for example, minimisation of a figure of merit that describes the performance of the assembly.

Preferably, the method further comprises: determining an optimal longitudinal dimension for each of the sub-arrays using some optimisation technique, for example minimising a figure of merit that describes the performance of the assembly. In one form, a Nelder-Mead minimisation algorithm is used.

Preferably, the optimisation technique(s) is/are carried out on a computer programmed with optimisation algorithm(s).

The invention consists in the foregoing and also envisages constructions of which the following gives examples only.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred forms of the method and apparatus of the invention will now be described with reference to the accompanying figures in which:

Figure 1 shows a diagrammatic illustration of magnetic flux lines produced by a dipolar Halbach array;

Figures 2a and 2b show schematic views of a part of a Halbach array;

Figure 3 shows a perspective view of a Halbach array with one sub-array;

Figure 4 shows contour lines representing homogeneity of the magnetic field produced by the Halbach array of Figure 3;

Figure 5 shows a perspective view of a first preferred form Halbach array with two sub-arrays;

Figure 6 shows contour lines representing homogeneity of the magnetic field produced by the Halbach array of Figure 5;

Figure 7 shows a perspective view of second preferred form Halbach array with a plurality of sub-arrays;

Figure 8 shows contour lines representing homogeneity of the magnetic field produced by the Halbach array of Figure 7;

Figures 9a to 9d show graphs of Halbach array geometry and parameter changes in response to a change in separation between two centre sub-arrays, in accordance with possible preferred forms of the present invention;

Figure 10 shows the standard deviation of second order derivatives for a 10,000-trial Monte-Carlo simulation;

Figures 11a to 11f show graphs of Halbach array geometry and parameter changes in response to a change in separation between two centre sub-arrays for arrays with two, four, six, eight, ten and twelve sub-arrays, in accordance with possible preferred forms of the present invention;

Figure 12 shows a perspective view of a third preferred form Halbach array;

Figure 13 shows contour lines representing homogeneity of the magnetic field produced by the preferred form Halbach array of Figure 12 respectively;

Figure 14a shows a sub-array former design;

Figure 14b shows an assembled sub-array; and

Figures 15 to 19 show various stages of assembly of the preferred form array.

DETAILED DESCRIPTION OF PREFERRED FORMS

The applicants have invented modified arrangements of a dipolar Halbach array, which offer improved homogeneity. The preferred form arrays are designed such that the homogeneity of their magnetic fields can be enhanced through a process of setting to zero the second derivatives of the principal component of the magnetic field in each direction.

For the purposes of this description, the principal component of magnetic field is arbitrarily chosen to lie in the z-direction; thus the principal component of magnetic field is denoted B_z and the total magnetic field denoted B. The longitudinal axis is similarly chosen to lie in the y-direction. Finally, the three orthogonal directions along which the derivatives of the principal component of magnetic are evaluated are arbitrarily chosen to be the Cartesian axes, x y and z.

Halbach Array

The creation of a Halbach array is made possible by rare-earth metals. Traditional ferromagnetic materials are not able to hold their magnetisation in the presence of an opposing magnetic field. Thus, if a ferromagnetic material were used to create a magnet array whose properties relied upon superposition of fields from the magnetic elements of the array, the desired field would only exist for a short period of time. Since the field created by a Halbach array relies on such a superposition of magnetic fields, ferromagnetic materials would be unsuitable.

By contrast, rare-earth metals are capable of holding their magnetisation in the presence of opposing magnetic fields of a similar magnitude, a property that is derived from the high magnetic coercivity of this material.

For the specific case of a homogeneously magnetised piece of rare-earth material, the current density distribution is that of a current sheet at the surface of the material. For this reason, a homogeneously magnetised piece of rare-earth material may be modelled simply as a current sheet with the same shape as the piece of rare-earth metal.

Furthermore, the fields produced by pieces of rare-earth material add linearly. It is therefore possible to design magnetic arrays using this material with relative ease. One such magnetic array design involves creating a multipole field from this material. This is the so called Halbach array.

Homogeneity of the Magnetic Field Produced by Halbach Arrays

Halbach (1979) has described an arrangement of magnetic elements which can lead to a uniform magnetic field distribution. In practice this array can be realised using rectangular cuboid magnets. Figures 2a and 2b show the typical form of this array in which each magnetic element at azimuthal angle φ, has the successive angular displacement $\beta(\varphi)$ such that:

$$\beta(\varphi) = \varphi(N+1) \qquad 1$$

For use in NMR, a magnet array is required to produce a field that is homogeneous. The rare-earth material is therefore magnetised such that a dipolar magnetic field is created. This corresponds to $N = 1$.

Consider an area between two circles of radii r_{inner} and r_{outer} filled with rare-earth material. Halbach (1979) showed that, for the particular case of the homogenous, dipolar geometry, one obtains the result:

$$\mathbf{B} = B_r \ln(r_{outer} / r_{inner}) \qquad 2$$

Where B_r is the remnant magnetisation of the rare earth material.

For the Halbach array with $N = 1$, the magnetic flux is contained within the ring of magnetised material in a dipolar configuration. The field that is produced is therefore homogenous and additionally has no stray field outside the ring of magnetised material. This type of Halbach array is therefore ideal for forming the B_0 field of an NMR system. What is more, the generation of a B_0 field that is orthogonal to the long axis of the array is particularly convenient for performing NMR experiments.

By convention, the direction of the B_0 field used in an NMR experiment is in the z-direction. It is for this reason that the principal component of magnetic field is chosen to lie in the z-direction.

The implication of equation 1 is that the magnetisation direction should be continuously varied around the circle of rare-earth material. The requirement for a continually varying magnetisation direction is presently impossible to physically realise, thus it has been proposed that the ring of material could be broken into segments which each had a magnetisation direction given by equation 1.

While it is possible to create an array in this way, such an approach requires a considerable degree of expertise in manipulating the raw rare-earth material and performing the subsequent magnetisation.

A simpler method of array construction has been proposed whereby the array is constructed from a number of identical, discrete, bar magnets (Raich 2004). However, any approximation to the continuously varying condition required by equation 1 will result in a departure from the condition required to make the array truly dipolar. Such an approximation produces a magnetic field that is still dipolar in nature, but does not have the same degree of homogeneity as indicated by the simple result of equation 2.

An analytical solution for a Halbach array constructed in the above way may be achievable; however, it is easier to develop a numerical model. Whilst equation 2 now no longer

completely describes the magnetic field produced by the array, the information given by equations 1 and 2 remain important to the design of a discrete magnet Halbach array. By choosing the relative magnetisation direction of successive magnets according to equation 1, similar behaviour can be seen to when compared to that predicted in the continuous case.

Halbach Array Field Homogeneity

As has been discussed previously, a homogeneous magnetic field within the Halbach array is desired for NMR applications. This is because the homogeneity affects the signal to noise, and thus the performance of the system.

In order to investigate the homogeneity of a Halbach array, some means of calculating the field from such an array is required, along with a method of improving the array for the condition of maximal homogeneity and field strength. An example means will be described later in this specification.

As for improving the homogeneity of the Halbach array magnetic field, there are several optimisation techniques that may be used. One such technique is to use a root finding approach. A root finding approach to optimisation requires some property of the array that can be set to zero by intelligently iterating the array parameters. The design of the dipolar Halbach array means the B_z component of the magnetic field of the array may, to first order, be regarded as being equal to B at any point inside the array. In this instance, the second derivative of the B_z component of the magnetic field produced by the array has the desired effect of increasing the field homogeneity when set to zero at the geometric origin of the array. Thus, a root finding method that can intelligently iterate the geometry of the array in such a way as to make the second derivative of the B_z component of magnetic field equal to zero in each direction can improve the homogeneity of the array to second order.

What is particularly attractive about a root finding approach to improve homogeneity is that the sum of second derivatives of the B_z component of magnetic field is zero. This may be understood from consideration of Maxwell's equations:

For any magnetic field, Maxwell's equations state:

$$\nabla.\mathbf{B} = 0 \qquad 3$$

Additionally for free space, Maxwell's equations state:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \qquad 4$$

Where J represents the current density where $\nabla \times \mathbf{B}$ is evaluated, $\frac{\partial \mathbf{E}}{\partial t}$ the rate of change of electric field with time at the same point and ε_0 the permittivity of free space.

The Halbach array is a time invariant magnetic field, thus $\frac{\partial \mathbf{E}}{\partial t} = 0$. Additionally there are no current carrying elements in the centre of the array (where $\nabla \times \mathbf{B}$ is evaluated) meaning J = 0. Therefore 4 may be simplified to:

$$\nabla \times \mathbf{B} = 0 \qquad 5$$

For equation 4 to be satisfied, each component of the vector $\nabla \times \mathbf{B}$ must equal zero. By differentiating equation 3 with respect to z, and then substituting the components of 5 as required it is possible to obtain the result:

$$\frac{\partial^2 B_z}{\partial x^2} + \frac{\partial^2 B_z}{\partial y^2} + \frac{\partial^2 B_z}{\partial z^2} = 0 \qquad 6$$

Consequently, if it is possible to find some condition that causes the second derivative of B_z to be zero in two directions, the third direction will additionally have a second derivative equal to zero.

It is desirable to minimise higher order derivatives of B_z in addition to setting the second derivatives of B_z to be zero. This has the effect of improving still further the homogeneity

of the magnetic field of the array. The symmetry of the array means that all odd partial derivative terms of B will be equal to zero. Thus, it is the higher order even derivatives of B_z that must be minimised.

Ideally, the minimisation process should set the higher order derivatives of B_z to zero; however, by so doing other features of the array, particularly the strength of the magnetic field, may be compromised. A minimisation process is therefore preferable, since there are significant improvements in homogeneity to be made by simply reducing the value of the higher order derivatives compared to a solution that only sets the second order derivatives of B_z to zero.

Using a method that does not set derivatives to be zero requires an algorithm that does not use root finding, since that optimisation technique may not converge on a solution, or may yield a solution may be of little practical use. Including the requirement for minimisation of higher order derivatives lends itself to the use of a minimisation algorithm. Such an approach inevitably results in a loss of control over the final physical geometry of the array; however, this is traded against better control over the properties of the magnetic field produced by the array.

There are numerous possible Halbach array geometries that have the desired second order homogeneity. As a result of this, the solution that emerges at the end of a root finding or minimisation optimisation is not guaranteed to be the globally optimum solution. In deciding which of these solutions is optimal, factors such as field strength, homogeneity and practicality of the design are considered. An array produced using a minimisation technique tends to have a lower field strength and greater homogeneity. By contrast an array that is produced using a pure root finding exercise has higher field strength, but lower homogeneity.

Magnetic Field Calculation

In order to perform the optimisation a means of calculating the field from a Halbach array should be provided. There are numerous finite element packages commercially available

that are capable of performing this calculation, as will be known to persons skilled in the art.

Whilst it is possible to calculate the magnetic field from a three dimensional object using finite element methods, the computation time may be prohibitively long. Since any real NMR sample is inherently three dimensional, the section of array that has maximal homogeneity should also be three dimensional. For this reason a different approach may be used for calculating the magnetic field. For example, a semi-analytical model for the Halbach array may be created using known analytical tools, such as MATLAB (The Mathworks Inc).

Magnetised rare-earth material can be modelled by a current sheet at the surface of the material with linear current density B_r/μ_0. For the purposes of the preferred forms of the present invention, cuboid magnets have been considered. Persons skilled in the art will appreciate that other magnet forms may be used instead, such as appropriately magnetised cylindrical bar magnets for example.

The field from a magnet may be calculated from the Biot-Savart law for a magnetic field produced by a current carrying wire, where the wire represents one edge of the piece of rare-earth magnet. By arranging four such wires into a square loop, it is possible to calculate the field at any point from the superposition of these wires. Subsequent integration of the magnetic field from this loop into the plane of the loop produces the required current sheet model of a cuboid magnet. It is possible to perform the integration analytically, instead of the numerical implementation based on a trapezoidal integration method described above.

The requirement for a Halbach array that produces a homogeneous field dictates the precise location and orientation of the component magnets relative to one another. Equation 1 shows how the relative orientation of the magnets is to be varied. Additionally, any Halbach array requires that the magnet centres are positioned at the same radius, R, from the geometric origin of the array.

A front view of one quadrant of a Halbach array is shown in Figure 2a. Figure 2b shows a plan view of a number of sub-arrays 20 in the Halbach array. Each sub-array comprises a number of permanent magnets 21 arranged in an annular array about a longitudinal axis L, as will be described in detail later.

Consider some point P at which the magnetic field from the array of Figure 2 is to be calculated. The point P is rotated into the same set of axes as the first magnet by rotating the point P through an angle $-\varphi$ about the centre of the magnet, where φ is shown in Figure 2 and is the angle of rotation as defined in equation 1 for $N = 1$. The co-ordinates of the point will now be relative to a set of axes whose z-direction is parallel to the direction of magnetisation of the magnet, and whose origin is the centre of the magnet.

The B_x, B_y and B_z components of the magnetic field at the rotated point P' are then calculated using the method outlined previously. The B_x, B_y and B_z components of magnetic field are then rotated back into the original frame of reference using the inverse rotation. The calculated values are then stored. This procedure is repeated for each of the magnets in the array, with the magnetic field from each successive magnet being added to the value already stored.

In order to precisely and accurately calculate the magnetic fields, a suitable algorithm is preferably used. Alternatively, the fields may be calculated using finite element methods. By creating a model of this nature, it is possible to calculate the magnetic field in any spatial location, with any combination of magnets. That the calculation is inherently three dimensional is an extremely important feature, since it allows accurate calculation of magnetic field along each of the Cartesian axes, and the crucial associated second derivatives.

Figure 2 shows how the array can be parameterised for the purposes of this calculation. Each magnet 21 is specified in terms of its length l, width w, height h and strength. It can be seen that the height of each magnet corresponds in direction to the longitudinal axis L of the assembly. The orientation and location of the magnets 21 are given by the radial distance R and the angles θ and φ, where θ is the angle between magnet centres and φ is

the angle through which the magnet is rotated about its centre. The number of sub-arrays 20 that make up the final array may be specified, as is the separation s between each of these sub-arrays. The number of magnets in a sub-array can also be chosen, although for reasons of symmetry this variable is preferably restricted to integer multiples of four.

In one preferred form of the method, a Newton-Rhapson algorithm is used to perform the root finding. This particular implementation of the algorithm is capable of calculating the n^{th} derivative in any number of directions, provided that the program had an equal number of array parameters to adjust. Thus, for an application that attempts to set the second derivative to be zero in one direction, the input to the Newton-Rhapson program must be the value of the second derivative of the field in that direction.

Providing the program is converging on the root, the output from the program is the perturbation to the chosen array parameter that will force the second derivative to be closer to zero. The field from the array is then calculated with the new array parameter and the second derivative of that field in the appropriate direction is fed back into the program. Once a value of the array parameter has been obtained that yields a magnetic field from the array whose second derivative is sufficiently close to zero, the program terminates.

In another preferred form of the method, a Nelder-Mead minimisation algorithm is used to perform the optimisation.

In a similar fashion to the Newton-Rhapson root finding method, a particular Halbach array geometry is parameterised, and then fed into the minimisation algorithm. The minimisation algorithm then calculates a figure of merit for this array geometry based on appropriately weighted values of the second and fourth order derivatives. It then makes a perturbation to the initial Halbach array geometry in an attempt to minimise the figure of merit. After many iterations, when the figure of merit is sufficiently small, the algorithm terminates and returns the optimised array geometry.

Halbach Array Geometry

A conventional form of a Halbach array is shown in Figure 3. The array comprises one sub-array 30 having sixteen permanent magnets 31 arranged in an annular arrangement about a longitudinal axis, *L*.

To measure the array's NMR performance on the basis of the expected signal to noise of an NMR experiment and mass of the array, an array performance parameter $f_m(r)$ may be used (Raich 2004):

$$f_\omega(r) = \frac{(\gamma \overline{B}_z(r))^{\frac{7}{4}}}{\Delta B_z(r) A} \qquad 8$$

Where $\overline{B}_z(r)$ is the average magnetic field inside a circle of radius *r*; $\Delta B_z(r)$ is the variation in magnetic field strength over the same area and A is the total area occupied by all of the magnets in the sub-array. The presence of A in the denominator tends to optimise for the lowest mass array design.

By adding more magnets to the sub-array, one observes an asymptotic behaviour in $f_m(r)$ for large numbers of magnets (~80), and a global maximum for four magnets. Whilst a four-magnet array may be the theoretically optimum design, the mass of such a system is somewhat prohibitive. By contrast, the cumulative errors associated with producing the very large numbers of small magnets required to see the asymptotic behaviour would mean that such behaviour would be unlikely to be physically observed. For this reason, building the sub-arrays using sixteen magnets represents a good trade off between optimal homogeneity and practicality.

Referring to the array shown in Figure 3, it is possible to find a one sub-array geometry that produces a second derivative of the magnetic field equal to zero in the z-direction alone. The second derivative is set to zero by using the root finding algorithm described earlier to iterate the radius of the array.

It is possible that the algorithm results in non-realisable geometries since the radius at which the second derivative is at zero may be infinite as a result of non-convergence of the optimisation algorithm, or may specify an array geometry that results in overlap of adjacent magnets, which is clearly unrealisable. Ideally the geometry will have a close packed configuration, such as shown in Figure 3, where the component magnets will almost be touching one another as this will generate the strongest possible magnetic field.

Both the preferred method optimisation algorithms discussed previously work by making perturbations to some initial Halbach array geometry. The success of the algorithm in producing a desirable and realisable array geometry following the optimisation process is consequently dependent on the quality of the initial array geometry. Thus, for a particular initial geometry, it may be impossible for the optimisation process to converge on a solution that has the desired magnetic field properties. Equally, the solution that emerges following the optimisation process may, for example, have so small a magnetic field strength as to be unusable for NMR experiments.

By way of illustration, when using a root-finding optimisation algorithm to set the second derivatives of B_z equal to zero in the x, y and z-directions, failure to set the length and width of the component magnets to be the same in the initial geometry often results in non-convergence of the optimisation process. Equally, an initial geometry with a radius that is substantially greater than the radius at which the close packed condition occurs may result in a solution that has a very small magnetic field strength.

Figure 4 shows a good quality magnetic field profile from a Halbach array such as that shown in Figure 3. This example array has had only the second derivative of B_z in the z-direction set to zero. The profile shows contour lines indicative of the variation in magnetic field strength at distances along the x and $z-$ axes within the Halbach array. For instance, the 0.01% contour line delineates the area in which the magnetic field strength varies by 0.01% at most. As visible in the profile, the effect of having set the second derivative equal to zero in the z-direction is that the dimension of the 0.01% contour line is larger in the z-direction than in the x-direction where no optimisation has taken place.

The Preferred Forms of the Halbach Array

The applicants have invented modified Halbach arrays that offer significantly improved homogeneity. That is achieved by arranging the sub-arrays within the array with particular spacings. Generally, the magnets within the sub-arrays will be arranged so as to produce a dipolar magnetic field according to equation 1. It will be appreciated that if desired for particular applications, the principle of the present invention could be used to create higher order magnetic fields; for example, a quadrapolar magnetic field may be envisioned. This higher order field may be achieved by varying the arrangement of the magnets in the sub-arrays according to equation 1.

In a first preferred form such as that shown in Figure 5, improved homogeneity is achieved by separating the sub-arrays that are disposed at or toward the centre of the magnetic assembly. Correct selection of that separation results in second order derivatives of the principal component of the magnetic field in an area within the assembly being substantially zero in each of the three orthogonal directions.

Further preferred forms are shown in Figures 7 and 12. In those preferred forms, the sub-arrays that are disposed at or toward the centre of the assembly are again provided with a separation such that second order derivatives of the principal component of the magnetic field in an area within the assembly are substantially zero in each of the three orthogonal directions. In addition, separations are provided between other sub-arrays in the assembly, with those separations disposed in such a way as to minimise fourth order derivatives of the principal component of magnetic field.

A modified Halbach array in accordance with the first preferred form of the present invention is shown in Figure 5. The Halbach array, indicated generally as 50, has two sub-arrays 51. Each sub-array 51 comprises a number of permanent magnets 52 arranged in an annular array about a longitudinal axis, *L*. As before, sixteen permanent magnets 52 are preferably provided in each sub-array 51.

The Halbach array in the preferred form is provided with a separation 53 between the two sub-arrays 51. With this design, the second derivative of the principal component of magnetic field generated by the array is substantially zero in each of the three orthogonal directions.

To find a sub-array geometry that produces a second derivative of the magnetic field equal to zero in all of the x, y and z-directions, a root finding or minimisation algorithm as previously described may be used. Using the root finding technique to iterate the array radius and separation between the pair of sub-arrays disposed at or towards the centre of the array, the second derivatives in the z and y – directions may be set to zero.

Preferably, an optimal separation for the two sub-arrays that are disposed at or toward the centre of the assembly is determined using an optimisation technique, and preferably a root finding technique. Preferably, an optimal radius for the two sub-arrays that are disposed at or toward the centre of the assembly is determined using an optimisation technique, and preferably a root finding technique such as by using a Newton-Rhapson root-finding algorithm. Preferably, an optimal separation between each of the sub-arrays other than said two sub-arrays that are disposed at or toward the centre of the assembly is determined using an optimisation technique, and preferably by minimising a figure of merit that describes the performance of the assembly. Preferably, an optimal longitudinal dimension for each of the sub-arrays is determined using an optimisation technique, and preferably by minimising a figure of merit that describes the performance of the assembly such as by using a Nelder-Mead minimisation algorithm.

The optimisation techniques are preferably carried out on a computer programmed with optimisation algorithms.

In the case of the minimisation algorithm, the longitudinal dimension of each of the sub-arrays, the separations between each of the coupled sub-arrays and the radius are iterated such that the second derivatives in the z and y – directions may be set to zero, whilst the fourth derivatives in the x, y and z-directions are additionally minimised. Under both

optimisation schemes, the length and width of the magnets are preferably identical to ensure the optimisation algorithm converges on a realisable Halbach array geometry.

Preferably, the required separation to set the second derivative of the magnetic field equal to zero along the y- axis of the array is less than the radius of the array. The separation may be smaller than 1 mm for certain geometries. By separating the Halbach array into two sub-arrays and by so doing setting the second derivatives of the magnetic field to be zero in both the z and y-directions, equation 6 shows that the second derivative in the x-direction will additionally be set to zero. The resulting array geometry will have a maximally flat magnetic field to second order in each of the three orthogonal directions, which in turn results in a homogeneous magnetic field.

Figure 6 shows the magnetic field profile of the array of Figure 5. In comparison with the profile in Figure 4, the contour lines shown in Figure 6 show a substantial increase in the size of the area that has better than 0.01% variation in the magnetic field strength. The main increase in the dimension of the 0.01 % contour line has been in the x-direction. A similar increase in the size of the homogeneous region can be seen in the z - y plane when compared to the field produced by a one sub-array design.

It is possible to implement a range of separations for which there exists a second order Halbach array. Figures 9a and 9b show how the parameters of length of magnet and radius of the array vary as the separation is varied. Figures 9c and 9d show how the array quality factors of magnetic field strength B_z and the area of the homogenous region of the array vary as the separation is varied. Referring to Figure 9d, there are clear improvements in the size of the homogeneous region to be obtained from a solution that has a larger separation. This gain is traded against slightly reduced magnetic field strength, as shown in Figure 9c, and a physically larger, and consequently heavier, array.

Robustness Considerations

In addition to the design characteristics of the preferred form Halbach array, it is also important for the expected magnetic field to be robust, given the manufacturing errors

associated with each of the design parameters. Since the homogeneity of the field depends on the value of the second derivative along each axis, the value of the second derivative forms an appropriate measure of the robustness of any proposed design for the present invention.

The robustness of each of the Halbach array geometries in Figures 9a to 9d was calculated using a Monte-Carlo simulation. The purpose of the Monte-Carlo simulation was to investigate how the second derivative of magnetic field varied if the Halbach array were created from non-ideal magnets, arranged in a non-ideal geometry. By finding the expected value and standard deviation of the distribution of the second derivative, it is possible to anticipate how close a realised Halbach array might be compared to the designed version.

Any time a design is realised, there will be manufacturing errors associated with each of the parameters that have been used to define the design. In fact, if a very large number of such designs are realised, the actual values of the defining parameters will follow a normal distribution with a mean value equal to the value of the design parameters. This observation allows a realistic simulation of the expected variation in the design parameters, and hence the value of the second derivative of the magnetic field produced.

The Monte-Carlo simulation therefore perturbs each of the defining parameters of one particular Halbach array geometry by some random, normally weighted amount, and calculates the resulting sum of the second derivatives of the magnetic field in the x, y and z-directions. This process is repeated for 10,000 trials. The mean and standard deviation of the calculated second derivatives from all of the trials is subsequently calculated.

A realistic Monte-Carlo simulation of this nature is reliant upon good estimation of the errors associated with the manufacturing process of the array. The manufacturing errors associated with the magnets themselves can be taken from the supplier's specification (Macmill International, Ningbo, China). For the N42 grade of Neodymium rare-earth magnets that have been used to construct the array, the manufacturer gives a value of B_r between 1.29 and 1.35 T. The mean value of B_r can therefore be taken to be 1.32 T.

Assuming the range of B_r quoted by the manufacturer approximately represents the 95% confidence interval of B_r, the standard deviation of B_r is therefore 0.015 T.

The manufacturers of the magnets again specify that the dimensional tolerances of their magnets as being ± 0.1mm. Again, assuming that this represents approximately the 95% confidence interval for the magnet dimensions, it can be presumed that the standard deviation of a particular magnet dimension is 0.05 mm.

The errors associated with the positioning of the magnets were estimated from standard engineering tolerances for machining. Using the same assumptions about the means of obtaining the errors, the standard deviation of the radius of the array and separation of each of the sub-arrays was set to be 0.1 mm. Finally, the standard deviation of the error in the angles θ and φ was estimated to be 1°.

The results from the simulations using these error distributions are shown in Figure 10. As visible in the figure, the reduction in standard deviation with increasing separation indicates that there is an improvement in the robustness of the geometry with increasing separation.

It is possible to further increase the robustness of a geometry by increasing the number of sub-arrays in the geometry. In the example described above, two sub-arrays with a separation between the two were used. As noted earlier, a first preferred form of the present invention homogenous to second order has some separation between the central sub-arrays. It is preferred, therefore, that the number of sub-arrays is even.

A modified Halbach array in accordance with a second preferred form of the present invention is shown in Figure 7. The Halbach array 150, has eight sub-arrays 151a-151h. Again each sub-array 151a-151h comprises a number of permanent magnets 152 arranged in an annular array about a longitudinal axis. As before, sixteen permanent magnets 152 are preferably provided in each sub-array 151a-151h.

In addition to the separation 153d provided between the central sub-arrays 151d and 151e, spacings are provided between at least some of, and preferably all of, the other sub-arrays

in the apparatus. The spacings can be chosen to minimise fourth order derivatives of the principal component of the magnetic field. As can be seen, the lengths of the magnets (in the y-dimension) vary along the array.

The following table outlines the parameters for the array shown in Figure 7. It will be appreciated that these parameters are one example only, and they can be modified while still providing a second derivative of B_z equal to zero in the x-dimension, as well as minimising the fourth derivative. In the form shown, the magnets have a width and length of 23 mm.

Parameter (all in y-dimension)	**Size (mm)**
Height of magnet 151a	33.8
Separation 153a	0.75
Height of magnet 151b	49.7
Separation 153b	0.82
Height of magnet 151c	49.9
Separation 153c	3.24
Height of magnet 151d	26.4
Separation 153d	0.73
Height of magnet 151e	26.4
Separation 153e	3.24
Height of magnet 151f	49.9
Separation 153f	0.82
Height of magnet 151g	49.7
Separation 153g	0.75
Height of magnet 151h	33.8

Contrasting Figure 6 with Figure 8, in the magnetic field resulting from the second preferred form of the present invention shown in Figure 7, the increase in both the x and z-dimensions of the 0.01% contour line are apparent as a result of having additionally minimised the values of the fourth derivatives of B_z as well as having set the second derivative of B_z equal to zero in the x-dimension.

Figure 12 shows a similar arrangement in which spacings 213a-253i are provided between all sub-arrays 251a-251g however there are ten sub-arrays and the lengths of the magnets in the y-dimension are substantially equal.

In that third preferred form, the Halbach array is provided with ten sub-arrays and a centre separation of 7 mm. The size of the homogeneous region, the robustness and the strength of the magnetic field of the array has been found to be reasonably well improved in this preferred form. The layout of the permanent magnets and sub-arrays in the third preferred form is shown in Figure 12, and the profile of the magnetic field generated by the third preferred form is shown in Figure 13.

For Halbach arrays comprising four, six, eight, ten and twelve sub arrays, robustness calculations were performed as for the two sub-array example. The gap between sub-arrays that did not form the central pair was held constant at 6×10^{-4} m. The overall length of the array was additionally held constant at 0.25 m. The results from these arrays are shown in Figures 11a to 11f.

Figure 11a shows the length of component magnets and Figure 11b shows the radius of the array required to achieve homogeneity to second order for different separations. Figure 11c shows the magnetic field strength at centre of array, while Figures 11d and 11e show the area of the magnetic field with a variation of less than 0.01%.

Figure 11f shows the standard deviation of second order derivatives for 10,000 sample Monte-Carlo simulation. This figure indicates that there are gains to be made in robustness by using more than two sub-arrays, as indicated by the drop in standard deviation with an increasing number of sub-arrays. Advantageously, Figure 11c shows that the gain in robustness does not significantly reduce the magnetic field strength of the array. Furthermore, Figures 11d and 11e show that the homogeneity of the magnetic field is not affected by increasing the robustness.

It should be noted that there could be an uneven number of sub-arrays, such as five, seven, nine, or more sub-arrays for example. In such a configuration, the separation is provided

between two of the sub-arrays that are generally centrally disposed within the assembly. For example, in an assembly having seven sub-arrays, the separation is suitably provided between the third and fourth arrays. For an assembly having an odd number of sub-arrays less than seven, it may be necessary to make the sub-arrays an uneven size to position the separation generally centrally within the assembly. However, for an assembly having an odd number of sub-arrays of seven or more, satisfactory results can be achieved with even sized sub-arrays.

Perhaps the only disadvantage in increasing the robustness of the array is the requirement for a larger array radius. Increasing the radius means that the component magnets must be physically larger to create the same amount of magnetic field. This has the undesirable result of increasing the size and weight of the array.

Construction of the Preferred Form Halbach Arrays

Construction of a Halbach array represents a number of engineering challenges. The crux of these challenges is to ensure that the array is safe to use, while ensuring the manufacturing errors are similar to, or ideally less than, those used in the Monte-Carlo simulation. The amount of force exerted by the component magnets in a Halbach array is substantial. The orientation of the magnets inside a sub-array is such that the magnets will be urged to twist around to reduce the magnetic force being exerted on them by neighbouring magnets. This sets up large forces internal to the sub-array. What is more, once manufactured, a sub-array has a net magnetisation that extends along its longitudinal axis. Thus, when putting the array itself together, the sub-arrays are trying to repel one another.

Once finally assembled, the array must be not only be sufficiently strong to resist the torque exerted by the magnets trying to twist from their position in individual sub-arrays but also be able to resist the magnetic repulsion that seeks to push the individual sub-arrays apart.

Referring to Figure 14a, a sub-array housing or former 130 is preferably used to house the magnets in the y-direction of the array, while leaving the ends of magnets exposed. The former 130 comprises a ring within which apertures 131 are located such that the placement of the permanent magnets in the apertures 131 results in an arrangement of permanent magnets in an annular array about a longitudinal axis. A former housing permanent magnets in accordance with the preferred form of the invention is shown in Figure 14b.

A generous amount of former material is provided both on the inside and outside of the sub-array former to provide necessary strength. In a preferred form, the sub-arrays are open-ended. In this form, it is possible to use laser cutting to produce the formers. A laser cutter is capable of a positional accuracy of ± 0.02 mm compared with ± 0.2 mm for more conventional machining techniques.

In addition, the amount of time it takes to produce one former using a laser cutter is approximately one hour, compared with approximately five hours for conventional machining techniques. The ability to use laser cutters therefore greatly reduces the machining time required to produce the formers to build the array, while increasing the precision to which the sub-arrays can be constructed.

Preferably, polymethyl methacrylate (acrylic) is chosen for manufacturing the sub-array formers. This material is cost-effective, readily available, sufficiently strong and easily cut with a laser cutter. Of course the use of acrylic is non-limiting and any other suitable material may be used instead.

The acrylic formers may be reinforced and coupled by running polyoxymethylene (acetyl) rods through the length of the array. These will contribute to the strength of the array by acting as strain relief within the sub-array formers by assisting in resisting the torque force exerted by the magnets. In addition to acting as reinforcement to the sub-arrays, the rods can be threaded at either end and then used to hold the array itself together. The rods can be formed from any suitable material.

The preferred form configuration of the improved Halbach array is based on a preferred manufacturing technique. Since it is relatively easy to make sub-arrays that are 24 mm thick due to the ready availability of 8mm acrylic sheet, the component magnets were chosen to have this longitudinal dimension. Since the overall longitudinal dimension of the array, the number of sub-arrays and separation of the central pair of sub-arrays have all been chosen, it is possible to create an array with the required homogeneity by entering the geometry represented by these values into the root-finding program.

The preferred form geometry (shown in the embodiment of Figure 12) resulting from consideration of construction techniques is shown below:

- Number of sub-arrays: 10
- Magnets per sub-array: 16
- Array radius: 95.1 mm
- Central separation: 7 mm
- Magnet dimensions: 30 x 30 x 24 mm
- Spacing between other sub-arrays: 0.6 mm

Figure 15 shows an assembly apparatus being used to bring together a new sub-array 140 onto the stack of sub-arrays 141. The figure also shows aluminium spacers 143 that are used to retain the magnets in the sub-arrays while the new sub-array is being lowered down. Acetyl rods 144 as described earlier are provided in the array to afford alignment and strength to the assembly. The rods 144 extend through holes provided on a top plate 145 and a bottom plate 146.

Figure 16 shows in further detail the top plate 150 and the wing nuts 151 that are used to push the new sub-array onto the stack of sub-arrays.

Once five sub-arrays are put together, it is removed from the assembly apparatus. This will form the first half of the preferred form Halbach array. Figure 17 shows the first half of the array 160 having five sub-arrays. The first half 160 includes a cover 161 on one side and a spacer 162 on the other side to retain the permanent magnets in the array while the

other half of the array is constructed. The other half of the array is also built using the assembly apparatus.

Once both halves are assembled, referring to Figure 18, the halves 170 and 171 are brought together. An aluminium spacer 172 is preferably used to ensure accurate separation of the two halves of the array. The array is preferably held together with appropriately threaded acetyl rods. Figure 19 shows the completed preferred form array.

The foregoing describes preferred forms of the invention. Modifications can be made thereto without departing from the scope of the invention as defined by the appended claims.

For instance, depending on the application, the placement of the permanent magnets in the sub-array may be modified. The following are non-limiting aspects of the preferred form Halbach array that may also be altered: the number of magnets, the number of sub-arrays, separation, radius, and magnet dimensions.

Further, while the preferred forms only show the separation of the sub-arrays as an air gap, it is envisaged that a separating material may be provided instead, as long as the material is at least substantially non-magnetic.

Further modifications are outlined in the "Summary of the Invention" section of the specification.

A preferred form apparatus is preferably suitable for use in NMR applications, including bench top testing of magnetic materials using magnetic fields. Field cycling NMR is an example of such an application.

A preferred form NMR apparatus will typically include other items as well as the magnetic assembly, such as a radio frequency transceiver coil, a radio frequency amplifier, a spectrometer, and possibly a computer to control the spectrometer, for example.

References:

Halbach, K. (1979). "Design of permanent multipole magnets with orientated rare earth colbalt material." Nuclear Instruments and Methods 169: 1-10.

Raich, H. B., P (2004). "Design and construction of a dipolar Halbach array with a homogeneous field from bar magnets: NMR Mandhalas." Concepts in magnetic resonance part B - Magnetic resonance engineering 23B(1): 16-25.

CLAIMS:

1. An apparatus for generating a homogenous magnetic field, comprising an assembly having a plurality of sub-arrays, each sub-array comprising a plurality of permanent magnets disposed in an annular array about an axis (hereafter "longitudinal axis"), wherein a separation is provided between two of the sub-arrays that are disposed at or toward the centre of the assembly along the longitudinal axis such that second order derivatives of the principal component of the magnetic field in an area within the assembly are substantially zero in three orthogonal directions.

2. An apparatus as claimed in claim 1, wherein the assembly has only two sub-arrays.

3. An apparatus as claimed in claim 1, wherein the assembly has more than two sub-arrays.

4. An apparatus as claimed in claim 3, wherein the assembly has an even number of sub-arrays, and said separation is provided between the two central sub-arrays.

5. An apparatus as claimed in claim 3, wherein the assembly has an odd number of sub-arrays, and said separation is provided between two of the sub-arrays that are generally centrally disposed within the assembly.

6. An apparatus as claimed in 5, wherein the apparatus has less than seven sub-arrays and at least some of the sub-arrays have different sizes such that the separation is positioned generally centrally within the assembly.

7. An apparatus as claimed in claim 5, wherein the assembly has an odd number of sub-arrays of seven or more, and the sub-arrays have a substantially consistent size.

8. An apparatus as claimed in any one of claims 1 to 7, wherein separations are provided between at least some of the sub-arrays, with the separations disposed in such a way as to minimise fourth order derivatives of the principal component of magnetic field.

9. An apparatus as claimed in any one of claims 1 to 8, wherein the longitudinal dimension of each of the sub-arrays disposed in the assembly is arranged so as to minimise fourth order derivatives terms of the principal component of the magnetic field.

10. An apparatus as claimed in any one of claims 1 to 9, wherein the separation(s) is/are occupied by air, another gas, or a vacuum.

11. An apparatus as claimed in any one of claims 1 to 9, wherein the separation(s) is/are occupied by a substantially non-magnetic material.

12. An apparatus as claimed in any one of claims 1 to 11, wherein the size(s) of the separation(s) is/are less than the radius of the annular array of the permanent magnets.

13. An apparatus as claimed in any one of claims 1 to 12, wherein each sub-array has at least four permanent magnets.

14. An apparatus as claimed in any one of claims 1 to 13, wherein all of the permanent magnets in a sub-array have substantially the same length and width.

15. An apparatus as claimed in claim 14, wherein all of the permanent magnets in the assembly have substantially the same length and width.

16. An apparatus as claimed in any one of claims 1 to15, wherein each sub-array comprises an annular plate having disposed thereon or therein the plurality of permanent magnets.

17. An NMR apparatus comprising an apparatus as claimed in any one of claims 1 to 16 arranged to create a zone of homogeneous magnetic field at some location within the assembly, and into a sample when provided.

18. A method of generating a homogenous magnetic field using an assembly comprising a plurality of sub-arrays, each sub-array comprising a plurality of permanent

magnets disposed in an annular array about an axis (hereafter 'longitudinal axis'), the method comprising the steps of:

arranging two sub-arrays that are disposed at or toward the centre of the assembly adjacent one another and along the longitudinal axis; and

providing a separation between the two sub-arrays that are disposed at or toward the centre of the assembly, such that second order derivatives of the principal component of the magnetic field in an area in the assembly are substantially zero in three orthogonal directions.

19. A method as claimed in claim 18, wherein the assembly has only two sub-arrays.

20. A method as claimed in claim 18, further comprising arranging one or more further sub-arrays adjacent each of said two sub-arrays that are disposed at or toward the centre of the assembly such that the magnetic assembly has more than two sub-arrays.

21. A method as claimed in any one of claims 18 to 20, further comprising determining an optimal separation for the two sub-arrays that are disposed at or toward the centre of the assembly using an optimisation technique.

22. A method as claimed in claim 21, wherein the optimisation technique is a root finding technique.

23. A method as claimed in any one of claims 18 to 22, further comprising determining an optimal radius for the two sub-arrays that are disposed at or toward the centre of the assembly using an optimisation technique.

24. A method as claimed in claim 23, wherein the optimisation technique is a root finding technique.

25. A method as claimed in claim 24, wherein the optimisation technique comprises using a Newton-Rhapson root-finding algorithm.

26. A method as claimed in any one of claims 21 to 25, further comprising determining an optimal separation between each of the sub-arrays other than said two sub-arrays that are disposed at or toward the centre of the assembly using an optimisation technique.

27. A method as claimed in claim 26, wherein the optimisation technique comprises minimising a figure of merit that describes the performance of the assembly.

28. A method as claimed in any one of claims 21 to 25, further comprising determining an optimal longitudinal dimension for each of the sub-arrays using an optimisation technique.

29. A method as claimed in claim 28, wherein the optimisation technique comprises minimising a figure of merit that describes the performance of the assembly.

30. A method as claimed in claim 28, wherein the optimisation technique comprises using a Nelder-Mead minimisation algorithm.

31. A method as claimed in any one of claims 21 to 30, wherein the optimisation technique(s) is/are carried out on a computer programmed with optimisation algorithm(s).

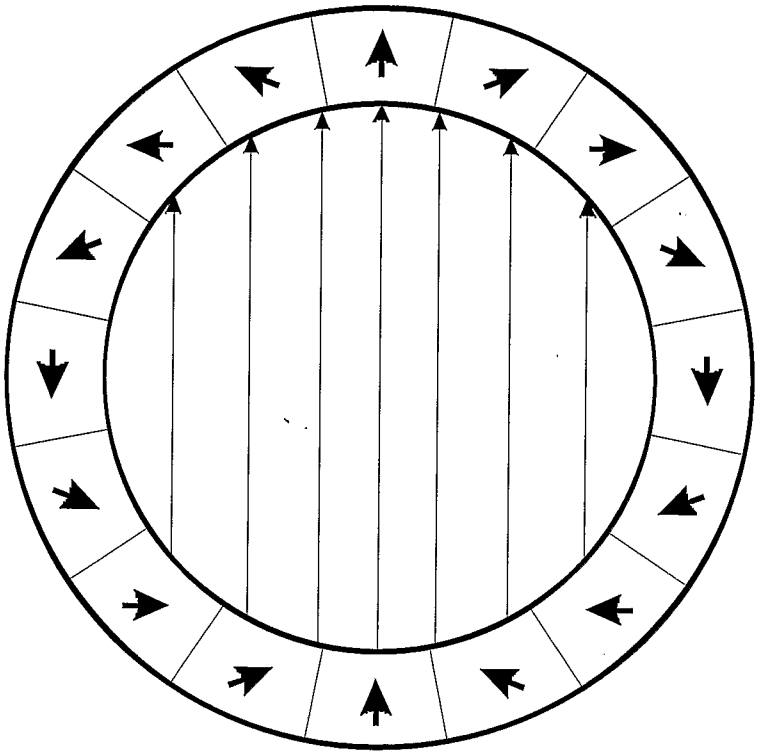


FIGURE 1

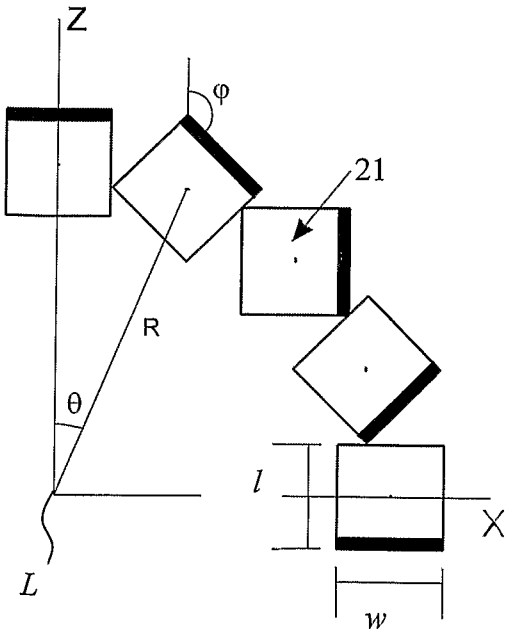


FIGURE 2a

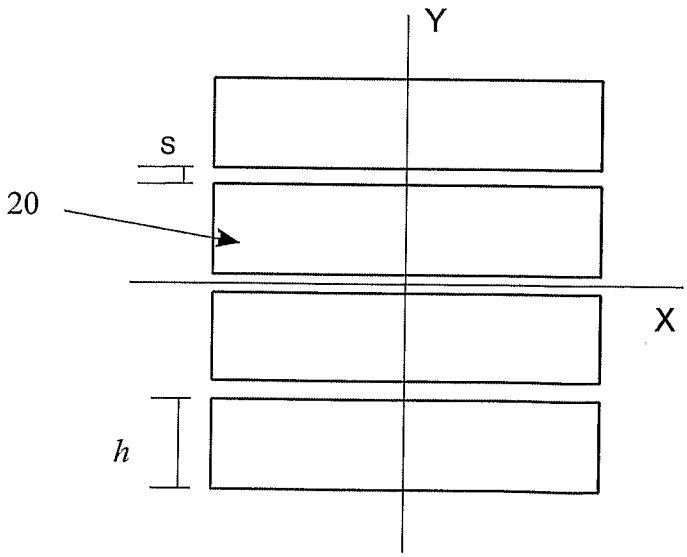


FIGURE 2b

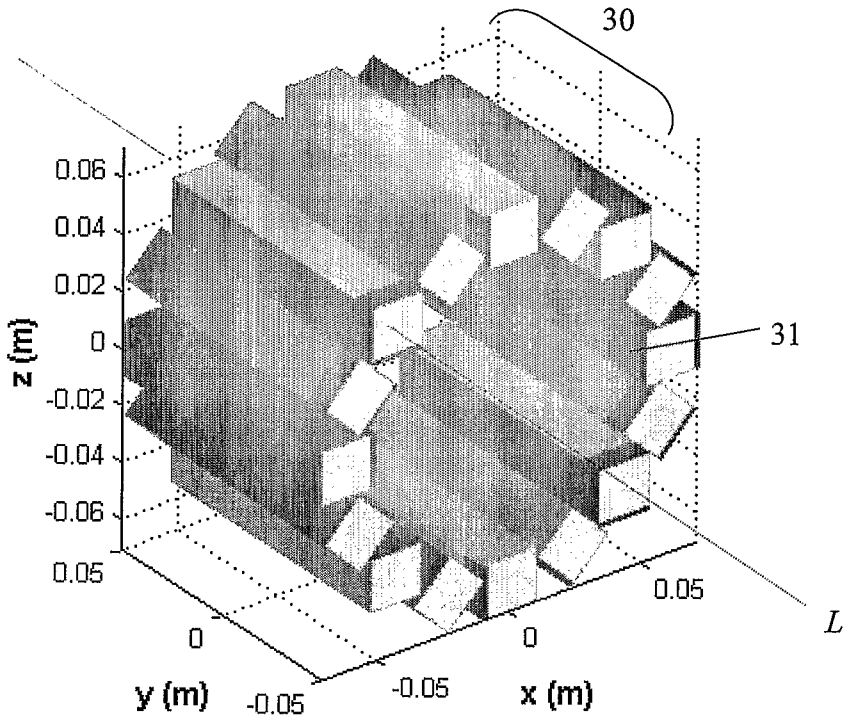


FIGURE 3

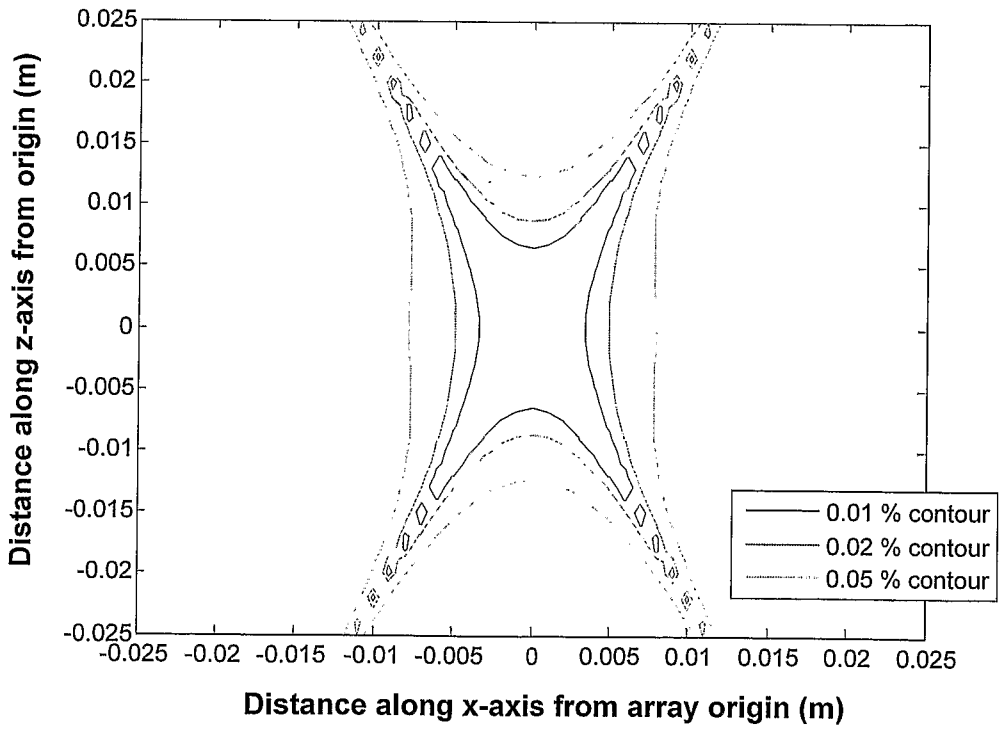


FIGURE 4

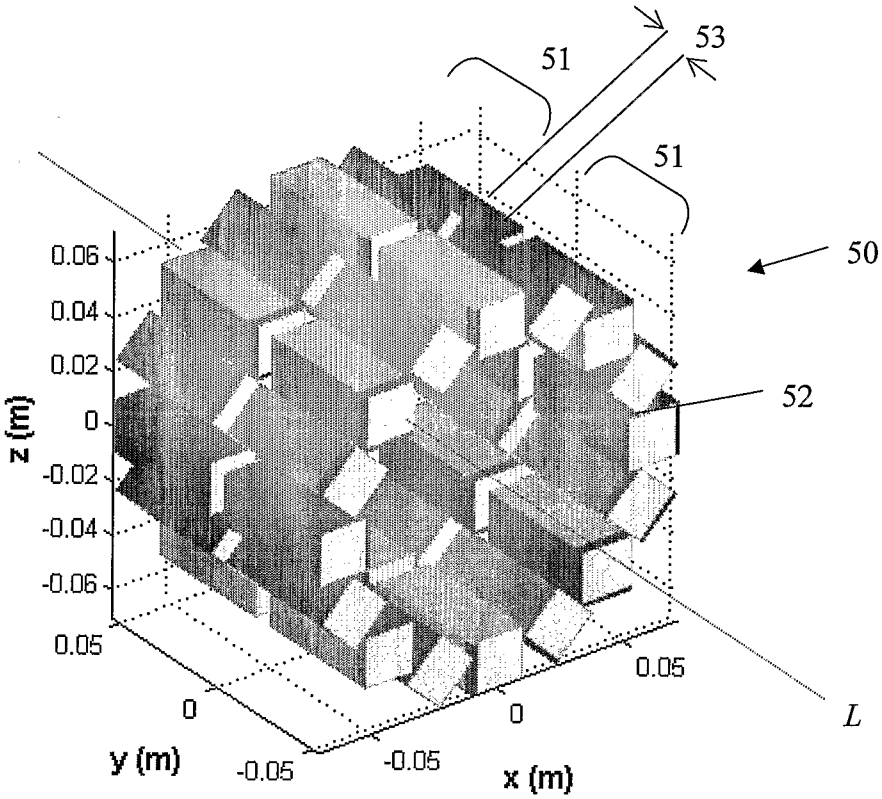


FIGURE 5

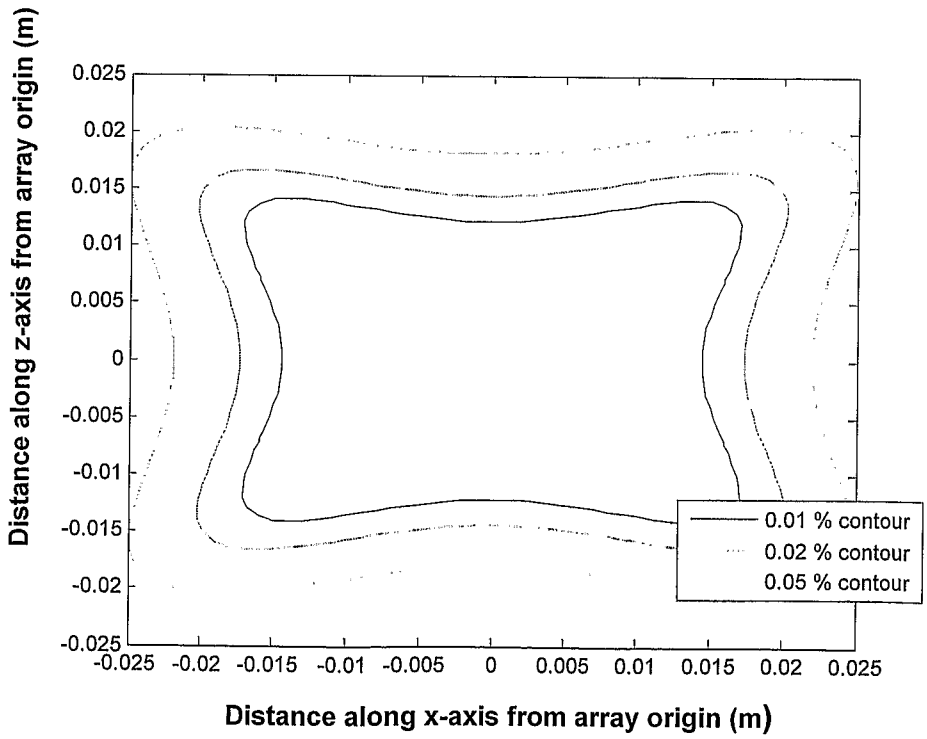


FIGURE 6

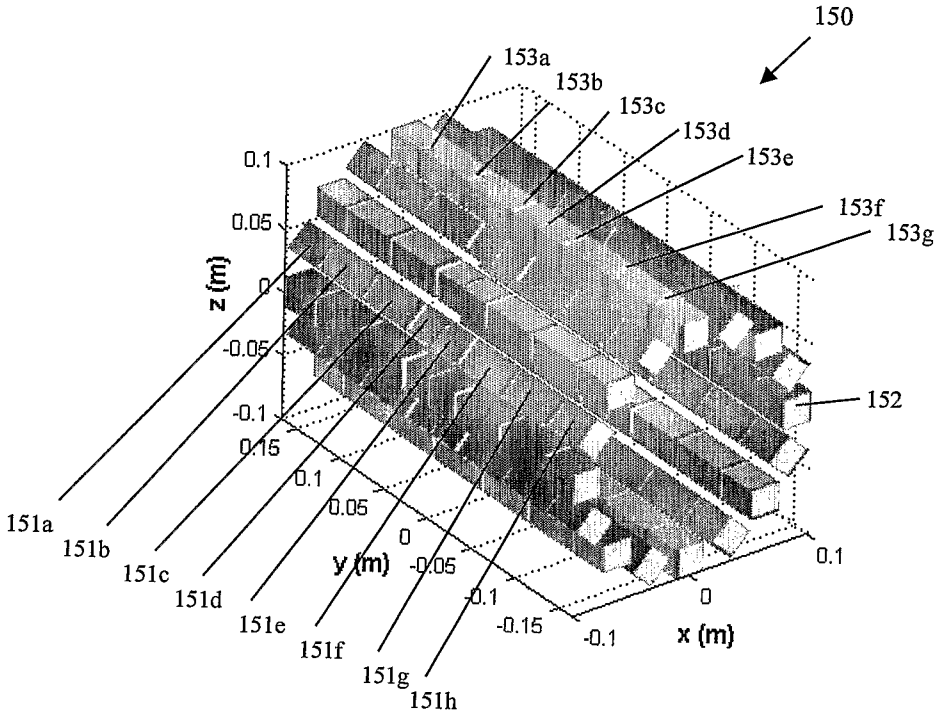


FIGURE 7

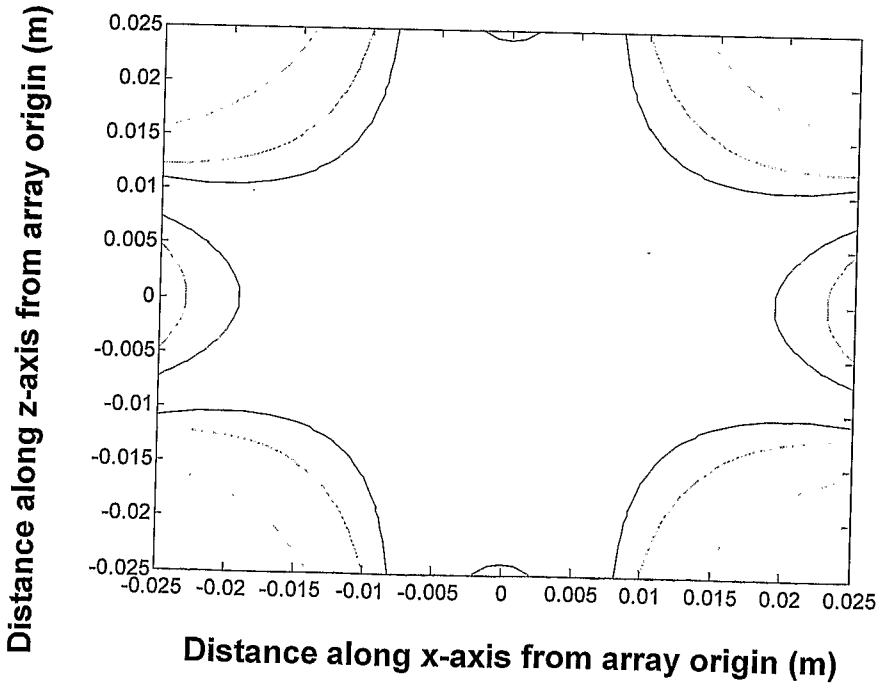


FIGURE 8

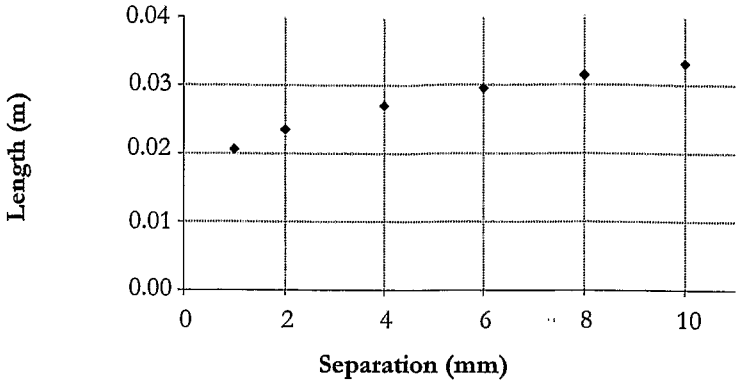


FIGURE 9a

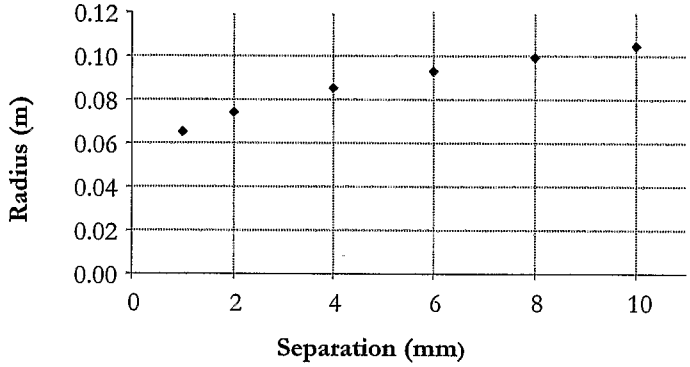


FIGURE 9b

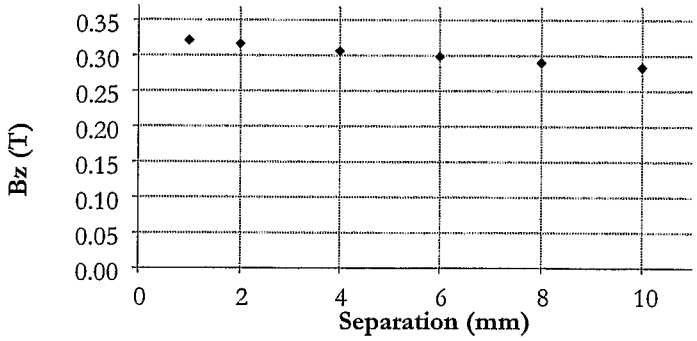


FIGURE 9c

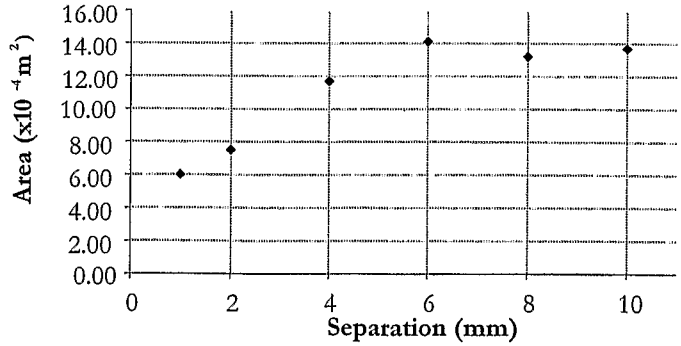


FIGURE 9d

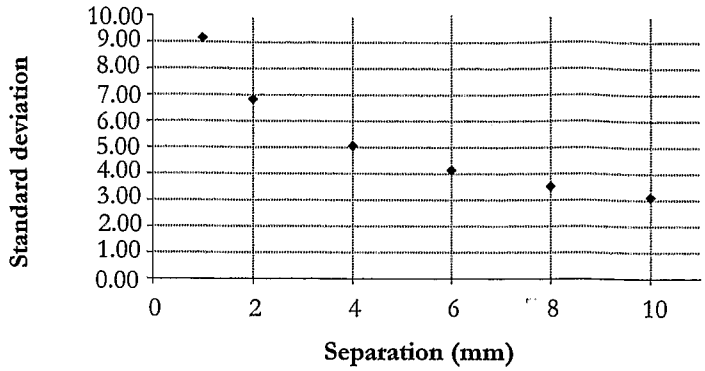


FIGURE 10

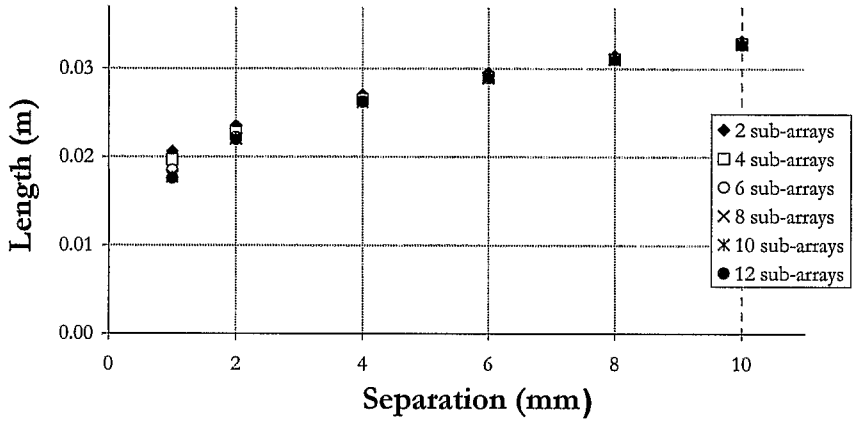


FIGURE 11a

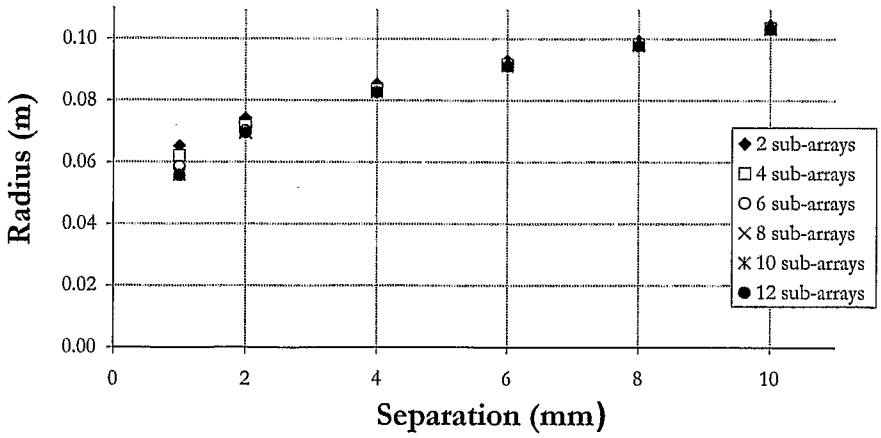


FIGURE 11b

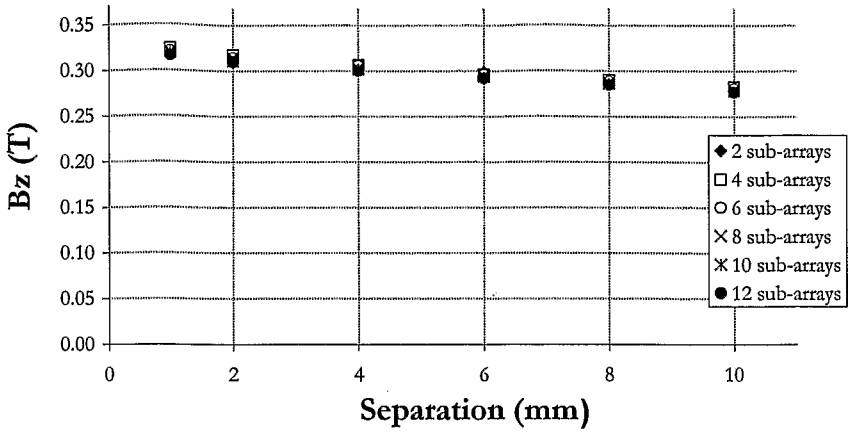


FIGURE 11c

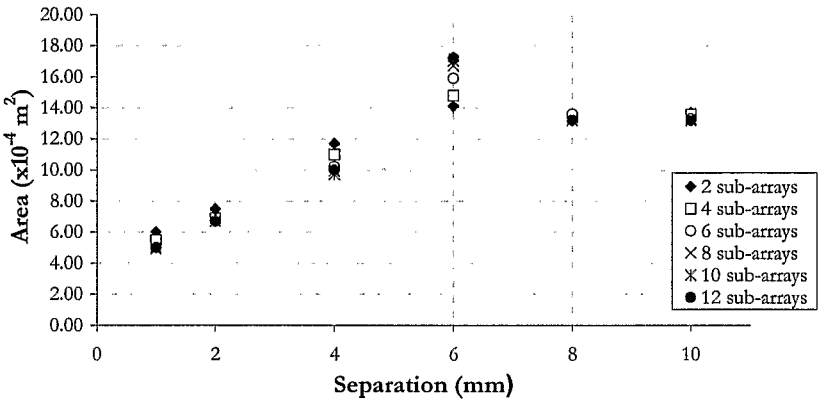


FIGURE 11d

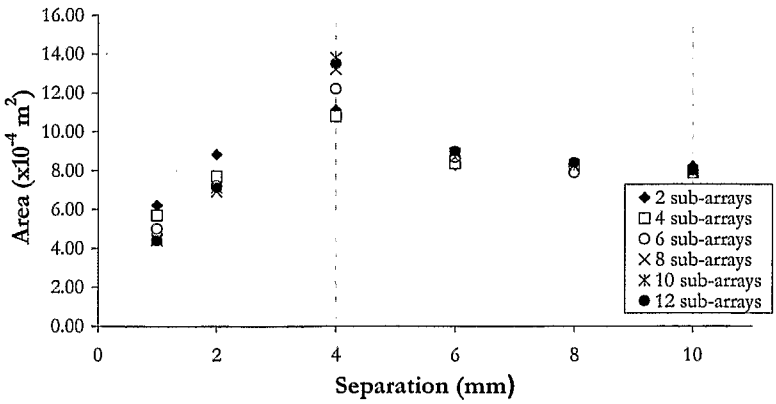


FIGURE 11e

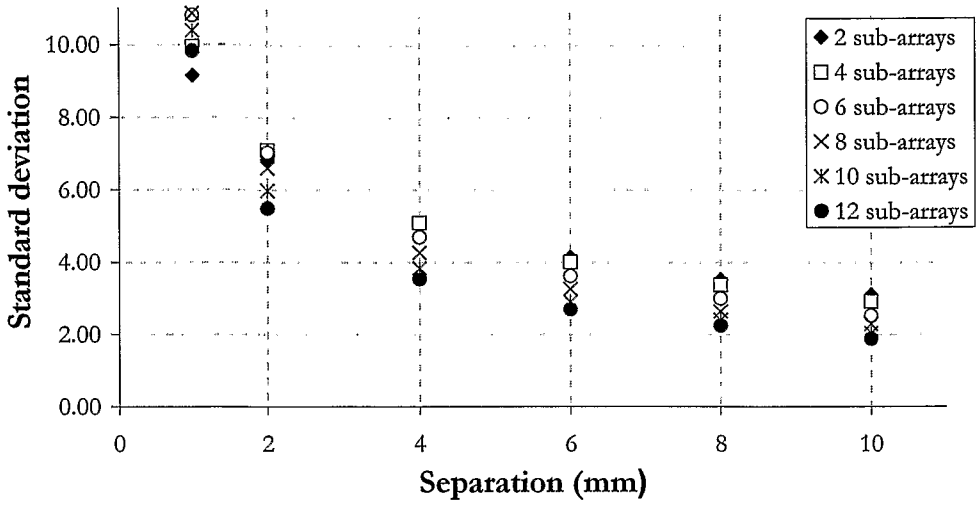


FIGURE 11f

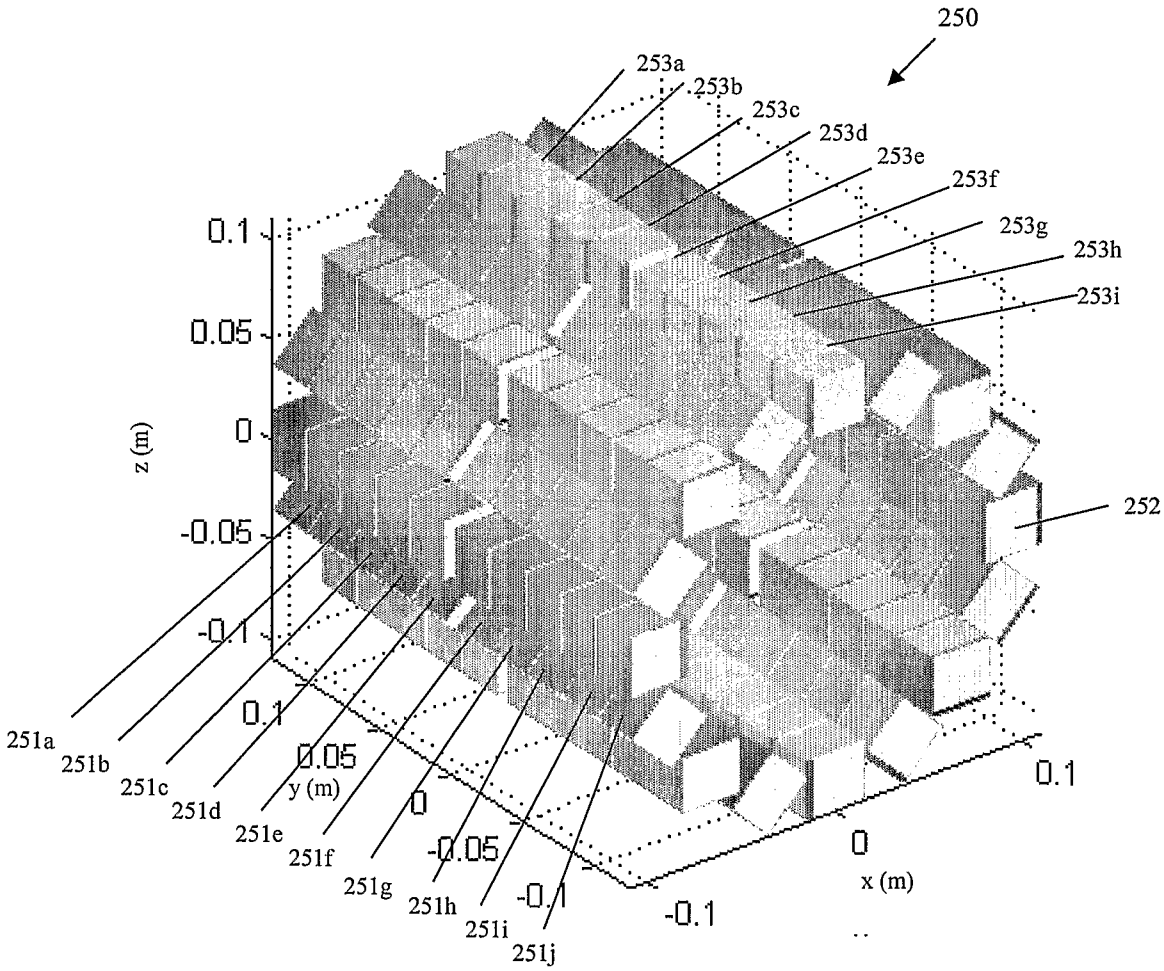


FIGURE 12

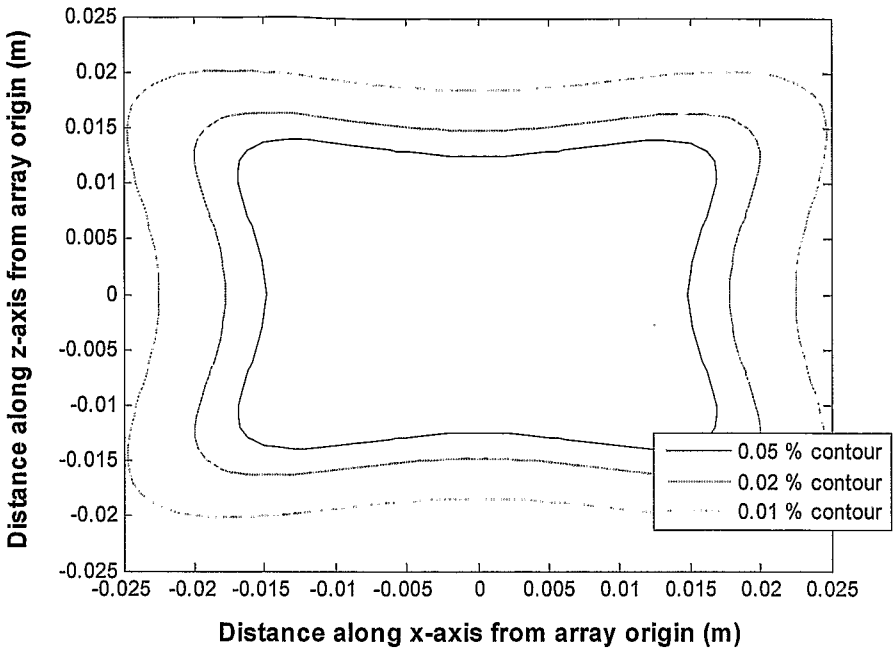

0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
Distance along z-axis from array origin (m)
-0.025 -0.02 -0.015 -0.01 -0.005 0 0.005 0.01 0.015 0.02 0.025
Distance along x-axis from array origin (m)
0.05 % contour
0.02 % contour
0.01 % contour

FIGURE 13

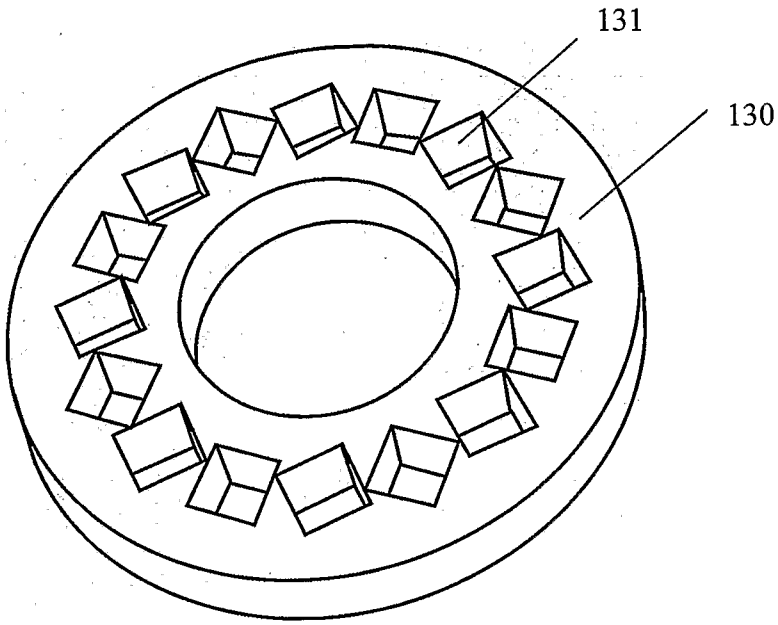


FIGURE 14a

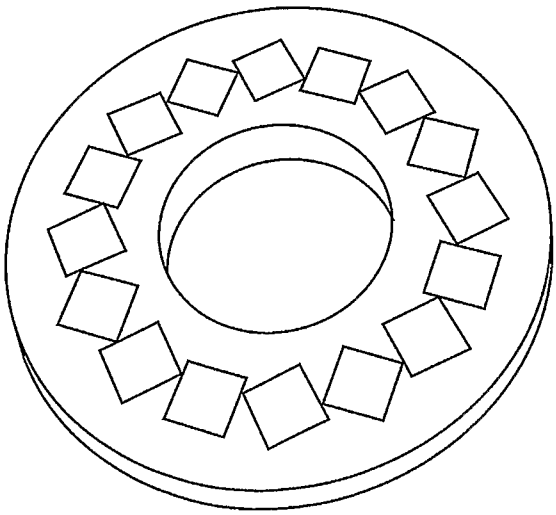


FIGURE 14b

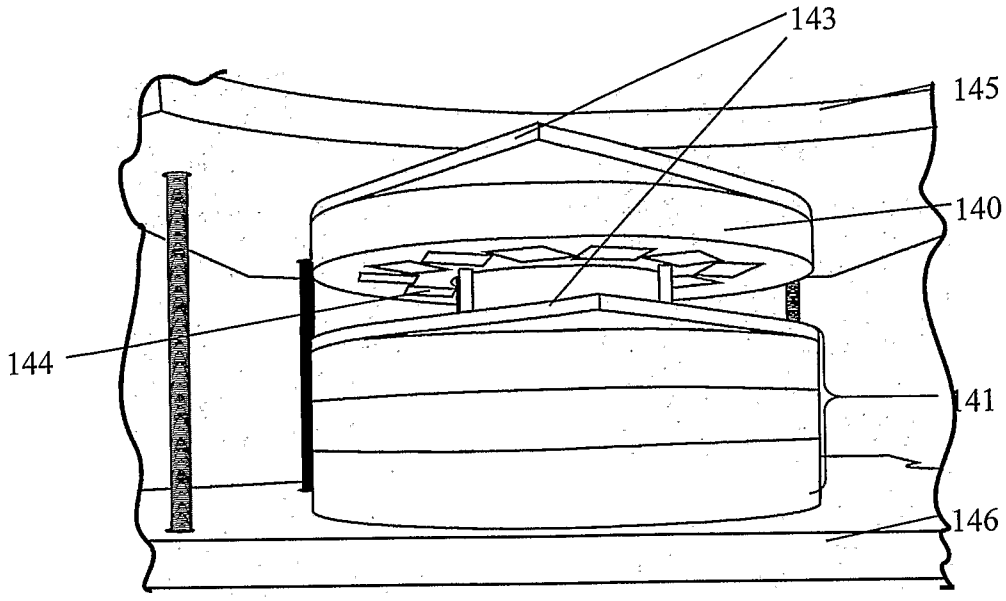


FIGURE 15

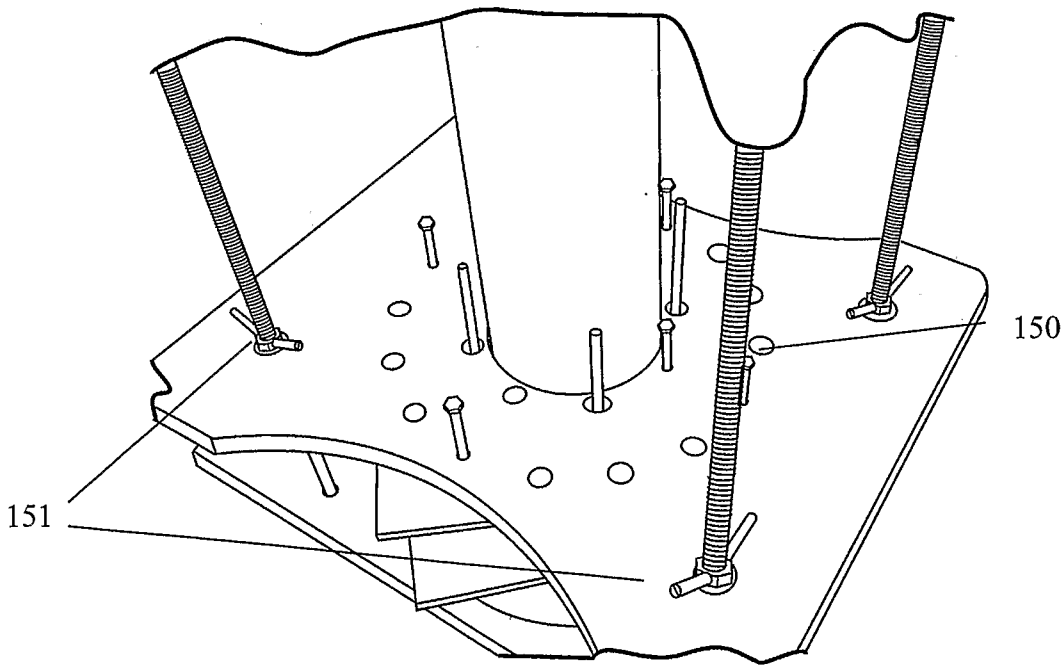


FIGURE 16

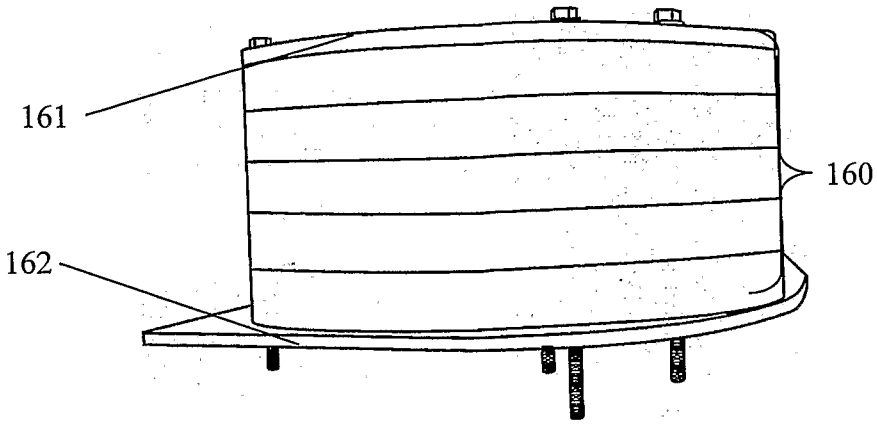


FIGURE 17

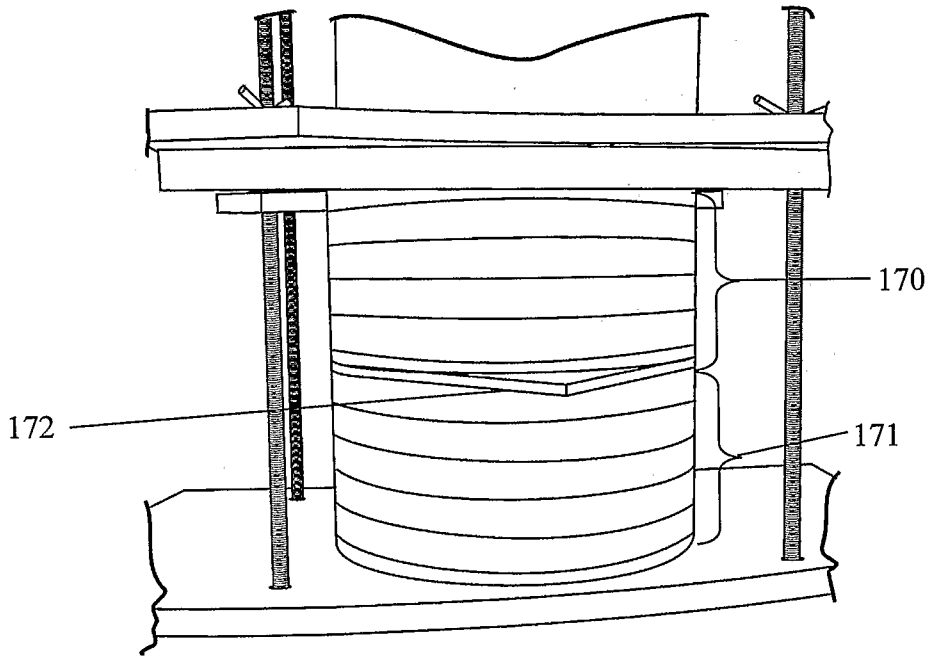


FIGURE 18

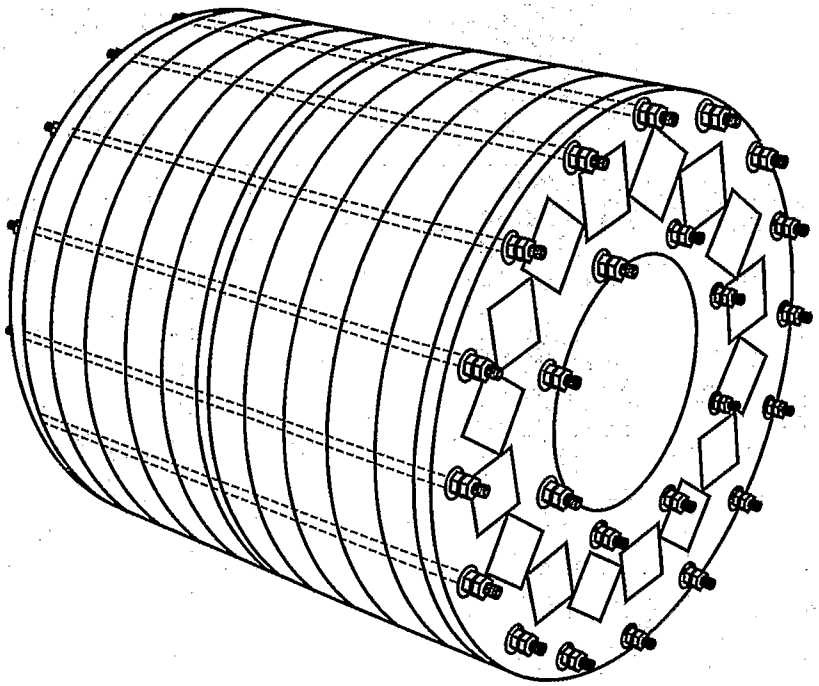


FIGURE 19

INTERNATIONAL SEARCH REPORT

International application No.
PCT/NZ2007/000082

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

H01F 7/02 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DWPI & keywords: Permanent Magnet, Homogenous, Annular, Sub-Array, Separate, Centre, Second Order Derivative, Zero, Orthogonal, Cartesian and similar terms; ESP@CE keywords: Magnet, Uniform, Second and Derivative; USPTO keywords: NMR, Permanent, Magnet, Second Order Derivative, Uniform and similar terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 717 876 A (MASI *et al*) 5 January 1988 column 4, line 46 – column 8, line 68; figures 1-3, 6, 7	1-31
A	US 2004/0140807 A1 (ABELE) 22 July 2004 See the whole document	1-31
A	US 2003/0011451 A1 (KATZNELSON *et al*) 16 January 2003 See the whole document	1-31

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 July 2007	31 JUL 2007
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	Authorized officer **Evan Sulcs** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : (02) 6283 2442

INTERNATIONAL SEARCH REPORT

International application No.
PCT/NZ2007/000082

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 748 063 A (CROW) 5 May 1998 See the whole document	1-31
A	US 5 739 687 A (HANLEY) 14 April 1998 See the whole document	1-31
A	US 5 495 222 A (ABELE *et al*) 27 February 1996 See the whole document	1-31
A	US 5 168 231 (AUBERT) 1 December 1992 See the whole document	1-31
A	EP 0 467 437 A1 (ESAOTE BIOMEDICA SpA) 22 January 1992 See the whole document	1-31
A	US 4 999 600 A (AUBERT) 12 March 1991 See the whole document	1-31
A	US 4 639 673 A (ZIJLSTRA) 27 January 1987 See the whole document	1-31

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/NZ2007/000082

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	4717876						
US	2004/0140807	EP	1462816	JP	2004283596	US	6707363
		US	6954070	US	6963200	US	2004/0135580
US	2003/0011451						
US	5748063	US	5642087	US	5717371	WO	1996/013045
US	5739687	EP	0774671	JP	9171068		
US	5495222	AU	20568/97	AU	23885/95	EP	0714521
		EP	0815471	EP	0883883	US	5475355
		US	5798680	WO	1995/028657	WO	1996/029614
		WO	1997/031381				
US	5168231	EP	0393092	FR	2623324	WO	1989/004494
EP	0467437	JP	5192309				
US	4999600	EP	0328537	FR	2605450	WO	1988/002923
US	4639673	EP	0171831	FI	852763	JP	61038452
		NL	8402249				

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX