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(54) Abstract Title

Iterative method for determining shim positioning in NMR apparatus

(57) An iterative method for placing shims to homogenise the magnetic field within the working volume of a magnetic resonance apparatus comprises subdividing the predetermined possible positions of the ferromagnetic shim elements into groups 1, 2, 3 which are characterised by their distance from the centre of the working volume. After the first iteration step, the shim elements in the most central group 1 are not changed. Then with each further iteration step, the elements in groups progressively further from the centre may also be fixed. This method improves the chance of convergence in the solution.

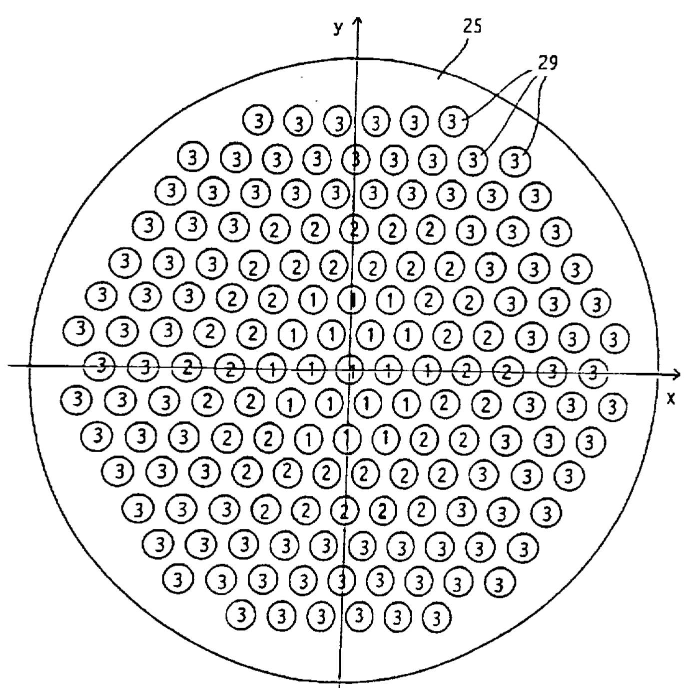

Fig. 2

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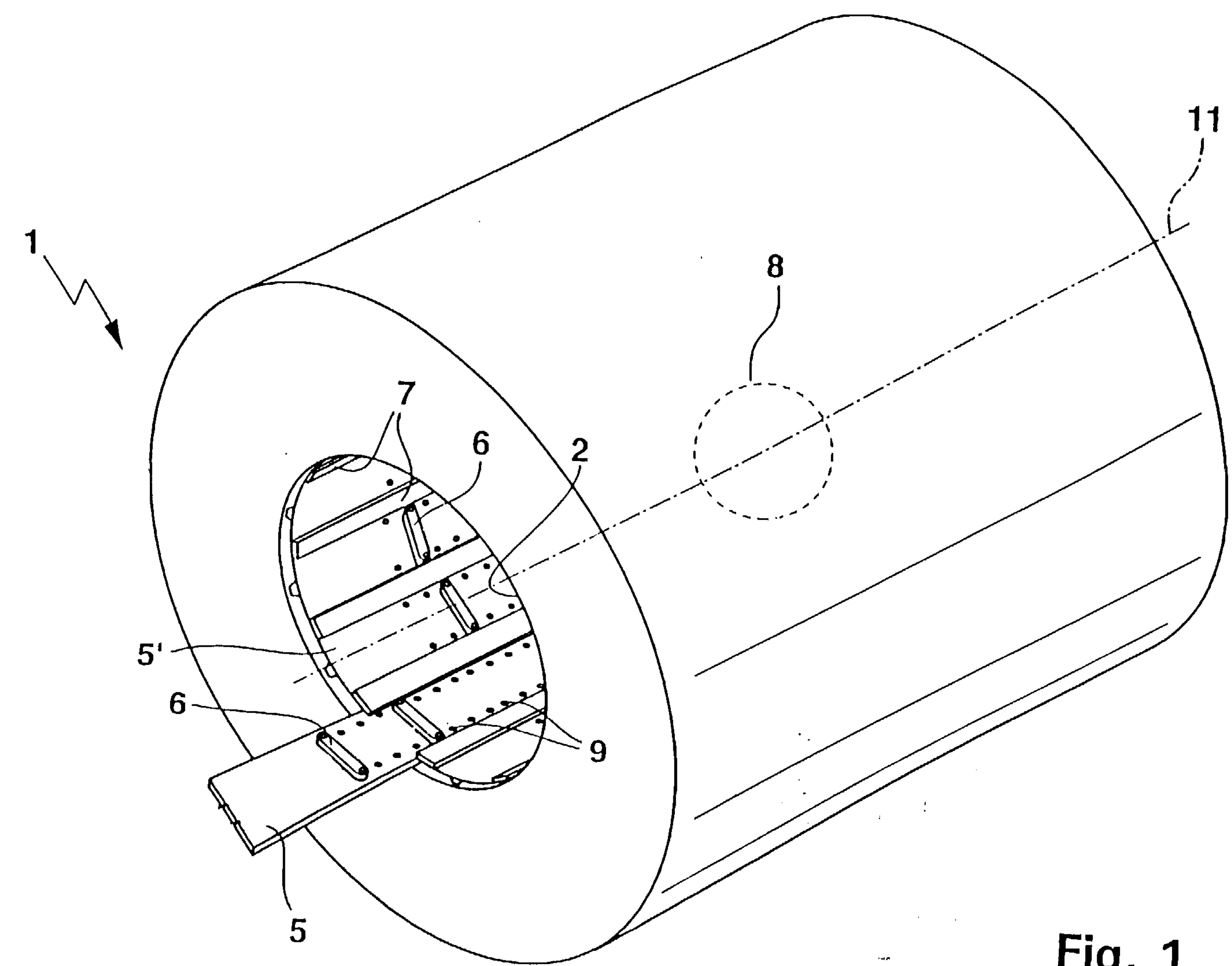

Fig. 1

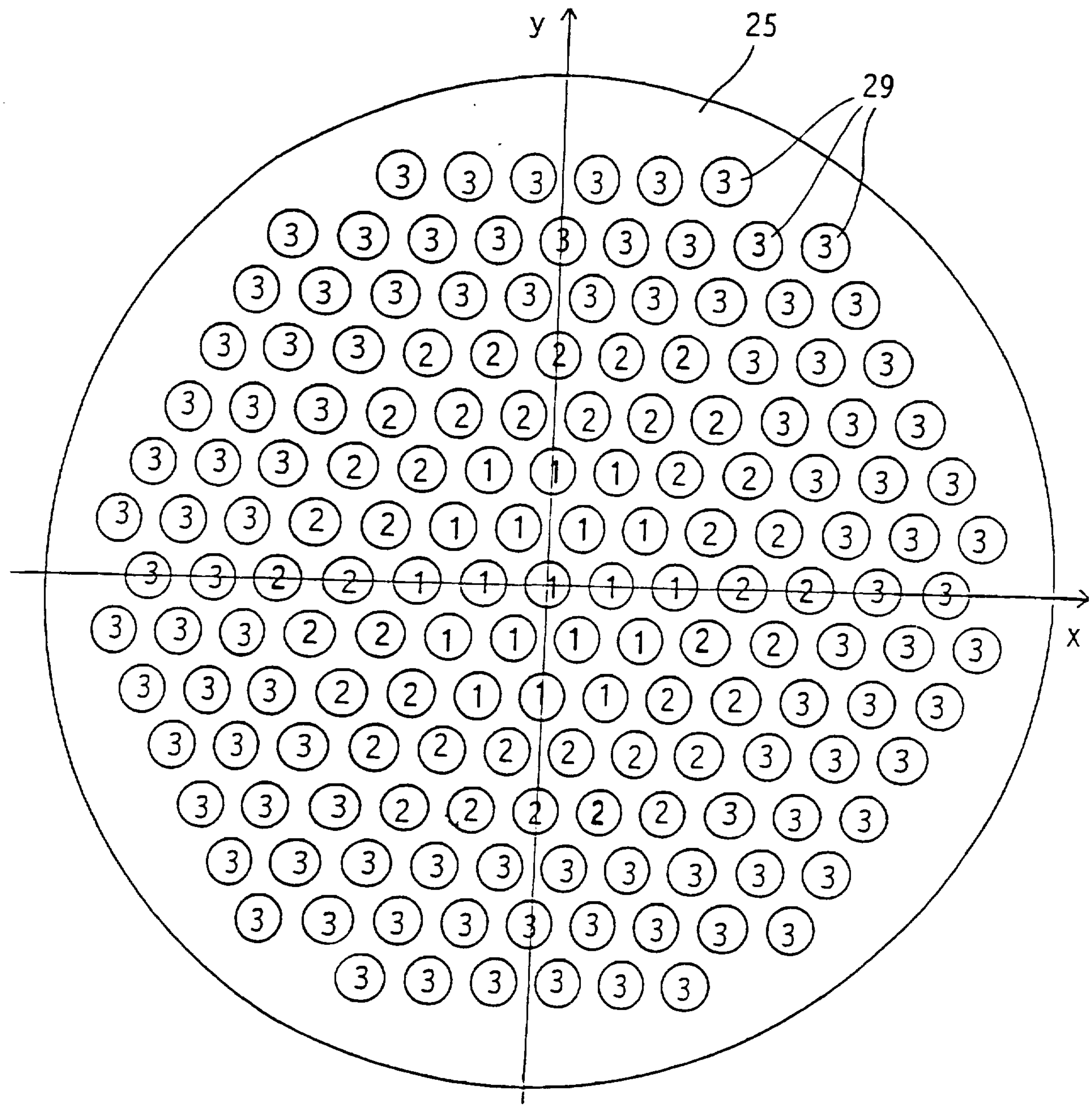

Fig. 2

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Method of homogenizing magnetic fields

The invention concerns an iterative method of homogenizing the magnetic field in the working volume of the main field magnet of a magnetic resonance apparatus by means of ferromagnetic homogenizing elements which are mounted at predetermined positions on one or more support bodies, wherein in a first measuring step, the profile of the magnetic field of the main field magnet in its working volume is determined by measurements, and the measuring values are used as input data record in a numerical calculation program which allows calculation of the occupation of predetermined positions by homogenizing elements in a first calculation step by means of said input data record in such a manner that the calculated entire field, i.e. the superposition of the magnetic field of the main field magnet with all homogenizing elements, in theory is approximately homogeneous, wherein in a first compensation step, the homogenizing elements are placed at the predetermined positions in amounts calculated in the first calculating step, and wherein subsequently, in one or more iterations, the profile of the magnetic field in the working volume is determined in a further measuring step, in each case, after which, for further improvement of the homogeneity, a modification of the occupation of the positions by homogenizing elements is calculated in a further calculation step and carried out in a further compensating step.

A method of this type is known e.g. from US 5,959,454.

Similar homogenizing devices with homogenizing elements of ferromagnetic material are known e.g. from US 5,045,794 or US 5,485,088 or US 5,959,454. US 3,622,869 discloses e.g. alternative methods of homogenizing by means of correction coils through which adjustable electric currents flow.

US 5,045,794 describes a device and a method of homogenizing the magnetic field of the main field magnet of a typical magnetic resonance tomograph for medical diagnosis with a tubular cylindrical bore for the reception of a patient, and an almost spherical working volume in the area of the geometric centre of the bore comprising ferromagnetic homogenizing elements. Guiding rails are mounted in a longitudinal direction on the surface of the tubular bore into which e.g. strip-shaped mechanical support bodies are inserted which can be provided with homogenizing elements of iron, of e.g. disc-shaped design. The mechanical support bodies in their guiding rails thus provide a plurality of predetermined locations or positions for fixing the homogenizing elements. In the magnetic field of the main field magnet, the homogenizing elements of iron are magnetized approximately to their point of saturation in a direction parallel to the axis of the bore. The relatively weak additional magnetic field of the magnetized homogenizing elements is superimposed to the relatively strong magnetic field of the main field magnet. The magnetic field in the working volume of the main field magnet is, in general, not sufficiently homogeneous to be used with the magnetic resonance apparatus due to the mechanical tolerances of the construction components of the magnet coil of the main field magnet. Through the choice of the geometric arrangement and the amount of homogenizing elements in the surroundings of the working volume, it is possible to create the spatial profile of the additional magnetic field generated by the homogenizing elements in such a manner that the original inhomogeneity of the magnetic field of the main field magnet is largely compensated. With main field magnets of a bore diameter of 90cm in a spherical working volume having a diameter of approximately 50cm, typical values of the remaining field disturbances are e.g. in the order of magnitude of a few ppm. In case soft-magnetic homogenizing elements e.g. of iron are used, the magnetization occurs only in the direction of the main field in the centre of the bore of the magnet, however, not in the opposite direction. When using disc-shaped homogenizing elements whose normal direction extends perpendicularly to the axis of the magnet bore, one obtains an almost fixed value for the magnetization, namely saturated magnetization even at already relatively small magnetic field strengths of the main field corresponding to magnetic inductances of more than 0.4 Tesla, due to the shape anisotropy of the homogenizing elements. In the range of the working volume of a main field magnet having a bore diameter of approximately 90cm the magnetic field profile generated by a small homogenizing element with dimensions of e.g. 40x40x0.3 mm^3 is almost identical with the magnetic field profile of a magnetic dipole with known dipole moment and is thus easy to calculate. Homogenization of the magnetic field in the working volume of the main field magnet by means of ferromagnetic homogenizing elements is effected basically in that at first the generally still inhomogeneous profile of the magnetic field in the working volume is measured in a first measuring step e.g. by measuring at a plurality of locations. Subsequently, the measured values are used as input data record for a numerical calculation program which, in a first calculation step, allows the calculation of a geometric arrangement of the ferromagnetic homogenizing elements at the predetermined locations, whose additional magnetic field profile largely compensates the original inhomogeneities of the magnetic field of the main field magnet in the working volume. In case of disc-shaped homogenizing elements it would be possible to stack several homogenizing elements on top of one another at several of the predetermined locations. Subsequently, the homogenizing elements are mounted on the mechanical support bodies at the predetermined locations in a first occupation step in the bore of the main field magnet corresponding to the geometric arrangement determined by the numerical calculation program. Subsequently the profile of the magnetic field in the working volume of the main field magnet, which is in general more homogeneous, is measured again in a second measuring step. The measuring values can be used again as input data record for the calculation of changes of the geometric arrangement of the homogenizing elements in the numerical calculation program, and the changed geometric arrangement of the homogenizing elements can be realized. This enables an iterative improvement of the geometric arrangement of the homogenizing elements for achieving a homogeneous magnetic field in the working volume of the main field magnet of the magnetic resonance apparatus.

US 5,485,088 and US 5,959,454, e.g., mention the use of permanent magnetic material as material for the ferromagnetic homogenizing elements. Homogenizing elements of permanent magnetic material have to be magnetized in a strong magnetic field which is stronger than the coercitive field strength of the material, before actually being used in the main field magnet in a magnetic resonance apparatus. In principle, they can then be used with any direction of magnetization, relative to the direction of the magnetic field of the main field magnet and even with the opposite direction. Furthermore, with disc-shaped homogenizing elements it is possible to generate a direction of magnetization parallel to the normal direction of the disc. This is required, e.g., with main field magnets having the geometry described in US 5,959,454. In order to allow the calculation of the profile of the magnetic field strength generated by the homogenizing elements of permanent magnetic material in the working volume of the main field magnet and thereby making them usable in practice for homogenizing methods at all, it is required that the state of magnetization remains constant or changes only slightly during installation of the homogenizing elements in the main field magnet. In this case only very few materials like NdFeB or SmCo alloys can be employed.

Basic advantages of homogenizing methods with ferromagnetic homogenizing elements consist in that with a large number of positions for the homogenizing elements there is a corresponding large degree of freedom of compensating even complicated field profiles of the not yet homogenized magnetic field of the main field magnet in contrast to methods with correction coils with adjustable currents with a relatively small degree of freedom corresponding to the number of the correction coils.

The fundamental disadvantages of homogenizing methods with ferromagnetic homogenizing elements consist in that the size of the homogenizing elements cannot be subdivided in any refined manner for practical reasons, and thus the precision with which deviations from the homogeneous profile of the magnetic field can be compensated, is basically limited in contrast to methods with correction coils with adjustable currents with which it is possible to precisely adjust the profiles of magnetic fields for compensation of inhomogeneous magnetic fields.

A basic precondition for the applicability of homogenizing methods with ferromagnetic homogenizing elements consists in that suitable distributions of the homogenizing elements on the predetermined positions can be determined from the profile of the magnetic field determined in a previous measuring step only theoretically, i.e. by means of numerical calculation programs. Subsequently, these methods can be used successfully only if the model, used in the numerical calculation method, for the theoretical calculation of the profile of the magnetic field strength generated by the homogenization elements, coincides to a sufficient degree with the actual profile of the actually used homogenization elements. In case the theoretical model corresponds with reality exactly, homogenization with only one measuring step, one calculation step and one occupation step is possible. In case of only minor deviations, homogenization is generally possible in several iterative steps in which the deviations from the homogeneous profile of the magnetic field are successively reduced. In contrast thereto, if the deviations between the theoretical model and reality are sufficiently large, the method according to US 5,045,794 e.g. is not successful even with iterative steps. Then the iterative method does no longer converge. Such deviations between the results of a theoretical model and the real magnetic behaviour of the homogenizing elements may, of course, be based simply on an unreliable theoretical model, but also on the mechanical tolerances in connection with the occupation of the support bodies by homogenizing elements and also tolerances with respect to strength and direction of magnetization of the homogenizing elements. Larger tolerances with respect to strength and direction of magnetization of the homogenizing elements in particular with homogenizing elements of permanent magnetic material are possible, since these values are influenced by the production method of the homogenizing elements and a more exact characterization of the errors occurring thereby would be too demanding in practice.

Whereas homogenization of the magnetic field of typical relatively large main field magnets for medical diagnosis having a tubular bore with bore diameters of approximately 90cm with ferromagnetic homogenizing elements of soft iron has shown to be good and established in practice, the application of the method to the homogenization of e.g. the considerably smaller main field magnet according to US 5,959,454 proves to be problematic and the described iterative method does no longer converge. For the above-mentioned reasons, the use of homogenizing elements of permanent magnetic material whose strength and direction of magnetization is inaccurate due to manufacturing, is required here. Furthermore, it shows that the main field magnet having the dimensions as exemplary described in US 5,959,454 has to be provided with homogenizing elements on the bottom of the depression V mentioned therein, which then have only a very small distance of approximately 3cm from the centre of the working volume instead of 45cm as with the above-mentioned magnet with a bore diameter of 90cm. Thus, mechanical tolerances generate relatively big errors in the magnetic field contribution produced by the homogenizing elements when the homogenizing elements are positioned. On top of that, there is the problem that the dimensions of the cylindrical homogenizing elements are relatively large with values of a diameter of 5mm and a height of 0.4mm in relation to their short distance from the centre of the working volume and subsequently, deviations of the magnetization or the position from the expected value have a relatively strong effect on the contribution to the magnetic field. Further reduction of the dimensions would inadmissibly hinder the handling of the homogenizing elements in the magnetized state due to the occurring magnetic forces.

It is to be expected that known iterative methods of homogenization basically no longer converge if the errors of the contributions of the homogenizing elements to the entire magnetic field almost reach the order of magnitude of the field inhomogeneities to be compensated.

In contrast thereto, it is the task of the present invention to modify a method of the initially described manner in such a way that reliable convergence of the iteration steps and thus improvement of the homogeneity of the main magnetic field is achieved even if the errors of the contributions of the homogenizing elements to the entire magnetic field reach almost the order of magnitude of the field inhomogeneities to be compensated.

This object is achieved in a surprising and also effective manner in that the predetermined positions of the homogenizing elements are divided into groups with different distances from the geometric centre of the working volume and that starting from the second calculation step and the second compensation step, the occupation of the positions of the group with the shortest distances from the centre of the working volume is not changed again.

Besides, each of the predetermined positions of the homogenizing elements is uniquely associated with a certain group, wherein however the distances of positions of different groups from the centre of the working volume may certainly overlap in certain regions. However, the mean value of the distances of the positions within a group results in a hierarchy of the groups among themselves, in each case, starting from the group with the shortest distances to the group with the largest distances from the centre of the working volume.

Due to the inventive measures, starting from the second calculation step and the second compensation step, only occupations of positions with larger distances from the centre of the working volume are changed. This reduces the influence on the magnetic field to be homogenized as compared to changes of homogenizing elements in the range closer to the centre, such that also with relatively large errors of the contributions of the homogenizing elements to the entire field, which may be caused e.g. by inaccurate positioning, deviations of the magnetic field characteristics of the homogenizing elements from the ideal state and the like, the remaining influence of those homogenizing elements which will be changed regarding their positions and numbers after the second step, will be considerably smaller than with conventional iterative methods in which all possible positions of homogenizing elements are available for a change in the respective following iteration. For this reason, there is the chance of convergence with the iterative method even with relatively large error contributions of the individual homogenizing elements, as long as the error contributions of the remaining homogenizing elements which are still to be varied, are smaller than the remaining error of the entire field to be compensated. The virtual disadvantage that the possibilities for variations of the occupations are limited after the second step of the iterative method, thus proves to be the key for the solution of the above-defined object of the invention since by the limitation of the further possibilities for the variation a new degree of freedom is gained.

One embodiment of the inventive method is particularly preferred in which, in further iterations, the occupation of the positions of the respective group being located at a subsequent larger distance from the centre does not change any more.

In this way it is possible to avoid that the relatively big errors of the compensation contributions from the groups at positions closer to the centre are transferred to the respectively following finer compensation step.

One variant of the method is also particularly preferred in which, in the first compensation step, homogenizing elements occupy only positions of the group having the shortest distances from the centre. In this way, the influence of the occupation of positions by homogenizing elements which are error-inducing themselves, is determined without disturbances, in each case, in the subsequent measuring step, thereby avoiding that the error contributions of elements from further remote regions have a disturbing influence on the measurement. This also reduces the work effort since in the first compensation step, only part of the predetermined positions has to be occupied with homogenizing elements. The influence of the homogenizing elements on the positions, which are remote from the centre and not occupied, on the entire field would be comparably small anyway.

In an advantageous further development of this variant of the method which also presents a consistent application of the principle of the embodiment of the inventive method described above, in further compensation steps the homogenizing elements each occupy only positions of the group located at a subsequent further distance away from the centre. The inventive method is particularly effective in this modification and requires the least work effort.

In practice it has proven to be particularly advantageous if the groups are divided such that within the group having the shortest distance of the predetermined position from the centre of the working volume, the ratio between the largest and shortest distance is less than 1.6, preferably smaller than $\sqrt{2}$.

In variants of the inventive method, the shortest distance of a predetermined position from the centre may be selected to be smaller than 5cm. With such a geometric arrangement where the homogenizing elements are located at such a short distance from the centre of the working volume, taking into consideration the relatively high error contributions of the normally used homogenizing elements, conventional compensation methods fail completely, while the inventive method offers a good chance of converging iterations.

It is also possible with modifications of the inventive method to select the ratio between the shortest distance of a position from the centre of the working volume and the cube root of the volume of the largest used homogenizing element to be less than 40, preferably less than 30. In this way, even if the homogenizing elements, which are close to the centre, have a very strong influence on the entire field, it is possible to achieve convergence of the iteration method which has hitherto not been possible with such "pathological cases" by means of conventional methods.

In order to be able to generate also negative magnetic moments by means of homogenizing elements irrespective of the strength and direction of the main field magnet to be compensated, in a particularly preferred variant of the inventive method, permanent magnets are used as homogenizing elements.

The use of the homogenizing elements in the form of plates is also particularly preferred such that it is possible to gain particularly and delicately controlled influence on the magnetic field at the predetermined positions by means of suitable stacking of the respectively calculated most favourable number of homogenizing elements at the respective position.

Further features and advantages of the invention are shown in the following description of embodiments of the invention with reference to the drawings, which show essential details of the invention, and to the claims. The individual features may be realized individually or collectively in any arbitrary combination in an embodiment of the invention. In the drawing:

Fig. 1 shows a schematic representation of the main field magnet in a nuclear magnetic resonance apparatus having homogenizing elements at predetermined positions; and

Fig. 2 shows a schematic plan view in the direction of the z axis onto a support plate with predetermined positions of the homogenizing elements.

Fig. 1 shows in a highly schematized manner a conventional superconducting main field magnet 1 of a nuclear magnetic resonance tomograph with an axial room temperature bore 2. The working volume 8 is located in the central area of the room temperature bore 2. The inner wall of the room temperature bore 2 is provided with axial guides 7 into which holders 5 can be inserted, comprising different positions 9 at which ferromagnetic homogenizing elements 6, e.g. shim platelets can be stacked and fixed. The holders 5 are inserted into the guides 7 and fixed. It would also be possible to provide a common cylinder-symmetrical holder.

The stacked shim platelets are each mounted onto a translator which may displace them in a radial direction with respect to the axis 11 in order to approach the positions 9.

Fig. 2 shows a support plate 25 onto which a calculated number of ferromagnetic homogenizing elements, e.g. in the form of permanent magnetic shim platelets, can be mounted at positions 29 in each case. The numbers in the circles for the positions 29 state in each case which positions are occupied in each iteration step corresponding to the group formed according to the invention.

The support plate 25 may be placed e.g. onto the pole shoe of a main field magnet or may be inserted into a magnet arrangement according to US 5,959,454 and e.g. fixed at the position of the gradient system provided therein.

Claims

1. An iterative method of homogenizing the magnetic field in the working volume (8) of the main field magnet (1) of a magnetic resonance apparatus by means of ferromagnetic homogenizing elements (6) which are mounted at predetermined positions (9;29) on one or more support bodies (5;25), wherein, in a first measuring step, the profile of the magnetic field of the main field magnet (1) in its working volume (8) is determined through measurements and the measuring values are used as input data record in a numerical calculation program which allows, in a first calculation step, the calculation of the occupation by homogenizing elements (6) at the predetermined positions (9;29) by means of said input data record, in such a manner that the calculated entire field, i.e. the superposition of the magnetic field of the main field magnet (1) with all homogenizing elements (6), is theoretically approximately homogeneous, wherein in a first compensation step, the homogenizing elements (6) are placed in amounts calculated in the first calculation step, at the predetermined positions (9;29) and wherein subsequently, in one or more iterations, the magnetic field profile in the working volume (8) is determined in a further measuring step, and afterwards for further improvement of the homogeneity a change of occupation of the positions by homogenizing elements (6) is calculated in a further calculation step and carried out in a further compensation step, characterized in that
the predetermined positions (9;29) of the homogenizing elements (6) are divided into groups with different distances from the geometric centre of the working volume (8) and that starting from the second calculation step and the second compensation step, the occupation of the positions (9;29) of the group with the shortest distances from the centre of the working volume (8) is not changed any more.

2. The method according to claim 1, characterized in that in further iterations, the occupation of the positions (9;29) of the respective group being located at a subsequent larger distance from the centre is not changed again, in each case.

3. The method according to one of claims 1 or 2, characterized in that in the first compensation step the homogenizing elements (6) occupy only positions (9;29) from the group with the shortest distances from the centre.

4. The method according to claim 3, characterized in that in further compensation steps the homogenizing elements (6) occupy only positions (9;29) of the respective group being located at a subsequent larger distance from the centre.

5. The method according to one of the preceding claims, characterized in that within the group having the shortest distances from the predetermined positions (9;29) from the centre of the working volume (8), the ratio between the largest and the shortest distance is smaller than 1.6, preferably smaller than $\sqrt{2}$.

6. The method according to one of the preceding claims, characterized in that the shortest distance of a predetermined position (9;29) from the centre is selected to be less than 5cm.

7. The method according to one of the preceding claims, characterized in that the ratio between the shortest distance of a position (9;29) from the centre of the working volume (8) and the cube root of the volume of the largest used homogenizing element (6) is selected to be smaller than 40, preferably smaller than 30.

8. The method according to one of the preceding claims, characterized in that permanent magnets are used as homogenizing elements (6).

9. The method according to one of the preceding claims, characterized in that the homogenizing elements (6) are selected to be platelets.

10. The iterative method of homogenizing the magnetic field in the working volume (8) of the main field magnet (1) of a magnetic resonance apparatus as hereinbefore described with reference to and as illustrated by the accompanying drawings.

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12.

Application No: GB 0000750.0
Claims searched: 1-10

Examiner: Peter Emerson
Date of search: 11 August 2000

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): G1N NG38D

Int Cl (Ed.7): G01R 33/387, 33/3873

Other: Online: WPI, JAPIO, EPODOC, INSPEC

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	EP 0710852 A1	(PICKER)	
A	US 5418462 A	(SUPERCONETICS)	
A	US 4771244 A	(GEC) - col 7 lines 6-14	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.