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(54) **MAGNETIC RESONANCE ANALYZING FLOW METER AND FLOW MEASURING METHOD**

MAGNETISCHE-RESONANZ-DURCHFLUSSMESSER UND -DURCHFLUSSMESSVERFAHREN

DEBITMETRE D'ANALYSE PAR RESONANCE MAGNETIQUE ET PROCEDE DE MESURE
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(74) Representative: **AMMANN PATENTANWÄLTE AG
BERN
Schwarztorstrasse 31
Postfach
3001 Bern (CH)**

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(73) Proprietor: **Wollin Ventures, Inc.
Marathon, FL 33050 (US)**

(72) Inventor: **WOLLIN, Ernest
Marathon, FL 33050 (US)**

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Description

[0001] This invention relates to a method of measuring the mean velocity of a fluid according to the preamble of claim 1. The invention further relates to a device for measuring velocity of a material according to the preamble of claim 14.

[0002] The idea of studying flow by magnetic resonance dates back to the work of the early pioneers as described, for example, in Mansfield, P; Morris, P.G.; "NMR Imaging in "Biomedicine"; Advances in Magnetic Resonance, Supplement 2; 1982; Academic Press, Inc. Orlando 32887; p.235 section 7.3.5. Prior art devices for flow measurement or flow mapping rely on two well-known methods viz. "Time-of-Flight" of saturated or unsaturated spins or "Phase-Encoding" by application of a gradient field along the direction of flow. (Cho, Z. et. al.; "Foundations of Medical Imaging;" John Wiley & Sons, inc., New York, 1993, p374-386.) Exemplary of the "Time-of-Flight" method is U.S. Patent No. 4,782,295 to Lew and of the "Phase-Encoding" method is U.S. Patent No. 5,532,593 to Maneval. Analysis of chemical composition by chemical shift is discussed in "Principles of Magnetic Resonance," third edition chapter 4, by Slichter, C.P., Springer-Verlag, N.Y. 1989.

[0003] However, the prior art time-of-flight techniques require repetitive Larmor r.f. pulses at intervals short with respect to T_1 , the spin-lattice relaxation constant, which varies with temperature and molecular composition. Prior art Phase-Encoding techniques require gradients in a spin-echo or stimulated echo sequence along a quasi-steady state flow vector.

[0004] US-5,757,187 teaches a method and device for magnetic resonance imaging, wherein electric fields are used instead of magnetic gradient fields. The device is characterized in that the birdcage of a conventional MRI device is supplied with a spatially circulating electric voltage. Accordingly, the birdcage is to be provided with three electrically isolated sets of connection.

SUMMARY OF THE INVENTION

[0005] Hence, it is an object of the invention to provide a simplified method for determining the velocity of a fluid.

[0006] Such a method is defined in claim 1. A corresponding device is defined in claim 14. The other claims define preferred embodiments of the method or the device.

[0007] Accordingly one preferred aspect of the present invention provides a universally applicable simplified method to non-invasively measure the mean value of, or to map the velocity profile of, the various domains of flow based on the dwell time of flowing spins within a defined space containing a uniform H_1 Larmor radio frequency excitation field.

[0008] Another preferred aspect of the invention provides a method to measure or map the signal received from moving spins within a defined space in the continuous presence of the H_1 Larmor radio frequency excitation field by periodically phase modulating the H_0 strong main magnetic field by a periodic gradient field so as to cause the spins to emit a line or band spectrum, centered at the Larmor frequency, whose sideband amplitudes are known functions of the amplitude of the center-band Larmor frequency signal emitted by the spins, said emitted center-band Larmor frequency signal amplitude being a known function of the dwell time of the spins within a defined space within the H_1 Larmor excitation field.

[0009] Another preferred aspect of the invention provides a method to continuously measure the very weak sidebands of the emitted signal from the phase modulated spins in the presence of the very strong H_1 central Larmor field by demodulating and then cross-correlating the received signal with integral multiples of the phase modulating frequency of the periodic gradient field.

[0010] In another preferred aspect of the invention, the pulsed Larmor radio frequency fields and pulsed gradient fields are eliminated, thereby reducing or eliminating eddy currents, transients, and Gibbs truncation artifacts.

[0011] Another preferred aspect of the invention provides a method to measure the velocity of the spins from the measurement of the dwell time of the spins within the known geometry of a defined portion of the H_1 Larmor excitation field, said known geometry being defined by a receiver coil preferably wound orthogonal to the H_1 Larmor excitation field coil so as to substantially decouple the noise from, and the signal from, the H_1 Larmor excitation field.

[0012] Another preferred aspect of the invention is to provide a measure of the flow velocity within the known geometry of a defined portion of the H_1 Larmor excitation field constructed from measurements dependent on the dwell time of the spins in a defined portion of the H_1 Larmor frequency excitation field as measured with the known adjustable strength of that H_1 Larmor frequency excitation field, and not significantly dependent on the unknown T_1 spin-lattice, the unknown T_2 spin-spin, the unknown D diffusion, or on other unknown parameters affecting spin magnetization, spin diffusion, or spin coherence. These unknown parameters affect the signal-to-noise of the measurements of this invention, but not significantly the defined end point of these measurements, according to this invention.

[0013] A further preferred aspect of this invention is to perform a simultaneous chemical and physical analysis of the flowing material.

[0014] A further preferred aspect of this invention is a flow meter for performing one or more of the above methods.

BRIEF DESCRIPTION OF THE DRAWINGS**[0015]**

Fig. 1 is a cross section of an embodiment of the nuclear magnetic resonance flowmeter constructed in accordance with one embodiment of the present invention, which cross section is taken along a plane including the central axis of the flow passage.

Fig. 2 diagrammatically illustrates a conducting or superconducting solenoidal main magnet for the H_0 field and an orthogonal birdcage Larmor r.f. H_1 coil which may be used in accordance with another embodiment of the present invention.

Fig. 3 is a sectional view of the flowmeter of Fig. 1, schematically illustrating the placement of gradient coils for producing a modulating field h_ϕ in the detector section.

Fig. 4 is a schematic illustration of a Larmor r.f. excitation (nutaton) coil for the detector section of the flowmeter shown in Fig. 1.

Fig. 5 is a schematic illustration of an r.f. receiving coil for the detector section of the flowmeter Fig. 1.

Fig. 6 is a block diagram of a signal processing circuit for use with the flowmeter of Fig. 1.

Figs. 7a through 7i are graphs and formulas illustrating the operation of the circuit of Fig. 6.

Fig. 8 is an overall system block diagram of one embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0016] Figure 1 illustrates an embodiment in which the strong relatively homogenous H_0 static magnetic field required in all magnetic resonance devices is placed perpendicular to the mean axis of flow. In Figure 1 there is shown a cross section of an embodiment of the nuclear magnetic resonance flowmeter constructed in accordance with the principles of the present invention, which cross section is taken along a plane including the central axis of the flow passage. The flow passage 1 extending from one extremity 2 to the other extremity 3 of the conduit 4 extends through a constant magnetic field generally perpendicular to the direction of the fluid flow, which constant magnetic field is provided by a magnet assembly 5 comprising a pair of pole face plates 6 and 7, a pair of permanent plate magnets 8 and 9, and flux path structures 10 and 11 connected to one another. The magnetic assembly 5 and the conduit 4 are packaged into one single integral assembly by means of two flanges 12 and 13 with fastening bolts and spacers 14, 15 and 16 made of a non-ferromagnetic material. The conduit 4 providing the flow passage 1 is made of three sections; the two end sections 17 and 18 made of a non-ferromagnetic material such as stainless steel, bronze, plastic or glass, and the NMR (nuclear magnetic resonance) detector section 19 made of an electrically nonconducting diamagnetic material of zero parity such as fluorocarbon plastics, glass or ceramic material. The NMR detector section 19 includes a transmitter coil 20 wound on the outside surface thereof and a receiver coil 21 wound on the outside surface of, or lying within, the NMR detector section 19 near the entry to the transmitter coil 20. The NMR detector section 19 is connected to the two end sections 17 and 18 in a leak proof arrangement that may include ring seals 22 and 23 or bonded coupling. The pole face plates 6 and 7 are plates with polished faces made of a high quality ferromagnetic material such as silicon steel, which are employed to provide a uniform magnetic field intermediate the two pole faces of the magnet over a sizable length in the direction of the fluid flow. The flux path structures including elements 10 and 11 are also made of a ferromagnetic material.

[0017] Figure 2 illustrates an alternate but equivalent arrangement where the H_0 field is aligned with the mean axis of flow. This figure shows a typical conducting or superconducting solenoidal main magnet for the H_0 field and an orthogonal birdcage Larmor r.f. H_1 coil as is well known in the art.

[0018] The length of either embodiment in Figure 1 or in Figure 2 is chosen to make the transit time of the fastest portion of the range of measurement of spin velocities comparable to the T_1 spin-lattice relaxation time so as to provide adequate magnetization making the detected signal-to-noise ratio statistically acceptable. Longer magnet sections improve the signal-to-noise ratio of the measurements, increase the cost of the construction and size of the device, but do not significantly affect the theoretical end points, as will become evident in the following development. The apparatus of Figure 1 is similar to the apparatus described in U.S. Patent No. 4,782,295 to Lew and the apparatus of Figure 2 is similar to the apparatus described in U.S. Patent No. 5,408,180 to Mistretta.

[0019] Figure 3 depicts one method, but not the only method, whereby a phase-modulating periodic gradient component h_ϕ of H_0 can be provided for the embodiment of Figure 1.

[0020] The phase-modulating periodic gradient is an Extremely Low Frequency (ELF) or a Very Low Frequency (VLF) gradient field. Fig. 3 illustrates a method for producing the modulating field 24 of amplitude h_ϕ in the detector section preferred for the embodiment of Fig. 1 in which the periodic field of frequency Ω is created by periodic currents through the gradient coils 25. A spacer 23 made of a nonconducting paramagnetic material of zero parity may be used to secure the detector section. Other conventional gradient coil arrangements, as are well known in the art, can be combined with

Figure 1 or Figure 2 to provide a periodic spatially ordered component to the H_0 main magnetic field (see Shenberg, Itzhak; Macovski, Albert; "Applications of time-varying gradients in existing magnetic resonance imaging systems"; Med. Phys., vol 13(2), p164-169 Mar 1982, N.Y., U.S.).

[0021] Fig. 4 illustrates the Larmor r.f. excitation (nutaton) coil 20 preferred for the detector section in the embodiment of Fig 1. Figure 4 shows how an H_1 Larmor frequency excitation field can be continuously applied perpendicular to the H_0 main magnetic field in the embodiment of Figure 1. Conventional H_1 r. f. excitation coils of various configurations are well known in the art for both the configuration of Figure 1 and the configuration of Figure 2. The strength of the H_1 field can be controlled by the amplitude of the radio frequency current in the r.f. coil through current amplifiers, as is well known in the art and this current strength can be varied to alter the signal distribution emitted by the spins in the receiver coil, according to this invention.

[0022] Figure 5 illustrates a preferred embodiment of a receiver coil for the configuration of Figure 1. Fig. 5 demonstrates the r.f. receiving coil 21 of length L_2 preferred for the detector section in the embodiment of Fig 1. This receiver coil, and others suitable for the configuration of Figure 1 and the configuration of Figure 2 are well known in the art. The receiver coil of Figure 5 is preferably placed near the entry of the flow of spins into the H_1 Larmor r.f. excitation field and is preferably wound orthogonal to the winding of the H_1 excitation field coil to substantially decouple power amplifier noise and signal, as is well known in the art. The length of the receiver coil is preferably short enough so that the transit time of the lowest flow velocities to be measured is short with respect to T_2^* spin-spin and D diffusion time effects, which decrease signal amplitude exponentially. This affects the signal-to-noise of the measurement, but not significantly the theoretical end point of the measurement according to this invention.

[0023] Figure 6 illustrates a preferred embodiment of a sideband demodulation detector 27 to reject the strong center band signal from the H_1 Larmor frequency r.f. excitation field and detect the amplitude of the relevant side bands by cross-correlation with integral multiples of the reference phase modulation frequency. (U.S. 5,757,187 to Wollin In Fig. 6, antenna 100 of the magnetic resonance flowmeter receiver coil 21 is coupled to an impedance matching circuit 102, feeding a noise matching preamplifier 104 through a protection circuit 106. The output of the noise matching preamplifier is fed to an RF amplifier 108, the output of which is directed to a double-balanced demodulator 110, 112. The output of the double-balanced demodulator 110, 112 is fed through a summing amplifier 114 to an alternating current integrator 116 and a low frequency amplifier 118. Each of the demodulators 110 and 112 is supplied by a quadrature output from the magnetic resonance master radio frequency oscillator 28, illustrated in Figure 8. The demodulated outputs are then added at summer 114 to provide a cross-correlated input to the integrator 116 (estimating the direct current $J_0()$ term) as well as to an amplifier 118 that, in turn, feeds additional sets of double-balanced demodulators 120, each of whose added cross-correlated outputs are also summed by summers 122 and integrated by integrators 124, thereby estimating the relative strength of each sideband element of the spectrum, $J_n()$).

[0024] Figures 7a - 7i provide a signal analysis of Figure 6 showing demodulation and cross-correlation techniques and the generalized output equation from which the flow velocity of the spins can be measured or mapped. As such, Figs. 7a - 7i provide is a stepwise mathematical analysis of the signal processing in the circuit of Fig. 6. (Poularikas, Alexander D., "The Transforms and Applications Handbook" CRC-IEEE press, Boca Raton, Florida, 1996;_pages 29, 185, 214, 221).

[0025] Figure 8 is an overall system block diagram of the invention. In Fig. 8 the flowmeter assembly 26 receiver coil output is fed to the synchronous demodulator and cross-correlation detector 27 for synchronous demodulation with the Larmor r.f. ω_0 oscillator 28 and cross-correlation detection with integral multiples of the phase modulating frequency Ω from the frequency divider 29. The output of the demodulator-detector 27 is fed to the controller 30 which controls the gain of the r.f. power amplifier 32, whose frequency is controlled by the Larmor r.f. ω_0 oscillator 28, and whose output adjusts the current in the H_1 Larmor r.f. coil of the flowmeter assembly 26, so as to set the output of the demodulator-detector 27 to a desired level, as set by the controller 30. This control loop is designed for rapid response, and the current output of the ω_0 r.f. amplifier 32 then measures the flow velocity as described herein. The frequency divider 29 is fed from the r.f. oscillator 28 and controls the frequency Ω of the amplifier 31, which feeds the phase modulating coils 25 in the flowmeter assembly 26. The gain of the amplifier 31 is controlled by the output of the controller 30 in a strongly damped slowly responding manner, as is well-known in servo-mechanism theory, to secure the highest signal-to-noise level, as described in this invention. The frequency of the ω_0 Larmor frequency oscillator 28 is also controlled by the output of the controller 30 in a very strongly damped very slow-responding manner to secure the highest signal-to-noise level by compensating for any varying load impedance on the H_1 r.f. coil, caused by physical changes or chemical shift as is well known in the art. ("Principles of Magnetic Resonance," third edition chapter 4, by Slichter, C.P., Springer-Verlag, N.Y. 1989. ch. 2.8 p 35-39). The current output of the Larmor r.f. power amplifier 32, is a desired measured quantity and is a function of mean flow velocity, as described herein, and is fed to a meter or other suitable indicator or recording device 33. The frequency of the ω_0 Larmor frequency oscillator 29 is a measure of chemical and physical composition of the flowing material ("Principles of Magnetic Resonance," third edition chapter 4, by Slichter, C.P., Springer-Verlag, N.Y. 1989.).

[0026] Prior art time-of-flight techniques are more complex, requiring repetitive Larmor r.f. pulses at intervals short

with respect to T_1 , the spin-lattice relaxation constant, which varies with temperature and molecular composition. Prior art Phase-Encoding techniques require gradients in a spin-echo or stimulated echo sequence along a quasi-steady state flow vector. This invention preferably does not employ pulse techniques, is relatively independent of spin relaxation and diffusion, and can rapidly respond to changes in mean velocity of flow in the high Reynolds number measurement mode, or to changes in the velocity profile in the low Reynolds number mapping mode.

METHOD OF OPERATION

[0027] In the measurement mode of operation the amplitude of the current in the H_1 Larmor frequency r.f. excitation coil is adjusted to control the amplitude of the measured sidebands in the detection circuit. The H_1 field is applied continuously, and preferably not pulsed. The maximum signal, or the minimum signal, or a particular value of the signal in a selected sideband, is preferably chosen as the end-point for measurement of the mean value of the velocity profile; and the magnitude of the current in the H_1 r.f. coil required to achieve the chosen signal level is a measured parameter and is a known or measured function of the dwell time of the spins in the defined geometry of the receiver coil, as will be demonstrated herein.

[0028] Alternatively, in the mapping mode (no embodiment of the invention) the amplitude of the H_1 Larmor frequency excitation field is preferably held constant, the amplitude of the phase modulating component of the main strong H_0 field is spatially distributed by "gradient coils" (Shenberg, Itzhak; Macovski, Albert "Applications of time-varying gradients in existing magnetic resonance imaging systems"; Med. Phys., vol 13(2), p164-169 Mar 1982, N.Y., U.S.) and the received sidebands are used in a matrix approximation of the equations at the end of Figure 7(i). Inverting the matrix or solving by Cramer's rule provides a spatial map of the signal distribution, as is more fully described in U.S. Patent No. 5,757,187 to Wollin

[0029] As shown in Fig. 8, the controller 30 compares the detected amplitude of the designer selected sideband to a designer selected control condition, i.e., maximum value (eq. 17), minimum value (eq. 18, 19), or some intermediate value chosen for optimum system performance and thereby creates an error signal of appropriate sense to adjust the gain of the Larmor r.f. power amplifier 32 to meet this design condition. The output current of the Larmor r.f. power amplifier 32 is proportional to the Larmor r.f. excitation (nutation) field strength H_1 in coil 20 and, therefore, is a measure of mean flow velocity (eq. 17, 18).

[0030] A slower calibration loop measures the mean square error signal output from the controller 30 and adjusts the amplitude of the phase modulating current (according to eq. 25).

[0031] Similarly an even slower calibration loop adjusts the frequency of the Larmor r.f. master oscillator 28 to compensate for changes in coil loading, as is well known in the art, ("Principles of Magnetic Resonance," third edition chapter 4, by Slichter, C.P., Springer-Verlag, N.Y. 1989.) permitting estimation of changes in chemical and physical composition of the flowing material.

THEORY OF OPERATION

[0032] It is well known that a solid or fluid medium of diamagnetic material with a non-zero spin or non-zero parity placed in a constant magnetic field becomes magnetized in accordance with equation:

$$m = K_1 H_0 (1 - e^{-t_1/T_1}) \quad (1)$$

(See, U.S. 4,901,018 to Lew)

where m is the magnetization of the medium, K_1 is the magnetic susceptibility, H_0 is the intensity of the large static near homogenous main magnetic field, t_1 is the mean dwell time of the spins in the H_0 field, and T_1 is the spin lattice relaxation time, which is a measure of the rate of transfer of energy from the spins to the surrounding medium. Before entering the measurement section, defined by the H_1 excitation field, the medium has acquired statistically significant magnetization. The length of the device from its input to the measurement section containing the H_1 excitation field is chosen to allow sufficient magnetization of the fastest moving spins to produce adequate signal strength in the presence of the total noise of the device to permit reliable estimation of the desired measurement in each mode of operation. This is preferably achieved by adding additional identical magnetizing sections for measuring or mapping at higher flow rates.

[0033] The H_0 main magnetic field cause the spins to precess near a Larmor frequency ω_0 where

$$\omega_0 = \gamma H_0 \quad (2)$$

with γ being the gyromagnetic ratio, a constant for each spin species. Periodically varying H_0 by phase modulating coils, as in Fig. 3, periodically varies ω_0 to produce ω_ϕ where:

$$\omega_\phi = \gamma (H_0 + h_\phi \cos \Omega t) \quad (3)$$

where h_ϕ and Ω are the amplitude and temporal frequency of the periodic component of H_0 and ω_ϕ is the instantaneous angular velocity of precession of the spins about the axis of H_0 . This amplitude h_ϕ can be made a spatial function by time-varying excitation of existing gradient coil sets for mapping velocity or perfusion distributions. (Shenberg, Itzhak; Macovski, Albert; "Applications of time-varying gradients in existing magnetic resonance imaging systems"; Med. Phys., vol 13(2), p164-169 Mar 1982, N.Y., U.S. and U.S. Patents 5,412,322 and 5,757,187 to Wollin)

[0034] The H_1 , excitation field is applied orthogonal to the H_0 field, as exemplified in Fig. 4, and is of frequency ω_0 . It produces excitation or nutation of the spins at an angular frequency ω_1 , where:

$$\omega_1 = \gamma H_1 = \frac{d\theta}{dt} \quad (4)$$

[0035] This nutation produces a component of magnetization perpendicular to the H_0 field which can be detected by the voltage it induces in the receiver coil whose area vector is perpendicular to the H_0 field, in accordance with Maxwell's Second Law, (see U.S. Patent No. 5,412,322 and 5,757,187 to Wollin, as detected in the coil exemplified in Fig. 5.

[0036] The voltage induced in the receiver coil has a band or line spectrum. This spectrum consists of sidebands equally distributed about the central Larmor frequency by integral multiples of the phase modulating frequency Ω whose amplitude distribution is defined by the various solutions to Sommerfeld's integral; i.e. Bessel, Neumann, or Hankel functions; and whose width is defined by the H_0 static field inhomogeneity and any applied or intrinsic static gradients as analyzed in Fig. 7.

[0037] Rejecting the central ω_0 frequency of the signal by demodulation in the presence of the H_1 Larmor r.f. field, permits measurement of the sideband amplitudes by cross-correlation with integral multiples of the reference phase modulating frequency Ω as shown in Figs. 6 and 7. This permits estimation of the sideband amplitudes without necessarily utilizing pulse techniques, providing that the spins retain significant coherence during their transit through the geometric volume defined by the receiver coil.

[0038] During or after excitation by the H_1 Larmor r.f. field, spins rapidly lose their phase coherence by many different mechanisms, some of which are adiabatic and, therefore, involve no change in entropy. Those that are not adiabatic involve either passive diffusion (governed by the heat equation) or turbulent displacement or random alterations in the local magnetic field. The net detectable magnetism m_t is exponentially related to the transit time t_2 through the H_1 field:

$$m_t = K_2 (m \sin \theta) e^{-\left(t_2 / T_2 + DK_3 t_2^3\right)} \quad (5)$$

[0039] Where θ is the colatitude of the nutation produced by the H_1 , field, T_2 is the spin-spin relaxation constant, D is the passive diffusion constant of the medium, and K_3 is a coefficient containing γ and the local gradient field strength. The effect of the exponential term is to reduce signal strength exponentially with the dwell time t_2 of the spins in the H_1 Larmor r.f. field, which effect dictates that short receiver coils be used in slow flow applications. Several such short coils may be arranged sequentially and connected in series to permit selection of the lowest range of flow velocities to be measured.

[0040] The receiver coil exemplary in Fig. 5 is preferably wound orthogonal to the H_1 Larmor radio frequency excitation coil to minimize noise coupling and excitation signal coupling between the excitation r.f. power amplifier circuitry and the receiver circuitry.

[0041] During transit through the H_1 Larmor r.f. excitation field, the spins nutate through a colatitude angle θ , as is

well known in the art (Slichter, C.P.; "Principles of Magnetic Resonance"; Springer-Verlag, New York; Third Edition, 1989, Chapter 2). The detectable transverse magnetization then varies as the spins traverse the receiver coil within the H_1 excitation field, since from eq (4):

$$\omega_1 = \frac{d\theta}{dt} = \gamma H_1 \quad (6)$$

$$\theta = \gamma H_1 t_2 \quad (7)$$

and from eq(1) and eq(5)

$$m_1 = K_1 K_2 H_0 \left(1 - e^{-t_1/T_1}\right) e^{-t_2/T_2^*} \sin \gamma H_1 t_2 \quad (8)$$

where T_2^* is the effective T_2 , which includes spin-spin relaxation, diffusion, and local field in homogeneity etc., as is well known in the art.

[0042] Defining

$$t_2 = \frac{\ell}{v} ; t_1 = \frac{L_1}{v} \quad (9); (10)$$

where v is the velocity of each element in the velocity profile of each flow domain. Then the total receiver coil transverse magnetization M_T for each element of v is

$$M_T = K H_0 \left(1 - e^{-\frac{L_1}{v T_1}}\right) \int_0^{L_2} e^{-\frac{\ell}{v T_2^*}} \sin\left(\frac{\gamma H_1}{v} \ell\right) \frac{d\ell}{v} \quad (11)$$

where K is a constant

H_0 is the main magnetic field strength, a design constant

H_1 is the excitation field strength, controllable in the device

L_1 is the effective length of the H_0 field, chosen for each maximum range of flow.

L_2 is the effective length of the receiver coil, chosen for each minimum range of flow.

ℓ is the distance traveled by each element of the medium through the sensitive volume of the receiver coil; eq. 9

T_1 is the spin-lattice relaxation time of the medium which typically ranges between 1-5 seconds.

T_2^* is the effective free induction decay damping coefficient which typically varies between 50-500 msecs.

v is the velocity of each element of the velocity profile

[0043] If the L_1 magnetizing sections are long enough, i.e.

$$L_1 \gg v T_1 \quad (12)$$

and the L_2 receiver coil is short enough, i.e.

$$L_2 < \ll v T_2^* \quad (13)$$

5 then

$$M_T = KH_0 \left(\frac{1}{\gamma H_1} \right) \left(1 - \cos \frac{\gamma H_1 L_2}{v} \right) \quad (14)$$

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for each element of velocity v in each velocity profile.

[0044] For a velocity profile of mean value v within the receiver coil, the maximum net magnetization M_T (max) is:

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$$M_T = KH_0 \left(\frac{1}{\gamma H_1} \right) (2) \quad (15)$$

20 when

$$\frac{\gamma H_1 L_2}{v} = \pi \quad (16)$$

25

or

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$$v = \left(\frac{\gamma L_2}{\pi} \right) H_1 \quad (17)$$

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[0045] The minimum net magnetization is zero or minimum when

$$\frac{\gamma H_1 L_2}{v} = 2\pi \quad (18)$$

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or

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$$v = \left(\frac{\gamma L_2}{2\pi} \right) H_1 \quad (19)$$

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[0046] For protons $\gamma = 2\pi (4.26 \times 10^7)(\mu_0) \left(\frac{\text{sec} - \text{amp}}{\text{meter}} \right)^{-1}$ or

$$v = (4.26 \times 10^7)(4\pi \times 10^{-7}) L_2 H_1 \quad (20)$$

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$$v = 53.7 L_2 H_1$$

with H_1 in amp/meter. For a four cm wide receiver coil, for example,

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$$v = 2.14 H_1 \text{ meters/second} \quad (21)$$

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[0047] Thus, adjusting H_1 field strength to obtain a specified sideband signal yields the mean velocity of flow.

[0048] As is more completely shown in Wollin, U.S. Patent 5,757,187, symmetrical even spatial spin signal distributions produce only even order sidebands and asymmetrical odd distributions produce only odd order sidebands; from Fig. 7 (i) and

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$$J_{(-n)}(z) = -1^n J_n(z) \quad (22)$$

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[0049] (Jahnke, E.; Emde, F.; Tables of Functions, 4th edition, Dover Publications, New York 1945, p. 128.) Therefore, if the velocity profile is symmetrical, only even order sidebands will be present, making detection of the second sideband preferable, with a maximum value of

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$$J_n \left(\frac{\gamma h_\phi}{\Omega} \right) \cong J_2(3.2) \cong 0.49 \quad (23)$$

or

35

$$\frac{\gamma h_\phi}{\Omega} \cong 3.2 \quad (24)$$

40

and

$$h_\phi \cong \frac{3.2}{337} \Omega \cong .95 \times 10^{-2} \Omega \quad (25)$$

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[0050] The minimum value of the phase modulation frequency Ω must be greater than the band width $\Delta\omega_0$ of the Larmor frequency (Shenberg, Itzhak; Macovski, Albert, "Applications of time-varying gradients in existing magnetic resonance imaging systems"; Med. Phys., vol 13(2), p164-169 Mar 1982, N.Y., U.S., eq.3) which is determined by the homogeneity of the main magnetic field H_0 and any applied or intrinsic static gradients. $\Delta\omega_0$ also determines the minimum Johnson-Nyquist noise power P_a which is identical in each sideband Fig. 7(c) as

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$$P_a = K_b \tau \Delta\omega_0 \quad (26)$$

where K_b is Boltzmann's constant and τ is the absolute temperature.

[0051] Measurement of a mean velocity of flow in a flow profile does not require absence of turbulence. Linear components of fluid momentum perpendicular to the mean axis of flow do not appreciably affect magnetization by the uniform magnetic field H_0 , spin nutation by the uniform H_1 excitation r.f. Larmor field, or signal reception by the short receiver coil since such linear components are small compared to the mean fluid momentum. Relatively slow components of rotational momentum permit adiabatic spin alignment with the main magnetic field H_0 ("Principles of Magnetic Resonance," third edition chapter 4, by Slichter, C.P., Springer-Verlag, N.Y. 1989, p. 23) and should not significantly dephase the spins if the time of transit through the receiver coil is short. However, strong translational and rotational components of momentum producing "eddy currents" are known to produce signal loss (Cho, Z. et. al.; "Foundations of Medical Imaging," John Wiley & Sons, Inc., New York, 1993, p374-386) and are avoided by proper methods of meter pipe design and, if necessary, by flow conditioners, as is known to those skilled in the art. (Spitzer, David W. "Industrial Flow Measurement," Instrument Society of America, 1990, p. 97).

[0052] In the slower laminar regimens of flow, at low Reynolds numbers, the velocity profile may be mapped (U.S. 5,757,187 to Wollin) or the mean value determined as above. However, very slow flowing spins near the pipe wall will be subject to signal loss by T_1 and T_2^* effects, tending to increase the measured mean velocity of flow.

[0053] For a non-uniform velocity profile, at lower Reynold's numbers, the effect of varying H_1 on the signal distribution or signal mean value is far more complex and is more completely developed for both mapping or measurement in U.S. 5,532,5923 to Maneval and in U.S. 5,757,187 to Wollin.

[0054] Therefore, as is shown above, controlling the current in the H_1 excitation coil to produce a selected side band amplitude in the receiver circuit output measures the mean velocity of flow. Non-uniform velocity profiles may be mapped by continuously inverting the matrix equation containing the sideband amplitudes, approximately the integral Fig 7(i) (U.S. 5,757,187 to Wollin). Tuning the r.f. ω_0 generator for maximum power match between the H_1 excitation coil and the flowing medium yields an estimate of the chemical and physical composition of the flowing material (Slichter, op.cit.).

[0055] It should be noted while nuclear magnetic resonance methods have been described above, the principles and embodiments of this invention are applicable to either nuclear or electron magnetic resonance.

[0056] While the above description has been concerned with determining the velocity of fluid in pipe using a flow meter, the method and apparatus of the preferred embodiments of the present invention may be used to determine the velocity of a moving pipe in a fluid (i.e., a speedometer). Therefore, since the flow meter described above and illustrated in Figures 1-3 measures the relative velocity between a pipe and a fluid, the flow meter may be attached to a boat or other body moving in a fluid to determine the velocity of the boat or other moving body relative to a stationary or moving fluid.

[0057] Furthermore, the principles and embodiments of this invention apply not only to liquid or gas fluid flow in pipes, but also to flow of other fluid materials, such as mixtures, slurries, aggregates, blowing particles, viscous plastic as well as to the conveyance of solid material through a flow meter device.

[0058] Preferred embodiments of the invention have now been described. It will be appreciated by those skilled in the art that such embodiments are intended to exemplify the invention. Various other embodiments of the invention will be apparent, which fall within the scope of the invention, as defined by the appended claims.

Claims

1. A method of non-invasively determining a mean value of a relative velocity between a material and a container, comprising:

applying a strong time-invariant magnetic field H_0 to the container;
 applying a Larmor radio frequency excitation field H_1 to a detection section of said container, orthogonal to the H_0 field, for exciting spins within the material;
 applying a phase modulating periodic component h_ϕ , the component being periodic in time and of a frequency Ω much smaller than the Larmor frequency, to the strong time-invariant magnetic field H_0 over said detection section of the container;
 receiving signals from said spins in the material in the detection section of the container, the spins precessing about the magnetic field being phase modulated due to the presence of the phase modulating periodic field, thus giving rise to a line or band spectrum, consisting of sidebands equally distributed about the central Larmor frequency; and
 determining the mean velocity from said signals, the method being **characterised in that** the mean velocity is determined from the strength of said Larmor frequency excitation field necessary to obtain a specified sideband signal.

2. The method of claim 1, wherein said container comprises a cylindrical pipe and said detection section comprises a section of the pipe to which the field component h_ϕ and field H_1 are applied.

3. The method of claim 1, wherein said Larmor radio frequency excitation field H_1 is applied to a signal sensitive volume of a receiver coil tuned near a Larmor frequency ω_0 .

4. The method of claim 3, further comprising:

demodulating the signals from the phase-modulated magnetic resonance spins received by the receiver coil by convolution with the frequency of the Larmor frequency ω_0 excitation field H_1 ; and
detecting the demodulated signals by cross-correlation with integral multiples of the modulating frequency Ω of the phase modulating periodic field component h_ϕ , to continuously measure the relative mean velocity.

5. The method of claim 4, wherein the strength of the Larmor radio frequency excitation H_1 field is adjusted to produce a maximum, minimum, or other defined level of the signals detected by the receiver coil or coils.

6. The method of claim 5, further comprising:

shifting the Larmor frequency ω_0 of the H_1 excitation field to create an impedance match to the material moving within the container; and
measuring changes in chemical and physical composition of the moving material manifested by a shift of their Larmor frequency.

7. The method of claim 4, further comprising adjusting an amplitude of the phase modulating periodic field component h_ϕ of the magnetic field H_0 to achieve a maximum obtainable detected signal output.

8. The method of claim 2, wherein the material comprises a liquid or gas fluid moving along an axis of the pipe.

9. The method of claim 2, wherein the material comprises a slurry, aggregate, blowing particles, a viscous plastic or solid material moving along an axis of the pipe.

10. The method of claim 1, wherein the container moves with respect to the material, so that the velocity of the container is measured.

11. The method of claim 1 wherein the container is stationary.

12. The method of claim 1, wherein the Larmor radio frequency excitation field H_1 is a continuous, non-pulsed field.

13. The method of claim 3, wherein the receiver coil is wound orthogonal to an Larmor excitation field H_1 coil so as to decouple a noise from, and a signal from, the Larmor excitation field H_1 .

14. An apparatus for determining a mean value of a relative velocity between a material and a container (4), the apparatus comprising a container;

means (5) arranged to apply a strong time-invariant magnetic field H_0 to the container;

means (25) arranged to apply a phase modulating periodic component h_ϕ , the component being periodic in time, to the strong time-invariant magnetic field H_0 over a detection section of the container;

means (20, 28) arranged to apply a Larmor radio frequency excitation field H_1 to said detection section of said container, orthogonal to the H_0 field, for exciting spins within the material;

means (21) arranged to receive radio frequency signals from said spins within the material in the detection section of the container;

a sideband demodulation detector arranged to detect the amplitude of sidebands caused by spins precessing about the magnetic field and which are phase modulated due to the presence of the phase modulating periodic field, thus giving rise to a line or band spectrum, consisting of sidebands equally distributed about the central Larmor frequency;

characterized in that the apparatus comprises a velocity determining circuit arranged to determine the mean velocity from the strength of said Larmor frequency excitation field necessary to obtain a specified sideband signal.

15. A velocity measurement apparatus according to claim 14, wherein the container (4) is cylindrical;

the apparatus further comprising a receiving coil (21) adjacent to a detection section of the container as the means arranged to receive radio frequency signals;

and wherein the velocity determining circuit is electrically coupled to the receiving coil.

16. The apparatus of claim 15, wherein the means (5) arranged to apply a strong time-invariant magnetic field H_0 comprises permanent or resistive magnets (8, 9) located adjacent to the pipe or a solenoid magnet wound around the container.

17. The apparatus of claim 16, wherein the means arranged to apply a phase modulating periodic component h_ϕ comprises a coil (25) wound adjacent to said detection section of said container.

18. The apparatus of claim 17, wherein the means arranged to apply a Larmor radio frequency excitation field H_1 comprises a cylindrical or a bird cage radio frequency emitting coil (20) adjacent the detection section of said container.

19. The apparatus of claim 18, wherein the means (21) arranged to receive radio frequency signals is a receiver coil (21) wound orthogonal to the Larmor radio frequency excitation field H_1 emitting coil.

20. The apparatus of claim 15, wherein the velocity determining circuit comprises:

a Larmor frequency oscillator (28) for producing a Larmor frequency signal which is fed to a frequency divider and an amplifier;
the frequency divider supplying a reference phase modulation frequency to
a sideband detector arranged to detect an amplitude of sidebands of a signal received by the means for receiving radio frequency signals, the detection being performed by cross-correlation with integral multiples of the reference phase modulation frequency;
wherein the amplifier is arranged to provide an output velocity signal, the gain of the amplifier is controlled by the sideband detector, and the output of the amplifier is connected to the means arranged to apply a Larmor radio frequency signal.

Patentansprüche

1. Verfahren zur nichtinvasiven Bestimmung eines Mittelwerts einer Relativgeschwindigkeit zwischen einem Stoff und einem Behälter, beinhaltend:

das Anlegen eines starken zeitinvarianten Magnetfelds H_0 an den Behälter;
das Anlegen eines Larmor-Hochfrequenz-Anregungsfelds H_1 an einen Erfassungsabschnitt des genannten Behälters senkrecht zum H_0 -Feld zur Anregung von Spins im Stoff;
das Anwenden einer phasenmodulierenden periodischen Komponente h_ϕ , welche zeitlich periodisch ist und eine viel niedrigere Frequenz Ω als die Larmor-Frequenz aufweist, auf das starke zeitinvariante Magnetfeld H_0 über den genannten Erfassungsabschnitt des Behälters;
das Empfangen von Signalen der genannten Spins im Stoff im Erfassungsabschnitt des Behälters, wobei die um das Magnetfeld präzedierenden Spins infolge der Anwesenheit des phasenmodulierenden periodischen Felds phasenmoduliert sind und damit ein Linien- oder Bandspektrums entstehen lassen, das aus gleichmässig um die zentrale Larmor-Frequenz verteilten Seitenbändern besteht; und
das Bestimmen der mittleren Geschwindigkeit anhand der genannten Signale, wobei das Verfahren **dadurch gekennzeichnet ist, dass** die mittlere Geschwindigkeit aus der zur Erzeugung eines festgelegten Seitenbandsignals notwendigen Stärke des Larmorfrequenz-Anregungsfelds bestimmt wird.

2. Verfahren nach Anspruch 1, worin der genannte Behälter ein zylindrisches Rohr beinhaltet und der genannte Erfassungsabschnitt einen Abschnitt des Rohrs beinhaltet, an den die Feldkomponente h_ϕ und das Feld H_1 angelegt werden.

3. Verfahren nach Anspruch 1, worin das genannte Larmor-Hochfrequenz-Anregungsfeld H_1 an ein signalempfindliches Volumen einer auf die Nähe einer Larmor-Frequenz ω_0 abgestimmten Empfangsspule angelegt wird.

4. Verfahren nach Anspruch 3, weiter beinhaltend:

das Demodulieren der von der Empfangsspule empfangenen Signale der phasenmodulierten magnetischen Resonanzspins durch Faltung mit der Frequenz des Anregungsfelds H_1 der Larmor-Frequenz ω_0 ; und
die Erfassung der demodulierten Signale durch Kreuzkorrelation mit ganzzahligen Mehrfachen der Modulationsfrequenz Ω der phasenmodulierenden periodischen Feldkomponente h_ϕ zur kontinuierlichen Messung der

mittleren Relativgeschwindigkeit.

5 5. Verfahren nach Anspruch 4, worin die Stärke des Larmor-Hochfrequenz-Anregungsfelds H_1 so eingestellt wird, dass ein Maximal-, Minimal- oder ein anderer definierter Pegel der von der Empfangsspule oder den -spulen erfassten Signale erzeugt wird.

6. Verfahren nach Anspruch 5, weiter beinhaltend:

10 das Verschieben der Larmor-Frequenz ω_0 des H_1 -Anregungsfelds, um eine Impedanzanpassung an den sich im Behälter bewegendenden Stoff zu erzielen; und
die Messung von Veränderungen der chemischen oder physikalischen Zusammensetzung des bewegten Stoffs durch eine Verschiebung von deren Larmor-Frequenz.

15 7. Verfahren nach Anspruch 4, weiter beinhaltend die Einstellung einer Amplitude der phasenmodulierenden periodischen Feldkomponente h_ϕ des Magnetfelds H_0 derart, dass ein grösstmögliches erfassbares Ausgangssignal erhalten wird.

20 8. Verfahren nach Anspruch 2, worin der Stoff eine Flüssigkeit oder ein Gas beinhaltet, welche(s) sich entlang der Rohrachse bewegt.

9. Verfahren nach Anspruch 2, worin der Stoff Schlamm, Stoffgemische, geblasene Partikel, zähflüssige plastische oder feste Stoffe beinhaltet, welche sich entlang der Rohrachse bewegen.

25 10. Verfahren nach Anspruch 1, worin der Behälter sich in Bezug auf den Stoff bewegt, so dass die Geschwindigkeit des Behälters gemessen wird.

11. Verfahren nach Anspruch 1, worin der Behälter ortsfest ist.

30 12. Verfahren nach Anspruch 1, worin das Larmor-Hochfrequenz-Anregungsfeld H_1 ein kontinuierliches, un gepulstes Feld ist.

13. Verfahren nach Anspruch 3, worin die Empfangsspule senkrecht zu einer Spule für das Larmor-Anregungsfeld H_1 gewickelt ist, um Störgeräusch sowie Signal vom Larmor-Anregungsfeld H_1 zu entkoppeln.

35 14. Apparat zur Bestimmung eines Mittelwerts einer Relativgeschwindigkeit zwischen einem Stoff und einem Behälter (4), wobei der Apparat einen Behälter beinhaltet;

Mittel (5) zum Anlegen eines starken zeitinvarianten Magnetfelds H_0 an den Behälter;

Mittel (25) zum Anwenden einer phasenmodulierenden periodischen Komponente h_ϕ , welche zeitlich periodisch ist, auf das starke zeitinvariante Magnetfeld H_0 über einen Erfassungsabschnitt des Behälters;

40 Mittel (20, 28) zum Anlegen eines Larmor-Hochfrequenz-Anregungsfelds H_1 an den genannten Erfassungsabschnitt des genannten Behälters senkrecht zum H_0 -Feld zur Anregung von Spins im Stoff;

Mittel (21) zum Empfang von Radiofrequenzsignalen der genannten Spins im Stoff im Erfassungsabschnitt des Behälters;

45 einen Seitenband-Demodulationsdetektor zur Erfassung der Amplitude von Seitenbändern, welche durch Spins erzeugt werden, die um das Magnetfeld präzedieren und infolge der Anwesenheit des phasenmodulierenden periodischen Felds phasenmoduliert sind und damit zur Entstehung eines Linien- oder Bandspektrums führen, das aus gleichmässig um die zentrale Larmor-Frequenz verteilten Seitenbändern besteht;

50 **dadurch gekennzeichnet, dass** der Apparat eine Geschwindigkeitsbestimmungsschaltung zur Bestimmung der mittleren Geschwindigkeit anhand der zur Erzeugung eines festgelegten Seitenbandsignals notwendigen Stärke des Larmor-Frequenz-Anregungsfelds beinhaltet.

55 15. Geschwindigkeitsmessapparat nach Anspruch 14, worin der Behälter (4) zylindrisch ist; wobei der Apparat als Mittel zum Empfang von Radiofrequenzsignalen weiter eine an einen Erfassungsabschnitt des Behälters angrenzende Empfangsspule (21) beinhaltet; und worin die Geschwindigkeitsbestimmungsschaltung mit der Empfangsspule elektrisch gekoppelt ist.

16. Apparat nach Anspruch 15, worin das Mittel (5) zum Anlegen eines starken zeitinvarianten Magnetfelds H_0 an das Rohr angrenzende Permanent- oder Widerstandsmagnete (8, 9) oder einen um den Behälter gewickelten Elektro-

magneten beinhaltet.

17. Apparat nach Anspruch 16, worin das Mittel zum Anlegen einer phasenmodulierenden periodischen Komponente h_φ eine an den genannten Erfassungsabschnitt des genannten Behälters angrenzend gewickelte Spule (25) beinhaltet.

18. Apparat nach Anspruch 17, worin das Mittel zum Anlegen eines Larmor-Hochfrequenz-Anregungsfelds H_1 eine an den Erfassungsabschnitt des genannten Behälters angrenzende zylindrische oder Bird Cage-Hochfrequenz-Sendespile (20) beinhaltet.

19. Apparat nach Anspruch 18, worin das Mittel (21) zum Empfang von Radiofrequenzsignalen eine senkrecht zur Sendespile für das Larmor-Radiofrequenz-Anregungsfeld H_1 gewickelte Empfangsspule (21) ist.

20. Apparat nach Anspruch 15, worin die Geschwindigkeitsbestimmungsschaltung beinhaltet:

einen Larmor-Frequenz-Oszillator (28) zur Erzeugung eines Larmor-Frequenz-Signals, welches einem Frequenzteiler und einem Verstärker zugeführt wird;
wobei der Frequenzteiler eine Referenz-Phasenmodulationsfrequenz liefert für einen Seitenband-Detektor zur Erfassung einer Amplitude von Seitenbändern eines vom Mittel zum Empfang von Hochfrequenzsignalen empfangenen Signals, wobei die Erfassung durch Kreuzkorrelation mit ganzzahligen Mehrfachen der Referenz-Phasenmodulationsfrequenz erfolgt;
worin der Verstärker in der Lage ist, ein Geschwindigkeits-Ausgangssignal zu liefern, die Verstärkung des Verstärkers durch den Seitenband-Detektor gesteuert wird und der Ausgang des Verstärkers mit dem Mittel zum Anlegen eines Larmor-Hochfrequenzsignals verbunden ist.

Revendications

1. Procédé de détermination non invasive d'une valeur moyenne d'une vitesse relative entre une matière et un récipient, comprenant:

l'application d'un champ magnétique puissant H_0 temporellement invariant au récipient;
l'application d'un champ d'excitation radiofréquence de Larmor H_1 à une section de détection dudit récipient, orthogonalement au champ H_0 , afin d'exciter des spins dans la matière;
l'application d'une composante périodique modulatrice de phase h_φ , ladite composante étant périodique dans le temps et ayant une fréquence Ω largement inférieure à la fréquence de Larmor, au champ magnétique puissant H_0 temporellement invariant sur ladite section de détection du récipient;
la réception de signaux desdits spins dans la matière dans la section de détection du récipient, les spins précessant autour du champ magnétique étant modulés en phase à raison de la présence du champ périodique modulateur de phase, engendrant ainsi un spectre de raies ou de bandes constitué de bandes latérales distribuées uniformément autour de la fréquence de Larmor centrale; et
la détermination de la vitesse moyenne à partir desdits signaux, le procédé étant **caractérisé en ce que** la vitesse moyenne est déterminée sur la base de la puissance dudit champ d'excitation à fréquence de Larmor nécessaire pour obtenir un signal à bande latérale spécifié.

2. Procédé selon la revendication 1, où ledit récipient comprend un tube cylindrique et ladite section de détection comprend une section du tube à laquelle sont appliqués la composante de champ h_φ et le champ H_1 .

3. Procédé selon la revendication 1, où ledit champ d'excitation radiofréquence de Larmor H_1 est appliqué à un volume sensible aux signaux d'une bobine réceptrice accordée à proximité d'une fréquence de Larmor ω_0 .

4. Procédé selon la revendication 3, comprenant en outre:

la démodulation des signaux des spins en résonance magnétique modulés en phase reçus par la bobine réceptrice par convolution avec la fréquence du champ d'excitation H_1 à fréquence de Larmor ω_0 ; et
la détection des signaux démodulés par corrélation croisée avec des multiples entiers de la fréquence de modulation Ω de la composante de champ modulatrice de phase périodique h_φ afin de mesurer continuellement la vitesse relative moyenne.

5. Procédé selon la revendication 4, où la puissance du champ d'excitation radiofréquence de Larmor H_1 est réglée de manière à produire un niveau maximum, minimum ou un autre niveau défini des signaux détectés par la bobine ou les bobines de réception.

5 6. Procédé selon la revendication 5, comprenant en outre:

le décalage de la fréquence de Larmor ω_0 du champ d'excitation H_1 de manière à créer une adaptation d'impédance à la matière se déplaçant à l'intérieur du récipient; et
la mesure de changements de la composition chimique et physique de la matière en déplacement manifestés par un décalage de leur fréquence de Larmor.

7. Procédé selon la revendication 4, comprenant en outre le réglage d'une amplitude de la composante de champ périodique modulatrice de phase h_ϕ du champ magnétique H_0 de manière à obtenir un signal de sortie détecté qui soit le maximum pouvant être atteint.

8. Procédé selon la revendication 2, où la matière comprend un liquide ou un gaz se déplaçant le long d'un axe du tube.

9. Procédé selon la revendication 2, où la matière comprend une bouillie, un agrégat, des particules soufflées, une matière plastique ou solide visqueuse se déplaçant le long d'un axe du tube.

10. Procédé selon la revendication 1, où le récipient se déplace par rapport à la matière, de sorte que la vitesse du récipient est mesurée.

11. Procédé selon la revendication 1, où le récipient est stationnaire.

12. Procédé selon la revendication 1, où le champ d'excitation radiofréquence de Larmor H_1 est un champ continu non pulsé.

13. Procédé selon la revendication 3, où la bobine réceptrice est enroulée orthogonalement à une bobine pour le champ d'excitation de Larmor H_1 de manière à découpler du champ d'excitation de Larmor H_1 un bruit ainsi qu'un signal.

14. Appareil pour déterminer une valeur moyenne d'une vitesse relative entre une matière et un récipient (4), l'appareil comprenant un récipient;

des moyens (5) agencés de sorte à appliquer au récipient un champ magnétique puissant H_0 temporellement invariant;

des moyens (25) agencés de sorte à appliquer au champ magnétique puissant H_0 temporellement invariant sur une section de détection du récipient une composante périodique modulatrice de phase h_ϕ , ladite composante étant périodique dans le temps;

des moyens (20, 28) agencés de sorte à appliquer un champ d'excitation radiofréquence de Larmor H_1 à ladite section de détection dudit récipient, orthogonalement au champ H_0 , afin d'exciter des spins dans la matière;

des moyens (21) agencés de sorte à recevoir des signaux radiofréquence desdits spins dans la matière dans la section de détection du récipient;

un détecteur à démodulation des bandes latérales agencé de sorte à détecter l'amplitude de bandes latérales créées par des spins précessant autour du champ magnétique et qui sont modulés en phase à raison de la présence du champ périodique modulateur de phase, engendrant ainsi un spectre de raies ou de bandes constitué de bandes latérales distribuées uniformément autour de la fréquence de Larmor centrale;

caractérisé en ce que l'appareil comprend un circuit de détermination de la vitesse agencé de sorte à déterminer la vitesse moyenne sur la base de la puissance dudit champ d'excitation à fréquence de Larmor nécessaire pour obtenir un signal à bande latérale spécifié.

15. Appareil de mesure de la vitesse selon la revendication 14, où le récipient (4) est cylindrique; l'appareil comprenant en outre une bobine réceptrice (21) adjacente à une section de détection du récipient en tant que moyen agencé de sorte à recevoir des signaux radiofréquence; et où le circuit de détermination de la vitesse est électriquement couplé à la bobine réceptrice.

16. Appareil selon la revendication 15, où le moyen (5) agencé de sorte à appliquer un champ magnétique puissant H_0 temporellement invariant comprend des aimants permanents ou résistifs (8, 9) adjacents au tube ou un aimant solénoïde enroulé autour du récipient.

17. Appareil selon la revendication 16, où le moyen agencé de sorte à appliquer une composante périodique modulatrice de phase h_{ϕ} comprend une bobine (25) enroulée à côté dudit récipient.

18. Appareil selon la revendication 17, où le moyen agencé de sorte à appliquer un champ d'excitation radiofréquence de Larmor H_1 comprend une bobine émettrice (20) de radiofréquence cylindrique ou en cage d'oiseau adjacente à la section de détection dudit récipient.

19. Appareil selon la revendication 18, où le moyen (21) agencé de sorte à recevoir des signaux radiofréquence est une bobine réceptrice (21) enroulée orthogonalement à la bobine émettrice du champ d'excitation radiofréquence de Larmor H_1 .

20. Appareil selon la revendication 15, où le circuit de détermination de la vitesse comprend:

un oscillateur à fréquence de Larmor (28) pour produire un signal à fréquence de Larmor, qui est alimenté à un diviseur de fréquence et à un amplificateur;
le diviseur de fréquence fournissant une fréquence référence de modulation de phase à un détecteur de bandes latérales agencé de sorte à détecter une amplitude des bandes latérales d'un signal reçu par le moyen de réception de signaux radiofréquence, la détection étant effectuée par corrélation croisée avec des multiples entiers de la fréquence référence de modulation de phase;
où l'amplificateur est agencé de sorte à fournir un signal de sortie de vitesse, le gain de l'amplificateur est commandé par le détecteur de bandes latérales et la sortie de l'amplificateur est reliée au moyen agencé de sorte à appliquer un signal radiofréquence de Larmor.

FIG. 1

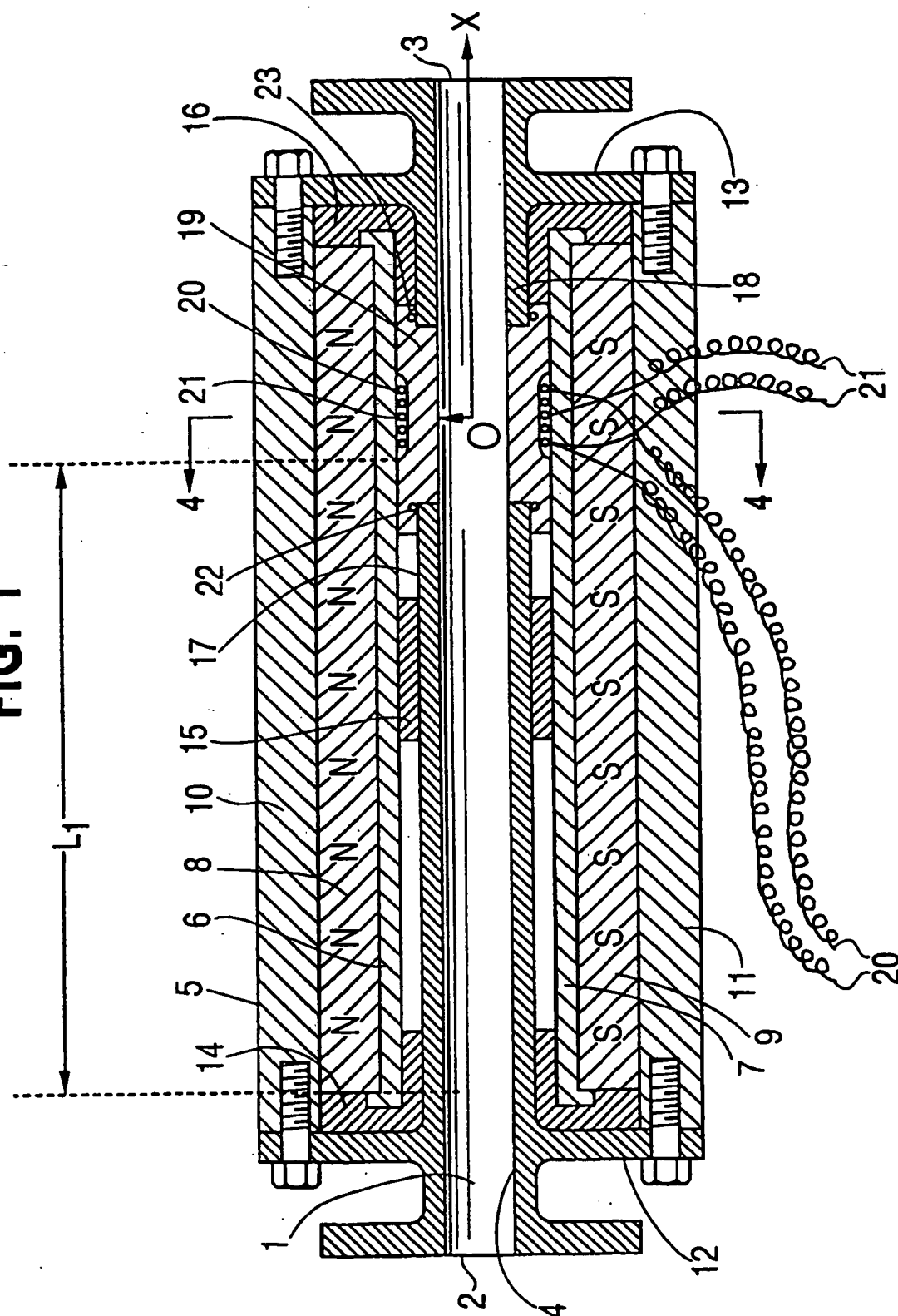


FIG. 2

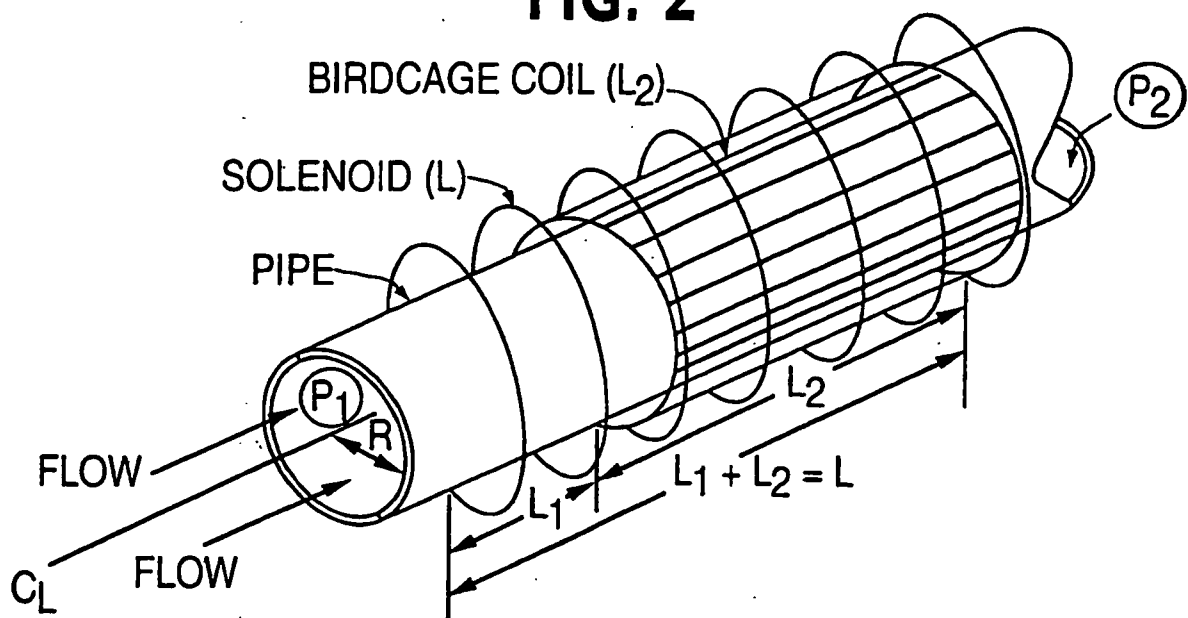


FIG. 3

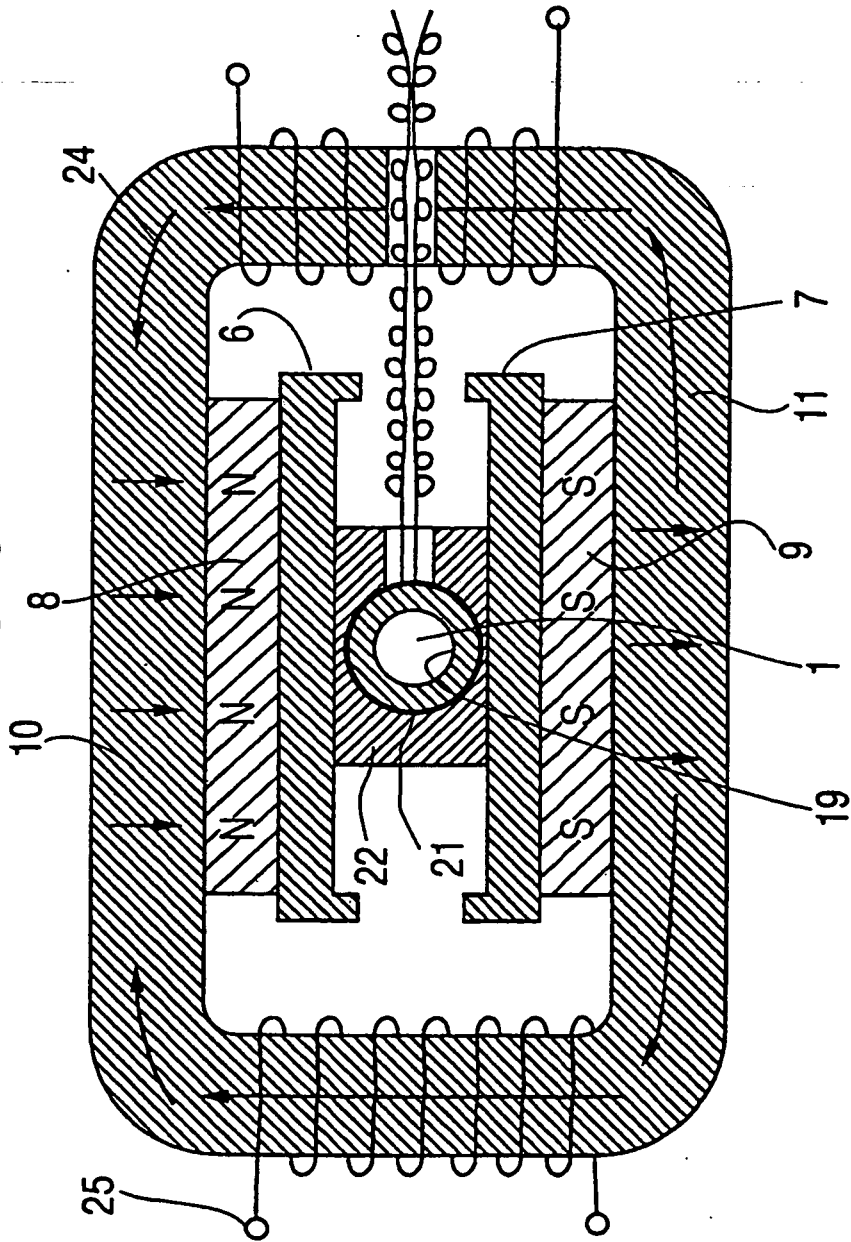


FIG. 4

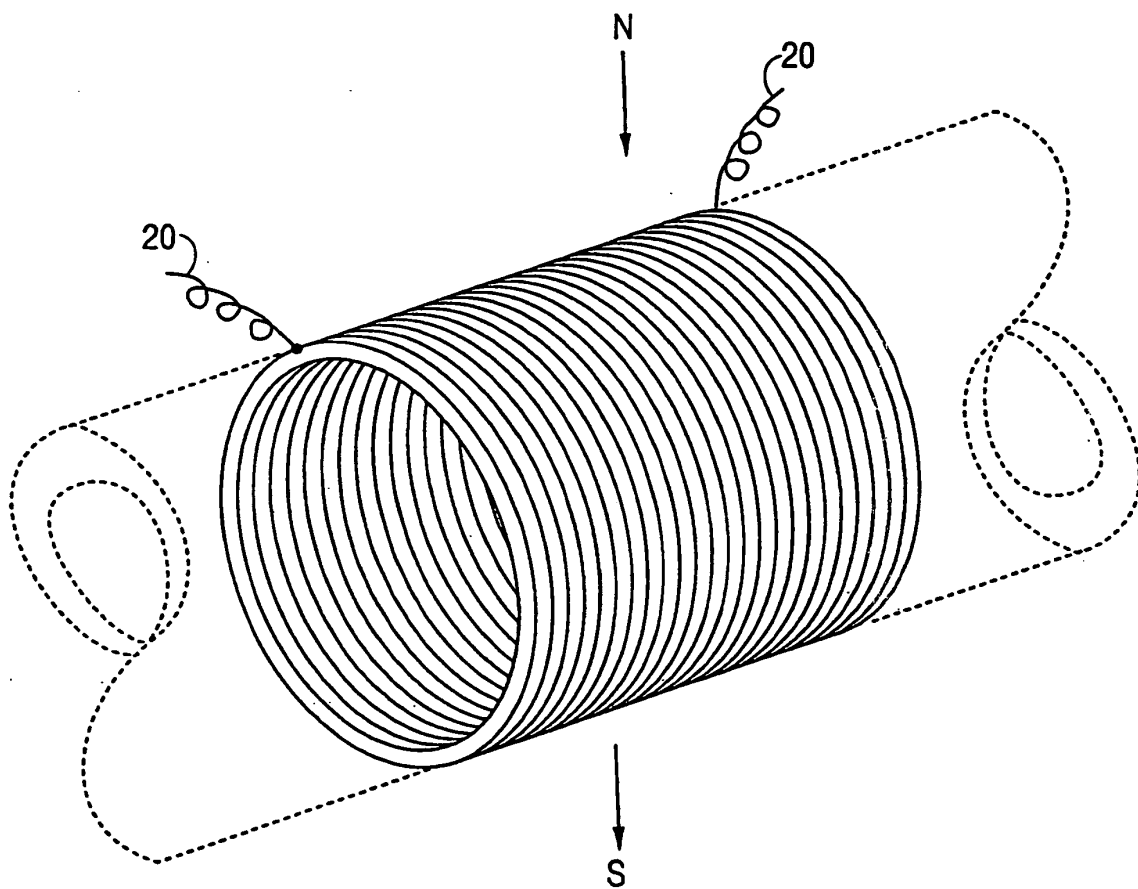


FIG. 5

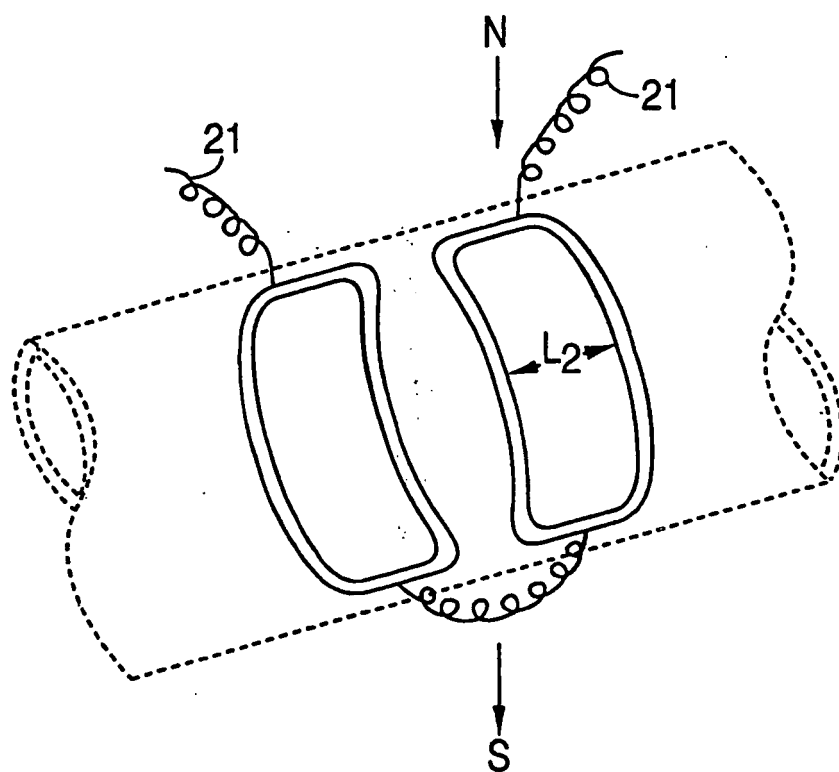


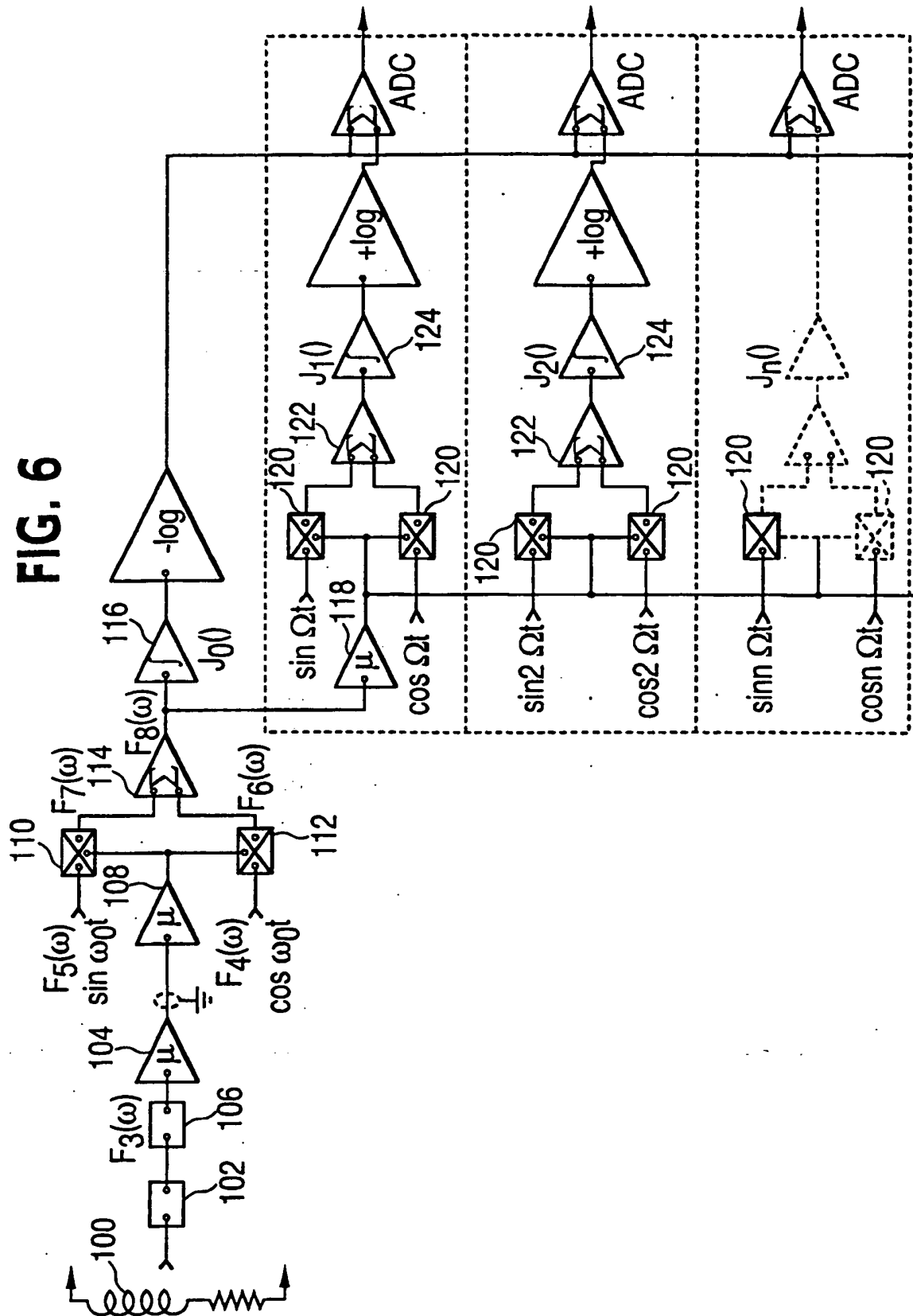
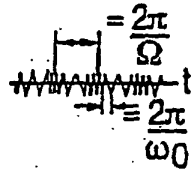
FIG. 6

FIG. 7a



$$f_1(t) = m_x \cos[(\gamma G_x) \sin \Omega t + \omega_0 t] \text{ FOR EACH LOCATION } x$$

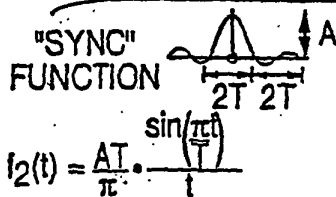
m_x IS THE SPIN DENSITY at x

ω_0 IS THE LARMOR FREQUENCY

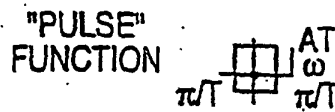
Ω IS THE PHASE-MODULATING GRADIENT FREQUENCY

$$F_1(\omega) = \pi \sum_{n=-\infty}^{+\infty} [m_x J_n(\gamma G_x) \delta(\omega - \omega_0 + n\Omega)]$$

FIG. 7b

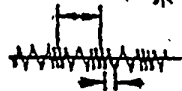


$$f_2(t) = \frac{AT}{\pi} \cdot \frac{\sin(\pi t/T)}{t}$$

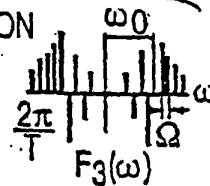


$$F_2(\omega) = (AT) P_{\pi T}(\omega)$$

FIG. 7c

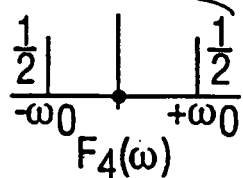


$*$ = CONVOLUTION



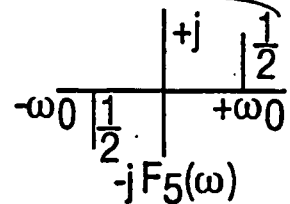
$$f_3(t) = f_1(t) \cdot f_2(t); \text{ } \mathcal{F} f_3(t) = F_1(\omega) * F_2(\omega) \triangleq F_3(\omega)$$

FIG. 7d

$$f_4(t) = \cos \omega_0 t = \frac{1}{2} e^{j\omega_0 t} + \frac{1}{2} e^{-j\omega_0 t}$$


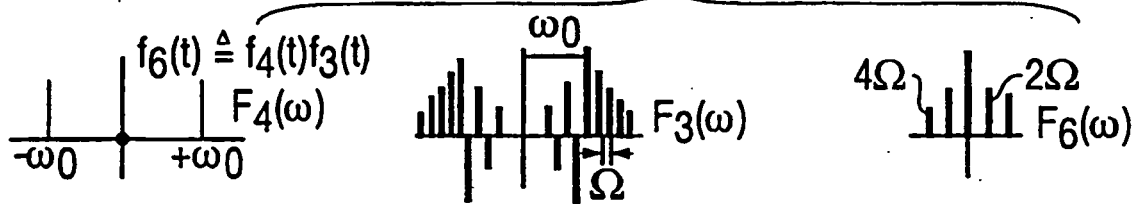
$F_4(\omega)$

FIG. 7e

$$f_5(t) = \sin \omega_0 t = \frac{1}{2j} e^{j\omega_0 t} - \frac{1}{2j} e^{-j\omega_0 t}$$


$F_5(\omega)$

FIG. 7f

$$f_6(t) \triangleq f_4(t) f_3(t)$$


$F_4(\omega)$ $F_3(\omega)$ $F_6(\omega)$

$$\mathcal{F} \{ f_4(t) \cdot f_3(t) \} = F_4(\omega) * F_3(\omega) = F_6(\omega)$$

FIG. 7g

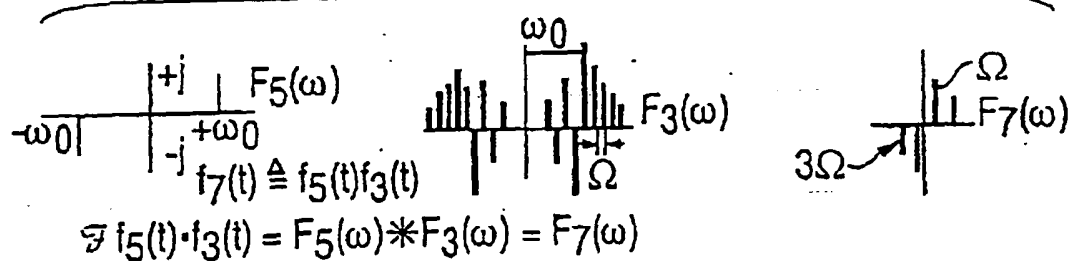


FIG. 7h

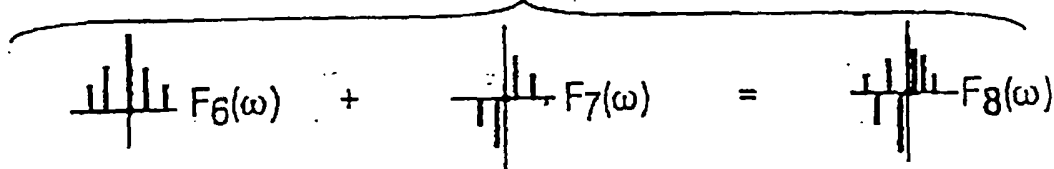


FIG. 7i

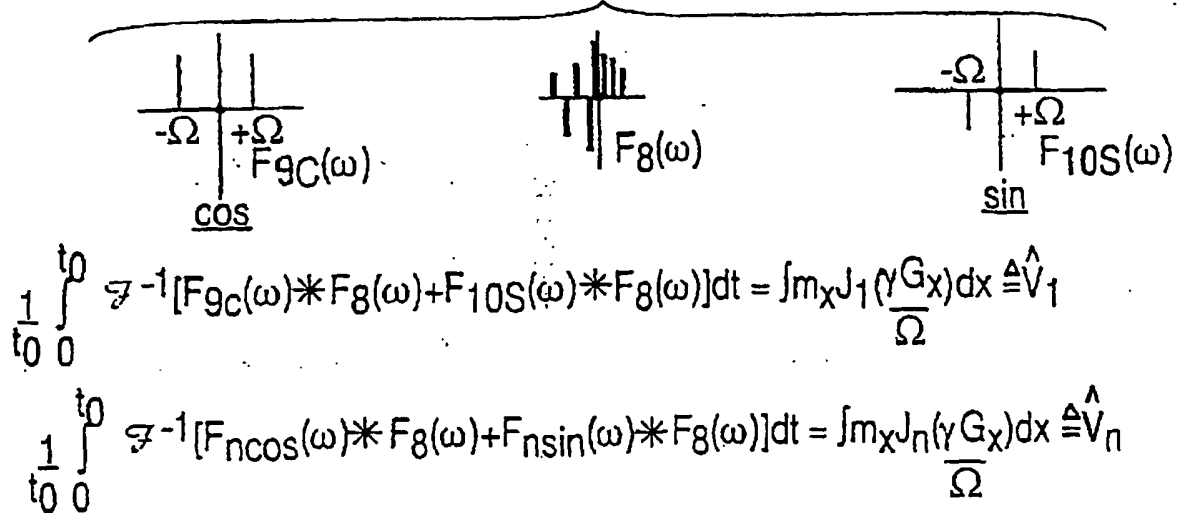


FIG. 8

