Magnetic Actuators in order to study Faraday Force

Takuo Sakon, Seiji Nitabaru, Takahiro Higasa, Yasushi Hara and Keisuke Nakagawa

Department of Mechanical and System Engineering,
Faculty of Science and Technology,
Ryukoku University, 1-5Yokotani, Seta,
Otsu City, Shiga Pref., 520-2194, Japan

Email: sakon@rins.ryukoku.ac.jp

(*Submitted:* 13-May-2016)

Abstract

We developed basic magnetic actuators that use the Faraday force by the magnetic field gradient. These actuators can be used in physics experiments for physics or engineering students. A conical coil was made by winding up a copper wire around a polyimide tube; electric current through the coil induces a magnetic field. Using magnetic actuators, students can study the relationship between the magnetic field gradient and Faraday force.

Keywords: Faraday force, magnetic field gradient, ferromagnet.

1. Introduction

Understanding magnetic force is one barrier to dealing with electromagnetism. In the subfield of condensed matter physics that investigates strongly correlated 4*f* and 5*f* electrons systems, electric field gradients are used to explain the interactions in electric quadrupoles and octapoles of atoms and ions. In regard to magnetic forces, the phenomenon of a magnet attaching to an iron plate occurs due to the magnetic field gradient. This article describes experiments conducted using coils and small iron rods that students can perform to understand the relationship between magnetic force and magnetic field gradient. Conducting wire was wound around a thin pipe made of polyimide resin to make a coil. A magnetic field and a magnetic field gradient were produced by passing an AC current through the coil. A small metal rod placed in the pipe vibrates on the application of current. In this experiment, magnetic force and potential from a magnetic field in the coil, which was generated by AC current and a magnetic field gradient, and the quantitative consideration reached about a phenomenon to vibrate. The magnetic force caused by the magnetic field gradient causes a magnet to attaches to magnetic bodies such as iron. The magnetic force called as Faraday force is written as [1]

$$F_m = \frac{1}{2}\frac{\chi_m}{\mu_0}\frac{\partial B^2}{\partial x}V = \left(\frac{\chi_m}{\mu_0}V\right)\cdot B\frac{\partial B}{\partial x} \qquad (1)$$

where χ_m is magnetic susceptibility, V is the volume [m^3], B is the magnetic flux density [T], and μ_0 is the magnetic permeability of vacuum.

Several scientific apparatuses use magnetic field gradients, for example, apparatuses for magnetic measurement, magnetic field generators, and nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) apparatuses.

1. Magnetization measuring system using a magnetic field gradient.
Capacitance-type magnetometers can be used to measure magnetization [2].A large magnetic field gradient occurs in the centre of the main coil where the sample is placed. The sample then experiences a large magnetic force in proportion to magnetization, which causes it to displace. The displacement is measured using by the capacitance method, and the magnetization is inferred based on the displacement.

2. Local large magnetic field generator [3].
A magnetic field generator that can produce a large magnetic field of the sub-tesla degree in the minute domain of the nanometre degree. A magnetic field gradient of up to 1MT/m was produced by diverting an electric current to each conducting wire.

3. NMR and MRI instruments.
NMR and MRI instruments, which are used in research and clinical settings, have a magnetic field gradient (slant magnetic field) coil [4].For example, for medical usage, the magnetic resonance of internal protons (hydrogen atoms) of the patient is important, but the magnetic field at which a proton resonates is fixed and the position of the proton that resonates is identified by generating a gradient in the magnetic field using a magnetic field gradient coil. Because water is easy to collect, the position of the affected part can be identified by the magnetic resonance phenomenon of the proton.

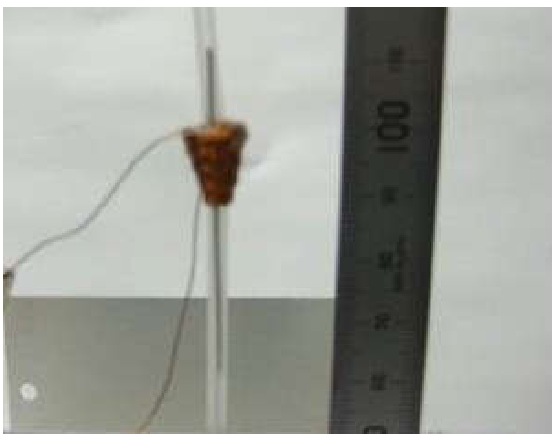
The abovementioned examples are of instruments that use magnetic field gradients and applied magnetic fields, but from a standpoint of the magnetic engineering, the application of a magnetic field to a trembler and a magnetism actuator is more interesting.

In this study, we developed a magnetic actuator that uses the magnetic force generated by a magnetic field gradient, which can be used in physics experiments for physics or engineering students. Specifically, we fabricated a conical coil by winding a copper wire around a polyimide tube and passed an electric current through the copper wire. Because a magnetic field is generated inside a coil when an electric current was applied to the coil, a rod placed in the coil vibrates. Thus, a magnetic actuator that uses this vibration phenomenon was developed.

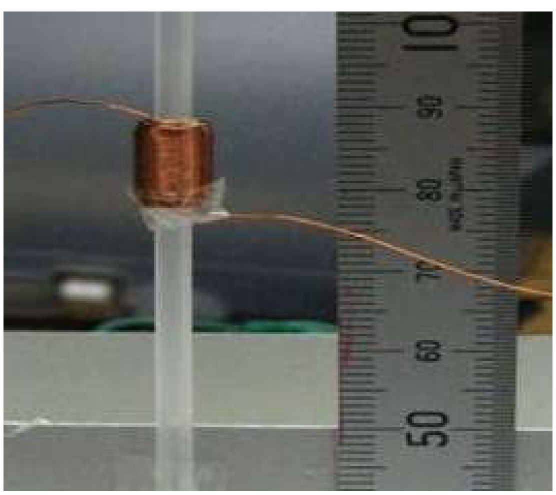
2. Experimental, Results and Discussion

2.1. Vertical magnetic actuators

To observe the Faraday force, two kinds of coils were used. One was a conical coil and the other was a uniform winding coil. Both coils were made by using polyimide-coated copper wire (0.2 mm in diameter) wound around a thin plastic cylinder that has a 2.5mm outside diameter and a 1.6mm inside diameter, as shown in Figure 1. For making the conical coil, copper wire was wound up at the first level 50 volumes, the second level 45 volumes,..., the 5th level 30 volumes, the 6th level 20 volumes, the 7th level 15 volumes,..., and the 9th level 5 volumes. The total number of volumes was250. The uniform winding coil was wound 50 volumes at5 levels. The electrical resistivity of each coil was 2.5 Ω. Both the coils have the same number of total volumes (250). When an AC current with a maximum value of 0.28 A and a frequency of 5.0 Hz was applied to the conical coil, an iron rod (Niraco Co., Ltd., Tokyo, Japan) placed in the coil (rod diameter 0.8 mm; rod length 50 mm) vibrated in the air, as shown in Figure 1(a). However, when the same AC current was applied to the uniform coil, as shown in Figure 1(b), the iron rod fell out of the tube. This is due to a pulling force (Faraday force) that acted on the iron rod in the conical coil. The iron-rod vibration amplitude was 4.8 $\times 10^{-3}$ m and the frequency was 10.0 Hz.



(a)



(b)

FIG. 1:(a) Conical coil.(b) Uniform winding coil.

The vibration of the iron rod was recorded on video. Students can use the video to determine the acceleration of the iron rod by noting the position of the top of the rod in several scenes as well as the corresponding times. The angular frequency ω is equal to $2\pi f$ = 62.8 Hz. Therefore, the acceleration a is$A\omega^2$ = 19.0 m/s^2. The Faraday force F_m is written as

$$F_m = ma_m = m(a+g) \quad (2)$$

Where m is mass of the iron rod (46.3 mg = 4.63×10^{-5} kg), a_m is an acceleration due to the Faraday force, and g is the acceleration due to gravity (9.80 m/s^2). Therefore, the Faraday force F_m is 1.30×10^{-3} N. The value of a_m is 28.8 m/s^2, which is three times larger than that of the acceleration due to gravity. Consequently, a conical coil is useful for magnetic levitation and as a vertical magnetic actuator.

2.2 Horizontal magnetic actuators

2.2.1 Experimental results

The vertical magnetic actuator in Section 2.1 is designed to vibrate vertically. Actuators vibrating horizontally or in oblique direction can also be useful. Two horizontal magnetic actuators were produced and tested. If a conical coil that is identical with the one used in vertical magnetic actuator is used, the rod will experience on only a pulling force into the coil, resulting in movement in one direction. To try to cause an iron rod to vibrate horizontally, two conical coils were used, as shown in Figure 2.

The sample was a 99.95% pure iron rod (Niraco Co., Ltd., Tokyo, Japan), which had a diameter of0.80 mm in diameter, a length L *of* 65.0 mm, and a mass m of 0.2597 g. In regard to the conical coil, copper wire was wound on the polyimide tube, the first level 100 volumes, the second level 95 volumes,..., the 11th level 55 volumes, the 12th level 45 volumes, the 13th level 40 volumes,..., and the 20th level 5 volumes. The total number of volumes was 1,000. The uniform winding coil was wound 100 volumes and 10 levels, with a total number of 1,000 volumes, as shown in Figure 3, in order to compare with the conical coils. The dimensions of the conical coils were 2.0 mm outer diameter, 1.7 mm inner diameter, and 20 mm width. The electrical resistivity of each coil was 11.0Ω.

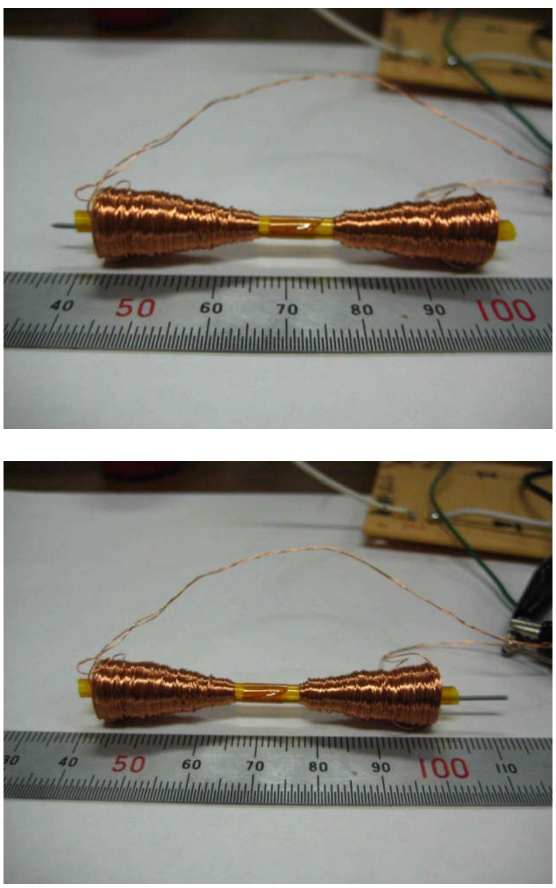


FIG. 2: Actuation of the iron rod by means of two conical coils with a frequency of 5.00 Hz and a function generator voltage output of 1.50 V_{pp}.

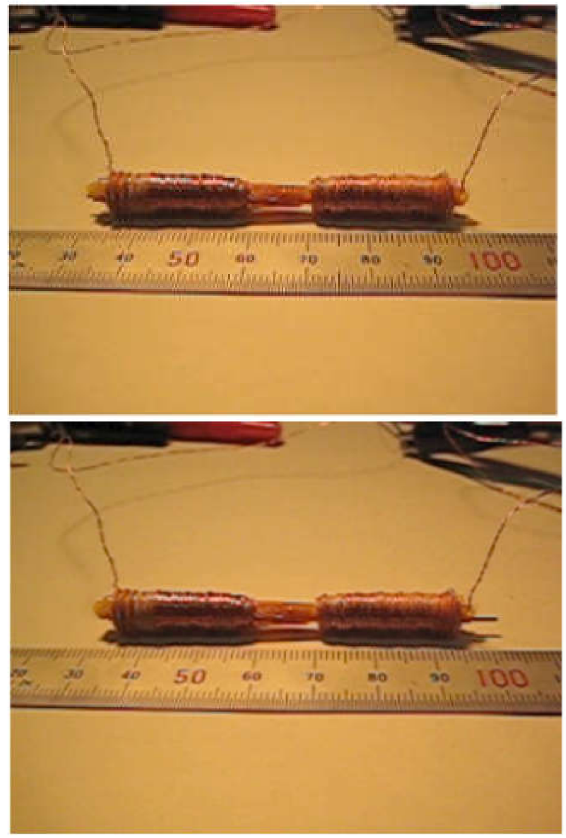


FIG. 3: Actuation of the iron rod by means of two coil of uniform winding with a frequency of 5.00 Hz and a function generator voltage output of 1.50 V_{pp}.

The circuit for the magnetic actuator is shown in Figure 4. Sine wave voltages were generated using a function generator (NI WF 1943, Yokohama, Japan). An audio amplifier (Marantz PM-17,Chofu, Japan) was also used to stabilize the output voltage. The coils were connected to the audio amplifier via speaker outputs. Diodes were used for half-wave rectification. Therefore, when the L coil was turned on and the magnetic fields applied to the iron rod, the R coil had no current. The results are shown in Table 1. The amplitudes Δx of the conical coil actuator were twice those of the uniform winding coil actuator. This result indicates that the conical coil is effective as a magnetic actuator.

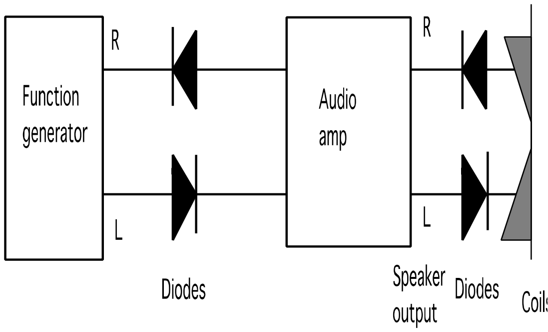


FIG. 4: Circuit for the magnetic actuator.

Table 1. Frequency and voltage dependences of the amplitude of vibration Δx.

Frequency f [Hz]	Function generator output Vo_{pp} [V]	Coil voltage Va_{pp} [V]	Uniform winding coil Δx [mm]	Conical coil Δx [mm]
3.00	1.40	2.10	0	6
3.00	1.50	2.50	8	15
4.00	1.40	2.10	5	7
4.00	1.50	2.50	8	18
4.00	1.60	2.90	10	stray out
5.00	1.40	2.10	4	5
5.00	1.50	2.50	8	19
5.00	1.60	2.90	14	stray out

2.2.2 Analysis of the Faraday force

The values of the Faraday force and potential were calculated by using Equation (1). In order to calculate the force, the magnetic susceptibility of their on rod is needed. The magnetic susceptibility was obtained using the magnetization of the rod at various magnetic fields, as shown in Figure 5.From Figure 5, the magnetic susceptibility χ_m was determined to be 5.65. The unit of Wb/m^2 is equal to the unit of T. The density of magnetic flux B [T] is written using the magnetic fields $\mu_0 H$ [T] and the magnetization M [Wb/m^2] as

$$B = \mu_0 H + M \tag{2}$$

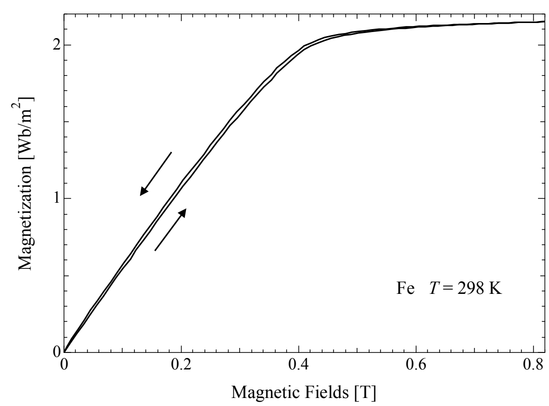
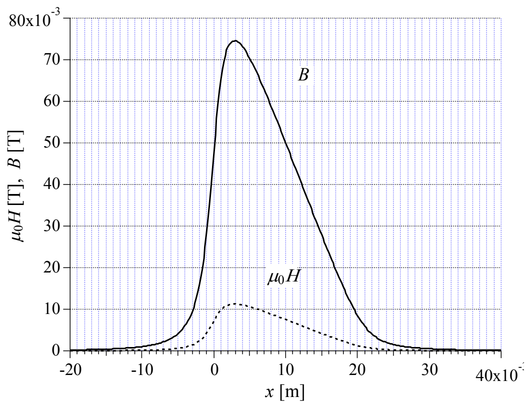


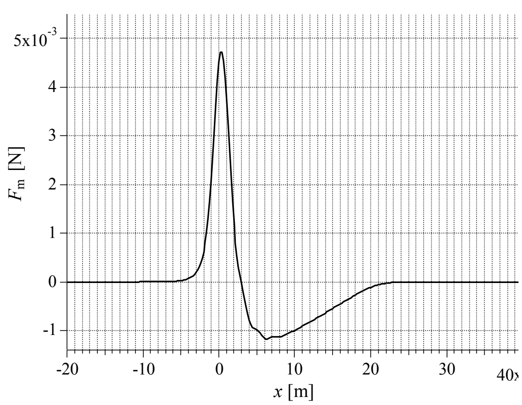
FIG. 5: Magnetization of an iron sample in various magnetic fields.

The calculated results of the magnetic field $\mu_0 H$(by using Biot–Savart law and the density of the magnetic flux B),the Faraday force acting on the iron rod, and the magnetic potential are shown in Figure 6 (conical coil actuator) and Figure 7 (uniform coil actuator). The Faraday force acting on the iron rod in the conical coil is 6.23×10^{-3} N (0.623 gram-force, gf). On the other hand, the Faraday force acting on the iron rod in the uniform winding coil is 2.46×10^{-3} N (0.246 gf). The Faraday force in the conical coil is two and half times larger than that in the uniform winding coil. Moreover, the distance between the lowest points of the potential of the conical coils is longer than that of the uniform coils. Consequently, the range of motion of the iron rod for the conical coils is larger than that for the uniform coils, as determined by experiments and calculations.

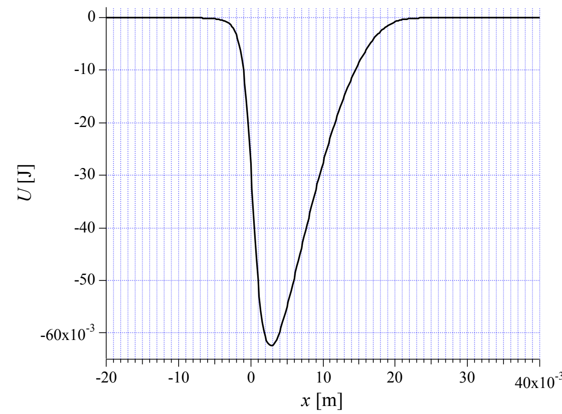
Students become more interested in this experiment when the teachers ask how the strength of magnetic force by which a magnet sticks to an iron plate compares with the strength of magnetic force applied by the magnetic field gradient of this experiment.



(a)

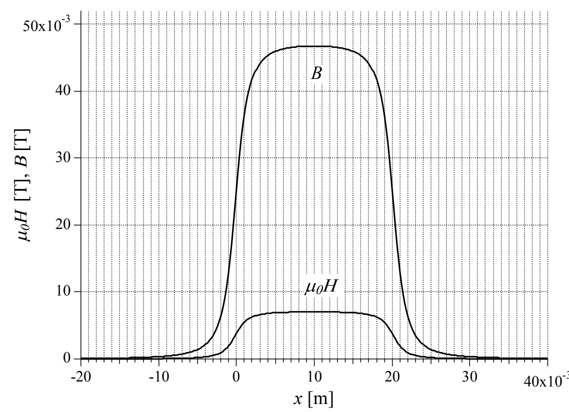


(b)

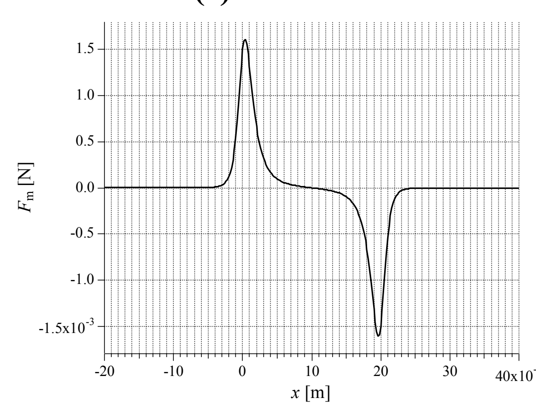


(c)

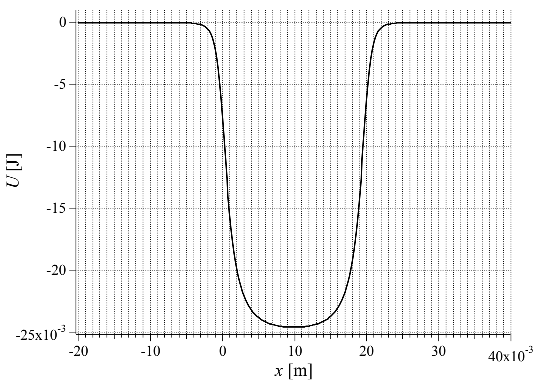
FIG. 6: (**a**) Magnetic field $\mu_0 H$ and density of the magnetic flux B in the conical coil.(**b**) Faraday force acting on the iron rod per 1 mm^3. (**c**) Magnetic potential of the iron rod per 1 mm^3.



(a)



(b)



(c)

FIG. 7: (**a**) Magnetic field $\mu_0 H$ and density of the magnetic flux B in the uniform coil.(**b**) Faraday force acting on the Iron rod per 1 mm^3. (**c**) Magnetic potential of the Iron rod per 1 mm^3.

3. Applications

We give the two examples of applications of actuators so that students understand the importance of these devices.

3.1 Application of the magnetic actuators

The millimetre-sized micro-miniature trembler is one of the applications of a conical coil. As elucidated in this research, it is small and can make a trembler that generates a large amount of power, especially compared to a uniform coil. A trembler can be used for stirring a solution or a solvent in a micro-laboratory [5].

3.2 Application of the Faraday force under a magnetic field gradient

In mechanical engineering, magneto rheological fluids (MRF) are useful in magnetic dampers and magnetic actuators [6]. A MRF (e.g., MRF-132LD) is filled in the cylinder of magnetic dampers. A magnetic coil is placed along the flow channel within the piston. Depending on the intensity of the magnetic field in the flow channel, the viscosity of the passing fluid and hence the capacity of the damper changes. An accumulator inside the cylinder accounts for the effective volume change due to the movement of the piston rod. The Faraday force generated by magnetic fields in the magnetic coil induces the flow of the MRF. As described in this paper, when using a conical coil, a large Faraday force is generated. It is inferred that the conical coil can be used for a viscous expensive liquid because the outbreak stress is not small.

4. Concluding Remarks

We developed basic magnetic actuators that use the Faraday force by the magnetic field gradient, which can be used in physics experiments for physics or engineering students. Students can make actuators and perform experiments if copper wire, resin pipes, iron rods, and AC oscillators are available. Cell phone cameras can be used to record videos to determine positions of the iron rods. A conical coil was made by winding up a copper wire around a polyimide tube. Passing an electric current through the coil generates a magnetic field in the coil. When an iron rod is placed horizontally in the axis of the coil, a Faraday force due tothe magnetic field gradient acts on the rod when electric current is passed though the coil. This force causes the rod to vibrate. Magnetic actuators were developed based on this vibration phenomenon. The movement of the rod in the vertical direction and vibration were realized with the conical coil. However, a uniform winding coil with the same number of the windings was used, the rod could not stay vertical in the coil and dropped even when AC voltage was applied. The magnitude of the Faraday force by the conical coil was approximately three times larger than the magnitude of the gravitational force. Furthermore, lateral vibration was realized by placing two conical coils horizontally. The conical coil actuator generated a large Faraday force 6.23×10^{-3} N (0.623 gf), compared to force generated by the uniform coil actuator 2.46×10^{-3} N (0.246 gf). Using the magnetic actuators, students can study the relationships between magnetic field gradients and Faraday forces. By performing these experiments and analyses, students should learn that the magnetic force is the result of a magnetic field gradient.

Appendix

We have applied a patent in Japan for the devices described in this paper(unexamined patent application No. 2015-126012).

References

[1]S. Nishijima, J. Magn.Soc.Jpn.**37**(2013) 333-37.

[2]T. Sakakibara, H. Mitamura, T. Tayama, H. Amitsuka,Jpn. J. Appl. Phys.**33**(1994) 5067-5072.

[3]K. Tsubaki, K.Yamaguchi,Physica E, **40**(2008)2220-2221.

[4]M. Abe, Y.Imamura, A. Kurome, M.Terada, Inclined magnetic field coil device and magnetic resonance imaging device, US Patent (US20100321019 A1), application date 29 Jan., 2009.

[5]C. D. Burnham,W. M. Dunne Jr., G. Greub, S.M. Novak, R. Patel,Clin. Chem.**59**(2013) 1696-1702.

[6]S. Soda, N. Iwata, K. Sunakoda, H. Sodeyama, H. Fujitani,Proc. SPIE's 8th Annual Int. Symposium on Smart Structures and Materials (2001)4330-24,1-10.