特 集 1
研 究 解 説

UDC 621.382.002.2

Levitation Types for Microsystems

マイクロマシンの浮上方式

Hannes BLEULER*
ハネス・ブロイレル

In this short review, different types of levitation mechanisms are presented and classified. Of special interest is the applicability to micromachines. One of the main limits of performance of many micromachines is due to fraction and wear effects. Therefore contact-free operation may be expected to drastically improve the potential of micromachines and thus to open up new possibilities of applications. This paper gives a review of different contact-free support techniques applicable to micro-machines.

1. Introduction

For micromachines, levitation, that is the absence of solid-solid contacts, is at the same time of special interest and, in a certain sense, easier to achieve than in the "macro" world. It is of special interest in order to avoid the dominant friction and wear effects which scale down only with the second power of length. Levitation is easier to achieve because loads such as weight and inertia forces scale down with the third power of length.

In a famous paper published in 1842, Earnshaw[1] proved mathematically that stable levitation of a pole is impossible in a repulsive or attractive force field in which force and distance are related by an inverse square law. This is known as Earnshaws theorem. Braunbeck[2] (1939) extended this analysis to electric and magnetic dipoles. This analysis has shown that stable levitation in vacuum is possible for three cases only:

1.) $\varepsilon - \varepsilon_0 < 0$, ε dielectric constant of the body, ε_0 of vacuum
2.) $\mu < \mu_0$, μ magnetic permeability of the body, μ_0 of vacuum
3.) Dynamic phenomena

The first case means that only a body with a dielectric constant (e) less than that of the medium can be levitated. Since no material has a dielectric constant ε less than that of vacuum, this leaves only the possibility of "levitating" a body with small ε in some medium of higher dielectricity. For instance, it is possible to stabilize the position of a bubble in a liquid in an electrostatic field. Braunbeck's analysis proves that stable levitation in all degrees of freedom is not possible with permanent magnets alone or together with ferromagnetic bodies. A weak levitation can be observed for many diamagnetic materials in a magnetic field while superconductors experience a strong levitation with the Meissner effect and the flux-pinning effect.

Some examples for levitation principles and devices will be given. Suspension of particles in liquids is not really "levitation" which usually implies support in vacuum or at least in a gas. The focus is not on aerodynamic effects either, although, as the flight of insects demonstrates, this field deserves thorough treatment. Two special cases of aerodynamic levitation will be given along with electrostatic, acoustic and optical phenomena. The emphasis will be on magnetic effects with the three main groups of superconductor levitation, passive levitation and controlled levitation.

2. Levitation Effects in a Gas

2.1 Levitation in a Jet of Gas

The effect considered here is the levitation of a spherical object in a jet of liquid or of gas. The lateral stabilization is due to a faster flow at the off-center side re-centering the body (Bernoulli force). A small off-axis sphere will, in

* Institute of Industrial Science, University of Tokyo (Toshiba Chair of Intelligent Mechatronics)

addition, rotate rapidly. The resulting Magnus force further increases lateral stability[3]. Levitation at pressures down to 1 Torr has been used to heat small spheres with diameters of about 4 mm to temperatures above 2000 degrees. In liquid state, they were only stable for about 5 to 10 sec.[4,5,6]

2.2 Squeeze Film Air Bearing

A squeeze film bearing is a special kind of air cushion which seems well suited to micro machine applications. It simply operates by a rapid oscillation of one of two surfaces with a gas between them. An example illustrates its capabilities: A small plate of 1 cm square can be made to levitate 4 μm above a piezoelectric transducer oscillating at 8 kHz with an oscillation amplitude of the actuator of only 6 nm[7]. Such bearings seem to have high stiffness and good damping properties. Loads of 500 Nm^{-2} have been reported[7], larger loads seem possible.

2.3 Acoustic Levitation

This method allows stable levitation of solids and liquids. It allows levitation at larger distance than the squeeze-film bearing (Fig. 1). As an example, a steel ball of 1 cm diameter needs a 1 kW siren at 3260 Hz[3,8]. Micro devices will need much less power. One condition is that the size of the body is much smaller than the wavelength of sound. Piezoelectric transducers operating at 20–40 kHz have been used together with an acoustic reflector for studying small samples of molten materials[9,10].

3. Optical Levitation

It is well known that the very weak radiation pressure of radiation on matter can be used for levitation of microparticles with high intensity laser beams (Fig. 1). The power required to levitate a mass m is of the order $mgc/2$ where g is the gravity acceleration and c is the velocity of light[11]. Although this formula gives 1.5 MW for levitation of 1g of mass, a steel particle of about 50 μm can be levitated with only 1.5 W of laser power. Experiments with particles up to 120 μm diameter have been reported. Fine position control (10–nm-order) of suspended particles is possible. The particles are trapped near the focus of the laser beam. The trapping of a few or even a single atom is possible[3]. The potential of levitation for micro instrumentation has been nicely demonstrated in a recent paper[12] on a scanning-force microscope with optical trapping, that is levitation, of the probe. The suspension stiffness of the probe could be reduced by a factor 10^{-4} compared to mechanical suspension[12]. Lower stiffness means detection of smaller force becomes possible with the same spatial resolution of the probe position measuring system.

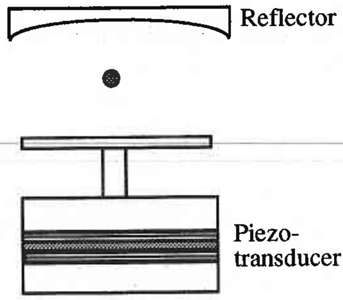

Fig. 1 Setup for acoustic levitation.

4. Electrostatic Levitation

As mentioned above, some dynamic process is necessary to stabilize electrostatic levitation. Such a stabilization is similar to the stabilization of the upright position of a pendulum with an oscillating pivot. The force itself is still purely electrostatic, as the stabilization procedure takes place at a frequency range so low that electromagnetic radiation or induction phenomena are not essential. Three such electrostatic levitation types can be discerned:

1.) Actively controlled electrostatic levitation
2.) Tuned LC electrostatic levitation
3.) Stabilization in an oscillating field (while $\nabla^2 \Phi = 0$)

1) and 2) are equivalent to the corresponding magnetic bearing techniques (section 3), with the only difference of having an electrostatic actuator in place of the electromagnet. Such an actuator consists basically of a series connection of two capacitors with the levitated body serving as one terminal for each capacitor.

An object as large as a silicon wafer or a CD disk can be supported at an air-gap in the mm order with a voltage of several 100 volts[13]. For smaller objects, smaller voltages will suffice. Much experience has been gained with all kinds of electrostatic micro actuators. The electrostatic force can be used for contact-free levitation with or without control. A difficulty of such actuators is the voltage breakdown when the air gap gets too small, a problem entirely unknown in magnetic bearings. Tuned LC-circuit operation (without active control) suffers from the absence of damping.

The third operation mode is less well known. Dynamic stabilization occurs in an oscillating force-field whose strength is proportional to the distance from a central origin[14]. Such a field can be realized by a quadrupole as shown in figure 2. A charged particle can be stabilized at the

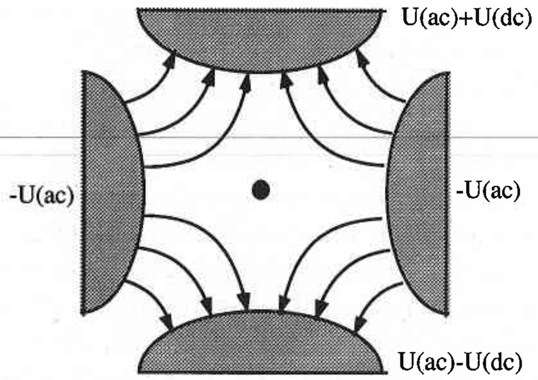

Fig. 2 Levitation of a charged particle in an oscillating electric quadrupole field. The constant potential U(dc) compensates for gravity while the oscillating field U(ac) stabilizes the equilibrium position at the center.

central point where the field strength is zero. To compensate gravity, a constant field has to be superposed to the oscillating field. Experiments with micro-particles are described in[15].

5. Magnetic Levitation Types

5.1 Levitation with Superconductors

As mentioned before, practical application of superconductors for levitation usually relies on the flux-pinning effect and not the Meissner-Ochsenfeld effect[16]. This means that the flux partially enters the superconductor. This pinning effect makes it possible to support a magnet above and below a super-conductor (or vice versa) in relatively stable, well damped positions. The rotor often has to be fixed in the desired position by some mechanism during cool-down. Pure Meissner-effect levitation on the other hand may permit undamped oscillations of the supported body[3].

A great number of applications for rotational and linear support have been reported[17,24], e.g. for inertia power-storage systems[18]. Recently, it has even been demonstrated that a ferro-magnetic body, not a permanent magnet, can be supported by a superconductor. A demonstration rotor of about 100 g weight has been suspended below a high-Tc superconductor stator of a few cm size[19]. The magnetic field is generated by a permanent magnet above the stator. Once the superconductor is cooled with liquid nitrogen, the magnet can be removed while the ferromagnetic rotor remains suspended due to the flux-pinning effect. The permanent magnet could be replaced by an electromagnet which has to be energized only at the moment when the stator becomes super conducting, the superconductor will then conserve the initial flux.

The Japanese MAGLEV prototype (JR) levitates at speeds above ca 100 km/h and not at standstill. The super conducting magnets on the vehicle are needed to increase the field strength up to practical levels, this type of operation is neither flux-pinning nor Meissner effect.

5.2 Passive Magnetic Levitation without Superconductors

5.2.1 Diamagnetic Levitation

The diamagnetic effect at room temperature (without superconductors) is so weak that it is not (yet) used for large scale technical applications. However, due to the scaling laws, it is quite possible to build various useful levitation devices in the micro-scale, as demonstrated e.g. by Pelrine[20]. He reports levitation of bits of permanent magnets in the order of 100 to 300 μm size above bismuth. Slightly larger bodies can be levitated if the weight is partially compensated by permanent magnets. Table 1 shows some diamagnetic materials[21].

5.2.2 Tuned LC-Type

This kind of levitation is based on the fact that the inductance of an electromagnet changes with the gap of an attracted ferromagnetic object. The bearing magnet is part of a LC-circuit (inductance-capacitor) connected to a

Table . Diamagnetic Materials

	Susceptibility $\mu_r 1$		Susceptibility $\mu_r 1$
Bismuth	−1.66	Mercury	−3.2
Copper	−0.95	Selenium	−1.7
Diamond	−2.2	Silicon	−0.3
Graphite	−12	Silver	−2.6
Germanium	−0.8	Sodium	−0.24
Gold	−3.6	Aluminum oxide	−0.5

constant AC source tuned slightly off resonance in such a way that the circuit approaches resonance when the levitated body moves away from the electromagnet. In this way a restoring stiffness can be obtained[22]. The main drawback is that such a system has no inherent damping. Nevertheless it was extensively applied, together with oil-dampers, for gyroscopes in missiles in the 1960s.

5.2.3 Levitation with Induced Currents

This levitation type relies on eddy current induced either by rapid relative motion or by an AC electromagnet. It is applied either for MAGLEV vehicles or for levitation and simultaneous melting of metals. The fact that eddy current losses are so high as to either melt the levitated body or to necessitate the use of superconductors shows that the main problem of this kind of levitation are high losses, besides the fact that damping is low. The problem of high losses is much less dramatic for micro machines due to the scaling laws. Siegwart[23] is reporting levitation of a thin aluminum plate of ca 2 cm diameter at a height 1 mm above 6 small coils connected to 18 kHz at 500 mA. A small hollow cylinder of 20 mm length and 5 mm diameter has been levitated and rotated at 1000 rpm with a similar method by the same authors. In these cases, thermal equilibrium in air is reached at about 70°C only. By extrapolation, one can assume even lower losses for smaller machines in air. This type of levitation is also possible in vacuum, although thermal equilibrium will be at higher temperatures than in air.

5.3 Actively Controlled Magnetic Levitation

5.3.1 Reluctance Force

This kind of levitation for micromachines is described in the paper "Active Micro Levitation" in this issue of "Seisan Kenkyu". Discussion is therefore omitted here.

5.3.2 Lorentz Force

Although the separation of reluctance and Lorentz force is not as clear as it may seem, it is proposed to keep the distinction in the engineering context. In a Lorentz force device, the force is perpendicular to the flux lines and thus tangential to the air gap. It changes sign with the current. In a reluctance device, the force is parallel to the flux lines, across the air gap. If one body is passive, the force is always attractive, irrespective of the sign of the current. For a Lorentz-force device, such as e.g. a voice-coil actuator, the rotor has preferably (not necessarily) to be a permanent magnet. The horizontal motion of the magnet levitated above a superconductor[24] is an example for a Lorentz force actuator. A Lorentz-force bearing uses this effect for levitation, an example is a synchronous motor-bearing combination[26].

5.3.3 Combinations of Motor-Levitation

For micromachines it is specially important to reduce the number of components. This is why a micro-levitation system will often have to be realized as a combination of motor and bearing. This kind of combination has a great potential for applications with conventional machines as well as with micro machines. Every electric motor already contains the electromagnetic actuators to produce a torque around the rotational axis. Radial forces can be obtained by modifying the power supply to the coils with an appropriate control. Bearing-motor combinations have been reported for reluctance motors[25], synchronous machines[26] and induction motors[27,28].

Induction motors, as applied e.g. in vacuum gauges, are the first choice for micro machine operation as the rotor structure may be very simple. The only requirement is electrical conductivity.

5.3.4 Sensorless Active Levitation: Combination Sensor-Actuator

There are several principles of so-called sensorless active magnetic bearings. Common feature of such techniques is the use of the electromagnetic actuator coils as sensor. Therefore the term "sensorless" is not strictly correct, it has nevertheless become common practice, e.g. for the control of induction motors, so it may be used for the similar case of magnetic bearings as well.

Most "sensorless" bearings realized up to now use some high frequency to separate the actuator and the position sensing function. This technique is used e.g. for vacuum gauges, small iron balls rotated at high velocity. Another possibility is to use a high-frequency switched power amplifier and an appropriate nonlinear filter to detect the position. Since the actuator frequency will be very high for micromachines, it will be difficult to separate sensing and actuation for this kind of sensorless bearings.

Our approach to sensorless bearings is entirely different. The usual current control is replaced by voltage control. This permits to use the bearing current, the only measured variable, as the plant output. It may thus be called a truly position-sensorless bearing. The static position and load are actually unobservable, dynamic load and position are. The main problem will be to detect the weak effect of the back-EMF on which this type of bearing relies. Position-sensorless active levitation has been obtained for an industrial magnetic bearing machine, a turbo-molecular pump, at our lab, for a machine with a rotor mass in the order of a few kg. Extrapolating these results to micro machines, one could expect a structure with fairly simple electro-mechanical hardware at the cost of quite a sophisticated controller. The combinations of actuator-sensor and actuator-motor are feasible for electrostatic devices as well.

6. Conclusion

There are many possibilities for contact-free levitation of small objects. This permits to avoid friction and wear problems of micro mechanisms. Some of these methods produce weak forces not suited for levitation of large objects. On microscale however, such methods can be applied successfully. Some active control levitation and actuation methods (motor-bearing combinations, position-sensorless active bearings) are still in development for normal-size machines. They promise to be very attractive for micro machines as well.

Contact-free operation of mechanical micro devices can drastically increase life-time, reliability, sensitivity and performance. As an example, the low stiffness of an optically levitated scanning force microscope has the potential to increase the force resolution by four orders of magnitude. Very high rotational speeds are possible. Since actively controlled devices already have built-in sensors, they can be used as detectors for various combinations of physical variables: Rate gyro, accelerometer, viscosity, pressure, force and others.

(Manuscript received, April 14, 1994)

References

1) S. Earnshaw: On the Nature of the Molecular Forces which Regulate the Constitution of the Luminferous Ether. Trans. Cambridge Philosophical Society, **7**, pp 97–112 (1842)
2) W. Braunbeck: Freischwebende Köper im elektrischen und magnetischen Feld. Zeitschrift für Physik, **112**, pp 753–763 (1939)
3) E.H. Brandt: Levitation in Physics. Science, **243**, pp 349–354, 1989
4) W.A. Oran, L. H. Berge, Rev. Sci. Instrum., **53**, 851 (1982)
5) P.C. Nordine, R.M.Atkins, Rev. Sci. Instrum., **53**, 1456 (1982)
6) L.H. Berge, W. Oran, J.M. Theiss NASA Tech. Briefs **6**, 105 (1981)
7) R.S. Fearing: "A Miniature Mobile Platform on an Air Bearing", Proc. 3. Int. Symp. on Micromachine and Human Science, Nagoya, 10. 1992
8) P.M. Gammel, A.P. Conquist, T.G.Wang, J. Acoust. Soc. Am., **83**, 496 (1988)
9) E.H. Trinh, Rev. Sci. Instr., **56**, 2059 (1985)
10) E.H. Trinh, C.J. Hsu, J. Acoust. Soc. Am., **80**, 1757 (1986)
11) E.R. Laithwaite: "Electromagnetic Levitation", proc. IEE **112** pp 2361 (12. 1965)
12) L. Ghislain, W.W. Webb: "Scanning Force Microscope Based on an Optical Trap", Optics Letters **18** no. 19, pp 1678 (10. 1993)
13) Ju Jin, 金本 学："静電浮上搬送機構の開発", ㈶神奈川科学技術アカデミー 平成５年度研究概要 (1993)
14) R.F. Wuerker, H.Shelton, R.V. Langmuir, J. Appl. Physics, **30**, 342 (1959)
15) S. Arnold, L.M. Folan, Rev. Sci. Instr., **58**, 1732 (1987)
16) H. Suzuki, M. Takashige, S.Tanuma: "Model of Magnetic Levitation Train by Oxide Superconductors", Int. Symp. Nonlinear Mathematical Problems in Industry (NLMPI), Iwaki, Japan (11. 1992)
17) 第５小委員会報告 平成５年３月 ㈶国際超電導産業技術研究センター (1993)
18) H. Higasa, F. Ishikawa, N. Kawauchi, S. Yokoyama, S. Nakamura, H. Imaizumi, N. Ito: "Experiment of a 100Wh-Class Power Storage System using High-Tc Superconducting Magnetic Bearing", 6th Int. Symp. on Superconductivity (ISS '93), Hiroshima (10. 1993)
19) Tsutsui, Higuchi. Reported in Nippon Keizai Shimbun, 21. 2. 1994
20) R.E. Pelrine: "Room Temperature Open Loop Levitation of Microdevices Using Diamagnetic Materials", Proc. Micro Electro Mechanical Systems, Napa Valley, IEEE Cat. No 90CH2832-4 (2. 1990)
21) R.S. Elliott: "Electromagnetics" IEEE Press (1993)
22) T. Higuchi, J. Jin "Realization of Non-Contact AC Magnetic Suspension" 34th Jap. Joint Automatic Control Conf. SICE, IEEE AC, Keio-Univ. Tokyo (1991)
23) R.E. Neubauer, D. Baumann, R. Siegwart: "Eddy Current Magnetic Suspension Systems for Linear and Rotary Microstep Actuators", Int Symp on Advanced Computation of Electromagnetic Systems, ISEM, Seoul Korea (6 1994)
24) Y.K. Kim, M. Katsurai, H. Fujita: "Fabrication and Testing of a Micro Superconducting Actuator Using the Meissner Effect", Proc. Micro Electro Mechanical Systems, Napa Valley, IEEE Cat. No 90CH2832-4 (2. 1990)
25) H. Bleuler, H. Kawakatsu, F. Moesner, M. Rohner: Towards Micro Magnetic Bearings. Seisan Kenkyu **45**, pp 85–88 (6. 1993)
26) Bichsel J 1991: "The Bearingless Electrical Machine" Int. Symp. on Magn. Susp. Techn., NASA Langley Res. Center, Hampton VA
27) R. Schöb: Beiträge zur Lagerlosen Asynchronmaschine, Doctor Thesis, ETH Zürich, Switzerland, 1993
28) Wehberg J 1991: "Elektrischer Antrieb und inte-grierte magnetische Lagerung am Beispiel eines hochtourigen Rotors", doctor thesis, Technical Univ. of Braunschweig, Germany