A thermo-magnetic wheel

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Who, in his childhood, was not astonished to see the linear momentum of a gentle breeze or a waterfall transformed to the angular momentum of a wheel? What wind and water have done for centuries, a thermal current can do today. A beam of absorbed radiation creates heat, a thermal current, which is directly and continuously transformed to a rotating wheel.

The development of high field magnets, such as those made of NdFeB (Neodymium-Iron-Boron) enables to use heat to rotate a wheel at room temperature. Such magnets, formed as small cylindrical discs, can be levitated in a magnetic dipole field [1,2]. If locally heated at the upper surface the levitated magnet starts to oscillate with increasing amplitude until it rotates like a wheel. It will do so as long as the heat flow is maintained. Radiation energy is transformed, at least partially, into rotational energy. The thermo-magnetic wheel is an example of self-exciting, oscillatory periodic motion that ends in a stable cycle limit, where there is a balance between energy input and dissipation [3].The amazing effect is illustrated by a video, which can be obtained from the author upon request.

Experiment

The experimental setup is sketched in Fig. 1 and pictured in Fig. 2. The lifting magnets [B] are blocks or cylinders of NdFeB, axially magnetized, with maximal field strength of B=0.5 T at the surface and about 6 mT at the position of the floating magnet. The bismuth discs are cylindrical, approximately 30 mm in diameter and 13 mm in thickness. The geometry of these magnets and discs is not crucial. The floating magnet generates a maximal magnetic field of 0.5 T and is 8 mm in diameter, 3 mm thick, and weighs 1.2g.

Stable magnetic levitation is excluded by the well-known Earnshaw theorem [4]. However, by placing a diamagnetic material, such as bismuth, at the right position, a three-dimensional potential well is created. In this well, stable levitation in free space is possible. The small magnet is supported by carefully adjusting the lifting magnets so as to create a free-floating position between the bismuth plates.

What is seen?

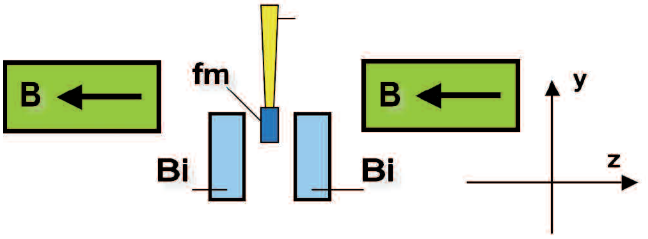
The motion of the magnet is recorded with both a video camera and a LASER beam. When the beam is reflected from a marked surface of the magnet, it hits a photocell. When the light is on, i.e. when a continuous heat input is present, motion starts from the equilibrium position, and the magnet behaves like a self-excited oscillator. The oscillation begins at an angular frequency ω(t) of about 2 rad/s. After several oscillations, ω(t) decreases to a minimum, due to the anharmonic motion at large angles. The motion then rapidly changes into a permanent steady-state rotation. Fig. 4 illustrates two typical examples of this motion.

A physical model

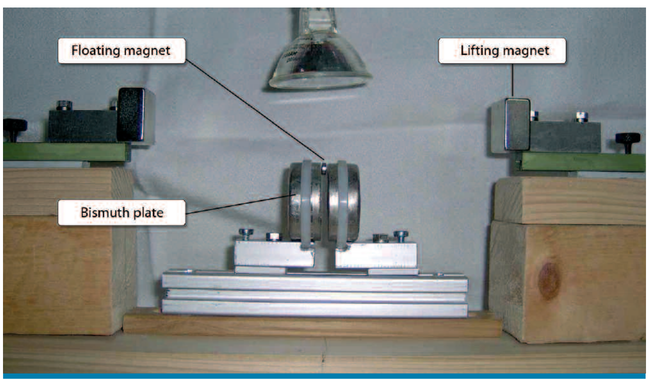
The thermo-magnetic wheel is modelled as a circular disc in harmonic rotational motion. The disc is suspended at a point, which we denote as magnetic suspension point [msp]. This point does not generally coincide with the centre of mass [cm]. Fig. 5 shows the system in the x-y plane normal to the z-axis.

The magnetic levitation force, which we denote by F_m, matches the weight F_w and has an action point, which lies higher than the gravitational centre of mass [cm]. The action point is not at [cm] because there are always slight inhomogeneities of the total magnetisation **M** with respect to the cylindrical geometry of the magnet. The magnet would be unstable in the z-axis direction without the Bi plates, and would quickly be pulled to one of the lifting magnets. With the diamagnetic bismuth plates, however, there are repulsive forces acting on the levitated magnet that obey an inverse 4^{th} power law with distance, leading to a stable equilibrium position.

If gently displaced from its equilibrium position, the magnet will oscillate about the magnetic suspension point [msp] in both the x and y directions, horizontally and vertically. This means that the magnet is suspended in the magnetic field in



▲ **Fig. 1:** The parts of the system are: The lifting magnets [B], the bismuth discs [Bi], the floating magnet [fm] and a radiation beam [rb].



▲ **Fig. 2:** The lifting magnets are quadratic blocks, 25x25 mm and 12 mm thick. They can be moved on a track. The floating magnet lies between the bismuth plates and floats without touching them. A 12V spotlight is the radiation source.

every direction. Without radiation the magnetic suspension point is fixed. The motion is given by the differential equation for harmonic motion:

$$I\ddot{\phi} + R\dot{\phi} + D^*\phi = 0 \qquad (1)$$

where the $\dot{}$ stands for the time derivative, I is the moment of inertia, R the coefficient of the friction torque $R\dot{\phi}(t)$, and D* = m g D, the coefficient of the restoring torque ($D^*\phi$), and D is the distance between the action points of the magnetic and gravitational forces. ϕ is the angle of rotation shown in Fig. 5.

We measured the natural angular frequency of the system to be $\omega_o = 2.1$ rad.s^{-1}, and we estimated a mean oscillation decay time to be approximately $\tau_{osc} = 50$s, so we can calculate all relevant oscillation parameters, R, D* and D. With I = 9.6 10^{-9} kgm^2 we get: $D = \omega_o^2 I/mg = \omega_o^2 r^2/2g = 3.6\ 10^{-6}$m, $D^* = \omega_o^2 I = 4.2\ 10^{-8}$ Nm/rad, and $R = I/\tau_{osc.} = 1.9\ 10^{-10}$ Nms/rad, where m = 1.2g is the magnet's mass and g is the gravitational acceleration.

What is the reason for the self-excitation?

This thermo-magnetic wheel shows a startling behaviour when a heat flow is applied from above. The magnet starts to oscillate from rest with increasing amplitude. Some immediate questions are: Why does the amplitude of this oscillation increase? What is the source of the oscillation energy? What is the energy-transfer mechanism, and what is the equation of motion for the angular displacement ϕ between 0 and 2π?

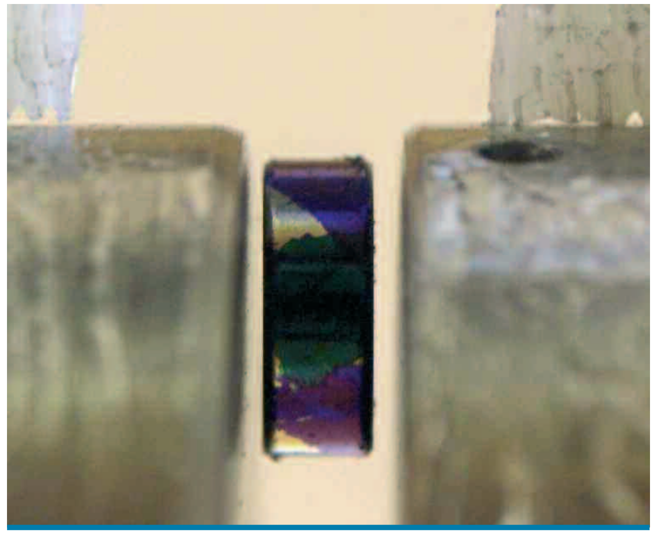
Let us consider the equilibrium position for the disc magnet sketched in Fig. 6. The potential energy U of the floating magnet with a magnetic dipole moment **M** in the magnetic field **B** of the lifter magnet is [2]:

$$U = \mathbf{M.B} + mgy = -MB + mgy \qquad (2)$$

where mgy is the gravitational energy. In the absence of heat the floating magnet will align with the field **B**. There is no magnetic torque. The resulting net force F_{net} = -grad U on the magnet is zero.

When the light is on, the upper magnet's surface is heated, and the local magnetisation decreases. Consequently the magnetic suspension point [msp] sinks gradually for about 1mm to a new equilibrium position inside the inhomogeneous lifting **B**-field. This shift of the [msp] generally leads to a misalignment of **M** and **B**, and a torque τ appears.

The heated region, which got a "thermal kick" at t = 0, moves away from the direct heat influx area and cools exponentially. Denoting the local magnetisation, i.e. the part of **M** which is affected by the thermal flow, as $\mathbf{M}_T$, we have: $\mathbf{M}_T = \mathbf{M}_o \exp(-t/t^*)$ [5]. The phenomenological constant t* describes the temperature decline of the magnetic dipole $\mathbf{M}_T$, as sketched in Fig. 6. $\mathbf{M}_o$ is the difference of the magnetic dipole between the initial and final states when the magnet rotates permanently, $\mathbf{M}_o = \mathbf{M}_{initial} - \mathbf{M}_{final}$.

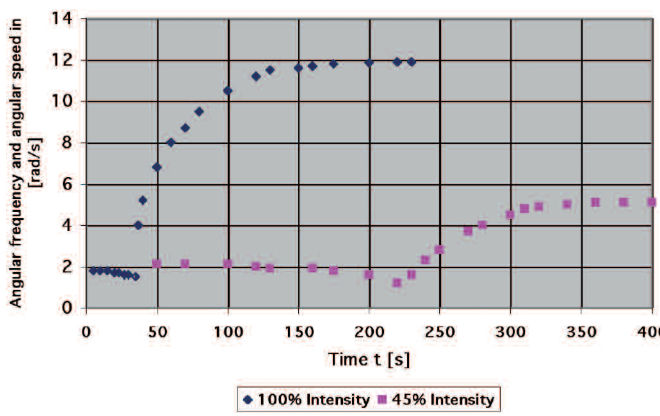


▲ **Fig. 3:** Magnified section of the floating NdFeB disc magnet between the diamagnetic bismuth plates. The levitated magnet is 8mm in diameter and 3 mm in thickness.

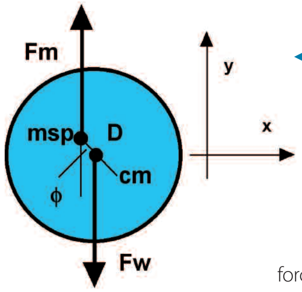
Since **M** and **B** are no longer aligned, a torque $\tau = \mathbf{M}_T \times \mathbf{B}$ acts on the magnet in addition to the gravitational one. This torque resembles the one observed in the gyro-magnetic experiment of Einstein and de Haas in 1915 [6]. There, the change in direction of the magnetic dipole **M** also causes a corresponding change in the angular momentum of a ferromagnet. Therefore there is a torque $\tau = \mathbf{M}_{Txy}\,\mathbf{B}_{xy}\sin(\phi)$ about the z-axis, where $\mathbf{M}_{Txy}$ and $\mathbf{B}_{xy}$ are the respective magnetic vectors in the x-y plane, and $\phi = t^*\dot{\phi}$ is the angle between them. We have

$$\tau = A\sin(t^*\dot{\phi}) \qquad (3)$$

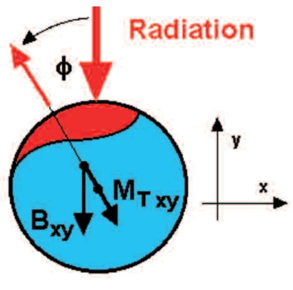
where A and t* are constants, chosen by best fit to the numerical solutions for the magnet's motion. The additional torque τ does not depend on time explicitly, but it acts on the pendulum •••



▲ **Fig. 4:** The angular frequency ω(t) is around 2 rad/s for the oscillation sequence. The angular speed ω(t) for the rotation is drawn as function of time for two heat intensities.



◀ **Fig. 5:** Levitated magnet as an oscillating disc. [D] is the distance between the centre of mass [cm] and the magnetic suspension point [msp] while ϕ denotes the rotational angle measured relative to the equilibrium axis defined by msp and cm. The z-axis is directed out of the XY plane. The static forces F_m and F_w are shown.



▶ **Fig. 6:** The magnet's position after receiving a "thermal kick" at t = 0 at the position $\phi = 0$. The position angle ϕ is $t^*\dot{\phi}$, where t* is the time constant of the local exponential temperature decay. The magnetic dipole $\mathbf{M}_T$ and the levitating **B**-field are shown. The static forces $\mathbf{F}_m$ and $\mathbf{F}_w$ are omitted.

••• just as the gravitational restoring torque does. If we add this torque to Equation (1) leaving, however, the small angle approximation, we get:

$$I\ddot{\phi} + R\dot{\phi} + D^*\sin(\phi) = A\sin(t^*\dot{\phi}) \qquad (4)$$

Equation (4) is a homogeneous, non-linear differential equation with no external independent function of time. We solve Equation (4) by numerical approximation using MATHEMATICA with the numerical values $\omega_o^2 = D^*/I = 4.4$ [s^{-2}], ϕ[0]=0, $\dot{\phi}$[0] = 0.2 [s^{-1}], R/I= 0.02 [s^{-1}], A/I = 0.9 [s^{-2}] and t*= 0.25 [s]:

$$\ddot{\phi} + 0.02\dot{\phi} + 4.4\sin(\phi) = 0.9\sin(0.25\,\dot{\phi}) \qquad (5)$$

In Fig. 7 we plot the angular velocity $\omega(t) = \dot{\phi}(t)$ obtained after numerical differentiation of $\phi(t)$. The angular displacement $\phi(t)$ is the numerical solution of equation (5). Fig. 7 is a quantitative correct picture of the observed self-excited oscillation and subsequent rotation. An oscillation is superposed on the rotation; it is due to the slight eccentricity of the thermo-magnetic wheel. Also, equation (5) gives solutions for the cases when light does not hit the magnet vertically, but is displaced by $\pi/2$ or π, i.e. when $\phi_{torque} = \phi \pm \pi/2$ or $\phi_{torque} = \phi + \pi$; these cases are experimentally confirmed. This mechanism of self-excitation by a continuous thermal flow resembles very much the wind-driven oscillations observed in 1940 at the Tacoma Narrows bridge in the USA [7].

After the transient self-excited oscillations end, the magnet continues in rotation with a constant mean angular speed $\omega(t)$. The temperature of the magnet reaches a constant value, T^∞, and the thermal gradient goes away. A new, dynamically stable state is reached. The active magneto caloric forces, which initiated the oscillation, become a small torque. This torque matches the minute external torque due to air drag and, perhaps, eddy current dissipation.

Is the thermo-magnetic wheel a heat engine?

Yes, because this simple room temperature experiment transforms radiation heat directly to rotational motion of a wheel. This amazing effect can be described completely within the framework of a thermo-magnetic self-excitation mechanism. The thermal flow through the levitated magnet provides energy to sustain the oscillation and subsequent rotation. However, its potential as a source of mechanical power is presently not very attractive. A rotating magnetic field is, in principle, a Faraday disc generator. We estimate the heat energy flowing per second through the magnet to be around 10 mJ, while the rotating energy of the magnet is less than 1μJ. This minute rotational energy cannot compete with solar-based energy converters.

This analysis describes an angular pendulum that transfers energy between radiation-, magnetic- and gravitational fields. The model adequately explains the observations. This thermally driven "heat wheel" combines gravity, magnetism and electromagnetism, as well as thermodynamics and mechanics, in a simple demonstration that is unique and unusual. ■

About the author:

Claudio Palmy received his Ph.D. in superconductivity from the Swiss Federal Institute of Technology Zürich, ETHZ, in 1970. After a short time as a visiting professor in Sao Paulo, Brasil, he became a physics professor at NTB, Interstate University of Applied Sciences of Technology Buchs, Switzerland. Since 2004 he has worked on magnetism at the Alpine Institute of Physics Stuls, Switzerland. E-mail: cpalmy@bluewin.ch

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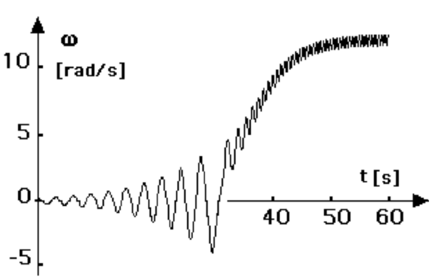

◀ **Fig. 7:** Calculated angular velocity $\dot{\phi}$ (t) = ω(t) for a levitated magnet in a vertical (y-axis) temperature gradient at room temperature.