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When Pigs Fly: Can it be done with magnetism?

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Abstract
A pig is capable of levitating in stable equilibrium under a sufficiently strong applied magnetic field. A model based on the relationship between magnetic force and gravity, when the net force is equal to zero, was used to determine the strength of a magnetic field when applied in one direction needed for levitation. For an average adult pig (0.75 m in height) this equates to a minimum magnetic field of 32.4 T. Whilst possible, it does not equate to natural flight.

Introduction
When people talk about things that will never happen, it is usually accompanied by the adynation "when pigs fly". However this paper argues the case that, due to the diamagnetic nature of almost all living things, pigs can at least levitate if placed into a strong enough magnetic field. This idea was inspired by and work into levitating a frog by Berry and Geim in 1997 [1-3]. The paper applies only the relevant parts of the paper, simplifying the model to account for the author's level of knowledge.

Figure 1 – A doctored photograph of a winged pig. With levitation, wings are unnecessary (image taken from [4]).

Theory
Diamagnetism is a quantum mechanical effect that is present in all materials, but the paramagnetic and ferromagnetic properties of many materials mean that the comparatively weak diamagnetic force is often overwhelmed [5].

Diamagnetism occurs due to the readjustment of electron orbits in a magnetic field [1]. In living things, a basic assumption can be made that water molecules convey the diamagnetic properties of the whole organism. In bulk materials, diamagnetism is only observed if net atomic moments are equal to zero [5].

Stable magnetic levitation can occur in isolated regions of the magnetic field of a solenoid. This has been proven for small objects (live frogs and grasshoppers), which will levitate in a magnetic field of 16 T [2]. This was a major breakthrough in the field, proving the obstruction presented by Earnshaw's theorem does not apply to induced magnetism, which states that 'no stationary object made of charges masses and magnets in fixed configuration can be held in stable equilibrium by magnetic forces' [6].

Model
Levitation of an object will be defined by the balance between magnetic force and gravity. Under stable levitation, these are the only two forces acting upon the object, and there must be a net force of 0 N. This can be seen in the following free body diagram (figure 2).

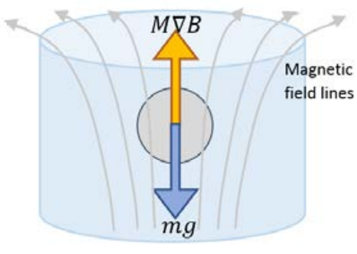

Figure 2 – Free body diagram of stable levitation of an object inside a solenoid

The work relies heavily on Berry and Geim, though a few assumptions have been made based on the knowledge of the author or as simplifications [2]. The following derivation holds, assuming that the magnetic field inside a vertical solenoid is equal to B(r), and the force of gravity acting upon an object is

$mg = \rho V g$. The object being levitated has mass m, volume V, density ρ, and magnetic susceptibility χ. The symbol μ_0 stands for the permeability of free space ($4\pi \times 10^{-7}$ Hm^{-1}), whilst g stands for the acceleration due to gravity (9.81 ms^{-1}).

In diamagnetic materials, $\chi < 0$, and so $\chi = -|\chi|$. The induced magnetic moment, $m(r)$, can now be solved to a close approximation:

$$m(r) = -\frac{|\chi| V B(r)}{\mu_0}. \quad (1)$$

The total magnetic energy of the object is calculated by integrating the work, $-dm \cdot B$, as the field increases from zero to $B(r)$. This term and the gravitational effects on the object combine to give the total energy, which can be used to calculate the total force in equilibrium:

$$E(r) = mgz + \frac{|\chi| V}{2\mu_0} B^2(r) \quad (2a)$$

$$F(r) = -\nabla E(r) = -mge_z - \frac{|\chi| V}{\mu_0} B(r) \nabla B(r) \quad (2b)$$

In a solenoid, which has rotational symmetry about e_z, in this simplifies one direction to:

$$F = -\frac{|\chi| V}{2\mu_0} \nabla B^2(r) \quad (3a)$$

$$\nabla B^2(r) = -\frac{\mu_0 \rho g}{|\chi|} \quad (3b)$$

$\nabla B^2(r)$ is the vertical field gradient, it is equal to the magnetic field strength times the magnetic field gradient. In a solenoid that is correctly orientated, this can be simplified to $B^2(r)/l$ [2]. Thus, in order for an object to levitate, vertical field gradient must be greater than $(\mu_0 \rho)/|\chi|$.

Calculations

For this model, the following assumptions have been made:

- The object is treated as spherical to simplify the calculation.
- The volume is included in the original calculations, so that, at equilibrium, masses will cancel.
- The magnetic field is applied in only one direction, and thus only the gradient of magnetic field is pertinent.

The pig was modelled with water as the base material, as water forms a large component of living tissue, in order to simplify the equation to give one set of values for χ and ρ. Water has $\chi = -8.8 \times 10^{-6}$, and ρ = 1000 kgm^{-3} [7]. For a Bentheim Plack Pied pig, the average height is equal to 0.75 m [8]. Since the pig was treated as spherical for simplicity, this value was equal to the length across which the magnetic field was applied.

Using these values and assumptions, and with a simplification of the model used for levitation of frogs in Berry and Geim [2], the minimum strength of the magnetic field for levitation of a pig can be calculated:

$$\frac{B^2(r)}{l} > \frac{\mu_0 \rho g}{|\chi|} \quad (4a)$$

$$B_{min} = \sqrt{\frac{\mu_0 \rho g l}{|\chi|}} = \sqrt{\frac{(4\pi \times 10^{-7}) \times (0.75) \times (9.81) \times (1000)}{|-8.8 \times 10^{-6}|}}$$

$$B_{min} = 32.4\, T \quad (4b)$$

This calculation does not include the dimensionless quantity β used by Berry and Geim, since this is a field that can only be calculated experimentally [2].

Conclusion

In conclusion, study of diamagnetism does show that it is possible for pigs to levitate. However, due to the size of the object, and the effects that gravity have upon said object, the minimum field strength needed to levitate an adult pig would be 32.4 T. While fields of this strength have been created (Florida State University's National High Magnetic Field Laboratory have assembled solenoid with field strength 45 T but with a bore diameter of 32 mm), none of these are large enough to accommodate a pig [9]. Other major limiting factors in designing a practical experiment include prohibitive costs, and the health implications. Whilst magnetic applications in the medical field have been shown non-detrimental to humans, the field strength comparatively smaller (1.5-3.0 T fields are typical for magnetic resonance imaging) [10]. However, whilst long term exposure to strong magnetic fields can have detrimental effects to living tissue, placing a living organism inside a solenoid with a strong magnetic field will not have significant detrimental effects [11, 12]. Furthermore, since the pig will be levitated in equilibrium, it does not quite equate to true flying, since the pig will not be able to move. The search for true pig flight thus remains beyond possibility.

References

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