Investigation of the Huber effect and its application to micromotors

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ABSTRACT

The micromotor is an extremely small device a few millimetres or less in size. Micromotors in the order of microns are realised by MEMS technology. Important applications in biomedicine include ultrasound probes for blood vessels,[1] microrobots for colon intervention,[2] smart pills and nanolitre pumps. Other uses include actuators for MOEMS and small variable capacitors. One exciting implication of micromotors is that they can be powered by rectifying mechanical vibrations (Feynman-micromotor[3]). MEMS are playing an important role in our daily life as these systems are widely used in optics, communication and information systems, fluidics, biotechnology and medicine, scanning probe microscopes, automobiles and aerospace.

There are a number of technical challenges with micromotors, including the need to reduce stiction and increase torque. The precise geometry of the motor is usually tightly coupled to the stiction effect – the sticking of adjacent surfaces after release due to static friction. Piezoelectric, electrostatic and electromagnetic effects have been investigated to produce the electromotive force for the micromotor. However, we propose a micromotor design based on the Huber effect[4 5 6] , as this will allow a new range of geometries and hence possibilities for managing stiction.

To date, there have been no reported attempts at using the Huber effect, and this is possibly due to it being a poorly understood phenomenon. The reason for this is that large motors that utilise the Huber effect are self-destructive and hence have never been reliably characterised. Such motors are shown to be able to operate from a dc or ac source, and this property may be valuable in some MEMS applications.

Keywords: Huber effect, Micromotors, MEMs

1. INTRODUCTION

The Huber effect was discovered by J. Huber in 1959.[4] It is most easily explained using the ball bearing motor first used by Milroy,[8] consisting of two ball bearing races with a shaft connecting the inner races completing the circuit. When the shaft is given an initial motion and direct or alternating current of sufficient magnitude is applied to the outer races, allowing current to flow through bearings and shaft, the shaft will continue to rotate in the direction of motion. The motor will usually not be self-starting, requiring an initial motion before rotation will occur. On occasions (especially when a large current is applied) the motor will begin to rotate independently. The motor also has the unusual property of rotation in either direction regardless of the polarity of current, even for dc.

The ball bearing motor requires an extremely large current to sustain rotation, even for a motor design of small dimensions. Because of the large current a large amount of heat is produced. The heat produced by this motor is so large that when run in air it rapidly becomes so hot that expansion of the balls, seizing and excessive sparking leading to self-destruction ultimately occur. This will usually take only a few seconds of continuous running. Due to the large amount of heat produced, the motor has a very poor efficiency and has been considered completely impractical. Because of this, very little research has been done on the Huber effect. However interest is renewed, as MEMS now allows the possibility of very small motors, thus scaling down the effect of destructive currents.

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Part of the SPIE Conference on Electronics and Structures for MEMS
Royal Pines Resort, Queensland, Australia • October 1999
SPIE Vol. 3891 • 0277-786X/99/$10.00

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2. PREVIOUS THEORIES

Since its discovery, many theories have been presented on the origin of the Huber effect. None of these theories however display irrefutable proof, nor conclusive experimental evidence that any particular theory is the definitive source of this phenomenon. One theory that was first presented by Gruenberg,[9] attributes this phenomenon to an electromagnetic effect. In this paper the torque produced by the motor is the result of an interaction of primary and induced current densities and magnetic fields. It states that there is an initial current density J_0 and associated magnetic field B_0 flowing within each ball. When the ball is rotating, charge redistribution occurs causing a further current distribution J_1 and associated magnetic field B_1 to be produced. The interaction of J_0 and B_1, and J_1 and B_0 is then responsible for the torque observed. Torque is only developed once the motor is rotating and thus has no starting torque, as observed. When self-starting does occur this is attributed to remnant magnetisation of the bearings from previous running. Analysis performed by Gruenberg led to the following relations for torque and current, where a, b and k are constants.

$$T = k\omega I^2$$
$$I^2 = a + b\omega$$

A further paper presented by Weenink,[10] showed by similar analysis to Gruenberg that the torque produced by this method was actually equal to zero and that Gruenberg's non-zero torque calculation was due to an algebraic error. He also extended Gruenberg's calculations to include second order terms and again found that torque was equal to zero.

A slightly different electromagnetic theory was proposed by Moyssides and Hatzikonstantinou.[11] Here they claim that the torque produced is a result of the interaction of applied and induced currents and their associated magnetic fields within the balls, with the current flowing in the shaft along the central axis and its magnetic field.

Another theory of the driving force responsible for the Huber effect is that of spark breakdown presented by Polivanov, Netushil, and Tatarinova.[12] They suggest that sparking occurring between the section of a rotating ball previously in contact with the race and the race itself is the cause of the torque produced. The sparking is explained as a result of the Lenz law. A rotating sphere in contact with a conducting plate will have a new current distribution continually established. Lenz law causes the old current distribution to tend to be preserved, resulting in the old current distribution no longer intersecting the surface of the ball at the contact with the conducting surface. The only way for this current distribution to be preserved is through an arc discharge occurring.

A further theory presented by Marinov,[13] suggests that the ball bearing motor is in fact a thermal engine with thermal expansion of the ball at the point contacts with the race responsible for rotation. The thermal expansion occurs due to the larger resistance seen at the point contact. Current applied to the motor causes the small part of the ball in contact with the race to be heated and thus expand while the remainder is unaffected resulting in the ball becoming slightly ellipsoidal. With an initial rotation, the local expansion imparts torque to the ball in the direction of the rotation. The entire ball will absorb the heat from the local deformation and return to the original size. At the new point contact another local expansion will occur and rotation is sustained. Marinov attributes self-starting to the races not being perfectly smooth, thus with perfectly machined bearings self-starting is impossible.

Some experimental testing performed by Watson, Williams and Crimp,[14] has provided quite interesting results. These tests have been performed on a ball bearing motor similar to that first used by Milroy,[8] immersed in kerosene to minimise arcing, pitting and corrosion, and to maintain a constant temperature environment. They have found that the speed-current relationship is in fact linear and not the square law relation presented by Gruenberg. They also produced torque-current characteristics for constant speed values and found the relationship was linear, again contradicting Gruenberg's square law relation.

3. APPLICATIONS TO MICROMOTORS

In determining suitable applications of the Huber effect as applied to micromotors, some insight into the cause of this phenomenon is required. It is necessary to obtain repeatable, reliable running characteristics of motors utilising this effect, such as the ball bearing motor before any applications can be assessed.

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The ball bearing motor utilising the Huber effect or some adaptation may be a possibility to overcome some of the problems currently faced when constructing micromotors. At present polysilicon is the major material used in MEMS construction. A number of problems that can affect the mechanical behaviour arise when using polysilicon, including residual stress, stress gradients through the film thickness and variations of the effective Young's modulus throughout the multicrystalline structure, as presented by Bustillo, Howe and Muller.[7] A number of complex ways have been devised to deal with these shortcomings. The Huber effect may be a much less expensive solution to these problems, as the ball bearing motor utilising this effect is constructed of metal, leaving it less susceptible to problems of stress while achieving a constant Young's modulus due to the uniform material used.

Another major problem faced in the design of micromotors is the problem of stiction. This is the sticking of structures to the substrate after rinsing and drying. Again many methods have been devised to alleviate the problem of stiction. Use of the Huber effect could totally eliminate the problem of stiction as there is no contact between moving parts of the motor except inside the bearing race, which is of simple design and designed in a way that rotation will occur freely.

There is also the possibility that the Huber effect could considerably reduce the manufacturing costs of micromotors. The ball bearing motor is of particularly simple design and incorporating this as a micromotor could eliminate the costly procedure of surface micromachining.

While at present the ball bearing motor is a completely impractical device due to its self-destructive nature, there is the possibility that by scaling the device to a size suitable for a micromotor, the self-destructive effect could be reduced or eliminated. This is only speculative and a great deal more research would be required before this could be determined.

4. EXPERIMENTAL SETUP

In early stages of the experiments, a ball-bearing motor (motor 1) with a rotating cylindrical brass tube connected to the outer races was used. The motor consisted of two bearing races of 16mm outer diameter at each end inside of the tube with outer diameter of 19mm and length of 60mm. Two small screws connected at either end to the inner race provided the electrical contacts. The motor was operated in water, which was deionised and demineralised to absorb the heat produced. But after several measurements of speed and current were taken when the motor was operated, the motor showed signs of arcing and corrosion and finally seized up. It was found that this was a result of corrosion of the ball bearings due to the large current used.

To solve the problem, an improved ball-bearing motor (motor 2) was constructed. The motor was made up of an inner metal shaft of length 105mm connected along the central axis of two bearing races with inner diameter of 5mm and a distance of 38mm between bearings. The rotating part of the new motor is the inner shaft through the inner races of the ball bearing motor. This is done to reduce friction due to drag of the larger diameter tube and also reduce the inertia of the motor, thus minimising the starting current. Measurements of speed and current were taken using alternating and direct current supplies and was run vertically with the end of the shaft protruding from household type kerosene to reduce pitting and corrosion. The results of the tests showed that the performance and the efficiency of the new motor had improved significantly from the previous design. All speed measurements were carried out using an optical tachometer.

A transformer connected to a mains fed variac was used to supply a high alternating current supply to drive the motors. The step-down transformer can supply up to 70 A of current. In order to obtain the DC characteristic of the motors, a DC supply that converts a 3-phase supply to direct current was used, capable of supplying up to 50 A of direct current.

To reduce arcing, corrosion and pitting of the ball bearings, all testing was performed in a liquid medium contained in a perspex container. The liquid substance is also used to absorbed the huge amount of heat produced during the running of the motor in order to prevent the motor from seizing up and self-destructing. So far, as mentioned above, deionised, demineralised reverse osmosis treated water and a household type kerosene was used.

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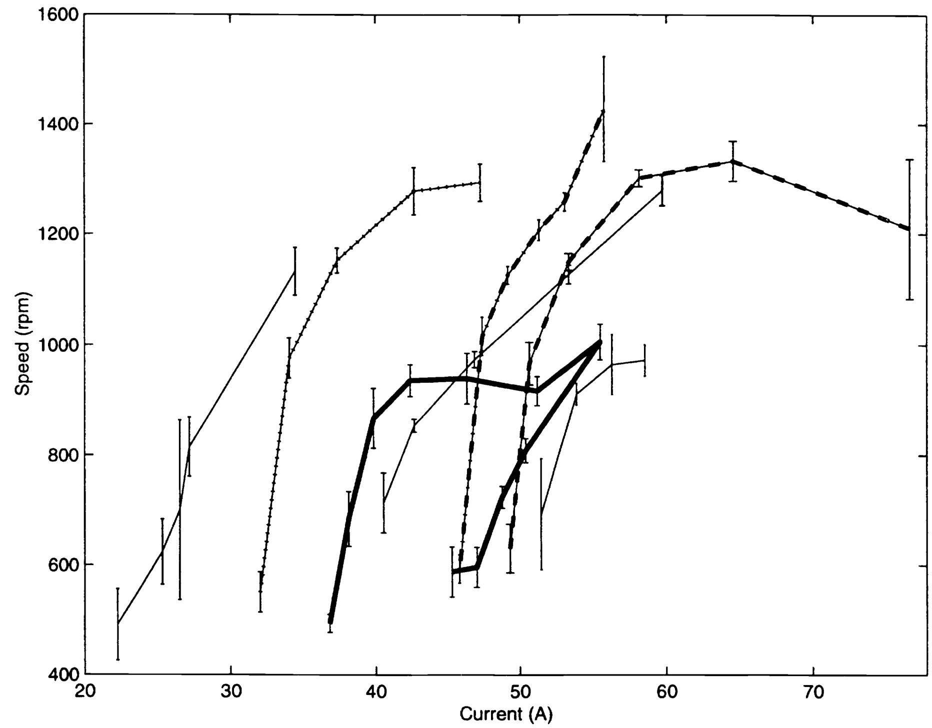

Figure 1. Speed - Current(AC) motor characteristics operating under Demineralised and Deionised Water.

5. RESULTS

The six curves in Figure 1 show the results of the speed-current tests operating immersed in demineralised and deionised water, powered by ac current and using the first motor design (motor 1). Four of these identical motors were constructed to test for repeatability and variation in results under different external settings.

The speed-current curves present in Figure 1 do not show a consistent relationship between speed and current. Each motor showed a variation in starting current and ranged from 22 A to 49 A.

The results obtained here do not agree with the Watson, Williams and Crimp[14] results and do not support the linear relationship between speed and current presented in their paper. Looking at curves on Figure 1, one of the curves(dark line) clearly resembles a hysteresis loop, obtained by running the motor from starting current, increasing the current and then reducing the current until rotation ceased. This would indicate the action of an electromagnetic effect. It can also be explained due to a back emf present.[14] However we can not look lightly on the fact that pitting and corrosion is occurring under these long operating periods. The effect of corrosion is clearly evident here where the speed has drastically decreased and starting current has been raised by 10 Amps.

Motor design 2, operated in kerosene, suffered less pitting and corrosion than the initial design of motor 1, which was operated in deionised and demineralised water. However these effects were still clearly observable and did have an affect on the results obtained.

The speed-current curves of Figure 2 shows those performed with motor 2 and are a significant improvement compared to curves show of Figure 1. The curves shown in Figure 2 were carried from minimum to maximum operating current with a starting current approximately 11 A to 14 A. None of these curves show an perfect linear relation between speed and current as those carried out by Watson, William and Crimp.[14] However this deviation from the linear characteristic may be a result of pitting and corrosion which was still occurring but to a lesser extent than motor 1.

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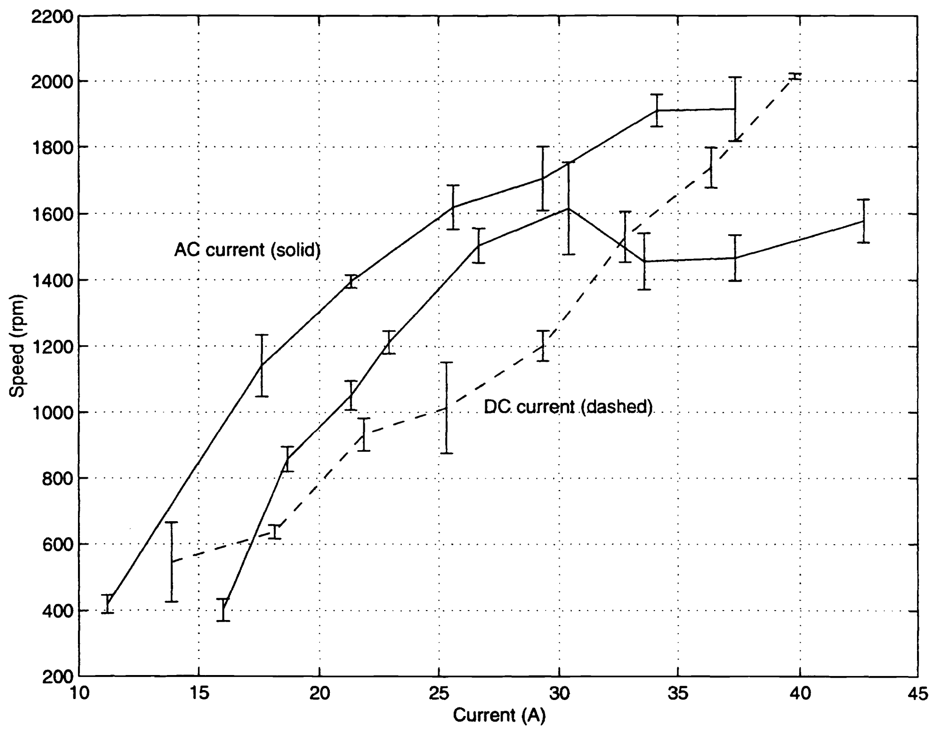

Figure 2. Speed - Current motor characteristics operating under Kerosene

Temperature readings taken during the tests performed to obtain the curves of Figure 2 showed substantial temperature gradients within the kerosene. During operation temperature near the motor and temperature recorded adjacent to the container wall differed approximately 5 degrees Celcius. At high operating current, the difference would sometimes reach 10 degree Celcius. Initial and final temperatures recorded had difference ranging from 10 to 15 degrees Celcius.

6. PRESENT WORK

As can be seen from Figure 2, an almost linear characteristic was obtained. To further improve the accuracy of results, a rotary optical encoder is currently being designed to replace the existing optical tachometer. Its usage will reduce the errors in readings due to reflection of external lights experienced with the optical tachometer and the encoder has high resolution (500 pulses per revolution) which can measure high rotational speeds accurately. This will enable real-time measurements to be performed which will markedly reduce the number of readings required for accuracy and thus the time required performing these readings, hence reducing pitting and corrosion.

Since there are still signs of pitting and corrosion of the ball bearings when using kerosene, a liquid with a lower viscosity will be used. The liquid called hexamethyl disiloxane is a silicone oil, which will be used with the aim of minimising the current needed to run the motor due to less drag introduced by the low viscosity silicone oil.

7. CONCLUSIONS

Testing performed to date has yielded indifferent results. While the results seen in Figure 2 do not strictly support a linear relationship between speed and current, it is possible that the relationship is in fact linear with pitting and corrosion of the bearings responsible for the levelling of the curves. This point is supported further by inspecting the sections of the curves produced at lower currents, which are essentially linear. Pitting and corrosion would have only

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a minor affect in this region, with the levelling occurring at higher currents, later in to the test where these effects have become more pronounced. Figure 1 also supports this, with the sections of the curves produced at lower values of current also essentially linear.

There is not enough evidence at present to determine if one or any of the existing theories is correct in explaining the existence of the Huber effect, nor is it possible to conclude irrefutably that the relationship between speed and current is indeed linear. There is however no doubting that there is a need for further investigation of the Huber effect, especially with the possibility of its use in MEMS applications. Once this effect can be reliably characterised and the source of this phenomenon undoubtedly determined its suitability in various MEMS application can be determined.

ACKNOWLEDGEMENTS

Assistance of the EEE department technical staff is gratefully acknowledged.

REFERENCES

1. O. Oshiro, *et al,* "Ultrasound imaging with micromotors," *Trans. IEE Japan,* **188-E**, 3, pp. 193-197, 1998.
2. P. Dario, *et al,* " A mobile microbot actuated by a new electromagnetic wobble micromotor," *IEEE/ASME Trans. Mechatronics,* **3**, 1, pp. 9-16, 1998.
3. M. Tabib Azar, *et al* "Novel highly scalable and very high torque micromotor for MEMS and MOEMS applications using the mechanical rectifications of oscillatory motion," *Proc. SPIE,* **76**, 8, p. 169-174, 1998.
4. J. Huber, *et al,* "Electrodynamische Kraftwirkungen au Einem auf Eisinbahschienen Beweglichen Radsatz," *Elektrotechnik und Maschinebau,* **76**, 8, pp. 169-174, 1959.
5. A.V. Netushil "The electromagnetic effect of Huber and its development," *Electrical Technology, Pergamon,* 3, pp. 57-64, 1992.
6. D.B. Watson and A.M. Watson "Linear ball-bearing motor," *IEE proc. Sci. Meas. Technol.,* **141**, 3, pp. 224-228, 1994.
7. J.M. Bustillo, R.T. Howe and R.S. Muller "Surface micromachining for microelectromechanical systems," *Proc. of the I.E.E.E.,* **86**, 8, August, 1998.
8. R.A. Milroy *et al,* "Discussion," *J. Appl. Mechanics,* **34**, pp. 525, 1976.
9. H. Gruenberg *et al,* "The ball bearing as a motor," *Am. J. Physics,* **46**, pp. 1213-1219, 1973.
10. M.P.H. Weenink *et al,* "The electrostatic torque on a rotating conducting sphere," *Applied Scientific Research,* **37**, pp. 171-182, 1981.
11. P.G. Moyssides and P. Hatzikonstantinou *et al,* "Study of electrical characteristics of the ball bearing motor," *I.E.E.E trans. on Mag.,* **26**, pp. 1274-1281, 1990.
12. K.M. Polivanov, A.V. Netushil and N.V. Tatarinova *et al,* "Huber's electromechanical effect," *Elektrichestvo,* **8**, pp. 169-174, 1973.
13. S. Marinov *et al,* "The intriguing ball bearing motor," *Electronics and Wireless World,* April, 1989.
14. D.B. Watson, M.R. Williams and C.S. Crimp *et al,* "Ball bearing motors," *I.E.E. Proc.-A,* **140**, 4, pp. 281-286, 1993.

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