Moving Coil or Moving Iron Controllable Actuators: How to make the good choice.

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1. Introduction

There is a strong demand of controllable actuators for both traditional and new applications. A controllable actuator should be able to accelerate, break, inverse the motion of the load, all along the stroke. It means the force produced by the actuator should be proportional (at least roughly) to the applied electric excitation, and in particular, the sign of the actuation force could be changed all along the stroke.

As an example of traditional mass application of magnetic actuators which would benefit of controllability, there are the circuit breakers. They would improve the life time of their electric contacts by “soft landing” using controllability [1]. In circuit breakers for AC current, there are also interests for synchronization of the opening or the closing of the circuit breaker with the 0 current in order to avoid electric arcs [2]. In this application, the stroke of the actuators is in the range of 1 to 10 millimeters and the required force bandwidth is above 100Hz.

Many new applications requiring controllable actuators are found in mechatronic or adaptronic systems [3]. A typical application is the active control of vibration (AVC). For this kind of applications there are mainly two kinds of controllable actuators: piezoelectric actuators and moving coil actuators (also called Voice coil or Lorentz actuators). Piezoelectric actuators offers large forces (up to 1kN or more) but even with amplified piezoelectric actuators (see for example [4]), displacements are limited to 1mm. Moving coil actuators offer large displacements (up to 10mm) but if acceptable actuator mass is lower than 1kg, forces are very low, typically less than 50N in steady state. So there is a gap in performances between both solutions. The fact is what is required for several embedded AVC applications such as meet in air&space or automotive is precisely into this gap: Displacements in the range of 1 to 5mm and force bandwidth of more than 100Hz, with actuators mass less than 1kg. These requirements are similar to previous one.

To meet these all requirements, there are two possible starting points. One is to consider improvement of moving coil actuators, the other is to consider improvement of moving iron actuators.

The Moving Coil Actuators are based on the Laplace (or Lorentz) force which is strictly proportional to the applied current. A coil is placed into a magnetic field perpendicular to the coil winding. A magnetic force to coil winding is produced all along the third direction proportionally to the applied current into the coil.

The usual Moving Iron Actuators are more generally called electromagnets. They use the magnetic attraction force that exists between two soft magnetic parts in presence of a magnetic field. This force is due to a minimization of the system magnetic reluctance. It is generally much higher than Laplace force used in Moving Coil Actuators. Typically, for a similar mass one can expect a 10 times higher force. It is why Moving Iron Actuators are the most popular magnetic actuator type. In principle, the magnetic force is intrinsically quadratic meaning that only attraction forces can be produced, so they are not controllable. To get it back, a return spring is added, leading to one fixed position at rest. Such an actuator even with a return springs is generally not able to perform fine control functions.

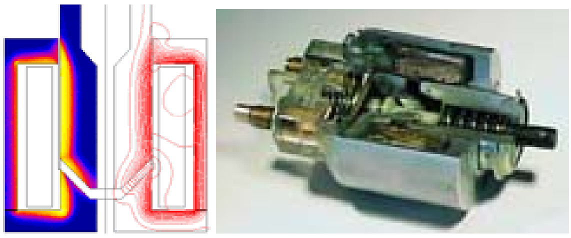

Figure 1: Standard Moving Iron Actuator with a conic air gap and a return spring : FEM FLUX & Structure

A new trend consists in trying to improve the controllability of moving iron actuators, while keeping their force density superiority.

One new approach used for circuit breakers consists in using appropriate current laws. Although they prove their effectiveness in the test conditions [1], these laws cannot anticipate disturbances due to wear or temperature and are very specific to the application.

Another approach consists in combining a moving iron and a moving coil into one actuator. This approach has been exploited for example in a new actuator concept patented by Schneider Electric [5]. However this actuator provides only partial controllability as it adds a reluctant attractive force to a voice coil, which makes it unpractical as regard AVC applications for example.

Following a similar approach by combination and using its experience on moving coil actuators [6], moving magnets actuators [7] and moving iron actuators, Cedrat Technologies has developed new specific Moving Iron

Controllable Actuators, called MICA [8]. This actuator circumvents previous controllability limitations of standard Moving Iron actuators while keeping high forces capabilities.

This paper aims at presenting the properties of the MICA Moving Iron Controllable Actuators after introducing the Moving Coil Actuators, these being the initiators and the competitors of MICA technologies.

2. Moving Coil Actuators

Moving Coil Actuators are rather simple structures. They can be customized thanks to following design parameters:

- The magnetic force is determined by the product of the coil current and the magnetic field. This field is produced by a magnetic circuit including a permanent magnet. Increasing force leads to a trade-off between the coil electric power and magnetic circuit mass.
- The heating of the coil is the main force limitation of a moving coil. Its thermal behavior results not only of the previous trade-off but also of the heat exchange design. As the coil is not in contact with iron, the heat drain is difficult especially in vacuum application. In this case thermal drains can be implemented.
- The guiding can take benefit of the absence of transverse forces in a moving coil to use an elastic guiding. This is interesting to get a wear-free and hysteresis-free actuator.

As an example, a moving coil actuator for high precision positioning and compatible with space technology specifications, called VC-1 has been designed and successfully tested by Cedrat Technologies [6]. General space technology requirements are the use of no degassing material, no lubrication, low mechanic time constant, low electrical power consumption, and thermal energy evacuation through radiating and conducting exchanges (no convection because of operation in vacuum environment). In particular, as the electric power on board satellites is very limited, their design is performed with a special care of the force produced versus electric power. These have been accounted in the design, the realization and the test of a successful VC-1 prototype. Thanks to a good design of thermal drains, the actuator presents a rather high force capability.

The VC-1 (figures 2 & 3) is a cylindrical actuator of 71mm in diameter and 49mm in length. Its total mass is 500gr. The moving part is a central feed through shaft. The stator is based on a NdFeB hollow permanent magnet with a 1.3T magnetization and a standard magnetic steel for the magnetic circuit. Coil is guiding by flexural blades and is drained by flexible thermal drains to reduced heating.

The VC-1 stroke is 3 mm. The coil electric resistance is 0.11 Ohm. The force factor is 1.9N/A. It leads to a force-to-power ratio of 5.5N/W^{½}. After Thermal Vacuum qualification, the nominal force in vacuum is fixed to 13N for a continuous 5.5 W electrical consumption. Maximal force can be increase according to the duty cycle. Because of better exchanges, the nominal force in air is 30N. This lead to a force-to-mass ratio of 60N/kg. The peak force could reach 100 N with a 5% duty cycle. Although sometimes useful for transient applications, this large force is not exploitable in AVC.

The actuator has passed successfully the life time test of 10^7 cycles. However after this, thermal drains showed some fatigue signs.

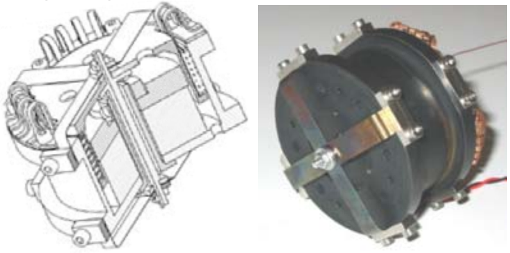

Figure 2 : VC-1 Voice Coil Actuator

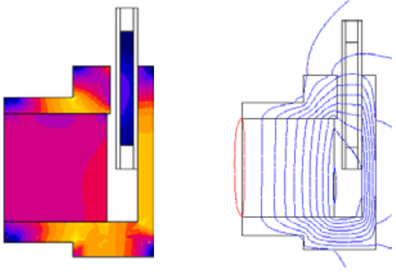

Figure 3: VC-1 Voice coil cross section, accounting for axial symmetry (z vertical axis) : FLUX FEM analysis

The fields of improvement of the moving coil force are limited as there are only few design parameters. However, this has been explored by optimizing the magnetic circuit shape using FLUX FEM software [9] and by using high performance magnetic materials in second step.

The geometry of the second generation actuator called VC-2 is shown on figure 4. This new geometry has resulted of an optimization process performed using FLUX software, targeting an improvement of magnetic force, keeping:

- the same total mass and the same materials,
- the same coil and ampere turns as VC-1.

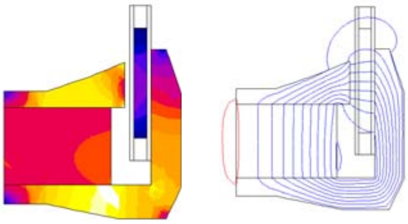

Figure 4: VC-2 Voice coil cross section, accounting for axial symmetry (z vertical axis) : FLUX FEM analysis

To improve further the force, high performance magnetic materials have been introduced as a third case (VC-2b) :

- permanent magnet with magnetization of 1.4T
- magnetic flux conductor with saturation magnetization of 2T

The forces versus position, of the three actuators VC-1, VC2, VC-2b are compared using the same applied current. It appears that the VC-1 force can be improved of about 20% with the VC-2 new geometry and even of 40% with

VC-2b if high performance magnetic materials are used. Thus, the force factor is 2.7N/A. It leads to a force-to-power ratio of 7.7N/W$^{\frac{1}{2}}$. The nominal force in air is 42N giving a force-to-mass ratio of 84N/kg. Note that force is proportional to the applied current, but it depends on the position as the magnetic field in the coil area is not uniform.

This work shows that Moving coils actuators can be improved, but only in a limited amount. Coil heating remains a strong force limitation.

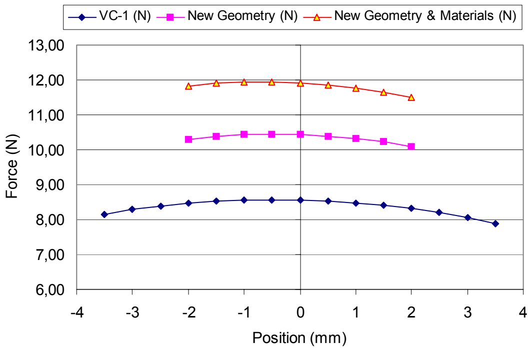

Figure 5: Force vs position of VC-1, VC-2 (new geometry) and VC-2b (new geometry & materials), for current of 4.5A

3. Moving Iron Controllable Actuators

Several Moving Iron Controllable Actuators (MICA) actuators have been designed by Cedrat Technologies aiming at a good controllability as a moving coil with a higher force versus power and a higher force per mass than a moving coil.

As a common feature, MICAs are based on a moving iron shaft and the coil is located in the stator. This provides two advantages over the moving coil:

- At first there is no moving coil, avoiding fatigue of moving wires supplying the moving coil.

- Secondly, the thermal drain of the coil is performed by the stator iron, which is thermally efficient and mechanically reliable.

The particular design of the MICA 40 (figure 6) was targeting a size a bit smaller than the VC-1, a stroke of 3mm, as the VC-1 and a controllable steady state force in the 40N range. Its length is 80mm and the side of the square section is 39mm. Its weight is 0.358kg. Its coil is made of 282 turns, leading to a resistance of 1.86 Ohms.

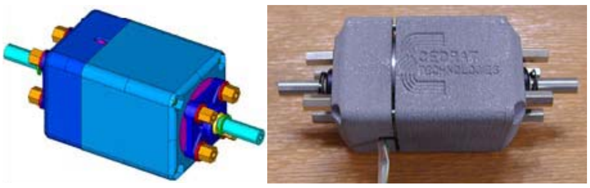

Figure 6: MICA40-3 CAD Assembly & prototype

The forces are computed with FLUX for different currents and different position along the 3mm stroke (figure 7), accounting for non linearity of magnetic materials. The model predicts the force is almost proportional to the current and can be inverted whatever the position, as a moving coil. According to the model, a force of 18N is achieved with a current of about 2A, with an electric power 3.7W. The nominal force of 41N, giving a force-to-mass ratio of 114N/kg, is achieved with a current of about 4A with a power of 15W. Thus, the force factor is 9N/A. It leads to a force-to-power ratio of 10.6N/W$^{\frac{1}{2}}$. All these factors are well above those of VC1, VC2 and VC2b.

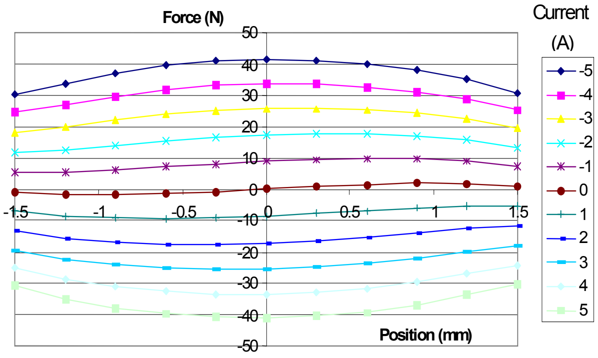

Figure 7: Force vs position of MICA40-3 for currents varying between –5A and + 5A.

The force test bench is shown in figure 8. It consists in measuring the force produced by the actuator versus the applied current in any position along the possible stroke, using a force sensor, a position sensor, a current sensor, a current generator and a micro positioning screw to position the actuator moving axis.

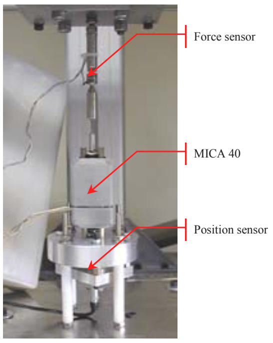

Figure 8: Force test bench of the MICA40-3

The measured forces versus applied current from –2A to +2A at different positions are shown on figure 9. They are closed to theoretical expectations. In spite of some hysteresis, which does not exists with moving coil, the controllability is demonstrated. The measured force at 2A is about 25N in the central position, which is higher than expected. The forces have been also measured at different frequencies from 0.1Hz to 300Hz. The actuator forces appear rather independent of frequency. The force versus current (figure 11) has been measured to assess some saturation effect. A force of 100N at 7.5A was achieved without clear saturation.

The thermal behaviour is presented on figure 11, by the self heating of the actuator when supplied with a DC current of 2A, and its cooling when current is switched off. An increase if 30°C is achieved in 5min.

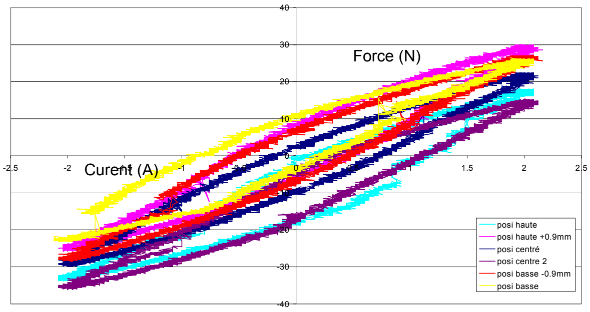

Figure 9: MICA40-3 Force versus current at different positions

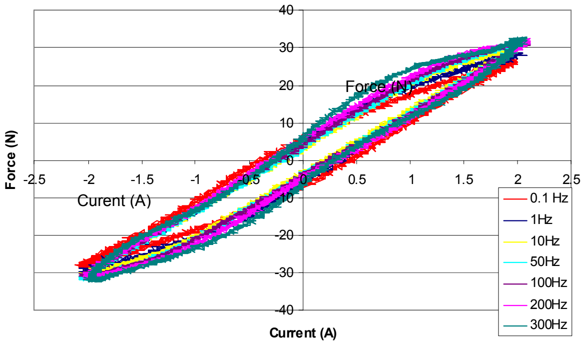

Figure 10: MICA40-3 Force versus current at different frequencies for the central position

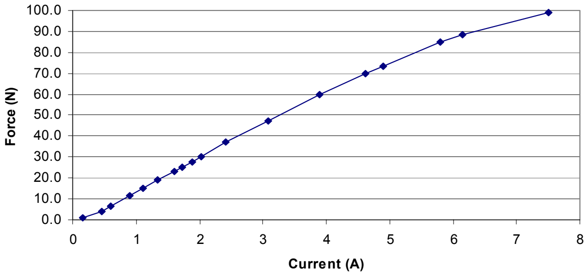

Figure 11: MICA40-3 Force versus current at 10Hz for the central position

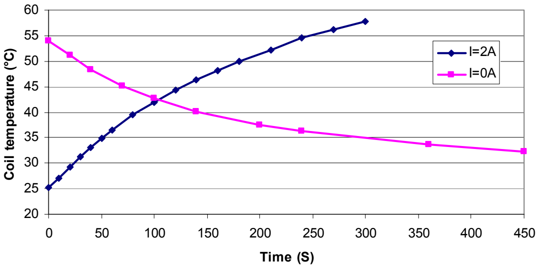

Figure 11: MICA40-3 self-heating when supplied at 2A and its cooling when current is switched off

The table 1 compares the moving coils VC-1, VC-2b, LA17-28 from BEI [10] to the moving iron MICA40-3. LA17-28 has a larger stroke but it is not guided. Such a stroke is not really useful in AVC applications. Force per mass and force per power are in favor of the MICA. For a similar force as VC-2b it requires almost 3 times less power while being lighter.

Several other MICAs have been developed for offering forces up to 200N [9]. These actuators have been successfully tested in AVC and vibration generators.

References	**Unit**	**VC-1**	**VC-2b**	**LA17-28**	**MICA40-3**
Notes		*Voice Coil*	*Voice Coil*	*Voice Coil (no guiding)*	*Moving Iron*
Stroke	*mm*	*3*	*3*	*15,2*	*3,6*
Nominal force	*N*	*+/- 30*	*+/- 42*	*+/- 28.5*	*+/- 40*
Continuous current	*A*	*15,7*	*15,7*	*1,6*	*2,6*
Force sensitivity	*N/A*	*1,9*	*2,7*	*17,8*	*15,4*
Winding resistance	*ohm*	*0,12*	*0,12*	*6,7*	*1,86*
Dissipated power	*W*	*29,6*	*29,6*	*17,3*	*12,6*
Side	*mm*	*D71*	*D71*	*D58.4*	*39*39*
Height	*mm*	*49*	*49*	*66*	*80*
Total Mass	*g*	*500*	*500*	*497*	*420*
Moving mass	*g*	*50*	*50*	*83*	*100*
Force / mass	***N/kg***	***60***	***84***	***57***	***95***
Force / power $^{1/2}$	***N/W $^{1/2}$***	***5,5***	***7,7***	***6,9***	***11,3***

Table 1 – Comparison of Moving coil & moving iron

4. Conclusion

Moving coil actuators and new controllable moving iron actuators are two types of controllable actuators that have been carefully studied and that can be compared. Moving coil actuators are hysteresis-free, but their coil heating limits their force capability. New controllable moving iron actuators offers higher force per power and higher force to mass ratio. They are also more robust. They offer a new solution for stringent mechatronic applications such as anti vibration control.

5. Acknowledgement

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6. References

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