MOVING IRON CONTROLLABLE ACTUATORS

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Abstract:

To meet the demand of controllable millimeter-stroke actuators, 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. Following this approach and using its experience on the different types of magnetic actuators, Cedrat Technologies has developed new specific Moving Iron Controllable Actuators, called MICA. This actuator circumvents previous controllability limitations of standard Moving Iron actuators while keeping their high forces capabilities. Compared with moving coils of the same force, the MICA are twice less in mass while requiring 3 times less electric power. Another significant advantage of the MICA is a much better heat dissipation and reliability as the MICA coil is fixed into the iron stator. These actuators have been successfully tested in Active Control of Vibration and vibration generators. The 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.

Keywords: Magnetic Actuator, Moving Coil, Control

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 Lorentz force which is strictly proportional to the applied current.

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. It is generally much higher than Lorentz force. Typically, for a similar mass one can expect a factor 10. 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.

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 in a new actuator patented by Schneider Electric [5]. However this 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. Using its experience on moving coil actuators [6], moving magnets actuators [7] and moving iron actuators, Cedrat has developed new specific Moving Iron Controllable Actuators, called MICA [8]. This 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.

Moving Coil Actuators

Moving Coil Actuators can be customized thanks to following 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. 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 requirements, called VC-1 has been designed and successfully tested by Cedrat [6]. General space requirements are the use of no degassing material, no lubrication, low mechanic time constant, low electrical power, and thermal energy evacuation through radiating and conducting exchanges. 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 the VC-1 prototype. Thanks to a good design of thermal drains, the actuator presents a rather high force capability.

The VC-1 (fig. 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.

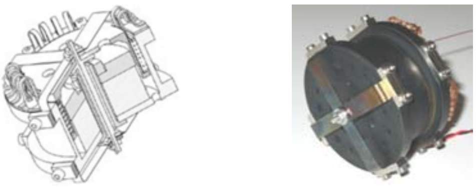

***Fig. 1**: VC-1 Voice Coil Actuator*

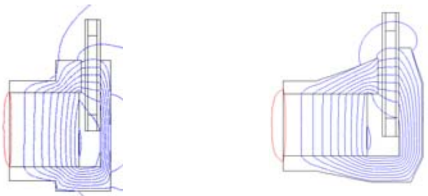

***Fig. 2**: FLUX FEM analysis of VC-1 and VC-2 cross sections, accounting for axial symmetry (z vertical axis)*

The VC-1 stroke is 3 mm. The coil resistance is 0.11 Ohm. The force factor is 1.9N/A. It leads to a force-to-power ratio of 5.5N/W$^{1/2}$. After Thermal Vacuum qualification, the nominal force in vacuum is fixed to 13N for a continuous 5.5 W electrical consumption. Max force can be increase according to the duty cycle. Because of better exchanges, the nominal force in air is 30N. It leads 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 a life time test of 10^7 cycles. However after this, thermal drains showed some fatigue signs.

Improvements of the forces are limited as there are only few design parameters. This has been explored by optimizing the magnetic circuit shape using FLUX FEM software [9] to define a new geometry VC2 and by implementing high performance magnetic materials in second step, giving the VC2b (see Fig.3). The VC-1 force is improved of 20% with the VC-2 and of 40% with VC-2b. Performances are in table 1 and details in [LDIA].

This work shows that Moving coils actuators can be improved, but only in a limited amount. Coil heating remains a strong force limitation. New technological works for space applications are in progress in an ESA TRP project “Moving Coil Motor”.

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.

A MICA general concept is shown of fig 3. The actuator is cylindrical with a z axis. A stator containing the coil presents 2 poles. A moving shaft presents 2 shifted poles. Permanent magnets (not shown) produce a magnetic bias Hsa and Hsb of the opposite air gaps having same direction. The coil is used to create opposite dynamic magnetic fields Hda and Hdb which can be reversed with the current. The total field in the air gaps can be increased or decreased. The shaft is attracted to the air gap having the largest total field. This allows the shaft to move in one direction or the opposite one. As will be shown a good linearity is even obtained, leading to an actuator competing with moving coil actuators.

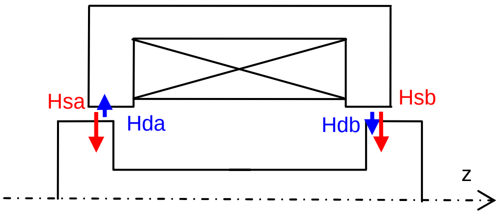

***Fig. 3**: MICA general concept*

MICA coil located in the stator provides two first advantages: 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.

***Fig. 4**: MICA40-3 prototype*

The MICA 40 (fig.4) is one realization targeting improvement of VC1-1 or VC-2 : a size a bit smaller with same stroke of 3mm 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.

The forces are computed with FLUX for different currents and different position along the 3mm stroke (fig.5), 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$^{1/2}$. All these factors are well above those of VC1, VC2 and VC2b.

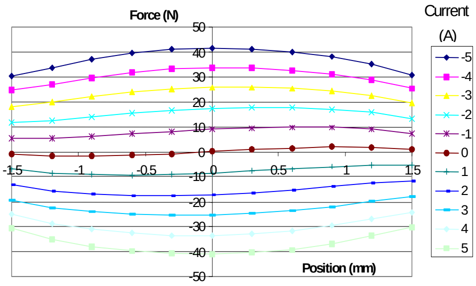

***Fig. 5**: Force vs position of MICA40-3 for currents varying between –5A and + 5A (FLUX result)*

The force test 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. 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 exist with moving coil, the controllability is demonstrated. The measured force at 2A is about 25N in the central position, which is higher than expected.

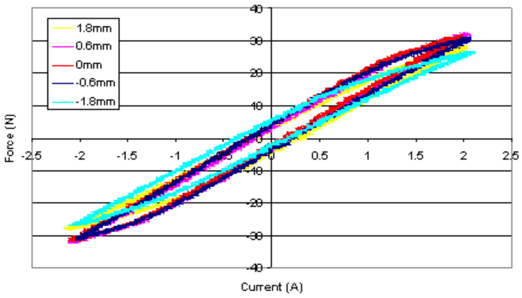

***Fig. 6**: MICA40-3 Force vs current at different positions*

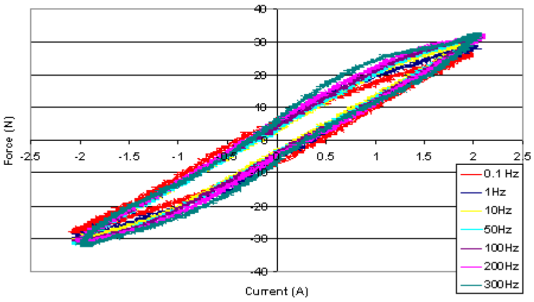

***Fig. 7**: MICA40-3 Force vs current at different frequencies for the central position*

The forces have been also measured at different frequencies from 0.1Hz to 300Hz. The forces appear rather independent of frequency. The force versus current (fig. 11) has been measured to assess some saturation effect. A force of 100N at 7.5A was achieved without clear saturation. The thermal behavior is presented on fig. 9, 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.

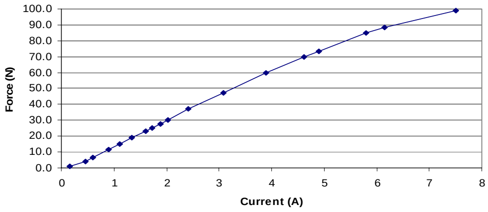

***Fig. 8**: MICA40-3 Force vs current at 10Hz for the central position*

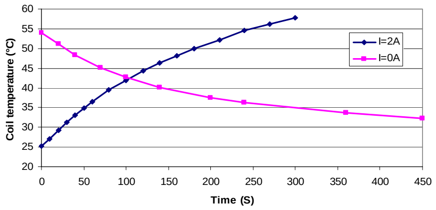

***Fig. 9**: MICA40-3 self-heating when supplied at 2A and its cooling when current is switched off*

The table 1 compares the moving coils VC-1, VC-2b, LA17-28 from BEI [9] 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.

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*

Several other MICAs have been developed for offering forces up to 500N [8]. These actuators have been successfully tested in AVC and vibration generators. The fig.10 shows a typical AVC test: the MICA 170 actuator is fixed to a mass and is excited with large vibrations amplitudes produced by an APA500L. Typically the amplitudes are 0.5mm from 10 to 500Hz. When the MICA170 is operated it reduces the vibrations on the mass by 15dB to 20dB according to the modes. It shows that the MICA technology, even not strictly linear, is controllable enough to perform control of large vibration amplitudes.

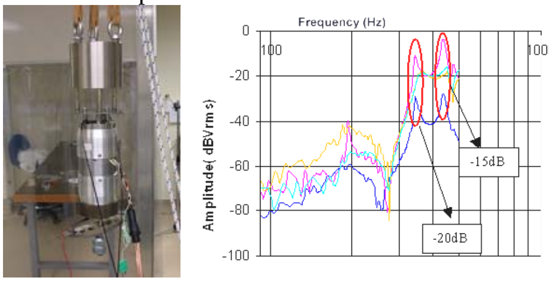

***Fig. 10**: MICA170-3 Vibration test : Experiment & results*

Conclusion

Moving coil actuators and new controllable moving iron actuators are two types of controllable actuators that have been studied and 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.

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