

Compact, Efficient and Controllable Moving Iron Actuation Chain for Industrial Application

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Abstract:

In the field of aeronautics, some parts of aircraft engines are tricky and costly to manufacture. In the low pressure turbine very thin pieces obtained by turning require a complex support. The R&D work performed here aims at improving the manufacturing process through the reduction of vibrations and active modification of the clamping conditions. For that purpose, Cedrat Technologies has designed a new innovative Moving Iron Controllable Actuator (MICA), which is embedded on the work-piece support. In the first part, the application goals and the main particularities of the developed MICA200M magnetic actuator are presented. To be easily driven in closed loop, the force is designed to be linear with the current and independent from the interface position. The MICA200M stroke is $\pm 2.5\text{mm}$ and its force constant reaches 11.6N/A for a current range of $\pm 15\text{A}$ in steady state. The nominal force of 174N for only 1 dm^3 size and 3.2kg facilitates the integration and allows acceleration up to 132G in transient operation thanks to reduced 0.25kg mobile mass. In the second part, results of complete experimental characterisation are detailed. Finally, a comparison analysis is done with COTS voice coil actuators and the article concludes with the benefits of the MICA200M.

Keywords: Actuator, Magnetic, MICA, Moving Iron, High Bandwidth, Current Switching Amplifier

Introduction

The ICT FP7 European project INTEFIX requires a high dynamics linear actuator suitable for anti-vibration applications like chatter reduction for the turning of thin work-pieces [1] for example the turbine casing. In the frame of this project, Cedrat Technologies has designed a new innovative Moving Iron Controllable Actuator (MICA). This paper presents in the first part the application goals and the main particularities of MICA200M magnetic actuator. Then, results of complete experimental characterisation are detailed. Finally, a comparison analysis is done with existing voice coil actuators and the article concludes on the benefits of the MICA200M.

Intefix project and actuation needs

The INTEFIX project aims at improving the machining of thin work-pieces thanks to the use of INTElligent FIXtures which includes the reduction of vibration, the compensation of constraints relaxation and the accurate positioning of work-pieces. The study case described here concerns the turning of the low pressure turbine casing (see Fig. 1). The objective is to improve the manufacturing process during finish turning, through the reduction of vibrations and active modification of the clamping conditions. Modifications performed on the current fixture include the integration of active vibration damping to reduce the vibrations during machining and the integration of active actuators to produce an active controlled deformation on the work-piece in order to improve the clamping conditions (see Fig. 2). The requirements of both types of actuation are

different. Vibration reduction requires large bandwidth actuation whereas the production of active controlled deformations requires significant stroke. Additionally, both need large forces and a compact profile as they are embedded actuators. Both functionalities are fulfilled with the MICA200M actuator.

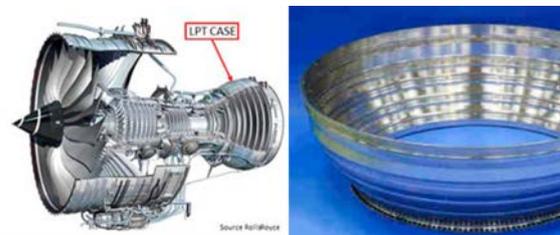


Fig. 1: Turbine casing work-piece



Fig. 2: MICA integrated in turning support

Principle of MICA actuator

MICA actuator, which is a patented technology of linear magnetic actuator, whose particular characteristic is its high and controllable force on an iron mobile part. The actuator force is proportional

to the current and stays homogeneous versus displacement. The functioning principle uses the polarisation of the air gap with magnets. The applied current modifies the symmetry on polarised air gap (Fig. 3[2]), and generates high force thanks to the air gap high induction magnitude.

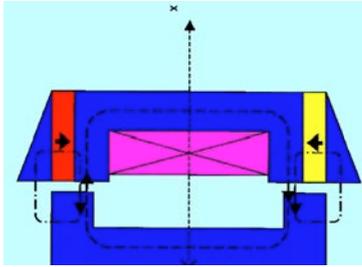


Fig. 3: MICA actuation principle

MICA200M: high tech for high performance actuator

The new MICA 200M is a small brother of MICA500L, integrating lots of new features in its design. The MICA500L actuator shows a 500N nominal force and the moving part is almost the full size of the ends of the actuator.



Fig. 4: MICA500L and MICA200M

On the new MICA200M (See Fig. 4) the mobile part has been optimised and reduced significantly. With half of the force, the mobile mass is reduced by a factor of 4. Dynamic operation of the MICA200M is thus enhanced.

In the MICA500L, the force versus displacement curves have been designed with negative magnetic stiffness to compensate partly for the blade stiffness and to reach the end stroke with a lower power requirement. With the new MICA200M, magnetic stiffness has been kept positive, and the total stiffness (including bearing stiffness and cogging force) has been optimised as a compromise for easy drive and low consumption to reach the stroke. The magnetic stiffness has been evaluated from measurements at 4.6N/mm (See Fig. 5). The total stiffness of the actuator is then 18.2N/mm.

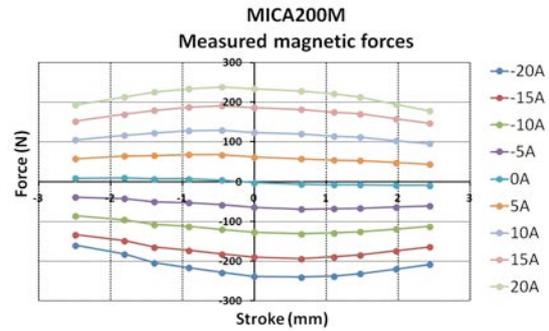


Fig. 5: MICA500L Magnetic force curves

The design of the bearing blades of the MICA200M ensures an infinite life time. They are friction free. The absence of wear increases the actuator reliability and also suppresses losses and any uncontrolled variations. A new design of blade has been made for the MICA200M, which ensures a stiffer radial guidance. Radial stiffness has been measured at $1.2 \cdot 10^6$ N/m. The bearing ratio radial/axial stiffness is 88 and 500N radial force results in 0.4mm misalignment only. They ensure frictionless operations tested up to 80M cycles at full stroke and are thus vacuum compatible.

The new MICA 200M has been designed for easy assembling using preassembled parts. The moving assembly integrates the moving iron block made of high magnetic performance FeCo, blades and an interface axis. The connector and the sensor electronic parts are added, and then a block of stator parts, which includes the in-house manufactured coils. The Final operation is the closure of the housing.

The main heat source comes from the Joule losses of the coils. In the MICA200M, the coil is fixed on the stator part improving heat dissipation thanks to a low thermal resistance. In case the MICA needs to be used at maximum conditions, an additional cooling is foreseen with a radiator fixed on the magnetic circuit close to the coil.

CSA96 is MICA partner for efficiency.

The actuator has been developed together with a power supply in order to be able to propose by Cedrat Technologies to customers a complete system which can be embedded into the customer application system.

Within the INTEFIX project harsh environment reliability issues in power transmission to the turning device are avoided by embedding the power source in the rotating part of the turning machine, together with the battery and the power drive. The simultaneous design of the actuator and its CSA96 power supply enables the design of an optimised chain thanks to compatible voltage, current and impedances.



Fig. 6: CSA96 prototypes

The CSA96 (See Fig. 6) is a compact (200 x 140 x 59 mm³) high power switching amplifier (See Fig.6) for magnetic actuators. It incorporates a 660W powerful 96Vdc (extendable to 200Vdc) power supply based on a resonant topology.

The amplifier is designed around full bridge topology using MOSFET transistors working at high frequency (50 kHz). The converter is capable of delivering up to 1920VA with high efficiency ($\eta=96\%$) and can recover all or most energy (stored electrically or mechanically in the actuator) in its high lifetime buffer capacitors.

The converter uses a wide bandwidth current controller digitally adjustable. The amplifier acts like a voltage to current converter with a gain of 4A/V with a maximum output current of 20A. The current loop allows easy force control.

The CSA96 integrates an optional wide bandwidth controller to perform position or velocity control at high sampling frequency. It includes several industrial interfaces for sensors: analogue ($\pm 10V$; or 4-20mA) as well as digital encoders. Although, the CSA96 has been designed to be adapted to the MICA200M actuator, it is nevertheless a fully independent supply component. The MICA200M includes a position sensor whose output is 0-5V for $\pm 2.5mm$ full stroke. Also integrated into the MICA200M actuator is a thermistor to monitor the coil temperature. This enables temperature control and avoids overheating. The MICA200M is designed for an internal measured temperature up to 155°C. Power wires and sensor data wires are connected through a unique standard connector.

Prototypes design & characterisation results

The MICA200M is integrated in a housing of 1.05dm³ volume with dimensions of 77.4mm x 111mm x 122mm. The nominal stroke is $\pm 2.5mm$. The force factor is 10.6N/A. Maximum current in steady state is 15Arms which corresponds to a force of 174N and an actuator constant of 24.2N/W^{1/2}. The actuator peak values corresponds to the maximum current acceptable for 10s time. Peak current is 35A for a peak force of 323N.

The total mass of MICA200M is 3.2kg including the elastic guidance, position sensor and connector. The steady force to mass is then 54N/kg. The MICA200M has been designed for large bandwidth

operation and therefore the moving mass has been reduced to 0.25kg which is a very low mass for an actuator of such a force. The dynamic behaviour becomes obvious when the acceleration is evaluated. With negligible mass load, steady state acceleration is 71G and the peak acceleration is up to 132G. Therefore the MICA200M actuator is especially suitable for embedded dynamic applications.

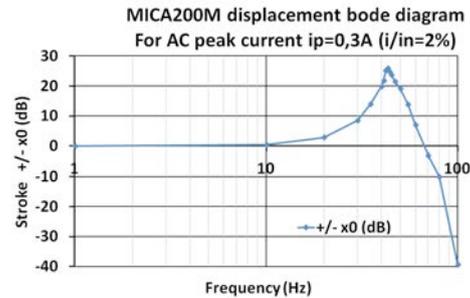


Fig. 7: MICA200M open loop Bode diagram

The resistance of MICA200M is 0.253 Ω and the inductance is 5.29mH. This corresponds to an electrical constant time of 20.9ms. The Bode diagram of displacement versus frequency (See Fig. 7) has been measured for constant supply current 0.3A peak, which is 2% of the nominal current.

The resonant frequency of MICA200M alone is measured at 43Hz. With a load mass, the resonant frequency is shifted according to the additional mass and load stiffness. The MICA200M Q factor is 19.8 and the bandwidth is 70Hz.

The step response of MICA200M from the central position has been measured in open loop (See Fig. 8).

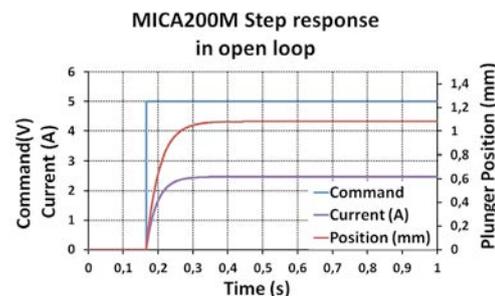


Fig. 8 Measured open loop step response

The applied voltage is 0.8V, which corresponds to 1.08mm displacement. The corresponding mechanical response time is 38.1ms. The final current here is only 2.5A, which is far lower than the 35A peak current. A command in closed loop control and higher voltage would give much lower time constant. The implementation of closed loop is in progress.

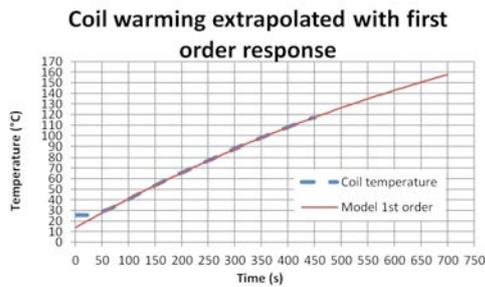


Fig. 9: MICA200M temperature on coil

Thermal behaviour of MICA200M has been measured for 18.8A DC current starting from 25°C ambient temperature. The temperature is given by the integrated coil's thermistor (See Fig. 9). The test has been stopped before 120°C in order to avoid any risk of over-heating. The extrapolation with a first order fit shows that the 150°C temperature is reached in 10 min. The thermal time constant of the first order model is close to 1000s.

Evaluation for positioning applications

The MICA200M measured performances have been compared to COTS voice coil (VC) actuators. As shown here, VC actuators and MICA actuators are both single axis linear magnetic actuators, with a positive or negative force proportional to the current and almost homogeneous versus displacement. Their use in closed loop is easy. They are known to be dynamic, and are used in applications which require a high bandwidth thanks to low moving mass.

The main technological difference concerns the moving part: The VC is composed of a simple coil without a heavy magnetic circuit and the MICA moving part is composed of moving iron part, which is small and light. It is interesting to compare the main characteristics of both actuators with a similar size. The VC actuator has been chosen from a well-known brand. It should be considered as highly optimised and might be a challenger for competing actuators.

The voice coil actuator dimension is 120xD76²mm³, whereas MICA200M size is 114x122x76mm³. Main performances are given in the following comparative table (See Fig. 10). Nominal values correspond to steady state, whereas peak values consider 10s actuation. The all-packaged (frictionless bearing and stroke sensor) MICA design has been focussed on its dynamic behaviour [3] measured with the G acceleration criterion. Thanks to a 3 times lighter mobile mass, the MICA shows accelerations from 2.1 times up to 3.9 times greater versus VC depending on the operating conditions.

	MICA200M	Voice Coil
Volume (dm ³)	1.08	0.75
Total Mass (kg)	3.2	2.4
Mobile Mass (kg)	0.25	0.744
Force (Peak/nom.)(N)	323/174	445/133
Acceleration (Peak/nom.)(G)	132/71	61/18
Stroke (mm)	±5	±12.5
Actuator constant (Peak/Nom.)(N/W ^{1/2})	19.2/24.2	21.7/21.7
Force/mass (Peak/nom.)(N/kg)	101/54	198/59
Actuator constant / mass * acc (Peak/nom.)(N/W ^{1/2} /kg)	792/536	544/164

Fig. 10: MICA/VC comparison table

The actuator constant of both actuators is equivalent, but in the steady state the MICA is 11% greater. Steady state is significant as the operating conditions limitation is thermal behaviour. Joule losses of MICA coils are lower and furthermore the cooling of the coil is easier. Indeed, the coil of the VC is surrounded by a high thermal resistance air gap.

The stroke of the Voice coil is 2.5 times greater. However the ratio stroke/mobile mass is still a factor 1.19 at the advantage of the MICA. One advantage of the voice coil is the ratio force over mass. This corresponds to the lower volume or mass of the Voice coil for equivalent forces. This has to be understood as a drawback of the MICA mobile mass optimisation.

In order to make a general synthesis, it is proposed to define a global merit criterion for the actuator comparison. The chosen criterion is the actuator constant divided by total mass and multiplied by acceleration. With this criterion the merit of MICA200M actuator is 3.3 greater than the Voice coil in the steady state condition.

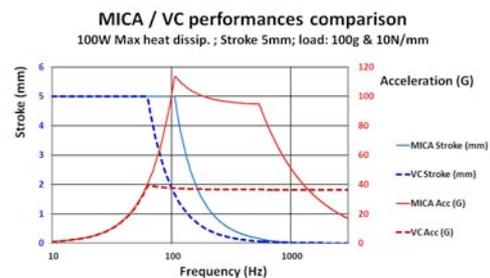


Fig. 11: Performance Comparison vs. frequency

Another way to compare the two actuators is to draw system comparisons for a given application. The chosen application is the capability to position rapidly a load of 100g mass with a stiffness of 10N/mm over a stroke of 5mm. Typical applications are active vibration damping[4], pick and place, stamping and optical shutter. Both actuators have been simulated for an AC command with 100W heat dissipation capability attempting to reach the 5mm stroke (See Fig. 11). The 100W dissipation is harder to achieve in Voice Coil due to the mobile coil,

whereas the heat in MICA is directly evacuated in the magnetic circuit and cooler radiator. Results show that the VC actuator reaches its peak current limits at 64Hz, whereas the MICA actuator reaches it at 106Hz. At 100Hz the Voice coil stroke is reduced to 2mm (40G on load) whereas the MICA stroke is still 5mm (100G on load).

Conclusion

A new actuation chain has been designed in the frame of the INTEFIX project. The application with multiple requirements is presented and the MICA actuation principle is explained. The performance improvements of the new MICA200M versus former MICA actuators has been listed as well as the characteristics of a dedicated designed power supply.

The main design and measured characteristics of the MICA200M actuator are 323N peak force, 132G acceleration, 5mm stroke for 1dm³ volume. Finally the new actuator performances are compared to a COTS voice coil actuator. The MICA actuator shows much better acceleration capabilities and even though some other features are lower, the global criterion for comparison gives a 3.3 factor advantage for the MICA200M. The simulated behaviour for an embedded high dynamic application shows also that the MICA200M achieves a 5mm stroke (5/2 more than for the VC) at 100Hz actuation.

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