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PRINCIPLES OF MICRO TORQUE MEASUREMENT - AN OVERVIEW

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Abstract – This paper gives an overview of rotating microsystems including the entire spectrum of dimensions from the sub-millimeter range to sizes of a few millimeters. Principles and instrumentation for micro torque measurement are described.

Keywords: micro torque measurement, rotating microactuators, micro tribology

1. ROTATING MICROSYSTEMS - INTRODUCTION

Various systems in the millimeter range and with submillimeter details have been designed in recent years. Since the 1980s, the needs for miniaturization of consumer products, office equipment and medical devices have increased rapidly. The first movable microsystems were simple mechanical resonant structures agitated by electrostatic forces to detect humidity by analyzing the resonant frequency, bulk micromachined valves and membrane pump prototypes using piezoelectric and thermopneumatic forces. Later in the 80s more sophisticated mechanical elements like springs, cranks, gears and other novel micromechanical structures were presented to facilitate rotational microdynamics and complex micromachines for the first time.

Apart from cameras and watches, it is envisaged that many wireless communications products with mass data storage requirements will also need micromotors. Medical catheters too may require micromotors for driving imaging elements and surgical tools, and gyroscopes and microscanners are potential applications. On the other hand users have demanded compact energy supplies for small, portable electronics like computers, digital assistants, cell phones, GPS receivers, etc. driven by high-speed microturbogenerators

An attempt to classify the solutions which are now known would result in two groups: on the one hand rotating microsystems in a more narrow sense, with overall dimensions in the submillimeter range; and on the other models of systems with macrodimensions which have been downsized by factors of n x 10 to n x 100. Many of the latter include details in microdimensions and have been produced at least in part with microstructuring methods. Obviously this range encompasses a large number of designs and an immense spectrum of sizes, rpm, torques and performance characteristics.

The number of publications on rotating microsystems which appear each year indicates the amount of activity in this sector. Beginning in the mid 1980s numerous microelectromotors with a wide range of operating principles have been developed, most of which apparently intended to achieve the greatest possible miniaturization (rotors with diameters to 100µm). The following years saw turbines, gears and pumps, and several groups began working on hybrid electromotors, thermal gas turbines and combustion engines starting in the mid 1990s.

The following overview of rotating microsystems will include the entire spectrum of dimensions from the sub-millimeter range to sizes of a few millimeters.

1.1. Electromotors

In 1988 a description of the first rotational electrostatic micromotor based on semiconductor manufacturing techniques was published. These early, small (diameter of 100µm) and weak machines were indicative of the development of micromachining capability but were never used in concrete applications. Since then a great deal of work has been done to improve the performance of millimeter- and submillimeter-size actuators, and some applications have been found [12].

Mechanical vibration (piezoelectric converters, ultrasonic motors): These motors transform the small-amplitude, high-frequency vibrations (of 10Hz and higher) of a stator with piezoelectric elements into rotational motion by using friction. Ultrasonic motors have the advantages of high energy density, high torque at low speed, quick response and quiet operation.

Magnetic forces: Electromagnetic micromotors are miniaturized variants of the classic electric motor. Coils are necessary and are planar or 3D. Fig. 1 shows an ultraflat hybrid motor (diameter of 12.5mm, height of 1.4mm). Coils are manufactured by photolithographic batch processing, and the permanent magnet rings consist of NdFeB, thus producing the highest possible torque (60µNm)

Synchronous (electrostatic) motors: The rotors of synchronous motors are driven by ponderomotive forces. The angular frequencies of the driving field and the driven rotor are synchronous (synchronous motors). Typically these motors need mechanical support (e.g. bearings or through the stator). Although the resulting additional friction makes it difficult to transmit mechanical energy, a few gears and coupling devices have been developed. Electrostatic forces appear to be more attractive for the design of micromotors as a result of the lesser amount of dependence on dimension at the microscopic scale. [13].

Fig. 1. Penny-motor [18]

1.2. Rotating micro-heat machines

Gas turbine generators: For compact power production; hydrocarbon fuels and gasses burned in air have 20-30 times the energy density of the best current lithium chemical-based batteries. Since the mid 1990s various MEMS-based micro gas turbines have been designed and produced based on 2D- and 3D-curved impellers

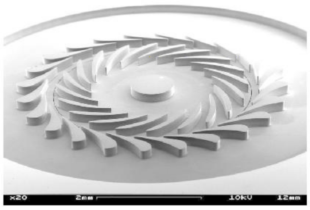

Fig. 2. 4mm rotor diameter radial inflow turbine [15]

1.3. Fluid- and gas-driven turbines (flow sensors)

Fluid turbine Fig. 3 shows an example of a simply shaped 2D rotor in a high gas stream functioning as a sensor for speed and mass flow.

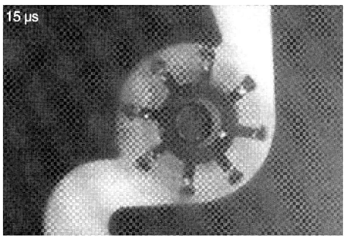

Fig. 3. Air-driven microturbine [17]

Regardless of the dimension and operating principle, all constructive solutions must take into account power supply, transformation of energy, ventilation, storage, energy release, and technological feasibility.

Testing will show if the actual behaviour of micromotors corresponds to the calculated characteristics. Assembly and manufacturing tolerances mainly influence the result. The available torque is typically around 10µNm or less.

The following table provides an overview of performance characteristics of rotating microsystems. When examining this data, one should remember that the principles designated with [16] are based on a diameter of 2mm.

TABLE 1. Examples of performance data

Motor principle	Torque (Nm)	Speed (rpm)	Input requirement
Harmonic electrostatic [16]	10^{-3} - 10^{-2}	< 100	20 – 100 V
Top-drive electrostatic [16]	10^{-7} - 10^{-6}	10^{3} – 10^{4}	20 – 100 V
Hybrid ultrasonic [16]	10^{-7} - 10^{-6}	120 - 150	5 – 10 V
Wave ultrasonic [16]	10^{-8} - 10^{-7}	180 - 200	5 – 10 V
Electromagnetic [16]	10^{-8} - 10^{-7}	10^{4}	~1 V
Gas turbine[17]	10^{-4}	$2.4x10^{6}$	15g/hr of H_2
Wankel engine[21]	10^{-2} – 10^{-3}	$2x10^{3}$	CO_2
Fluid turbine (flow sensor) [16]	10^{-6} - 10^{-5}	> 10^{4}	(Flow rate) 30 – 90 cm^3/min^{-1}
Gear box [20]	$3x10^{-5}$	6,000 – 30,000	7.5Nm, 100,000 rpm
Liquid micromotor [19]	?	420	2V, 10µA

2. PRINCIPLES OF TORQUE MEASUREMENT

The minimum requirement for the characterization of a motor is the measurement of torque and of rotational speed. Output energy of the rotating system is to be transformed to be measured (in one or more steps).

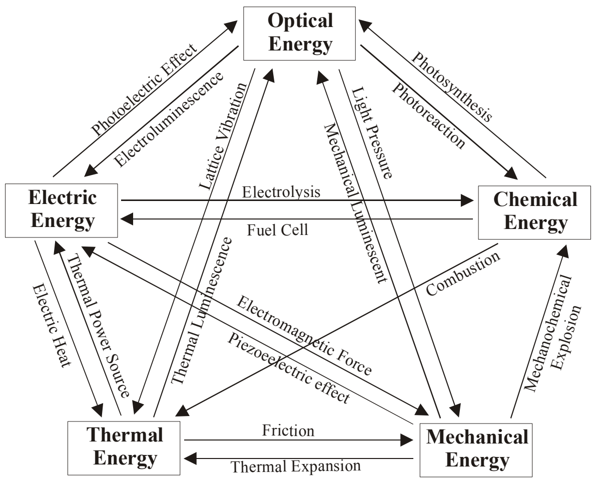

Fig. 4. Energy transformation between basic energies [8]

Different working conditions for the microactuators under test can be simulated by a suitable braking equipment. By varying the braking moment the rotational speed-over-torque-characteristic can be evaluated.

Instruments suited for such measurements consist of variable loading devices and a means of coupling this load to the actuator.

2.1 Fluidic brake

Load-torque measurements have been reported for hybrid-fabricated electrostatic and electromagnetic micromotors using external viscous coupling methods [1], [3], [4], [5].

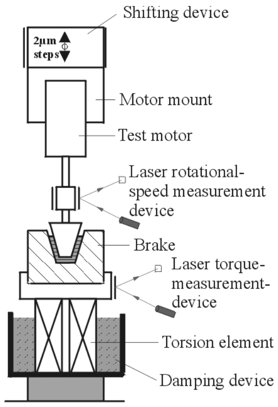

Fig. 5. Torque measurement with the aid of the so-called measurement cross [1], [5]

2.2. Cable brake principle

The cable brake is a closed force system, consisting of the cable (or string) and the cable disc which is fixed to the motor shaft (Fig. 6). The force along the string is determined using leaf springs and strain gauges.

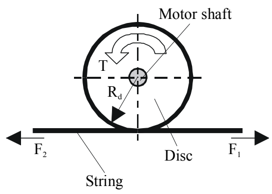

Fig. 6. Cable brake [5]

The string is wound around the aluminium disc, which has a chamfer to guide the string, in a single loop. Two different forces can be measured at the two ends of the string. The force difference is applied to the disc because of the friction between string and disc. This friction force acts upon the disc's circumference, creating a friction torque with respect to the middle point of the disc. The force difference can be measured and it is possible to calculate the friction torque applied to the disc (and to the motor) with the known disc radius. The torque T can be deduced by a simple equation (1).

$$T = (F_2 - F_1).(R_d + R_s). \quad (1)$$

Where R_d and R_s are the disc radius and string radius respectively.

2.3. Loading by a master motor

At the Centre de Transfert des Microtechniques (CTM) at Besancon, France an apparatus with a master motor coupled to the motor under test has been developed [6].

The master motor drives the rotating component under investigation and imposes a certain rotation speed. If an active micro-electro-mechanical component is tested for example this device is controlled synchronously to the rotor angle of the driving motor. Hence, the torque produced by the micro-electro-mechanical component or other significant values will essentially depend on the control signals applied. The control of both the master and the probe motors as well as the measurement of various probe signals is carried out by a computer under a real-time operating system,

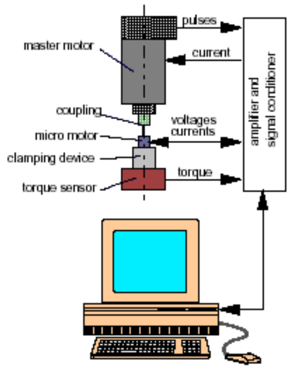

Fig. 7. Test stage by CTM [6]

A torque sensor (Fig. 8) for micromotors works within measuring ranges down to some µNm or less. The sensor is based on a very sensitive cross-shaped spring element. The deformation of the spring element is detected contactless by a laser triangulation system. The measuring range is defined by the characteristics and dimensions of the spring element.

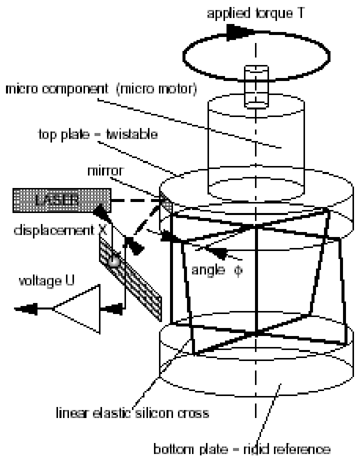

Fig. 8. Principle of torque sensor [11]

2.4. Bending of a Si-beam

Outer-rotor micromotors of pitch radii from 75 µm to 150 µm with designed rotor-stator gaps of 1 µm and 2 µm were fabricated and tested over a range of voltages [2], [10]. The device for direct torque measurement of outer-rotor micromotors consists of a 500 µm long beam attached to a partial rotor on one side, and a fixed pad at the other. Since the beam bends and does not rotate, the radius of the rotor ring attached to the beam cannot be simply chosen to be the same as the length of the beam. The radius of the rotor attached to the beam must be chosen to ensure that the rotor is able to maintain mechanical contact with the driving rotor throughout the deflection or the beam.

Once the beam deflection is calculated from the deflection angle, the output force that is delivered to the beam by the micromotor can be calculated. Since the deflections are up to 30% of the length of the beam, the small deflection approximations are invalid and the exact solutions must be obtained

Theoretical calculations of the micromotor torque are expected to be larger than the experimentally measured torque due to the addition of friction in the torque measurement device.

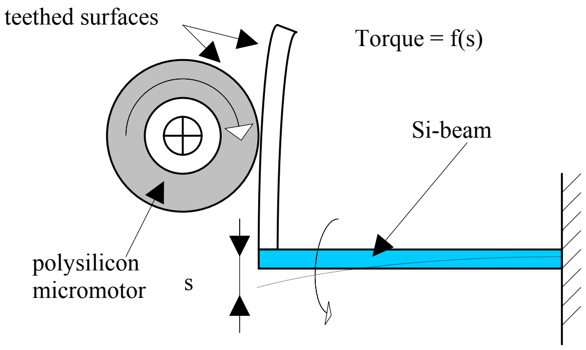

Fig. 9. Torque measurement of polysilicon micromotor by bending a Si-beam [2], [10]

Forces up to 1.04 μN, or torques up to 156 pN-m are available from the range of sizes of the outer rotor micromotors. The results showed that the force and torque increase with increasing micromotor radius and decrease with increasing rotor stator gap. As expected, the theoretical calculations of the micromotor torque are larger than the experimental measurements, due to uncharacterized friction.

2.5. Microdynamometer

For planar batch-fabricated microactuator geometries where the ability to implement a shaft is hindered by limited three-dimensional capabilities, a different approach is required. Christenson, et al. [7] describe a planar integrated microdynamometer system utilizing gear coupling and an electronically controlled electromagnetic brake to provide variable mechanical loading.

3. CONCLUSION

Several test stages have been developed for assessing the power output of rotating microactuators (torque in the range of few μNm and less). Especially for dynamic measurements and for planar microsystems without a shaft the main design problem to be solved is the coupling with an external load.

4. ACKNOWLEDGEMENT

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