MICRO TORQUE MEASUREMENT BASED ON THE CABLE BRAKE PRINCIPLE

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SUMMARY
This paper describes a micro torque measurement device based on the cable brake principle.

Keywords: torque measurement, rotational speed measurement, rotating microactuators, cable brake method

1 INTRODUCTION
Microactuators are one of the most important components of micro-electro-mechanical and micro-opto-electro-mechanical systems (MEMS and MOEMS). There are many microactuators that have been designed and successfully operated during the last years.

When micromotors are designed, special methods for miniaturisation are used, for instance, the similarity-method or by the use of various simulation and modelling software.

Using such an approach the mechanical behaviour of the motors is calculated based on the macroscopic domain and on the experience with motors, which have already been produced and tested. Testing will show if the actual behaviour of micromotors corresponds to the calculated characteristics. The two main parameters to be measured are angular velocity and torque.

1.1 Torque-rotational speed characteristics
Torque measurement of a rotary or stationary shaft is an important motor characteristic. By measuring torque and angular velocity, the motor’s power output can be determined.

Torque measurement of an operating system is important for monitoring and estimating the proper functioning of subsequently added machines and overloading of these systems is thus avoided. Like many measured variables, torque must also be sensed indirectly. Here, the main problem is that in many cases torque has to be measured on a rotating machine element.

There are many methods for torque measurement but most of them are based on measuring torsion on the axis. For this purpose strain gauges or piezoelements (like in force measurement) are used. The main disadvantage of this method is the complicated signal processing involved. Therefore, contact-less systems such as inductive (non-contact torque measurement based on the phase difference method) or telemetric method (torque sensors based on the magnetoelastic effect) are preferred.

In most of the rotating microactuators, the available torque is typically around 10 µNm or less. Thus it is quite obvious that there is a need to develop high precision torque measurement systems.

1.2 Torque sensors
The various methods of sensing torque can be categorised as follows (Profos, Pfeifer, 1992):

1.2.1 Reaction principle
One of the simplest methods of torque measurement is to suspend a pendulum motor housing and to consider it as a free body. By driving the motor its torque acts on the motor housing and displaces it from the equilibrium position. The displacement can be measured with the help of a force or displacement sensitive element (e.g. strain gauge, optoelectronic sensors, inductive sensors, and capacitive transducer etc.).

1.2.2 Torsion principle
Basically the torsion principle can be divided into two classes:
- sensor elements that detect the strain and the compression of the shaft surface of a rotating system or
- the sensor system detects the twist angle.

In the first case, strain gauges in the Wheatstone-full-bridge arrangement can be glued onto the shaft (in order to compensate parameters like temperature, non-torsional stresses, etc.). Other possibilities are to use SAW (surface acoustic wave) resonator sensors, which, similar to the strain gauges, are glued to the shaft, or to use strain sensitive fibre optic sensors applied like the strain gauges, or magnetostrictive sensors and even magnetoelastic amorphous metallic ribbons attached on the shaft with fixed transmitter and receiver, etc.

In the other case, sensor wheels, disks, or perforated disks are placed to both sides of a torsionally stable/resistive section on the shaft. The rotation of these sensing elements and their phase positions with respect to each other is a measure of the torque under stress. The rotation of these sensing elements can be measured normally with the capacitive, inductive, magnetic or optical sensors.

1.3 The brake principle
The brake device is a very important element of such a test bench. It must guarantee a stable speed at a predetermined point of operation. Generally the brake
system is based on dry friction (e.g. cable brake etc.) or on viscous friction. Among the different systems, there are (Duffait, Nogarede, 1997):

1.3.1 Dry friction brakes

- The Prony brake consists of a set of jaws squeezing the output shaft. A dynamometer (or, for the large systems, a weight at the end of an arm) allows the balancing of the brake at an angular position relative to the torque to be measured. Since the braking torque is not perfectly constant this system is more appropriate for the characterisation of high-torque machines with low rotational speeds.
- Tape brake: This device is very simple and it can be adapted for micromotors. A tape or a wire is rolled up on a pulley, which is fixed at the output shaft. On the one end of the wire a dynamometer is fixed while at the other end a weight provides the necessary braking torque. A string is wound around an aluminium disc in a single loop. The force along the string is determined using leaf springs and strain gauges. This kind of brake is convenient for torque values, which are within a range of few µNm. The suitable choice of a friction material will guarantee a constant value of the friction torque during the measurement.
- Powder brake: This principle is based on the braking effect caused by magnetic powder, which is located in the gap between the stationary and the moving parts. The braking effect can be adjusted by changing the value of the magnetic field. The braking torque is approximately proportional to the current flowing through the induction coil.

1.3.2 Eddy current brake

Another electromechanical brake system, which is well adapted for high-speed micromotors, is the eddy current brake system. Here the motor shaft will be equipped with a small disc. This small disc should be made from a conductive material. A dual-coil sensor for example will be placed on the front of the disc. One coil is used as an electromagnetic source, while the other is for the sensing of the magnetic currents induced on the conductive disc.

When the disc is rotating, eddy currents produce the magnetic field, which opposes that of the source coil, thus resulting a disbalance and brakes the disc. The higher the electromagnetic source, the larger the change in the magnetic impedance and the larger the braking torque. The braking torque is proportional to the current flowing through the source coil.

1.3.3 Viscous brake system

This principle is based on the use of the viscosity of a fluid or of a force field. There are for example systems which use a set of ribs immersed into a liquid or hydraulic-brake system. The device developed by IFWT of the TU Vienna uses the friction effect of a conical shaped brake body, which is fixed on the motor shaft and immersed into a brake liquid with a known viscosity.

1.3.4 Electric generator, current input measuring

Here a generator with well-known characteristic will be coupled with the test motor. By measuring the output current of the generator it is possible to determine the torque of the tested motor.

The other worth-mentioning method is based on the current detection on motors, where the current input is used as a measure of the torque.

1.3.5 Test device for the torque-rotational speed characteristics

The general structure of such a device consists of the regular elements of a measurement chain. Since the goal is the measurement of the dynamical characteristics, it is necessary to join the components so that the resistance and the torque-rotational speed (including brake or driving device, inertial load, etc.) can be estimated. The purposes of the device developed for the measurements of the torque-rotational speed characteristics are the following:

- Measurement of torque versus speed in the steady-state, useful for motors and driven components like bearings, micro gears, etc. or
- Measurement of transient phases (starting or stopping phase, step mode): torque versus time, rotor position versus time or, torque versus rotor position.

2 CONCEPT, DESIGN AND REALISATION

In accordance with the mentioned main problems, the following method for measuring the torque of micromotors was realized. The cable brake is a closed force system, consisting of the cable (or string) and the cable disc (Fig. 1). The force along the string is determined using leaf springs and strain gauges. The steel leaf springs are rectangular. The dimension of the leaf spring is governed by its material, the measured range of force and the range of deformation.

The spring retainer clamps, the leaf spring and one of the holders are movable in the X-direction with a micrometer. Thus, the string force can be adjusted very precisely.

Because the maximum stress occurs at the clamped end of the leaf spring, the strain gauges have been located as closely as possible to the fixed end.

![Fig. 1: Cable brake](image-url)
The circuit of strain gauges is arranged as a Wheatstone bridge so that the thermal expansion and overlaying of normal strain will be compensated. The relevant relationship between force (F) and the output voltage (U_m) can be expressed as follows (eq. 1):

\[ U_m = \frac{6 \cdot U_o \cdot k \cdot x \cdot F}{E \cdot b \cdot h^2} \]  

(1)

The parameters k and E are the gauge factor and Young’s modulus respectively.

The string was chosen according to its thermal expansion, diameter and slip. The most suitable string for this purpose is as thin and smooth as possible, which will improve slide friction between string and disc. Considering this, we obtained the best results with polyamide string and silk thread. The string is wound around the aluminium disc, which has a chamfer to guide the string, in a single loop.

Experiments with discs of different diameters (4, 7 and 10 mm) were executed. Comparisons of the results of measurements with various discs show that discs with a smaller radius lead to more exact results.

This can be explained as follows: in a disc with a smaller diameter, a smaller increase in torque per force difference produced (F_diff = F_2 - F_1) occurs (eq. 2). Thus, the resolution and accuracy will be improved, and it is suitable for measuring small amounts of torque, especially in mini- and micromotors.

For this purpose, a plastic disc with a diameter of 1 mm has been designed and produced (Fig. 3) for a micromotor with diameter of about 2 mm.

When the disc is not moving, the force in the string is constant, and no force is applied to the disc. When the disc is rotating and the string is stretched, the string causes friction and brakes the disc.

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 (eq. 2).

\[ T = (F_2 - F_1) \cdot (R_d + R_s) \]  

(2)

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

The cable brake system is not free of vibrations. To overcome this problem, a mechanical vibration damping system is used. Thus, each leaf spring has been equipped with a metal strip, which is dipped in a highly viscous fluid (Fig. 4).

Moreover, because of the resulting force difference and friction between motor shaft and shaft bearing, a friction torque (T_f) is produced. This friction torque is less than 1 percent of the total torque and has been taken into account by means of a correction factor (eq. 3).

\[ T_{motor} = T_f + T_{measured} \]  

(3)

The rotational speed of the motor is monitored with an optical counter.

3 EXPERIMENTAL RESULTS

Experiments with a test motor, which is described in Table 1 have been performed. The operating conditions of a DC motor are described by its static characteristic...
curve, which depends on the constructional parameters of the motor.

A characteristic curve gives the useful torque of the motor corresponding to a specified speed at a nominal voltage. As mentioned previously, these two parameters are the basic factors required for obtaining a certain motor characteristic. The typical speed of rotation/torque characteristic for the motor A4B-01-S at the nominal voltage of 1.3 V is shown in Fig. 5. As expected, the speed of rotation decreases linearly with increasing torque.

The deviation from the theoretical characteristic curve is negligible. The reproducible accuracy of the test is good. In the first case the resolution of the system is 0.1 µNm by taking into account the resolution of strain gauges, the measuring instrument and the disc diameter. According to (Beitz, et al, 1990) the relative error can be calculated at 7.5 %. $I_{n}$, $I_{H}$, $M_{H}$, $n_{n}$, $U_{N}$ and $P_{max}$ represent no-load current, stall current, stall torque, no-load speed, nominal voltage and maximum power output respectively.

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<table>
<thead>
<tr>
<th>Motor type</th>
<th>A4B-01-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø Motor (mm)</td>
<td>4.2</td>
</tr>
<tr>
<td>Ø Shaft (mm)</td>
<td>0.7</td>
</tr>
<tr>
<td>$I_{n}$ (mA)</td>
<td>40</td>
</tr>
<tr>
<td>$I_{H}$ (mA)</td>
<td>105</td>
</tr>
<tr>
<td>$M_{H}$ (µNm)</td>
<td>40</td>
</tr>
<tr>
<td>$n_{n}$ (rpm)</td>
<td>15000</td>
</tr>
<tr>
<td>$U_{N}$ (V)</td>
<td>1.3</td>
</tr>
<tr>
<td>$P_{max}$ (mW)</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 1: Characteristics of the tested minimotor

However, because of the friction between string and disc, this principle can be applied only to measurement of the torque generated by continuously rotating motors and other rotating elements such as microturbines, etc. and can not be applied to step motors. The start and stop behaviour between the steps would cause a stick-slip effect between string and disc. Hence, an accurate measurement of string forces would be impossible.

In the second case, it is possible to record micromotor characteristics at the sub-µNm range (Fig. 5).

4 CONCLUSION

The miniature cable brake permits the measurement of torque produced by miniature motors in the µNm range with a resolution of 0.1 µNm and rotational speeds up to 50,000 rpm. The relative error is about 7.5 %. Work on further system miniaturization for application on micromotors is in progress.

5 REFERENCES

[1] Austrian patent no. AT 393167 B.