

A TORQUE TESTING STAGE FOR ROTATING MICRO-ELECTRO-MECHANICAL DEVICES

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ABSTRACT

Within the European project HAFAM (Handling and Assembly of Functionally Adapted Microcomponents) a testing stage for characterizing rotating micro-electro-mechanical machines has been developed. The objective of this micro torque testing stage is to provide a flexible and modular means for assessing the performance and the quality of both active and passive micro machine components, e.g. micro motors or micro ball bearings. This task has been accomplished by using the following principle.

A 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, real-time Linux.

A graphical user interface offers the possibility for an easy machine control, signal evaluation and post processing for the final evaluation of the devices under investigation.

INTRODUCTION

Micro-mechanical devices, and in particular rotating micro-mechanical devices such as micro motors and micro actuators, or passive components like micro ball bearings and spiral springs can nowadays be found in a variety of consumer goods. Before these micro-mechanical devices can be used and implemented, however, their performance and quality has to be assessed.

In the framework of a European project, CTM (Centre de Transfert des Microtechniques), a R&D centre in the field of micro technology, has developed a testing stage for characterizing such micro mechanical devices.

Generally speaking, characterizing a micro motor or any electric motor is based on a profound understanding of the electro-mechanical system in terms of the energy flow and transformation. Depending on the motor principle different approaches have to be applied, e.g. a piezoelectric motor has to be supplied with sinusoidal voltages near its eigen frequency whereas the rotor speed will be a function of the excitation frequency. The measurement principle for an asynchronous motor is different again, and for a DC or a synchronous motor, too. How can the torque-speed characteristic be determined for a variety of different motors?

The common sense approach will be to control the motor with the appropriate voltage and to use a brake system to control the rotor speed, i.e. the rotor speed is a result of the brake effort applied. Then the motor torque, speed and current can be measured, which yields the power consumption and hence the efficiency if the entire speed domain is scanned by changing the brake effort. This approach shows already that there must be a constitutive relation between speed and torque one of which can be fixed.

The torque testing stage presented here employs the inverse principle to accomplish this characterization task: it imposes a speed whereas the resulting torque depends on the motor control and its synchronization to the rotor speed and angle. In order to accomplish this control task, the free and open source real time operating system RTLinux [1] is used.

Before the measurement principle is explained in detail, however, the test system used is presented in terms of the principles employed.

PRINCIPLES OF OPERATION

Before a test stage for assessing a micro-electro-mechanical device can be designed, the physical parameters to be characterized and measured have to be defined. Since the test bench presented here is used for rotating machinery, the torque measured is the most interesting parameter, both as function of the rotation speed and the rotor angle. Therefore, a reliable torque sensor is needed.

Torque sensor principle

In general, a sensor applies some physical principles to extract the variable of interest from the physical system, in this case the torque created or caused by a micro component. Figure 1 gives a sketch of the MTE torque sensor principle used.

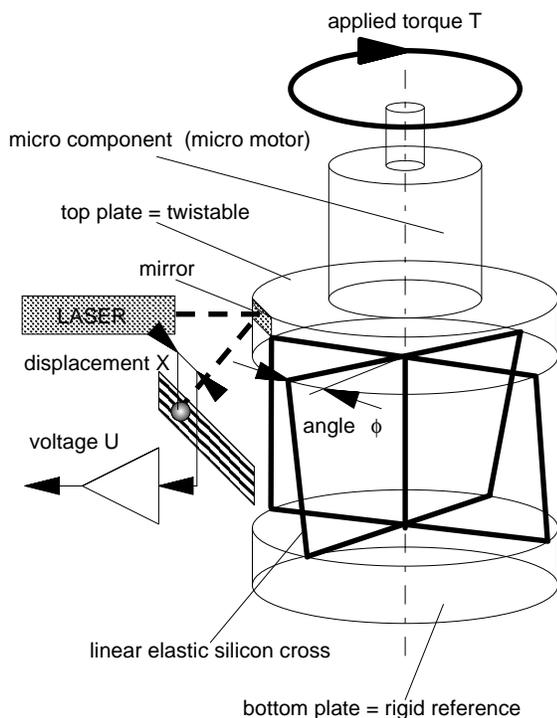


Figure 1: Principle of MTE torque sensor

The heart of the sensor is a silicon cross mounted vertically between two rigid plates. The ensemble is rigid in radial direction, but very sensitive for torsion. In effect, this cross can be considered as linear angular spring, i.e. once a torque T is applied to it, the top plate will twist against the bottom plate by an angle proportional to the torque applied. Hence, the torque sensor used in this setup maps the torque T applied on an angular displacement ϕ .

This small angular displacement ϕ is transformed into a linear displacement X of a laser spot on a sensitive surface by means of a mirror and a LASER beam, i.e. by LASER triangulation. Furthermore, the displacement is transformed into a voltage U corresponding to the linear displacement X , the angular displacement ϕ , and finally the torque T .

If a probe micro component is mounted on the sensor top plate and some torque is applied to it, or the component creates some torque against the inertial system, exactly this torque is measured.

Measurement principles

As already mentioned in the introduction, a strong master motor imposes a speed and the torque created or caused by the micro component (active or passive) at this speed is measured. The torque exchanged between both master motor and the micro component can then directly be measured at this speed, synchronously to the rotor angle as function of this angle as all other variables measured. Figure 2 gives an idea of this principle.

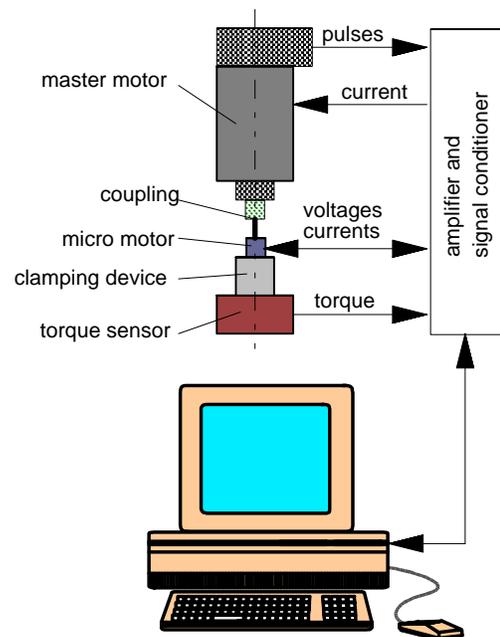


Figure 2: Principle of driven mode

As for active components such as micro motors the torque depends on the control of the micro motor and its type. For example, a synchronous motor employs the principle of a rotating magnetic field dragging a permanent magnet at the same speed. The torque is then a function of the phase angle between field vector of the rotating field and the field vector of the permanent magnet, the so-called load angle.

One possibility to assess the synchronous motor is to keep the rotor axis at zero speed and let the field vector rotate at a small speed. Then a figure for torque versus phase angle can be traced which gives the maximum holding torque of the motor (see Figure 3).

In order to determine this maximum torque at a given rotor speed, the magnetic field created by the motor coils has to be synchronized to the rotor speed with the phase between both controlled. Then the phase range has to be scanned through yielding a function torque versus phase

angle. Its maximum value has to be saved for all rotation speeds with the function maximum torque versus speed being the result (Figure 4).

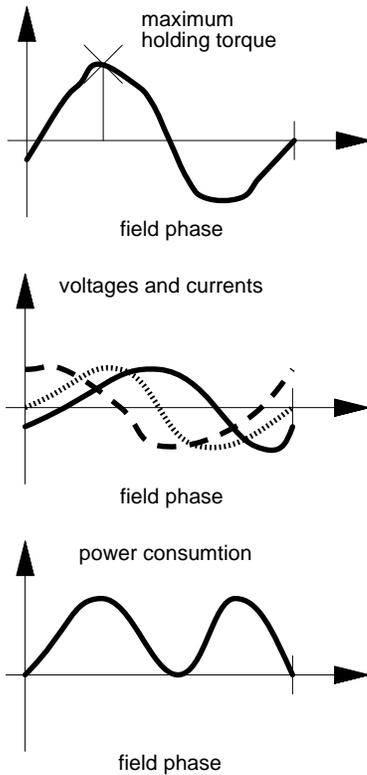


Figure 3: Torque-field phase characteristics of a stepper motor

Software principle

Figure 2 already anticipated the measurement principle with an explanation for a synchronous motor. Now this procedure is explained in terms of software. At a given rotor speed the incremental coder will produce TTL impulses which are conveyed to a counter board in the computer. Note that the resulting frequency is 240 kHz at 40000 rpm for 360 impulses per revolution which is too much to be treated by the computer in real time, at least for the computer used. For this reason the counter board is programmed to count from a speed dependent value (later on called “down sampling factor”) down to zero and triggers an interrupt afterwards

A synchronous motor is usually driven by sinusoidal functions creating a rotating magnetic field which takes the permanent magnet with it. If the computer outputs these voltage functions perfectly synchronized to the rotor angle during rotation, the load angle will remain constant. Thus, a load to the probe motor is simulated and this angle can simply be changed by changing an offset of a pointer to the functions to be output. At the same time the coil currents can be measured which together with the output voltage gives the power input into the motor. The produced torque

can be measured synchronously to the external coder impulses which are equivalent to the rotor angle. The power losses and hence the efficiency can then be calculated.

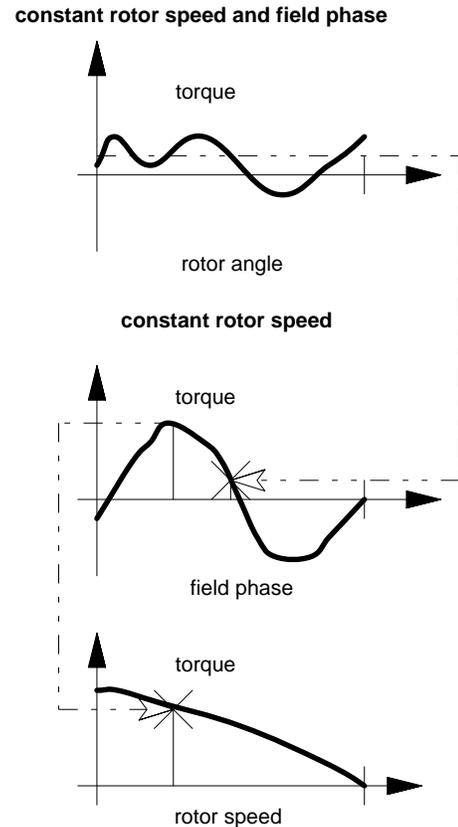


Figure 4: Torque-speed characteristics of a synchronous motor

TORQUE STAGE SETUP

Figure 5 shows how the experimental setup looks like. The essential parts of the system, the computer, a rack containing control electronics, and the mechanical setup itself are shown.

The micro mechanical device to be tested is held by a clamping device which is directly mounted on the torque sensor (a cylindrical shiny box) for a range of $\pm 50 \mu\text{Nm}$ which depends in general on the type used. This sensor is then mounted on another sensor, the ATI force sensor. The entire setup is fixed on a xyz translation table to make the correct alignment to the master motor on top of the setup. This master motor is equipped with an incremental coder of 360 impulses per revolution and drives the micro mechanical device using a special micro coupling being rigid for torsion, but elastic for all other degrees of freedom. In case of an active probe device, a connector for 3 channels is mounted on the right of the setup.

All electronics necessary to drive the sensors and actuators is built into a rack. It contains the amplifier of the

torque signal converting the laser spot displacement to $\pm 5V$, an amplifier for the ATI torque sensor mapping forces to 0-5V. Additionally, the coil currents of a micro motor are measured mapping $\pm 1000mA$ to $\pm 5V$. Furthermore, the rack comprises the power stage for the master motor mapping $\pm 5V$ to $\pm 4A$ as current setpoint, and the power stage for the micro motor with three channels of $\pm 12V$ output voltage mapped to a $\pm 5V$ setpoint.



Figure 5: Micro torque testing stage

In order to output 4 signals, one for motor current setpoint and three for the coils of the micro motor, respectively, the ICPDAS 12bit output board pioda4 has been used. A ICPDAS pcidas1800 DAQ board has been employed to measure the torque, three currents, three voltages, the motor speed and the ATI forces at 12bit resolution. For the synchronization purpose, a ICPDAS piod48 has been utilized. A P200 was used with everything usually built in a desktop computer. On the OS side, FSMLab's RTLinux 3.0 [1] using kernel 2.2.19.

TORQUE STAGE SOFTWARE

Once started, the torque testing stage presents itself with a window like in Figure 6. From here the user can follow the menus and later execute different measures or measurement cases.

In total four different pull down menus are available, File, Calibrate, Options and Display. For each sensor, there is an entry in the Calibrate pull down menu, namely:

- Rotor angle, the UNINOVA angular sensor
- Rotor speed, the rotor speed of the master motor
- Torque, the measured torque using the MTE torque sensor
- Voltages, the voltages of the probe motor, either EMF or measured
- Currents, the currents in the probe motor coils, either induced or measured

- Forces, forces of the ATI force sensor

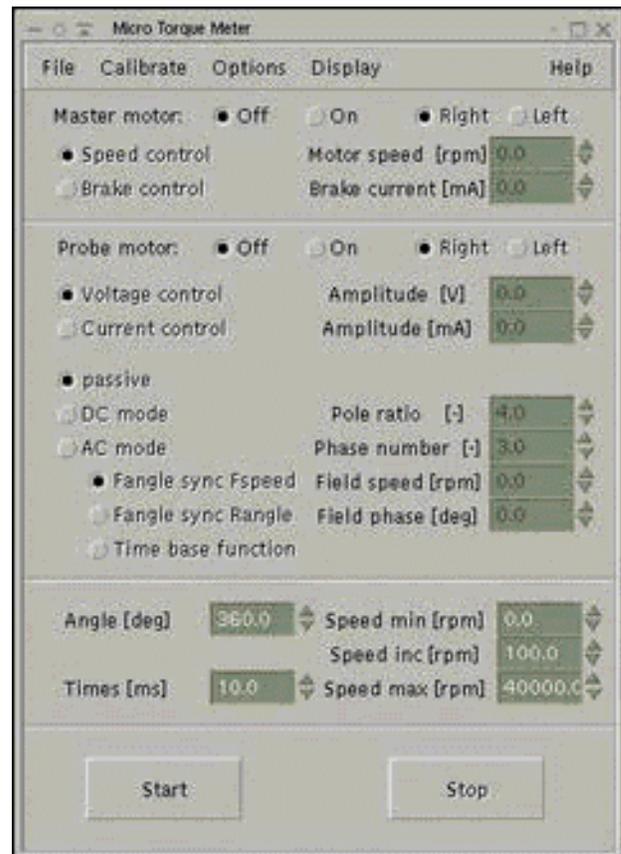


Figure 6: xmc main window

Clicking one of this menu will start the measurement and calibration process. The user can now enter the gain and offset values in order to adapt the effective output to the value expected. Figure 7 gives an example for the torque sensor.

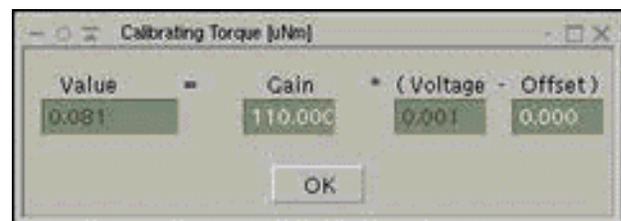


Figure 7: Calibration of the torque sensor

The options menu offers two entries, automatic mode, for execution of procedures, and transient mode, for transient measurement.

Display menu combines all different measured sensor signals and different abscissae like Time, Rotor angle, Rotor speed, Field Angle, Field Phase Field Speed, and yields a multitude of displays. Clicking on one of the displays will tag the measure and the abscissa for later use. Once the

measurement is started, this will be updated correspondingly. Figure 8 gives an example.

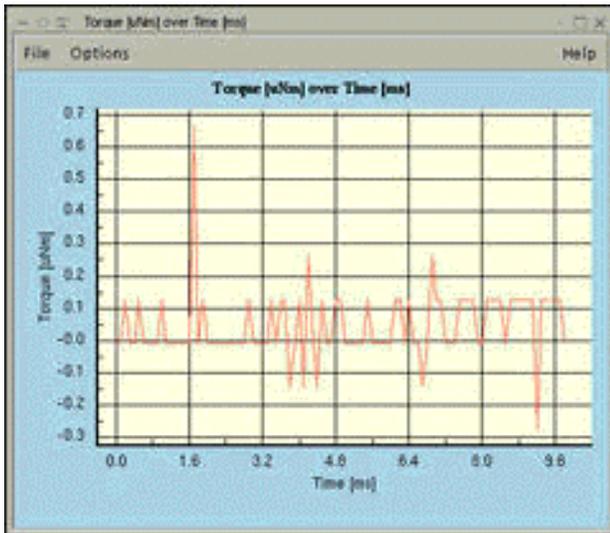


Figure 8: Torque over time display

The torque testing software offers several user plenty of user entries:

- Master motor speed or brake mode, enable and direction button,
- Master motor speed or brake mode numerical entries,
- Probe motor current or voltage mode, enable and direction button,
- Probe motor current or voltage numerical entries,
- Probe motor types, DC, AC with time, field synchronous and master motor synchronous mode,
- Entries for display constraints like minimum and maximum speed, angle and time ranges,
- Input fields for the number of channels, ratio between field speed and electrical speed, field speed and phase,
- Start and stop buttons,

The combination of the switch buttons will enable or disable certain numerical entries following a certain concept, e.g. If the master motor is selected and the speed mode, the user can enter a speed value. In another case, if the probe motor is selected to be an AC type of motor, a window will pop up for the functions profile as it can be seen in Figure 9. Here you can import predefined profiles.

MEASUREMENT CASES

All options, menus, displays, entries and switches provide a variety of possible combinations and measurement cases. In the next sections, some reasonable combinations are presented. For all cases presented, the direction can be set to RIGHT or LEFT, as for the probe motor to

VOLTAGE or CURRENT mode which will affect only the values in the results.

Master motor off and probe motor off

In this case, the measurement system is entirely passive and it is reasonable only to measure the functions of time, even though other displays will show some nonsense. This mode might be useful to verify the correct measurement or some mechanical tests with the bench.

Master motor on and probe motor off

If the master motor is on, there are basically two possibilities, either brake control which can only work if an electrical brake is connected to the system, or rotor speed control if a controlled master motor is connected to the electronics. This is the only reasonable case here. In this case passive components can be measured, like ball bearings and the like.

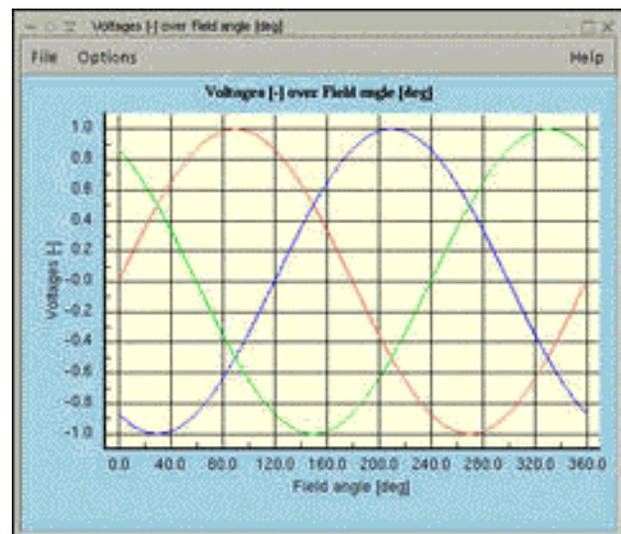


Figure 9: Voltages over field angle function

Master motor off and probe motor on

In this case, probably neither a master motor nor a brake is mounted on the system, but the probe motor is used solemnly. Here the following choices might be interesting:

DC mode

A transient period of a DC motor can be traced, e.g. select a voltage, select TORQUE / TIME and push START. Then the transient behavior of a DC motor can be visualized.

AC mode

With time based functions or field angle synchronous to field speed, a transient period of an AC motor can be traced, e.g. select a voltage function by importing any predefined function, select TORQUE / TIME and push START. Then the transient behavior of a AC motor can be visualized.

Master motor on and probe motor on

This is the most versatile combination. A master motor can impose a speed, and depending on the probe motor some diagrams can be obtained. In the following two are described for which there is an automatic mode.

DC mode

In this case, select a VOLTAGE for the DC probe motor and a speed for the master motor. The resulting torque can be traced using TORQUE / TIME or any other display. For this case, an automatic handler is available and by selecting the AUTOMATIC option, the minimum and maximum speed can be entered in the respective numerical entries. By pressing the START button, the stage software will scan the speed range and trace the TORQUE / SPEED diagram.

AC mode

With field angle synchronized to rotor angle, synchronizing the probe motor output to the rotor angle of the master motor which is equally the rotor angle of the probe motor rotor, is a challenge for the real time operating system. Select a VOLTAGE, then import a voltage function as profile. For a given rotor speed, this function will be output synchronized to the rotor angle with the torque being a function of the field phase, i.e. the angle between the rotor magnet and the field vector. The resulting torque can be traced using TORQUE / TIME or any other display, like TORQUE / FIELD PHASE. By changing the phase, the torque will change, too.

For this case, an automatic handler is available and by selecting the AUTOMATIC option, the minimum and maximum speed can be entered in the respective numerical entries. By pressing the START button, the stage software will scan the speed range and trace the TORQUE / SPEED diagram or the TORQUE / FIELD PHASE.

EXPERIMENTAL RESULTS

As an example for a measurement, the test bench has been used for testing a synchronous motor contributed by a project partner within the HAFAM project. The setup as described above creates a rotating field at 60 rpm, but controls the rotor speed to be zero. With a typical tri-phase voltage functions of 1V amplitude applied to it, the torque depending on the phase angle between permanent magnet and field vector can be seen in Figure 10 for a rotor speed equal to zero.



Figure 10: Measured torque over field angle for speed equal to zero.

CONCLUSION

It has been shown that the approach with a master motor imposing a certain speed and controlling the micro device by a computer is a versatile means for a torque testing stage and can be adapted to many types of motors and measurement, even for the measurement of the EMF for synchronous motors. The concept proposed was implemented using the free real time operating system RTLinux in order to guarantee synchronization and predictability.

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