Strain-gage-based torque-measuring test bench for stepping motors

by Dieter Szymanski

Stepping motors are applied in many different types of equipment because they provide a low-maintenance link between electronic and mechanical devices. Owing to the wide application range of stepping motors, producers have found it necessary to optimize motors to specific tasks. This article describes a fully automatic test bench used to evaluate and record stepping-motor performance characteristics. Attention is focused on design of the torque-measuring system which employs strain gages as sensing elements in a specially developed measuring cage.

The spread of microelectronics into all fields where monitoring and control are of importance has opened up a myriad of application areas for the stepping motor as a source of drive and motion. The chief use of the stepping motor is as a positioning device for machines and instruments because its rotor can be turned through very small angles and held in any angular position by means of a holding torque.

Since stepping motors are often used as precision drives, very strict demands are made on the accuracy of their movement. The need for a high degree of accuracy has necessitated the specialization of motors for individual applications. Consequently, there exists a wide variety of models, each designed for a narrow application range. Capabilities range from step angles of 0.5 to 45 degrees, torques from less than 5 Ncm (0.4lb-in.) to greater than 1000 Ncm (88 lb-in.), and drive frequencies up to 50 kHz.

Due to such diversity it is necessary to define and determine various parameters before a specification is developed. These parameters are needed at the development stage in order to check the suitability of the motor for a given task as well as to optimize it appropriately, and at the quality-control stage to check various performance characteristics.

To evaluate stepping motor performance it is necessary to measure performance parameters under different operating conditions. The test bench described here, together with its computer control system, performs this task.

There are two different types of stepping motors: Those with an "active" rotor which incorporate a field winding or permanent magnet and others called reluctance motors in which the rotor lies in a magnetic field and tends to align itself such that the magnetic resistance is a minimum. Nearly 90 % of all stepping motors are of the active-rotor type. For the sake of clarity, however, the principle of stepping-motor operation will be explained with reference to the reluctance motor as illustrated in **Fig. 1**.

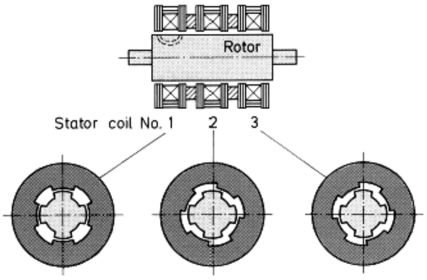

Fig. 1: Stepping motors have three or more coaxial but slightly offset stator windings to position rotor

Reluctance motors possess at least three identical stator sections with a toothed internal circumference and a geometrically corresponding soft iron rotor. The cog of each stator section are offset from the next by a step angle such that when current flows through stator coil No. 1 the rotor comes to rest where the resistance of the magnetic circuit is a minimum (see Fig. 1, stator No. 1). This position is called the magnetic-detention point. Due to the offset of the stator sections, the rotor rotates clockwise if the current is applied to the stator coils in the sequence 1,2,3,1. Counterclockwise rotation is obtained by applying current to the stator in the sequence 3,2,1,3.

In order to discuss in detail the concepts behind the torque measuring system, it is necessary to become familiar with some basic terms used to describe stepping motor operation and performance:

Step: Rotation of the motor spindle through one step angle.

Stepping frequency: Equal to the driving-pulse frequency of the motor, as long as motor operates without a step error.

Static phase angle: The angle at which the rotor is displaced from the magnetic-detention point by a given static torque when the drive frequency is zero.

Operating torque limit: The maximum torque which can be exerted on the motor at a given drive frequency without causing a step error.

Dynamic phase angle: The angular difference between the actual position of a rotating rotor and its magnetic-detent position at the instant of the drive pulse.

Description of the test bench

One of the basic objectives in the design of the test bench was to be able to accommodate as great a variety of stepping motors as possible. Principle features of the technical specification were as follows:

- Fully automatic acquisition and evaluation of measured values.
- Testing of motors with step angles of up to 30 degrees.
- Testing of motors with phase currents up to seven Ampere and variable-current operation.
- Measurement of torque up to 400 Ncm (35 lb-in.).
- Resolution in angular measurement of 0.01 deg.
- Fully automatic test sequence.

The test bench designed to meet these requirements can be divided physically into a mechanical and electrical part. The mechanical part, shown in **Fig. 2**, can accommodate stepping motors of a variety of designs and relatively wide range of sizes. The motor being tested is run against a brake in order to measure the torque. The torsion angle of the rotor is measured with an incremental angle resolver. The heart of the electronic part of the test bench is a central processing unit (CPU) which controls the motor being tested and also evaluates the measured data.

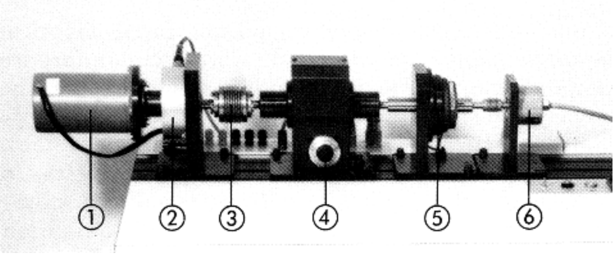

Fig. 2: Mechanical part of the test bench:

① Stepping motor
② Torque measuring cage
③ Metal-bellows coupling
④ Measuring adapter
⑤ Magnetic-particle brake
⑥ Incremental angle resolver

Measuring motor torque

In this particular test-bench design, motor torque is not measured directly on the shaft but rather indirectly by measuring the reaction torque exerted on the stator. A torque-measuring cage designed for this purpose is shown in **Fig. 3**. The reaction torque of the stator is transmitted through the cage to the stationary test bench. The measuring cage incorporates four bars which transmit the torque to be measured, each bar being fitted with two strain gages.

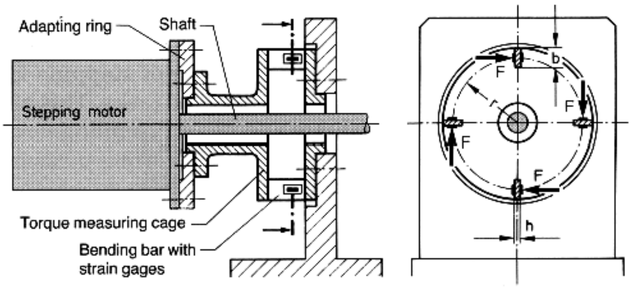

Fig. 3: Measuring cage between motor and bench measures reaction torque produced by rotor on stator

The measuring cage was designed to satisfy the following requirernents:

- The weight of the flange-mounted stepping motor must not affect the results.
- The natural frequency of the cage must not be too low because coupled-mode vibration can affect the results of high-power motors, especially in the low drive-frequency range.
- The torsional stiffness of the cage must be sufficient not to greatly affect the measurement of the rotor torsion angle, even with torques up to 400 Ncm (35 lb-in.), but still retain adequate sensitivity at the strain-gage measuring points.

The theoretical concept behind measuring-cage operation is illustrated in **Fig. 4a** where a bar is fixed at both ends and force F and moment M_o act on each end. The force F arises from the effective motor torque M_M acting on the cage

$$F = \frac{1}{4}\frac{M_M}{r} \tag{1}$$

where r is the radius of the point of application F on the bar. Employing the designations used in Fig. 4a gives the moment M_o as follows:

$$M_o = \frac{1}{2}Fl\ . \tag{2}$$

Applying the differential equation of the elastic curve of the bar

$$y'' = -\frac{M(x)}{EI} \tag{3}$$

and integrating twice gives the deflection of the bar which in this case is identical to the circular measure of the twist between the two halves of the cage. E is the modulus of elasticity of the bar material and I the moment of inertia of the bar cross section. $M(x)$ *is* the bending moment at the point x in the blade:

$$M(x) = F\left(\frac{l}{2} - x\right) . \qquad (4)$$

Integrating Eq. (3) twice and substituting the boundary conditions gives the maximum deflection:

$$y_{\max} = \frac{Fl^3}{12EI} . \qquad (5)$$

Combining Eqs. (1) and (5) gives the correlation between the motor torque M_M and the maximum deflection of a bar:

$$y_{\max} = \frac{M_M l^3}{48EIr} . \qquad (6)$$

The angle of twist cp of the two halves of the measuring cage with respect to each other is given by:

$$\tan\varphi = \frac{y_{\max}}{r} . \qquad (7)$$

For very small values of $Y_{\max}$, tan $\varphi \approx \varphi$ and therefore the angle is given by:

$$\varphi = \frac{y_{\max}}{r} . \qquad (8)$$

The torsional stiffness $c = MI\varphi$ can be obtained from Eqs. (6) and (8):

$$c = 48EI\frac{r^2}{l^3} . \qquad (9)$$

Employing the equation

$$\omega = \frac{c}{I_m} \qquad (10)$$

gives the natural frequency ω of the torsional vibration system when the mass moment of inertia I_m of the rotationally oscillating mass is known. The vibrating mass is made up of the stator of the stepping motor, the adapter flange, and part of the measuring cage between the stepping motor and the bars.

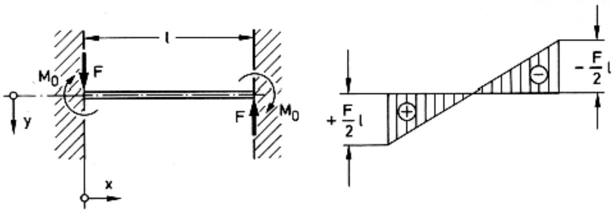

Fig. 4: Schematic diagram of measuring-cage bar
a) Forces and moments exerted on bars
b) Distribution of bending moment along bars

It can be seen from Eq. (10) that high torsional stiffness is essential for obtaining as high a natural frequency as possible. On the other hand, high stiffness limits sensitivity of the strain-gage measuring circuit. From the distribution of bending moment over the length of the bar as shown in **Fig. 4b**, it can be seen that the maximum bending moment occurs at the fixed ends. Consequently, the strain gages must be attached to the bars as close as possible to the fixed ends in order to obtain the best sensitivity to changes in reaction torque. **Fig. 5** shows a photograph of the measuring cage in which the strain gages on the bars can be clearly seen.

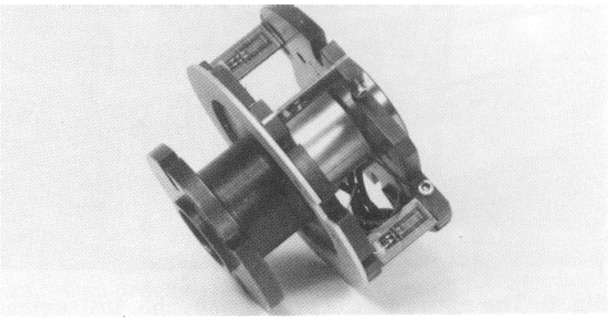

Fig. 5: The actual measuring cage and stepping-motor coupling with strain gages clearly visible on bars

The strain ε in a bar in relation to the motor torque can easily be calculated from Hooke's Law for uniaxial stress, thus:

$$\varepsilon = \frac{\sigma}{E} . \qquad (11)$$

The bending stress σ occuring on the surface of a bending bar with section modulus W_B is given by:

$$\sigma = \frac{M_b}{W_b} \qquad (12)$$

and introducing Eq. (4)

$$\sigma = \frac{F\left(\frac{l}{2} - x\right)}{W_b} \qquad (13)$$

with Eq. (1) as well:

$$\varepsilon = \frac{M_M\left(\frac{l}{2} - x\right)}{4ErW_b} . \qquad (14)$$

Thus, Eq. (14) substituted in Eq. (11) gives the strain at the point x on the surface of the bar:

$$\sigma = \frac{M_M\left(\frac{l}{2} - x\right)}{4rW_b} . \qquad (15)$$

The eight strain gages attached to the bars of the cage are connected in a full-bridge circuit, each arm of the bridge composed of strain-gage pairs working in sympathy.

Signal conditioning and testing sequence

The signals originating from the torque-measuring cage are processed by a 225-Hz carrier-frequency instrument amplifier (HBM Type MG 50.D7.S31). This instrument possesses three different measuring ranges and two 10-turn potentiometers for coarse and fine zero adjustment. The amplifier converts signals into a dc signal proportional to the measured value. In this case, the series-connected digital display converts the

Fig. 6: The entire test bench: Removable instrument amplifiers, computer, and mechanical apparatus

analog signal to binary-coded decimal code (BCD) with an adjustable integration time. The integration time is set at 20 ms so that the system can respond to rapid changes in measured torque.

The incremental angle resolver used for measuring the angles is connected in series to a counter which also converts the angular values to BCD signals.

The internal CPU and a Hewlett-Packard Series-85 desktop computer are the principle electronic equipment in the test bench. In addition to an IEEE interface, the computer has the necessary instruction repertoire for optimum presentation of measured values. It can provide the results in graphical form if necessary, or can be extended for driving a matrix printer and other peripheral equipment.

In a question-answer sequence using the CRT display, the computer requests the entry of parameters needed for the test, e.g. operating mode, current selection, frequency range, etc. The parameters are entered, verified, and then transferred to the CPU. Upon completion of the sequence, the CPU transmits the measured values in the form of data blocks to the desktop computer for evaluation and display. The testing sequence is then begun and measured values are acquired.

A photograph of the test bench including desk-top computer is shown in **Fig. 6**. All electronic equipment, including the measuring amplifier, are in the form of removable subassemblies.

Operating modes of the test bench

A graph of operating torque limit as a function of stepping frequency as shown in **Fig. 7** provides an indication of the dynamic performance capability of the motor. At a stepping frequency of 450 Hz, there is a torque dip indicating resonance.

Stepping motors are able to produce a detent torque when only one phase is energized. It is this feature which enables them to perform precise positioning functions. **Fig. 8** shows the curve plotted from a test in which the detent torque of a motor was measured as a function of phase angle. The slope of the curve at the origin provides an indication of the positioning accuracy of the motor. The curve also shows the performance capability of the motor, the hysteresis, and the static phase angle.

An important indicator of the dynamic behavior of a motor is the graph of phase angle vs, drive frequency. The curves are typically plotted for different values of constant motor torque and are therefore called isotorque graphs. **Fig. 9** shows such an isotorque graph for a motor in which the curves have been plotted for the constant values of zero Ncm, 50 Ncm (4.4 lb-in.), and 100 Ncm (8.8 lb-in.). The phase angle is plotted on the ordinate as a percentage of the step angle. The isotorque graph provides an indication of the behavior of the motor throughout its operating range and is of particular interest when stepping motors are to be used in automatic control systems.

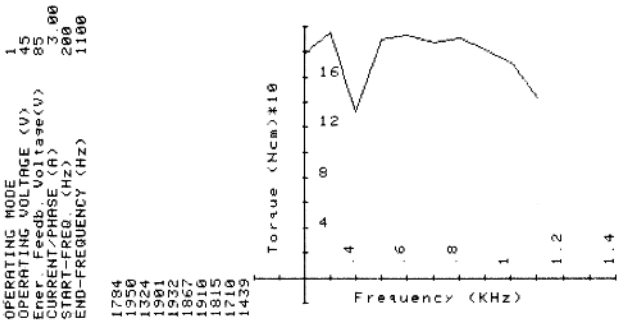

Fig. 7: Torque limit vs. stepping frequency provides an indication of dynamic-performance capability

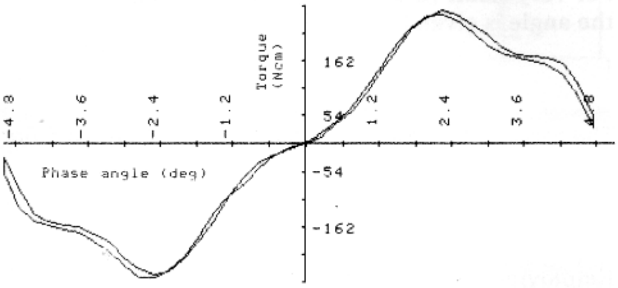

Fig. 8: Detent torque is measured as a function of phase angle to reveal the motor's positioning accuracy

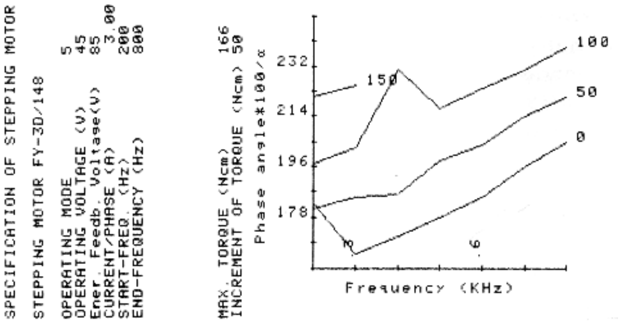

Fig. 9: Phase angle vs. drive frequency at constant torque values helps classify a motor's dynamic behavior

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