High Precision Torque Measurement System

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1 Introduction

The demand for economical drive concepts for vehicles that meet environmental guidelines is always accompanied by an increase in requirements for the test equipment. Highly dynamic, high-resolution torque measurements in the shaft train are essential for designing and optimizing engine-transmission combinations. Reproducibility is very good with modern torque transducers with strain gages. The overall accuracy of the torque measuring system is basically determined by the mechanical disturbance variables and by thermal and humidity effects that have not been compensated. The resolution limit, as the total of errors resulting from the measuring body and the strain gage application that cannot be compensated, exceeds the metrological possibilities of the electronics currently used in rotating transducers, with a DC amplifier, analog signal conditioning and frequency analog signal transmission.

The analysis of the measurement chain shows that because of temperature gradients and non-linear temperature coefficients, the thermoelectric voltages produce considerable measurement signal errors that are induced by disturbance quantities and which up to now, have not been compensated. Additional wrong measurement values result from overloading or damage to the transducer.

The subject of the paper is the development of a contactless torque measuring system with a carrier-frequency amplifier (Fig. 1). Optimization of the temperature effect on the measurement signal by the high level of symmetry of the measuring bridge is supplemented by digital compensation of the residual temperature effects. Digital signal conditioning and transmission make it possible to achieve the current high accuracy of non-rotational torque transducers in a rotating shaft train as well.

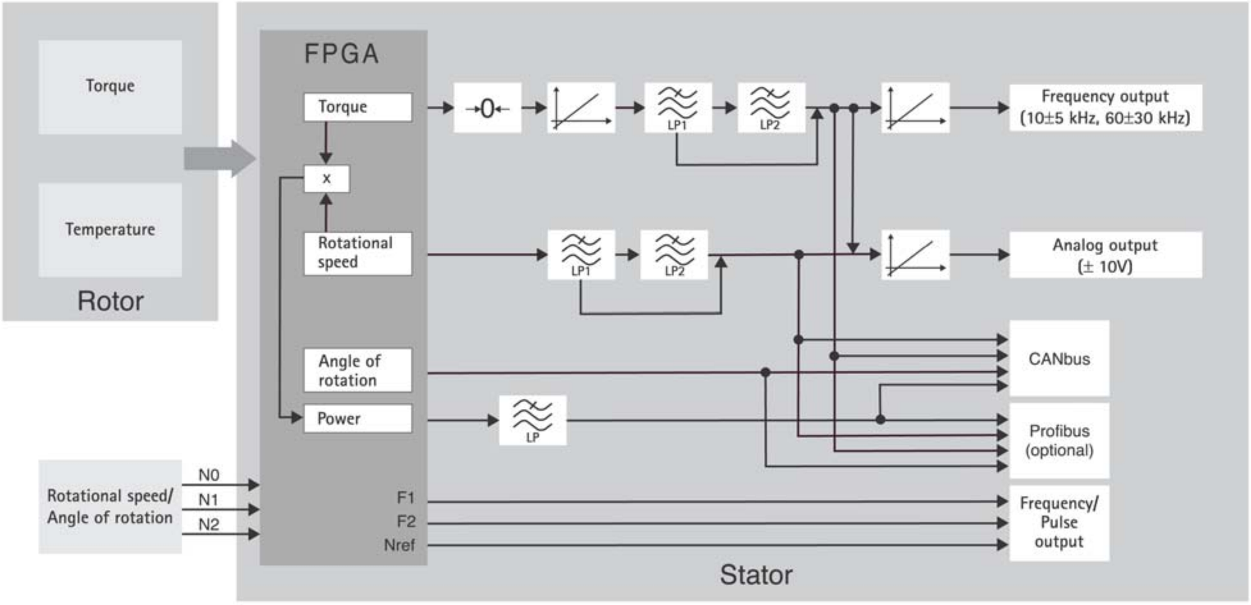


Fig. 1: Signal flow diagram of torque meter T12

2 Torque transducer construction

For high-precision torque measurements, transducers are used as a transfer standard with an accuracy class of 0.03. These are measuring bodies working according to the radial or axial shear principle and mapping the torque as a change in resistance in a resistive strain gage measuring bridge [1]. The arrangement of the strain gages in the bridge circuit is such that the temperature effects on the zero signal and on the span are compensated passively. The signal of these passive transducers is evaluated during reference measurements with a stationary carrier-frequency amplifier, where the signal bandwidth is usually restricted to less than 1 Hz.

For measurements in a rotating shaft train, contactless power and signal transmission is essential. These active transducers have primary electronics integrated in the rotor, which condition the measurement signal of the strain gage bridge and transfer it to the fixed part, the stator. DC amplifiers, which are noted for their low power demand and small size, have been used in the rotor up to now.

3 Influence quantities in torque measurement technology

The accuracy of the transducer is defined by the superposition of the measurement signal with the background noise and the environmental influences. A distinction is always made between systematic and random properties (Fig. 2).

The systematic content can be corrected in the primary or secondary electronics by suitable compensation algorithms. Random errors include all signal components that have not been determined. It is not possible to reduce the random errors of the static characteristic curve without reducing the measuring frequency range of the transducer, e.g. by filtering. Even using a filter, it is not possible to reduce the random content caused by temperature and humidity effects. So the random properties of the torque transducer, together with the uncompensated systematic properties, determine the accuracy of a compensated system. The characteristic quantities u_{Zn} for the random properties are determined as the variance of the measurement results from a sufficient number of measurements [2].

A further cause of measurement signal error lies in damage to the transducer by overloading. This damage can usually only be detected from an incorrect zero signal or during recalibration.

To make it possible to compare the characteristic error quantities, all the random and systematic errors are related to the nominal signal range u_N of the transducer at $\vartheta_0 = 30°\mathrm{C}$ and are displayed as reduced errors.

$$F_Z = \frac{u_Z}{u_N} \cdot 100\% \qquad (1)$$

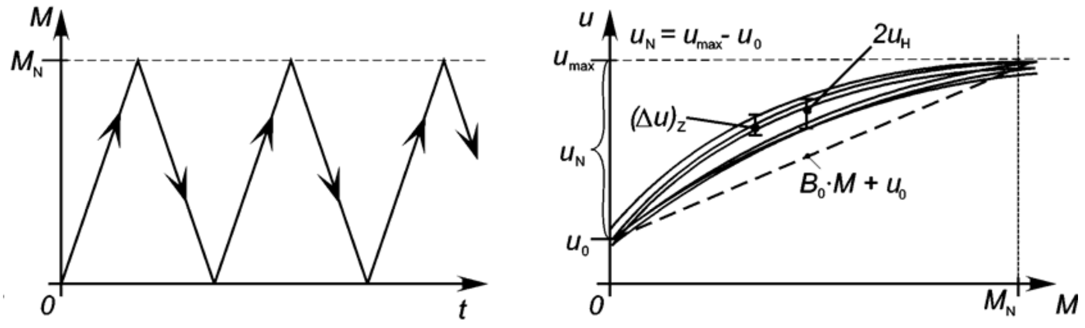
The following properties were examined:

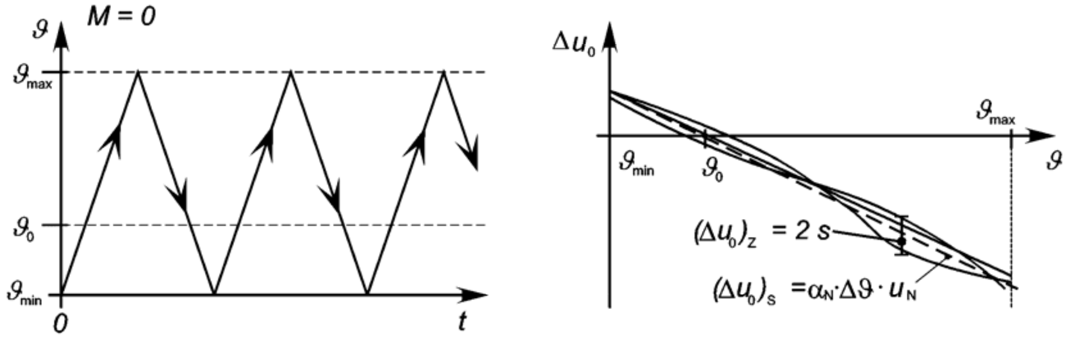
- Systematic characteristic values:
  - dynamic properties
  - zero signal u_0, nominal signal range u_N
  - linearity and hysteresis errors d_lin, h
  - temperature influence on zero signal α_N
  - humidity influence on zero signal φ_N,
- Random errors:
  - random errors induced by torque u_{ZM}
  - random errors induced by disturbance variables $u_{Z\vartheta}, u_{Z\varphi}$
  - background noise u_{Ze}

Fig. 2 gives an overview of the effect of systematic and random errors on the static characteristic curve of torque transducers.

The compensated sensor system shows a residual error, which is made up of the non-compensated systematic properties (e.g. thermoelectric voltages and humidity influence) and random errors. While the degree of compensation k of the systematic properties u_{sys} depends on the method of compensation used, the random residual error u_Z is only formed by the sum of the random errors. This sum is defined as the transducer uncertainty.

$$u_Z = \sqrt{{u_{Ze}}^2 + {u_{ZM}}^2 + {u_{Z\vartheta}}^2 + {u_{Z\varphi}}^2} \qquad (2)$$


Static characteristic curve


Additive temperature influence

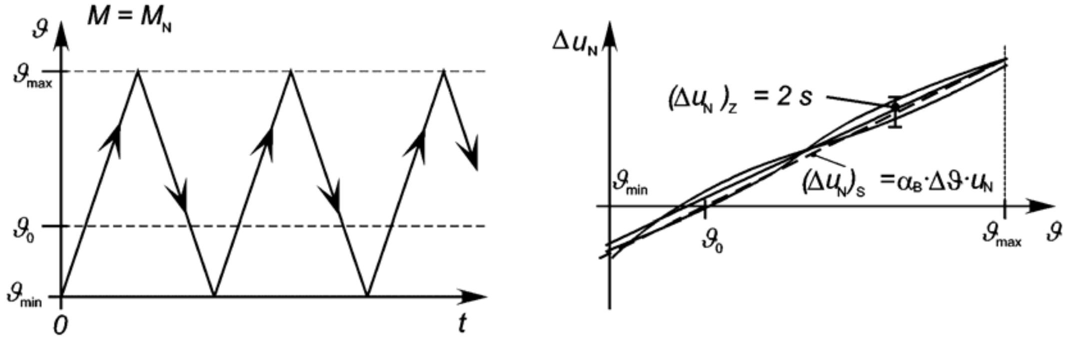

Temperature influence on span

Fig. 2: Systematic and random static sensor errors.

4 Method of error correction

The temperature dependency of the characteristic curve and the linearity of the transducers are regarded as properties that can be compensated. These errors can be corrected by taking relevant action in the hardware or by suitable algorithms in the software. Hardware solutions are preferable here to a software solution. The temperature effect can already be greatly reduced by the symmetry of the measuring bridge and by passive compensation measures. Digital correction by measuring the transducer temperature and by polynomial approximation is reliant on temperature measurement with very good reproducibility. This is why this method is only used to correct residual errors.

The action of the humidity effect must be minimized by the mechanical design. This is why the strain gages, as well as the rotor electronics, are located in a quasi hermetically sealed, reserved additional space.

Analysis of the errors has shown that when they are evaluated with a carrier frequency amplifier, passive torque transducers have far better reproducibility than active transducers with an integrated DC amplifier. A further examination of the influences in the frequency range provides the causes for this behaviour. The strain gage connection is a series connection of line resistances and thermoelectric voltage sources. An even temperature distribution over the entire transducer achieves a reproducible rotor temperature dependency, which can be digitally compensated. Should temperature gradients occur, non-compensated thermoelectric voltages will develop at all the solder joints of the strain gage bridge and at all joints of the DC amplifier. To keep these influences as low as possible, the entire circuit is arranged symmetrically. However, there remains a residual error which, for one pair of solder joints between copper and constantan, 1 mm apart, can be estimated as follows:

$$u_{th} = 42{,}5\,\tfrac{\mu V}{K} \cdot \Delta\vartheta$$

$$\Delta\vartheta = 0{,}1\,\mathrm{K}$$

$$\Rightarrow u_{th} = 4{,}25\,\mu\mathrm{V} = 0.07\,\%$$

This observation applies for an excitation voltage of 5 V DC with a temperature difference of $\Delta\vartheta = 10$ K over the entire measuring body. The thermoelectric voltages act as a slow, additive influence on the measurement signal. In the graphic of interference in the frequency domain (Fig. 3), the interference is found at frequencies close to 0 Hz.

An additional, non-compensatable interference signal is caused by the thermal noise of the resistors and the semiconductor used in the amplifier. The following rms value u_r is produced for the resistance noise:

Noise voltage :

$$u_r = \sqrt{4k \cdot T \cdot R \cdot \Delta f}$$

Temperature : $T = 300\ \mathrm{K}$

Bridge impedance : $R = 1{,}4\ \mathrm{k\Omega}$

Bandwidth : $\Delta f = 6\ \mathrm{kHz}$

Boltzmann constant : $k = 1{,}38 \cdot 10^{-23}\ \mathrm{J/K}$

$$\Rightarrow u_r = \sqrt{4k \cdot T \cdot R \cdot \Delta f} = 373\ \mathrm{nV} = 0.0062\ \%\ \text{(relative to a nominal signal range of 6 mV)}$$

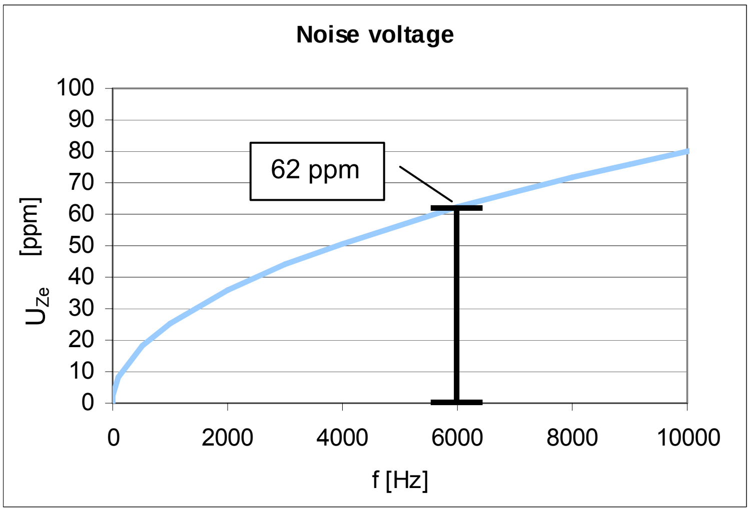


Fig. 3: Noise voltage in frequency domain.

By using a carrier-frequency amplifier, the torque signal is mixed to a frequency range between 13.2 kHz and 25.2 kHz with two sidebands from its original frequency range of 0 Hz to f_g = 6 kHz (Fig. 4). You now have the opportunity to suppress the DC voltage effects of thermoelectric voltages and some of the resistance noise by means of a bandpass filter. This will eliminate most of the non-compensatable errors. Choosing a high carrier frequency of f_{TF} = 19.2 kHz retains the very good dynamic properties of the torque transducer. The resultant bandwidth is 6 kHz (-3 dB).

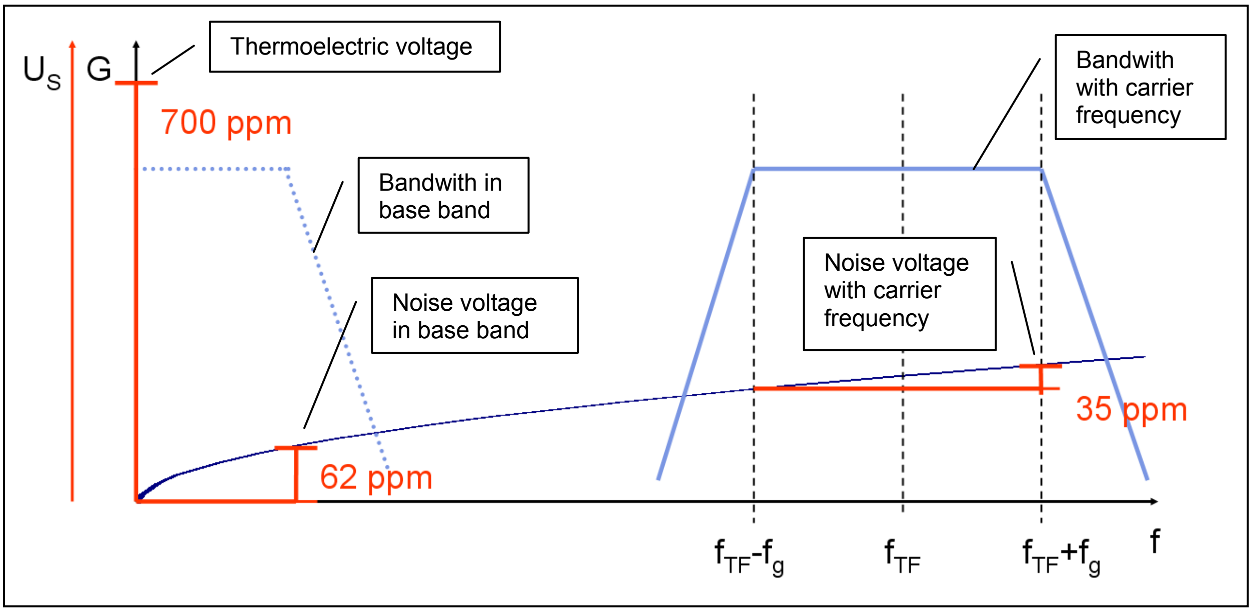


Fig. 4 Noise figure with carrier frequency amplifier.

5 Results

Measurements with the carrier-frequency amplifier have shown that non-compensatable random errors could be greatly reduced. This is the only way that the T12 torque transducer can be specified for an accuracy class of 0.03. The measurement results displayed below were recorded with a 3 kNm transducer of the smarttorque® series. The temperature curve of the zero signal (Fig. 5a) for three temperature cycles between 10°C and 60°C, shows that the random content of the temperature effect is below $u_{Z\vartheta} = 0.003\,\%$. The reproducibility of the static characteristic curve (Fig. 5b) is also in the order of magnitude of $u_{ZM} = 0.002\,\%$ with a hysteresis of around 0.008 %. The specified uncertainty of the calibration machine is achieved here, as far as reproducibility is concerned. The linearity error of the transducer being examined is less than the hysteresis.

This high-precision torque functionality was supplement in the smarttorque® series by speed and angle of rotation sensor technology. The result is a measurement system that provides the user with the most important parameters of the shaft train: torque, speed, angle of rotation, rotational power and temperature.

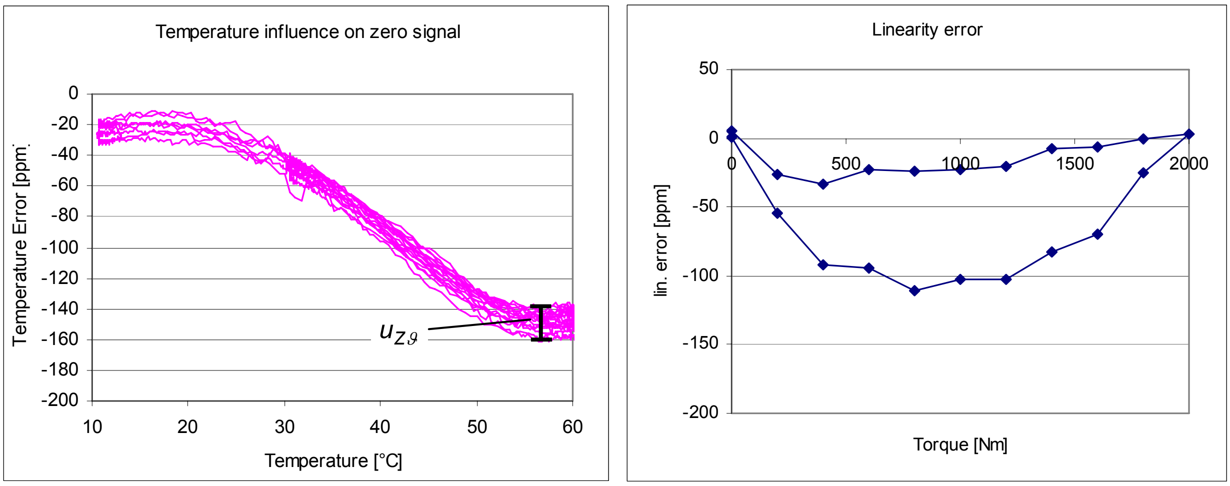


Fig. 5 a) Temperature influence on zero signal; b) linearity error

The validity of the measured values is ensured by the rotor's self-monitoring function. The system monitors the operating state of the measuring bridge and the most important functions of the carrier-frequency amplifier, so that if there is a defect, a warning signal is output or the measured values are identified as invalid. The maximum transducer loadings are also recorded, so that overload damage can be detected. The measurement signals are output at a bandwidth of up to 6 kHz at a scalable frequency output and an analog output. At the same time, it is possible to achieve sampling rates of up to 4.8 kS/s on two channels with CAN and Profibus.

A software assistant is used to parameterize the extensive functions of the T12 torque transducer via CAN, making it possible to access all the settings and to perform standard measurement and analysis tasks. The user management allows to hide and to lock critical parameters in normal user mode.

6 References

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[3] Lenk, A.: Heuristische Fehlermodelle für Meßgeräte. Studie Meßwerterfassung 3/89. Technische Universität Dresden. Institut für Technische Akustik 1989.