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HIGH PRECISION TORQUE MEASUREMENT SYSTEMS IN DYNAMIC AND STATIC APPLICATIONS

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Abstract − This paper describes the advantage of carrier frequency amplifiers in rotating torque flanges. It gives an overview of the systematic effects and random errors which disturb the torque measurement and shows how the measurement errors can be suppressed by means of carrier frequency technology. The resulting high reproducibility and linearity of the new torque flange with digital signal processing and transmission is shown in torque and temperature plots. The dynamic behaviour of this torque measurement system is analyzed and the results are used to develop a new high dynamic rotational torque flange. The benefits of these two systems in different applications are compared.

Keywords: torque transducer, carrier frequency, contactless measurement

1. BACKGROUND

The demand for vehicle drive concepts that are economical and in line with environmental directives involves ever increasing requirements on the test equipment used. High-dynamic, high-resolution torque measurements in the shaft train are indispensable for the design and optimization of motor/drive combinations. Today's strain-gage based torque transducers offer excellent reproducibility. The overall accuracy of the torque measurement system is mainly determined by mechanical interference variables and by uncompensated thermal influences as well as humidity effects. The resolution limit, as the total of errors resulting from the measuring body and the strain gage installation that cannot be compensated, is beyond the technical possibilities provided by the electronics presently used in rotating transducers. These electronics include DC voltage amplifier, analog signal processing, and frequency-analog signal transmission.

2. 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.

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 [1].

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 $\vartheta_0 = 30°C$ 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}

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.

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

The Analysis of the measurement chain shows that thermal voltages resulting from temperature gradients and non-linear temperature coefficients cause the major interference-induced measurement signal errors; these remain uncompensated as yet [2].
More measurement errors result from overloading or damaging of the transducer. Linearity errors are smaller than hysteresis errors. That's the reason for the linearity error being uncompensated [3].

3. 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 effects 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 and wire 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:

$$\begin{aligned} &u_{th} = 42{,}5\ \tfrac{\mu V}{K} \cdot \Delta\vartheta \\ &\Delta\vartheta = 0{,}1\ \mathrm{K} \\ &\Rightarrow u_{th} = 4{,}25\ \mu\mathrm{V} = 0.07\,\% \end{aligned} \qquad (3)$$

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. 1), 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 results from the resistance noise:

$$\begin{aligned} &\text{Noise voltage:} \\ &u_r = \sqrt{4k \cdot T \cdot R \cdot \Delta f} \\ &\text{Temperature:} \quad T = 300\ \mathrm{K} \\ &\text{Bridge impedance:} \quad R = 1{,}4\ \mathrm{k\Omega} \\ &\text{Bandwidth:} \quad \Delta f = 6\ \mathrm{kHz} \\ &\text{Boltzmann constant:} \quad k = 1{,}38 \cdot 10^{-23}\ \mathrm{J/K} \end{aligned} \qquad (4)$$

$$\Rightarrow u_r = \sqrt{4k \cdot T \cdot R \cdot \Delta f} = 373\ \mathrm{nV} = 0.0062\,\%$$

(relative to a nominal signal range of 6 mV)

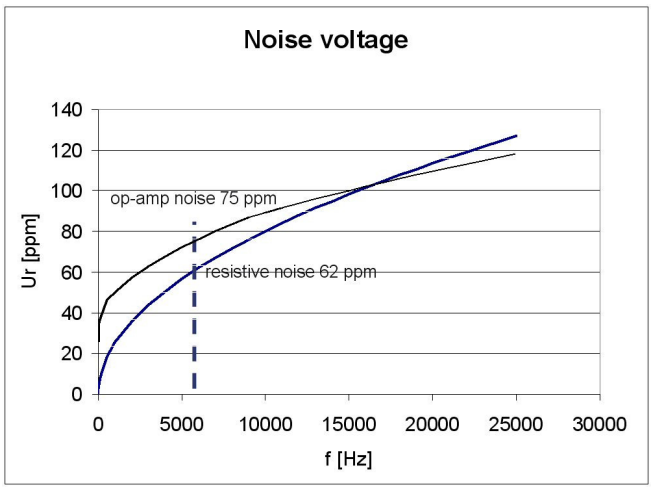

Fig. 1. Noise voltage depending of filter bandwith.

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. 2). You now have the opportunity to suppress the DC voltage effects of thermoelectric voltages and some of the operational amplifier 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).

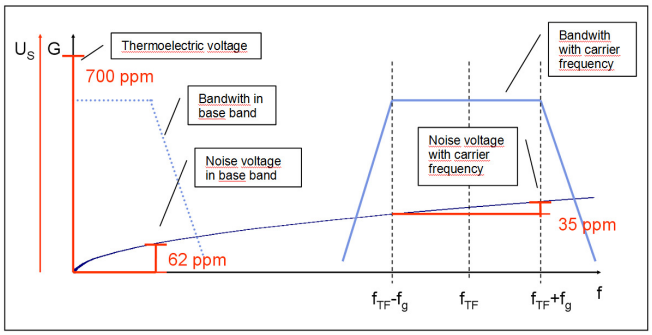

Fig. 2. Noise voltage and temperature errors with and without carrier frequency amplifier.

4. RESULTS WITH CARRIER FREQUENCY AMPLIFIERS

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. 3) for three temperature cycles between 10°C and 60°C, shows that the random content of the temperature effect is below $u_{Z\vartheta} = 0{,}003\,\%$.

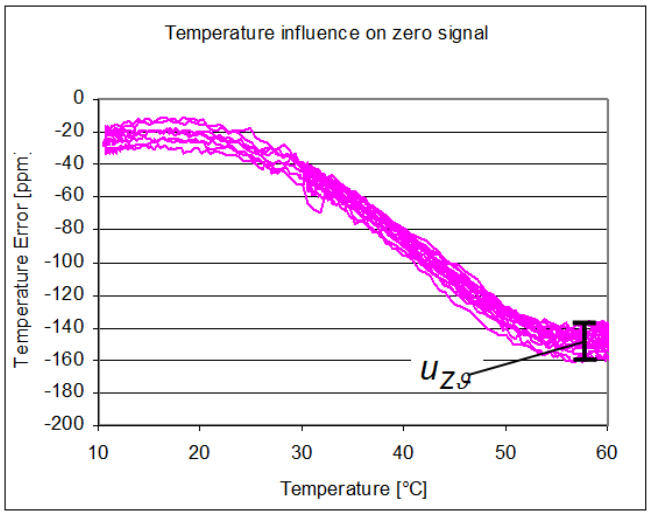

Fig. 3. Temperature influence on zero signal.

The reproducibility of the static characteristic curve (Fig. 4) 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. That's the reason why there is no additional linearity correction included in the T12 compensation algorithms.

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.

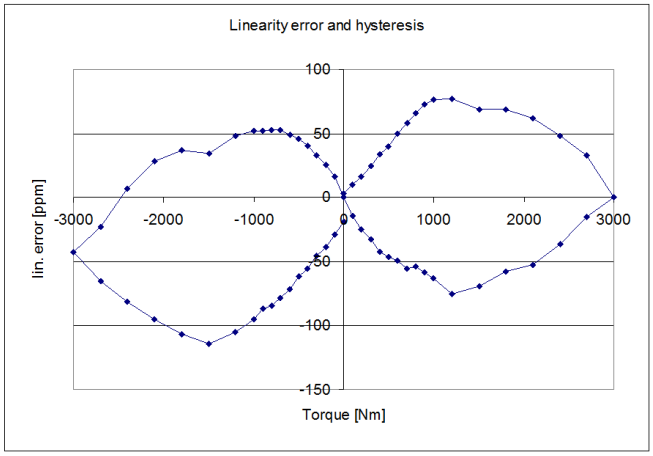

Fig. 4. Linearity error and hysteresis.

5. HIGH DYNAMIC MEASUREMENT

As mentioned above the corner frequency of the T12 torque flange is 6 kHz because of the use of carrier frequency technology. For high dynamic powertrain test benches the dynamic properties of the torque flange must be enhanced. This is done by a new DC rotor electronics with digital signal transmission to the stator and a extended digital signal processing unit additional to the stator. This new rotor electronics is miniaturized to guarantee low mass and low inertia in the rotating part. The result is a robust torque flange, which is able to handle high rotational speed and high rotational acceleration in combination with a signal bandwith of 10 kHz. In powertrain test benches this torque flange can be used to control the high dynamic torque which is applied by low inertia dynamometers. This opens possibilities to apply realistic loads on complete all wheel drive systems including simulation of driver behaviour, vehicle, track, tire and road surface so that tests can be moved from road to test rig (fig. 5.).

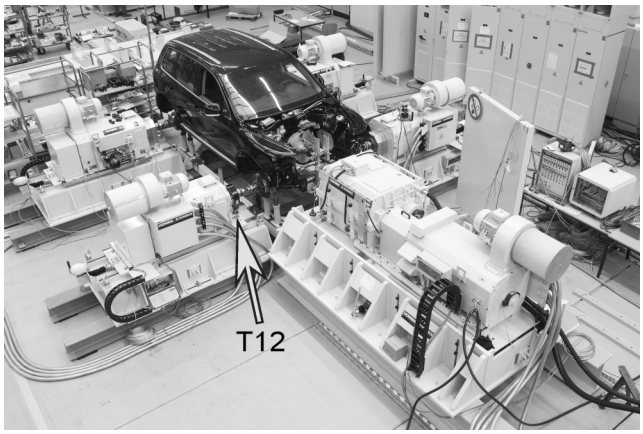

Fig. 5. 4WD driveline test stand. (Horiba)

Consistently minimizing the sources of interference enabled a product tailored to test stand applications such as the T40 torque flange to be developed. The concept involves distinction between the fully functional measurement flange for standalone operation and the digital signal processing unit providing high flexibility. The test stand operator can now use the external signal processing unit for filtering, scaling and integrating the measurement signal through analogue outputs or bus interfaces into the measurement task as required, with the signal properties directly at the measurement flange not being affected and available for test stand control (fig. 6.).

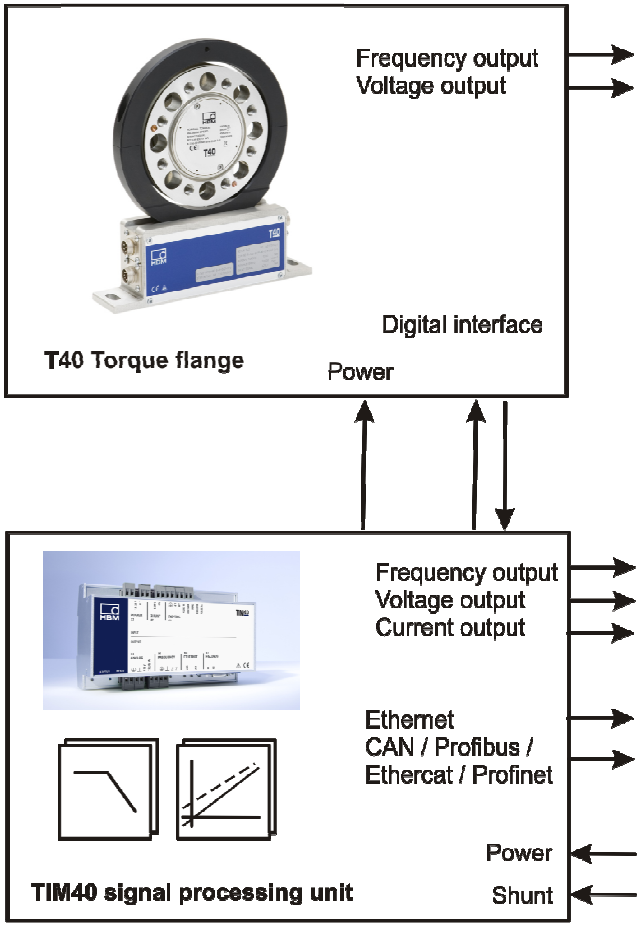

Fig. 6. T40 – TIM40 system.

The rugged rotor design involving a transmitter coil integrated in the flange (fig. 7.) together with the reduction of the wiring effort to a single pcb increases reliability and reduces down time. The permissible vibrational stress could be substantially increased so that during the tests acceleration of over 35 g in the frequency range of up to 2 kHz did not result in any failures.

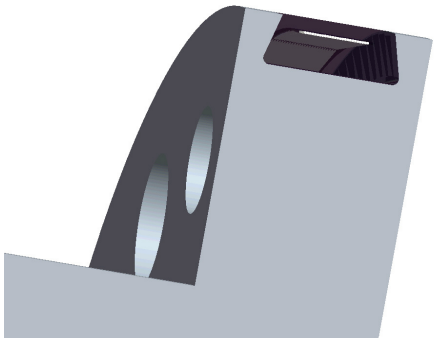

Fig. 7. Dovetail guide rotor design

6. SELECTED EXAMPLE APPLICATIONS

Firstly, target applications include highly-dynamic measurements on performance, functionality and optimization test stands, for example for transmissions, and, secondly, a level of accuracy resulting from technology that has never been achieved before. The following characteristics apply, for example, to the torque signal on the fieldbuses using T12:

- Linearity error including hysteresis < ±0,02 %, optional < ±0,01 %
- Rel. standard deviation of reproducibility < ±0,01 %
- Influence of temperature on sensitivity < ±0,03 % / 10 K
- Influence of temperature on zero < ±0,02 % / 10 K, optional < ±0,01 % / 10 K

Users expect their investment to be secure over the coming decades, especially where engine, transmission and roll test stands are concerned. This is where to use HBM's T12 digital torque transducer. It acquires both the important measurand of torque as well as rotational speed and computes the mechanical output power with high dynamics. It is also possible to measure angle of rotation and temperature. The complete measurement signal conditioning is integrated in the transducer. This greatly increases the quality of the signal and achieves the best uncertainty worldwide.

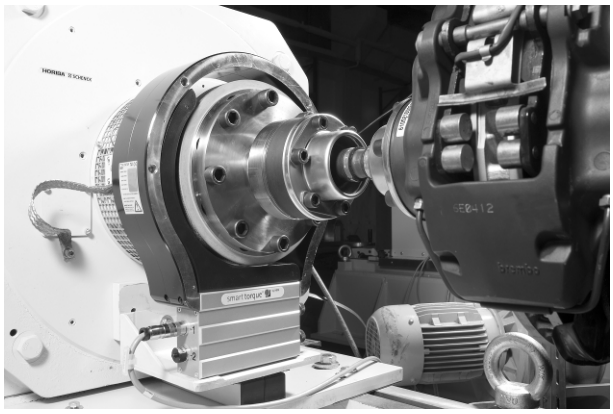

Fig. 8. T12 / 5 kN·m in 4WD driveline test stand (Horiba)

Its compact design saves space and thus costs in test stand construction. Because the rotor weighs less, the load on the bearings is reduced and the lower mass moments of inertia result in smaller dynamic moments during acceleration and braking. This can be seen, for example, in a four-wheel-drive transmission test stand made by Horiba (fig. 5.).

This test stand [4] is used in the development and testing of 4-wheel drives. The test stand has a base area of about 8 * 8 m and enables many different simulations, e.g. cornering ability to be made. A fueled combustion engine can be used, but more importantly, the engine can be simulated by an electrical machine with torque transducer. This achieves a considerable cost reduction, as supply logistics are not required and helps preserve the environment as there are no exhaust emissions. Figure 8 shows a detailed view.

Figure 9 shows the T12 digital torque transducer integrated in a brake for engine test stands. In this case, torque is used as both a pure measurement quantity and, even more important, as a control variable for many different operating modes.

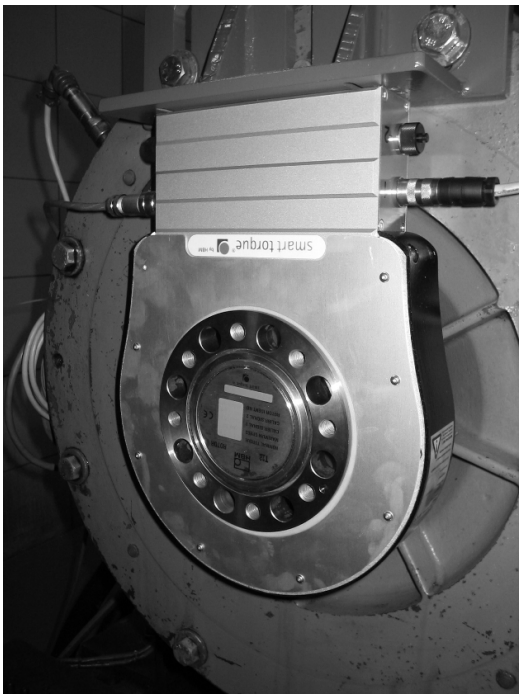

Fig. 9. T12 / 2 kN·m nominal (rated) torque with protection against contact on a brake for an engine test stand (source: APL Automobil-Prüftechnik Landau GmbH)

7. CONCLUSIONS

The paper deals with the development of a high precision contactless torque measurement system using a carrier frequency amplifier. The temperature effect on the measurement signal is optimized through high symmetry of the measuring bridge and digital compensation of remaining temperature effects. Digital signal processing and transmission enable the current high accuracy of non-rotating torque transducers to be attained in the rotating shaft train too.

In new high dynamic applications the signal bandwith of the torque flanges needs to be increased up to 10 kHz. In this case, the limits of the carrier frequency amplifier are exceeded. A new concept for an advanced DC-amplifier and a very fast digital signal processing unit solves this problem. The paper compares the properties of the high dynamic and the high precision torque flanges and shows some typical applications of the new torque transducers T12 and T40.

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