Power measurement on large drives with combustion engines

1. Providing a power signal

Modern drive concepts with large combustion engines require precise and fast response of the engine's control systems (e.g. for fuel supply) to respond to abruptly varying loads. Here, it is essential to ensure that sufficient power is supplied at any time and that, at the same time, the engine features low fuel consumption and safe operating parameters. This requires that a power signal is provided which - with vehicles, compressor and pump systems - needs to be generated using special measuring devices. In general, there are three different approaches:

a. The power signal is provided indirectly by measuring specific auxiliary quantities such as flow rate, temperature, and pressure and then computing the power. With this approach, the power signal's uncertainty of measurement is very high. An additional drawback is that the values of the auxiliary quantities are not synchronous to the processes determining the engine power.
b. The power signal is provided indirectly by measuring specific auxiliary quantities on the input shaft. This includes all methods involving measurement either of the strain resulting from shaft torsion on its surface or of the shaft's torsion angle. In both cases, the power is computed following the measurement of the auxiliary quantities.
c. The power signal is provided directly by measuring torque in the input shaft.

The following article compares direct power measurement with indirect power measurement on and in the drive train respectively (approaches b. and c.) with regard to the uncertainties of measurement that can be achieved.

2. Fundamentals of computing drive power

The power transmitted by a rotating shaft is given by

$$P = \varpi \cdot M = \frac{\pi \cdot n}{30} \cdot M \tag{1}$$

where M is torque and n rotational speed. Torque is given by

$$M = \tau \cdot W_{shaft} \tag{2}$$

where τ is the shear stress and W_{shaft} the shaft's moment of resistance. The distinctive feature of a shaft that is subjected to torsion only is that both principal normal stresses have the same absolute value, i.e.:

$$\sigma_1 = -\sigma_2 \tag{3}$$

Since in this case, the center of Mohr's circle is positioned in the origin of its coordinate system, the shear stresses correspond to the absolute value of the principal normal stresses. It follows that

$$\tau = |\sigma| \tag{4}$$

where $|\sigma|$ is the absolute value of the normal stress. The following applies in addition:

$$W_{shaft} = \frac{\pi \cdot d^3}{16} \tag{5}$$

assuming that the input shaft is a cylindrical solid shaft. Resulting from (1) … (5) power is given by

$$P = \frac{\pi \cdot n}{30} \cdot |\sigma| \cdot \frac{\pi \cdot d^3}{16} = \frac{\pi^2 \cdot n \cdot d^3}{480} \cdot |\sigma|$$
(6)

The normal stress of a torsion shaft is:

$$|\sigma| = \frac{E}{1-\mu^2}(1-\mu) \cdot |\varepsilon_{45°}|$$
(7)

where E is the modulus of elasticity, μ Poisson's ratio and $|\varepsilon_{45°}|$ the absolute strain value on the torsion shaft's surface in the principal strain direction. Resulting from (6) … (7) power is given by

$$P = \frac{\pi^2 \cdot n \cdot d^3}{480} \cdot \frac{E}{1-\mu^2}(1-\mu) \cdot |\varepsilon_{45°}|$$
(8)

<u>Example A:</u> Determining strain $|\varepsilon_{45°}|$ using strain gauges
The single error to be allowed for results from the tolerance of the gauge factor, see table 1.

<u>Example B:</u> Determining strain $|\varepsilon_{45°}|$ by measuring the torsion angle φ
The following applies:

$$|\varepsilon_{45°}| = \frac{\varphi}{4} \cdot \frac{d}{l} \quad (9)$$

The single errors to be allowed for result from the tolerances of the input drive's diameter d and length l as well as the measurement error φ, see table 1.

Considering (8) and (9) the power determined by measuring the torsion angle is:

$$P = \frac{\pi^2 \cdot n \cdot d^3}{480} \cdot \frac{E}{1-\mu^2}(1-\mu) \cdot \frac{\varphi}{4} \cdot \frac{d}{l}$$
(10)

3. How big are the tolerances that need to be allowed for?
All the parameters to be taken into account for (8) and examples A and B are subject to tolerances. They can be assessed as follows:

Parameter	***Symbol***	***Tolerance (approx.)***
Rotational speed	n	0.1%
Shaft diameter	d	0.01%
E modulus	E	3 … 5%
Poisson's ratio	μ	3 … 5%
Gage factor	k	1%
Torsion angle	φ	0.1%
Length of torsion shaft	l	0.01%

Table 1: Assessment of tolerances

Example A requires the strain gauge positioning tolerances s as well as the temperature error resulting from lacking or limited thermal compensation to be considered in addition. The values of these tolerances are determined by the quality of the strain gauge installation and will therefore not be taken into consideration here.

Without further error analysis, table 1 shows that the total error of the measuring devices described above (approach b.) is primarily determined by the tolerance of E and μ. It can thus not be less than 3%, however, in practice, it is often substantially higher.

4. How can the measurement uncertainty of the power signal be reduced?
To significantly reduce the high uncertainty of measurement of the methods specified in approach b. it is necessary to calibrate the shaft section equipped with the measuring device to the maximum torque to be expected. For this purpose, a loading device has to be used to apply torque to the shaft section step by step, up to the maximum value and to measure the output signals supplied by the measuring device at every calibration step. With an approximately linear characteristic curve and a sufficient number of measurement points, it is possible to achieve an uncertainty of measurement that roughly corresponds to that of the calibration machine.

However, it will be difficult to implement this method in practice. Transporting the shaft section of a large drive with an installed measuring device to the calibration machine or vice versa might be difficult. In addition, the shaft section needs to be mechanically adapted to the calibration machine - a complex process which, however, is indispensable for load application.

The solution to this dilemma is to measure torque in the drive train instead of on the drive train (Approach c.). For this purpose, a torque flange, which should already be taken into account during the design phase, is mounted between the drive side and the driven side.

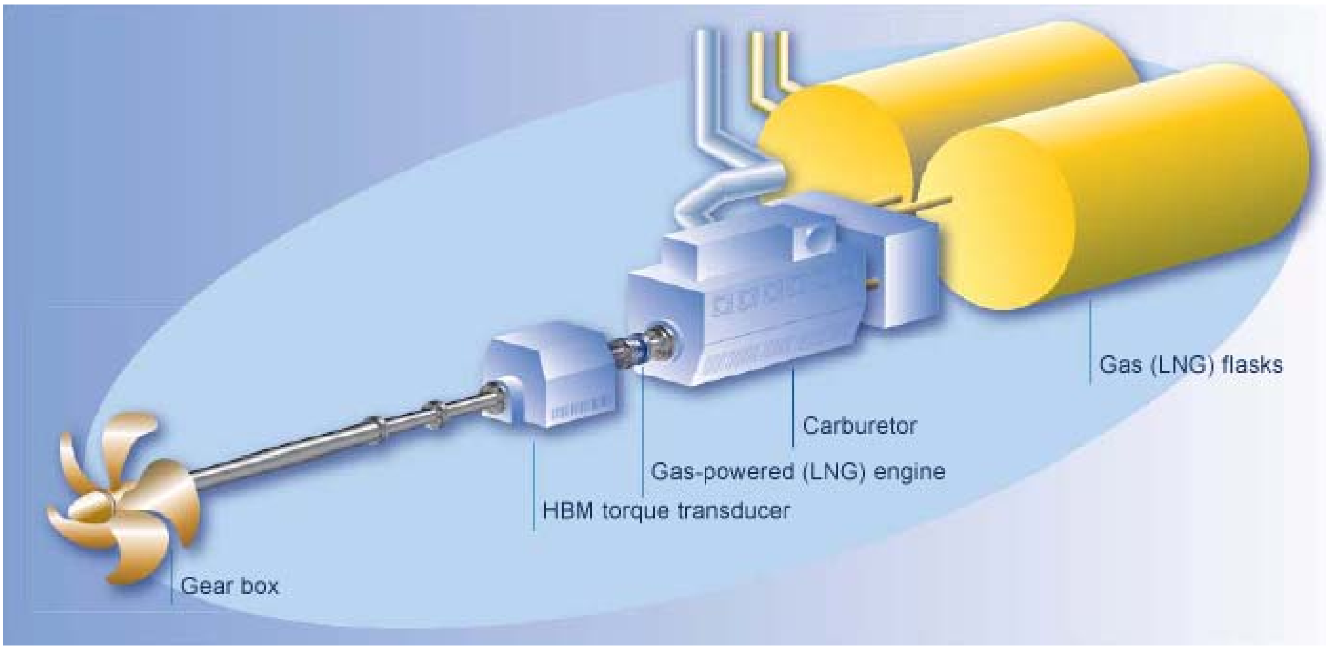

Fig. 1: Mounting of a torque flange in a drive train

Fig. 2: Torque flange with a nominal (rated) measuring range of 2 MNm
Photo: Hottinger Baldwin Messtechnik GmbH

According to (1) the power is then given by the directly measured quantities of torque and rotational speed.

The torque flange is calibrated up to its nominal (rated) measuring range or part of it by the supplier and certified accordingly in advance. Depending on the type and size of the measurement flange, the resulting uncertainties of measurement amount to 0.03% and 0.1% of the nominal (rated) or partial measuring range. This uncertainty of measurement is already related to torque and not to an auxiliary quantity, e.g. strain or torsion angle. Due to the integrated thermal compensation, the parameters specified for the measurement flange are valid for a wide temperature range.

Installing, exchanging and recalibrating a torque flange is relatively easy. Furthermore, it offers some additional features which - depending on the application - provide significant added value:

- High resolution (16 ... 19 bit) of the torque signal for recording of minimal amplitude variations
- Large bandwidth (up to 6 kHz) of the dynamic torque signal for recording of highly dynamic processes in the drive train (e.g. torsional vibration)
- Short signal propagation time for very fast control in the event of varying load conditions
- Robust design and high signal stability for use in extreme ambient conditions
- Excellent repeatability and long-term stability values for use over long periods of time without corrective action
- Visualization of characteristic torque curves for specific cycles enabling data for Condition Based Maintenance (CBM) to be provided.

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