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Torque measurement on a single cylinder engine test bench with an HBM measurement flange

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Introduction

Dynamic torque measurements on single-cylinder engine test benches are now on the agenda in most of the research and development units of automotive manufacturers and suppliers. The effect of the combustion run, the mixture formation or the internal cylinder pressure for different cylinder geometries and the various fuel injection strategies, for example, are examined in order to optimize the engines on the test bench.

As the measurable difference gets ever smaller, the consistent development of internal combustion engines demands ever higher standards of torque measurement. The important requirements for torque measurement are high stationary and dynamic accuracy. Hysteresis phenomena also play a crucial part.

Previously, torque measurement on single-cylinder engine development test benches was usually performed by a pendulum bearing electric machine combined with a force transducer. Measuring torque with a measurement flange, on the other hand, is regarded as problematic. The reason for this is the uncertainty with regard to the loading of the torque flange caused by the lower-frequency torque oscillations of a single-cylinder test bench. High torque peaks and high cyclic irregularities are also to be expected.

This is why the design of the test bench, the choice of a suitable torque transducer (measurement flange) and the subsequent signal conditioning are extremely important. First the size of the measurement flange must be such that the loads that occur do not exceed the rated load. Contrast this always-to-be-met demand with the fact that large-sized torque transducers are often expensive and, of course, measure less accurately in the lower measuring range.

The test described and performed here with a machine with a rigid stator mounting and a torque flange from HBM, shows that with a suitable mechanical test bench design, it is quite possible to use a torque flange and this even leads to advantages compared to measuring torque with a pendulum bearing mechanism.

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Pendulum-bearing electric machine

When measuring torque by means of a pendulum bearing, the stator of the electric machine is rotatable. As a lever arm is attached to the stator, there is a measurable force at the free end. This force is detected by a force transducer and converted to a torque.

This method of torque measurement allows stationary torque to be detected extremely accurately. The torque peaks of the combustion engine are not critical for the force transducer either. Compared to the torque flange, the mass of the rotor and stator, as well as the air gap of the electric machine lie between the combustion engine and the transducer. These masses and the mechanical decoupling caused by the air gap produce extremely high damping of the vast torque fluctuations of a single-cylinder combustion engine.

However, the low-pass characteristics of the mechanical system make it impossible to measure the torque dynamically. This means that high-frequency oscillating torques cannot be measured. Not only that, but with accelerated processes, the inertia of the electric machine rotor is included in the signal, which results in a considerable difference between the measured shaft moment and the actual shaft moment.

Pronounced hysteresis phenomena, which can only be reduced by a vast and very costly mechanical outlay, are a further disadvantage of torque measurement with a cradle dynamometer. Other possible interference factors are the cable routing of the power terminal for the pendulum bearing electric machine, the friction in the pendulum bearings and the current of air for a separately ventilated electric machine.

Machine with rigid stator mounting combined with a torque flange

With this method of torque measurement, the stator of the electric machine is permanently mounted to the base. On the driven side of the electric machine, the torque flange is integrated directly into the shaft connection. An engine test bench of this category is shown in **Figure 1**. This was used in the Vehicle Research Institute (FIF) at the Dresden University of Applied Sciences (FH) for the investigations briefly described below.

Visible on the left is the electric machine with the connected torque flange, the flexible shaft connection and, on the right, the single-cylinder diesel engine.

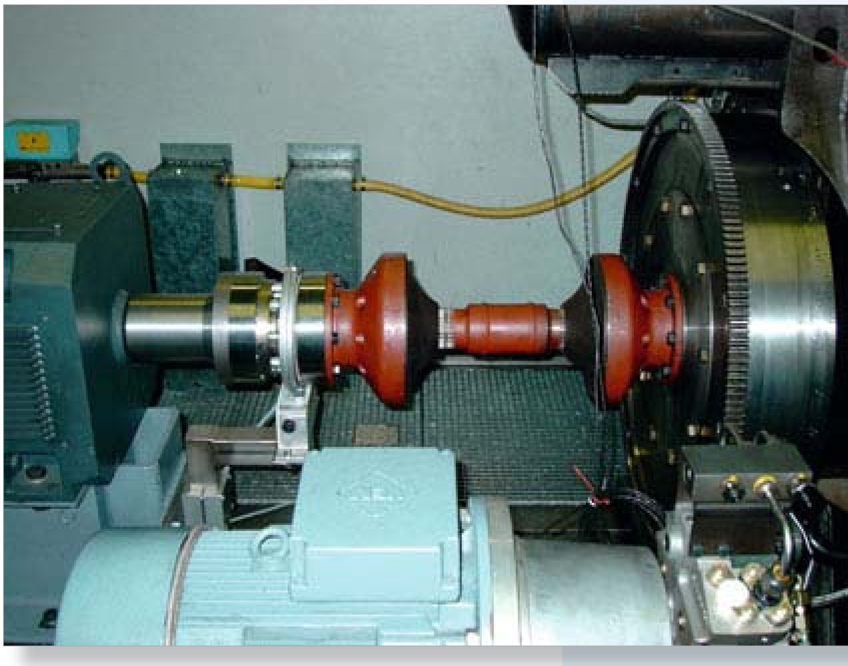

Fig. 1: Engine test bench with torque flange

Figure 2 shows the test bench with the diesel engine in the foreground and **Figure 3** shows the installed measurement flange.

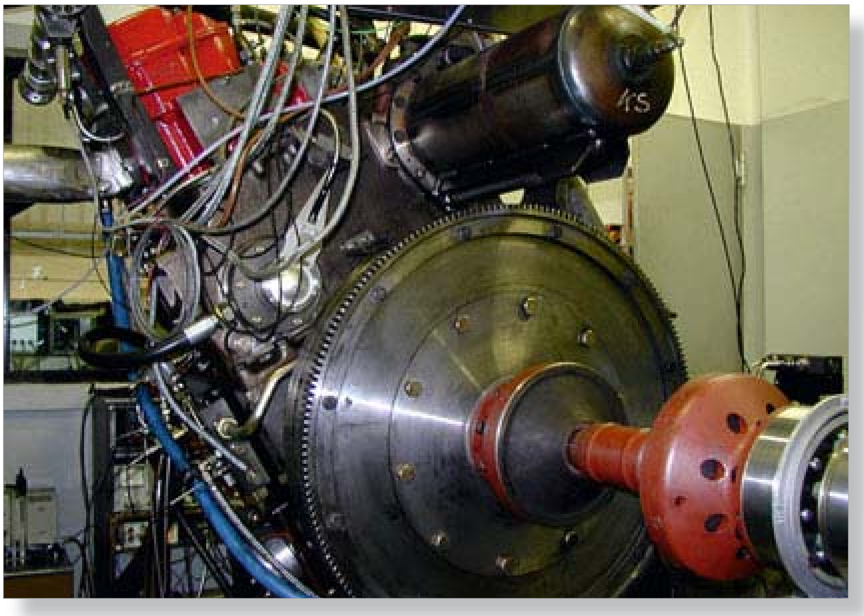

Fig. 2: Single-cylinder diesel engine on the engine test bench

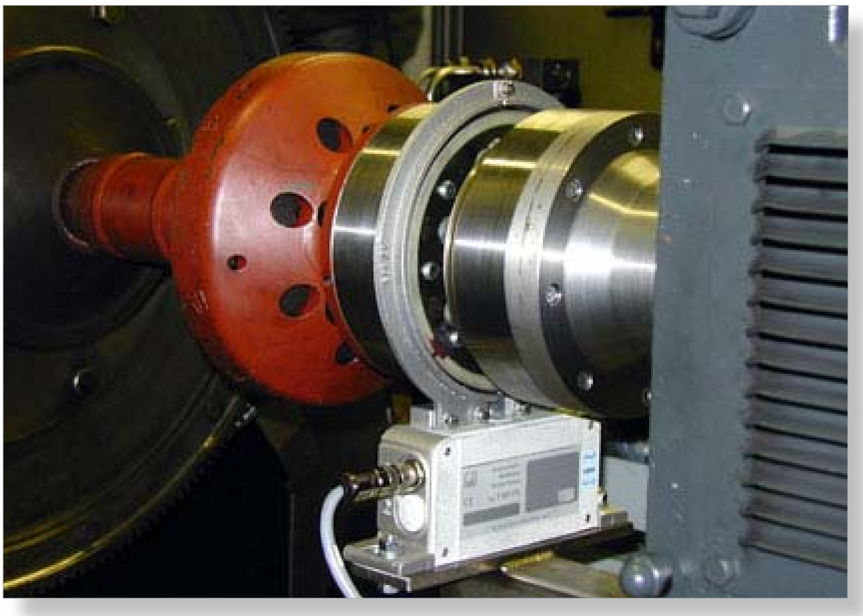

Fig. 3: T10FS measurement flange from HBM

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The Table below contains all the important specifications of the individual subassemblies.

Combustion engine	Electric machine
Single-cylinder, 4-stroke, MTU BR 382 diesel Displacement: 3,820 cm^3 Piston mass: 9.89 kg Max. torque: 680 N·m Max. internal cylinder pressure: 150 bar Mass moment of inertia (with centrifugal mass): approx. 25 kgm^2	Siemens GSM 1GG6 208 Mass moment of inertia (rotor): 1.3 kgm^2
Torque flange	**Shaft connection**
HBM T10FS Amplifier: MP60DP (500 Hz Bessel filter) Nominal (rated) torque: 3 kN·m Limit torque: 1.6 · 3 kN·m Permissible vibration bandwidth in accordance with DIN 50 100 (peak-to-peak): 4.8 kN·m	Type: GKN flexible shaft without centering bearing 128.50 Nominal (rated) torque: 1.8 kN·m Torsional rigidity: 1,500 N·m/rad

Table: Specifications of the individual subassemblies of the engine test bench

Care must be taken with the mechanical design of the test bench to ensure that the natural frequency of the test bench in the standard operating range is not affected by the torque fluctuations of the combustion engine. This is why, in most cases, a supercritical design is used. This means that the combustion engine achieves the natural frequency of the test bench at a speed below idling speed. So the natural frequency is only run briefly when starting and stopping the combustion engine.

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The behavior of the torque fluctuations in a resonance situation (the natural frequency of the test bench = the fundamental resonance frequency of the combustion engine) is of particular interest when choosing the torque measuring device. This is why the measurement results of starting and stopping have been shown as graphs (**Figs. 4–6**).

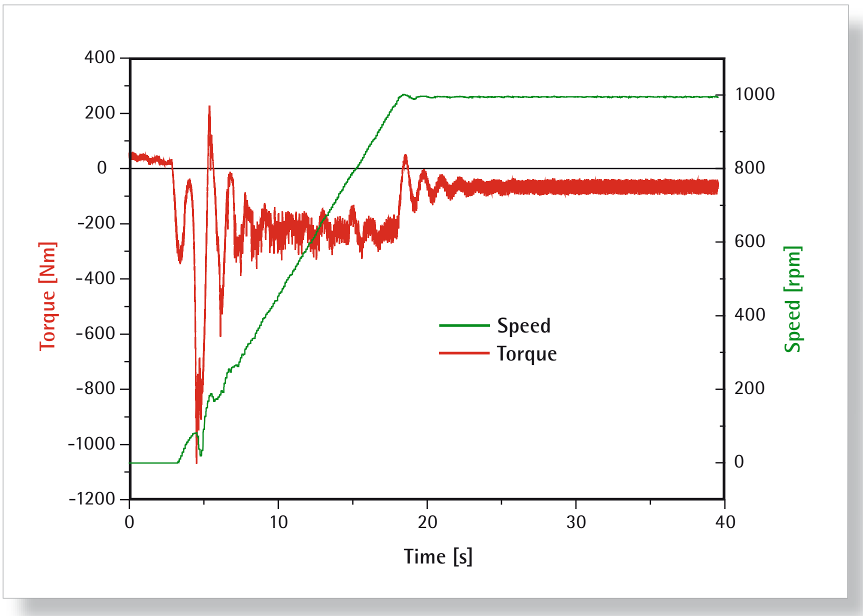

Fig. 4: Torque and speed curves when running the test bench up to speed

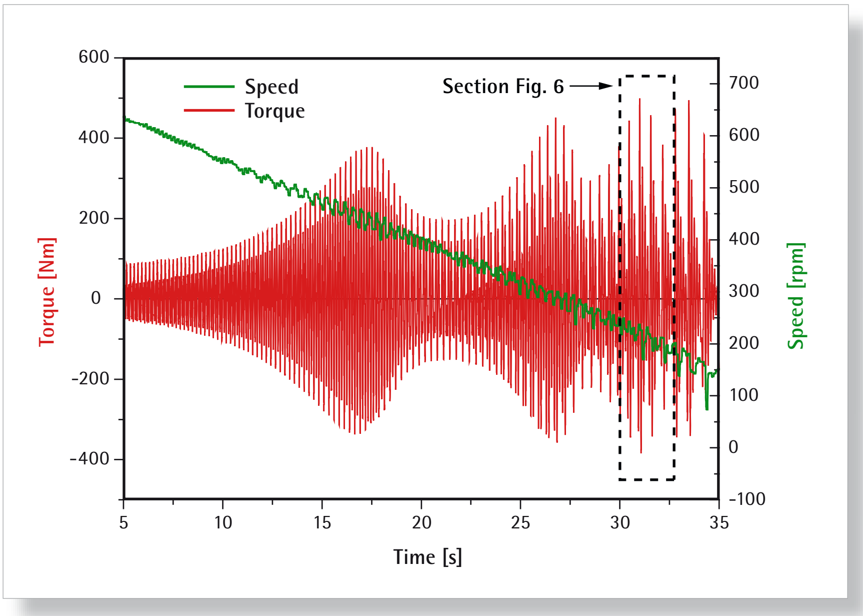

Fig. 5: Torque and speed curves when bringing the test bench to a stop

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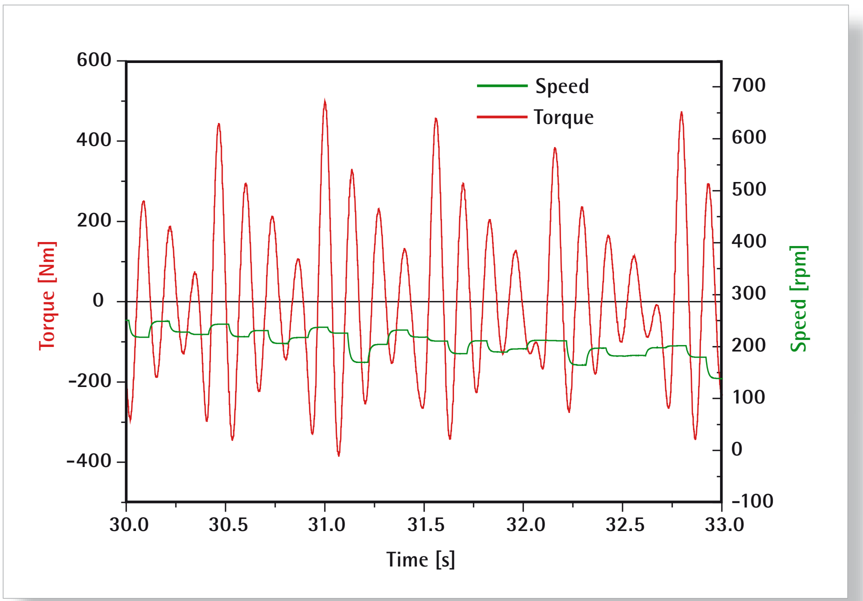

Fig. 6: Torque and speed curves when bringing the test bench to a stop (section in 30 - 33 sec time range, see Fig. 5)

When the test bench was shut down, the control of the d.c. generator was deactivated, so that the test bench could slow down freely. The signal curves in **Figures 5** and **6** show clear resonances during stopping. The maximum amplitude is about 500 Newton meters (N·m). This corresponds to a peak-to-peak value of about 1000 N·m. The maximum vibration bandwidth permitted by the torque flange of 4.8 kN·m can then be briefly utilized to about 20 %. When starting, the combustion engine is pulled up to speed by the electric machine. This briefly produces a peak torque of 1100 N·m.

For operating the test bench at above idling speed and resonance frequency, an upper limit for the torque fluctuations to be expected at the torque flange can be specified subject to the internal combustion engine torque as follows.

$$M_{welle} = \frac{J_{EM}}{J_{EM} + J_{VKM}} \cdot M_{iVKM}$$

M_{Welle} : Maximum torque oscillations to be expected at the measurement flange

M_{iVKM} : Internal torque oscillations in the combustion engine

J_{EM} : Mass moment of inertia of all masses on the electric machine side of the torque flange

J_{VKM} : Mass moment of inertia of all masses on the combustion engine side of the torque flange

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This calculation ignores all the elasticity of the shaft connection and assumes a rigid connection. The actual torque occurring above the resonance frequency is less than the torque calculated here. Which means that this equation can be used to define the maximum.

Basically, this equation shows us that when the J_{EM} values are high, torque increases at the measurement flange. In contrast, when the J_{VKM} values are high, the torque at the flange decreases.

With the test bench data, this produces at working point n = 1200 rpm and 650 N·m (nominal value).

$$M_{welle} = \frac{1{,}3\,\text{kgm}^2}{(1{,}3 + 25)\,\text{kgm}^2} \cdot 17\,\text{kNm} \approx 840\,\text{Nm}$$

The internal engine torque M_{iVKM} was calculated from the internal cylinder pressure curve and the geometry of the combustion engine at 17 kN·m as a peak-to-peak value. Because of the mass ratios, this means that the torque oscillations that can be measured in the shaft will be less than 840 N·m (peak-to-peak).

Practical measurements in the Vehicle Research Institute (FIF) at the Dresden University of Applied Sciences (FH) produced an actual torque oscillation of about 250 N·m (peak-to-peak). The difference between calculation and measurement arises because of the elasticity of the shaft connection, which is not considered in the calculation. The absolute value of the torque fluctuates between 525 N·m and 775 N·m (= 650 N·m ± 250/2 N·m). This loading is not critical for the torque flange.

Result

With the theoretical and metrological investigations performed here, it was possible to show that with an appropriate mechanical test bench design, only a small proportion of the oscillating torques inside the combustion engine are transmitted to the shaft, meaning that there is no problem in using a torque flange.

This has various advantages for torque measurement. Firstly, when designing the machines, it is possible to fall back on a conventional, standard machine. There is no longer any need for an expensive cradle dynamometer. The choice of suppliers who make standard machines is also far greater. Secondly, measuring with a measurement flange is more dynamic than using a cradle dynamometer. Measurement is a great deal more accurate and faster.

Control is also better when the machine has a rigid stator mounting. It is easier to control electrically than a cradle dynamometer and its overall behavior is also more stable. The sensitive pendulum bearings of cradle dynamometers are heavily loaded by the oscillating torques of the combustion engine – and this is particularly pronounced with a single-cylinder engine. This is why it is necessary to use a hydro-bearing as the pendulum bearing. The disadvantages are: more hydraulic expenditure, more space needed and a not inconsiderable additional cost. In contrast, a machine with rigid stator mountings can work with standard bearings.

Also, when using cradle dynamometers, the signal ripple is actually relatively well "filtered" by the moment of inertia of the rotor and damping via the air gap, before the signal arrives at the load cell. However, the dynamic mapping of the smaller frequency parts (3 to 10 Hz) is affected to a greater or lesser degree. Higher proportions are even fully filtered out. This means that all the high-frequency parts in the actual operating range of the combustion engine (at idling speed and above) are no longer mapped.

A further technical disadvantage is that the theoretical accuracy of the pendulum measurement can be impaired by design factors, as well as the mounting and other factors existing at the site of installation. These include:

- Inaccuracies in the effective length of the lever arm because of machining/manufacturing tolerances can lead to amplification errors. In particular, maximum effort is required to verify machining errors in the machine housing in the finished state.
- The undefined lateral and side forces of the cable routing to the body of the pendulum result in hysteresis errors as well as irregular zero point and amplification errors in the measurement.
- The undefined and often unstable support torques of the pendulum body caused by the current of cold air result in irregular zero point and amplification errors in the measurement.

So there is no doubt that conventional machines using standard measurement technology can be used without difficulty when measuring torque on a single-cylinder engine test bench. For fast and accurate measurement, as well as the technical advantages of a machine with a rigid stator mounting, it makes particular sense to use a standard machine with an HBM measurement flange.