

# RECENT DEVELOPMENTS OF DYNAMIC PRESSURE MEASUREMENTS IN COMBUSTION ENGINES

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## Abstract:

Precise knowledge of cylinder pressure is needed for optimizing engine performance. To ensure reliability of measurements, pressure sensors need to be calibrated at conditions that correspond to actual use, i.e., at dynamic conditions and elevated temperatures. VTT has developed a dynamic pressure calibrator based on reference sensor principle to enable cost-effective dynamic calibrations up to 35 MPa at temperatures up to 200 °C. Moreover, a novel cylinder pressure sensor that can withstand the harsh conditions inside an engine was developed and the performance was validated in laboratory and inside a marine engine.

**Keywords:** Dynamic pressure; cylinder pressure sensor; calibration; internal combustion engine

## 1. INTRODUCTION

Recent progress in development of dynamic pressure measurements have been taken in the EMPIR DynPT project [1]. An application that greatly benefits from improved dynamic pressure measurements is internal combustion engines (ICE) where accurate and reliable measurement of cylinder pressure is needed to optimize engine performance, i.e. to increase power and reduce fuel consumption and emissions.

Dynamic pressure sensors are typically calibrated at ambient temperatures using static pressure measurements standards, which might cause errors up to 10 % when sensors are used at dynamic conditions and elevated temperatures inside an engine. To provide traceability to the International System of Units (SI), the National Metrology Institute of Finland (VTT MIKES) has developed a dynamic pressure primary standard [2]. Although providing the most accurate realization of the unit — typical calibration uncertainties ( $k = 2$ ) around 2 % — it is not considered practical for day-to-day calibration work as it requires a highly skilled operator, and it is laborious to use. To address this issue, VTT MIKES has developed a secondary dynamic pressure standard to provide a cost-effective solution for calibration laboratories to

realize calibration services to a wide end-user community.

Another issue in ICE cylinder pressure measurements is the durability of cylinder pressure sensors limiting their use for real-time engine optimization. Although piezo-electric sensors are widely used and considered an industry standard for dynamic measurements in engine applications, durability is an issue especially in marine applications where measurement conditions are extremely harsh and a lifetime of 20 000 hours is required. To address this issue, VTT has developed a novel (patented) sensing technology based on capacitive measurement principle, where the sensing element is not in direct contact with the bending membrane, making the sensor very durable. Extensive calibration and testing, including real engine tests were performed to demonstrate that the VTT Cylinder Pressure Sensor (CPS) performance is comparable to a state-of-the-art piezoelectric sensor with respect to accuracy, linearity, repeatability, and temperature sensitivity.

## 2. DYNAMIC PRESSURE CALIBRATOR

The VTT MIKES secondary dynamic pressure standard was designed for calibrating dynamic pressure sensors in the pressure range from 2 MPa up to 35 MPa and temperatures up to 200 °C corresponding peak pressures and cylinder head temperatures inside a large combustion engine.

### 2.1. Operating principle

The calibrator is based on the reference sensor principle with traceability to SI through the VTT CPS calibrated at VTT MIKES using the dynamic pressure primary standard. The working principle is as follows (see Figure 1): An electromechanical actuator excites the impact mass (2), which hits the piston (3) giving rise to a pressure pulse inside the chamber (4) to which the sensors (up to 4 sensors) are connected through the sensor ports (5).

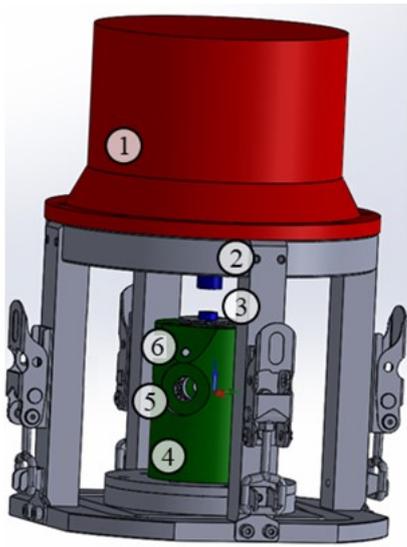


Figure 1: Schematic of VTT dynamic pressure calibrator with: (1) electromechanical actuator, (2) impact mass, (3) piston, (4) pressure chamber, (5) sensor port, (6) inlet for hydraulic fluid.

Pressure pulses generated with the calibrator have a half-sine shape and a duration of about 2 ms, which corresponds well to pressure pulses inside ICes.

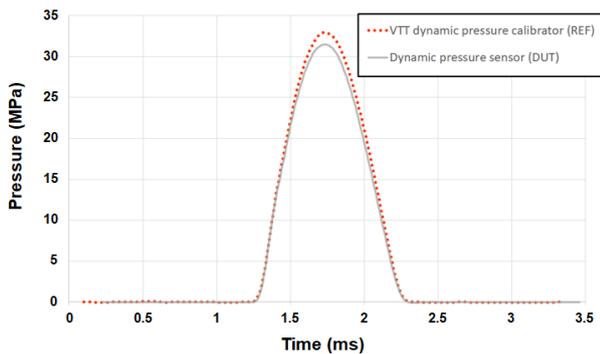


Figure 2: Pressure pulse generated by VTT dynamic pressure calibrator as measured with VTT CPS (REF) and a commercial dynamic pressure sensor (DUT).

## 2.2. Design considerations

*Actuator* - The actuator had to be reinforced to withstand the forces generated at impact. Moreover, the input waveform driving the actuator was optimised to achieve desired movement of the impact mass.

*Adapters* – Special adapters were designed to adapt various thread sizes ranging from 5 mm to 14 mm and to preserve symmetry of design, which is important for achieving equal pressure at the ports.

*Hydraulic fluid* – Flushing and degassing is necessary when filling the chamber with hydraulic oil in order to remove air bubbles, which might

otherwise distort the generated pressure pulse and cause significant errors.

*Heater* – A special feature of the calibrator is the PID controlled built-in heating elements, which enable calibrations at temperatures up to 200 °C.

## 2.3. Validation of performance

Extensive validation measurements were performed to investigate the performance of the calibrator [3]. One important aspect was to study the symmetry of sensor ports (4 ports) to ensure the equivalence of pressure generated at the ports. Tests were made with different adapter configurations for a commercial sensor (DUT). All results were within  $\pm 1\%$  in the pressure range above 5 MPa (Figure 3) with only a small noticeable effect of asymmetry caused by using adapters. Below 5 MPa, more scattering was observed, mainly due to the limited resolution of VTT CPS used as a reference.

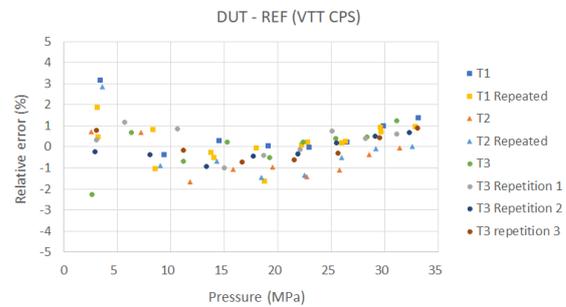


Figure 3: Calibration results of DUT. T1: without adapter, T2: with adapter, T3: T1 repeated.

A full uncertainty budget for a calibration performed with the calibrator at 30 MPa and room temperature is presented in Table 1. At the moment, calibration of the reference sensor is the dominating uncertainty source. Consequently, future developments of primary calibration methods will further lower the uncertainty.

Table 1: Uncertainty budget of the calibrator.

Source of uncertainty	Standard uncertainty
Calibration of REF	1.0 %
Spread of DUT	0.3 %
Reproducibility of calibrator	0.4 %
Symmetry of calibration ports	0.2 %
Influence of adapter	0.4 %
Combined standard uncertainty	1.2 %
<b>Expanded uncertainty (<math>k = 2</math>)</b>	<b>2.4 %</b>

Performance specification of the dynamic pressure calibrator is given in Table 2.

Table 2: Specifications of calibrator.

Dynamic pressure calibrator performance	
Pressure range	2 – 35 MPa
Pressure pulse duration	2 ms
Calibration temperature	20 – 200 °C
Traceability of measurement	ref. sensor*
Measurement uncertainty ( $k = 2$ )	2.4 %

\*SI traceable through VTT MIKES primary standard

## 2.4. Conclusion and future prospects

A novel dynamic pressure calibrator was successfully developed to enable cost-effective SI traceable calibrations of dynamic pressure sensors at conditions relevant to ICE applications, i.e. pressures and temperatures up to 30 MPa and 200 °C, respectively. This is an important step in disseminating traceability to a wide end-user community. One calibrator has already been delivered to a European calibration laboratory with the aim to launch the first accredited calibration service for dynamic pressure.

## 3. CYLINDER PRESSURE SENSOR

VTT has developed a new sensing technology for dynamic pressure measurements at harsh conditions, such as inside a maritime combustion engine, where cylinder pressures can reach up to 30 MPa. To demonstrate the performance of the developed technology, validation measurements were performed using the primary dynamic pressure standard of VTT MIKES. Calibrations were performed at elevated temperatures corresponding actual operating environment. This is important as sensors are known to have temperature dependent sensitivities. Finally, the sensor was validated through field measurements in a real maritime combustion engine. The VTT sensor was compared to state-of-the-art piezoelectric sensors to benchmark the performance.

### 3.1. Operating principle

The VTT dynamic pressure sensor is based on remote reading of the bending membrane (Figure 4). The sensing element is not in direct contact with the bending membrane, which makes the sensor very durable. Besides durability, a major advantage of the sensor is its unique patented capacitive sensing technology. This innovation enables reliable static calibrations of the sensor even though it is used for measuring dynamic pressures. This in turn makes the calibration of the sensor cost effective, because unlike dynamic calibrations, static calibrations can be carried out using existing pressure calibration instrumentation. Key performance specifications are given in Table 3.

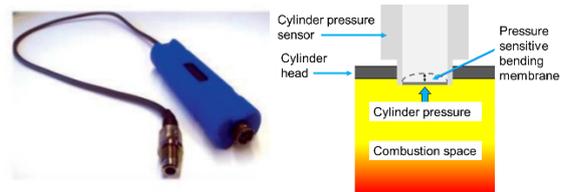


Figure 4: VTT CPS (left figure) is based on sensing the change in capacitance between the bending membrane and the static electrode (principle shown on the right).

Table 3: VTT CPS performance.

Parameter	Value
Measurement range	0...35 MPa
Over pressure	80 MPa
Temperature range*	up to 200 °C
Sensitivity	348 $\mu$ A/MPa
Output noise, rms 0 - 1 kHz	200 kPa

\*Calibrated up to 200 °C; tested up to 400 °C

### 3.2. Calibration procedure

The VTT MIKES dynamic pressure standard was used as a reference for investigating the performance of the VTT sensor. The measurement standard is based on the drop-weight method, in which an impact mass is dropped onto a piston, which compress the liquid inside a measurement chamber, giving rise to a pressure pulse with millisecond duration. The primary measurement (reference reading) is realised by interferometric measurement of the acceleration ( $\mathbf{a}$ ) of the impact mass when it hits the piston. When knowing the mass of the drop-weight ( $\mathbf{m}$ ) and the effective area of the piston cylinder assembly ( $\mathbf{A}$ ), dynamic pressure ( $\mathbf{p(t)}$ ) can be derived as:

$$p(t) = \frac{m \cdot a(t)}{A}. \quad (1)$$

As pointed out previously, it is important to perform calibrations at elevated temperatures corresponding to the actual conditions inside an engine. To realize this, the measurement head of VTT MIKES primary standard was modified to enable heating the sensor and measurement media up to temperatures of about 200 °C (typical for engine environment). In the modified measurement head, heating wire is wrapped around the sensor thread to enable controlled heating of the sensor under calibration, as well as the fluid in contact with the sensor (Figure 5). Details on the operation of the primary standard can be found in [2].

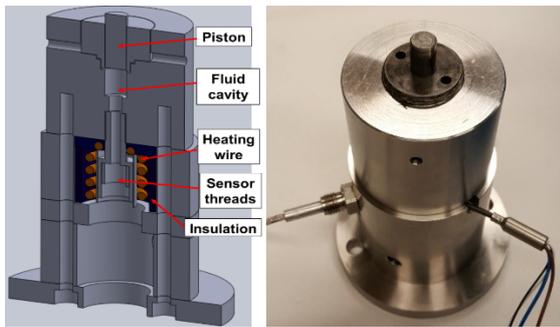


Figure 5: Modified measurement head with heating. The sensor is connected from below using sensor threads of the measurement head. The fluid inside the cavity is in contact with the sensor membrane, thus transferring pressure generated by piston compression to the sensor.

### 3.3. Calibration results

Calibration measurements were performed at peak pressures of 7 MPa, 12 MPa, 20 MPa and 30 MPa at temperatures of 20 °C, 120 °C and 180 °C. Generated pressure pulses have a half-sine shape and a duration of around 4 ms (Figure 6), i.e., the peak pressure and pulse shape correspond to pressure pulses inside an ICE. To benchmark the performance of the VTT sensor, calibrations were also performed for a commercial piezoelectric sensor.

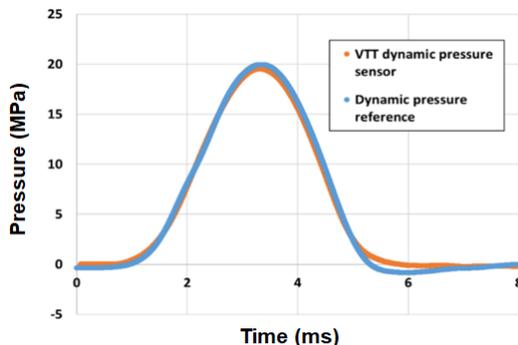


Figure 6: Pressure pulse generated with the VTT MIKES dynamic pressure standard and corresponding reading of VTT CPS.

Calibration results (Figure 7 and Figure 8) show that both sensors have similar characteristics with respect to linearity, repeatability, accuracy, and temperature sensitivity. Both sensors exhibit a slight drop in sensitivity at lower pressure values of around 10 MPa. This is typical for dynamic pressure sensors, and consequently sensitivity values are often stated for different ranges separately. Also, the repeatability is similar and within  $\pm 0.5\%$  of reading. The temperature sensitivity was about  $1\%/(100\text{ }^\circ\text{C})$  for both sensors. This value corresponds well with the manufacturer specifications stating a temperature sensitivity of less than  $\pm 0.02\%/^\circ\text{C}$ . Moreover, the temperature

sensitivity was found to be similar for different pressures.

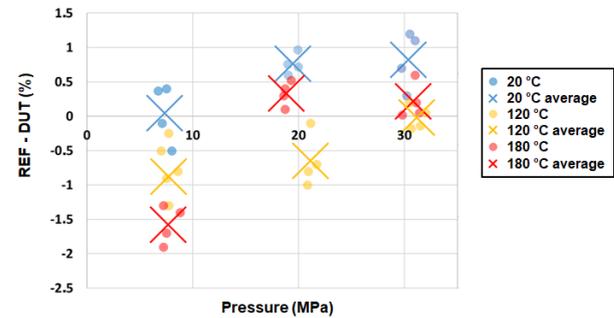


Figure 7: Calibration results for VTT CPS.

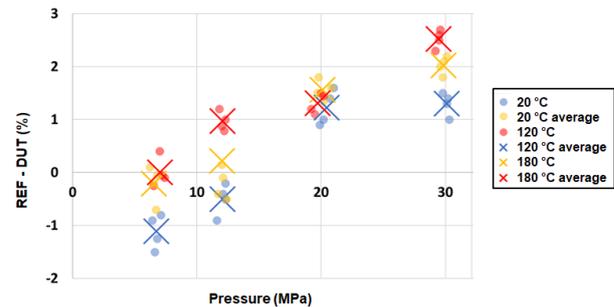


Figure 8: Calibration results for a commercial sensor.

One of the key features of the VTT CPS is that it can be calibrated at static pressures, unlike commercial piezoelectric sensors that only sense pressure changes. To investigate the validity of such a calibration, a static calibration with a pressure balance was performed and the results were compared to a dynamic calibration performed with the VTT MIKES dynamic pressure primary standard. The results of the static and dynamic calibration were found to agree within 0.4 % (Figure 9), which is well within the 1.5 % measurement uncertainty of the dynamic calibration. The results indicate that an initial adjustment and linearisation of the VTT CPS can be made using static calibration methods. This implies significant cost savings, as existing (static) pressure calibration equipment can be used. However, it is important to note that a static calibration will not provide SI traceability for a sensor used for dynamic measurements. To fully characterise sensor performance and ensure reliability of measurements, dynamic pressure sensors need to be calibrated against dynamic measurement standards.

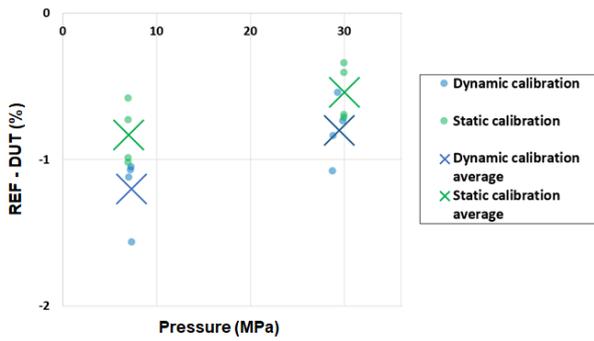


Figure 9: Comparison of static and dynamic calibration results of VTT CPS.

### 3.4. Engine tests

Cylinder pressure sensors are exposed to extremely harsh conditions, where cyclic pressure and temperature changes take place, as well as strong vibrations from the engine. To validate sensor performance and reliability in real operating environments engine tests are necessary. Engine tests were performed in a 4-stroke Wärtsilä marine engine (Vasa 4R32 LN DF) operated in diesel mode using light fuel oil (Figure 10). The performance of the VTT CPS was compared against Kistler piezoelectric sensors (type 7013Q03, Quartz Pressure Sensor for Engine Diagnostics). The Kistler sensors have been factory calibrated by the manufacturer. Before testing, the sensors have been in engine use only for 364 run hours, i.e., the sensors can be considered as “new” and in good operational condition.



Figure 10: Marine test engine. VTT CPS (D1) and Kistler sensors (K1 and K2) were mounted in the cylinder head of separate cylinders.

Sensors were mounted into the cylinder head using shoulder sealing in order to locate the sensors as close to the combustion chamber as possible, and thus minimize potential disturbances caused by the connecting volume. The sensors were installed into different cylinders due to limited space for mounting. Before engine tests, a static calibration was performed for the VTT CPS to adjust the sensor output (results shown in Figure 11).

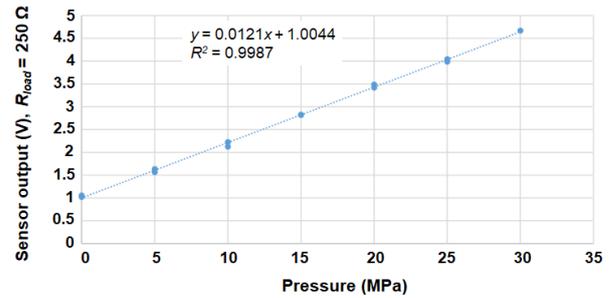


Figure 11: Linearisation of the VTT CPS output based on a static calibration.

### 3.5. Engine test results

Engine tests were performed at engine loads of 90 %, 75 %, 50 %, 25 % and 17 %. Each test run lasted for 3.5 hours. The shape of the pressure pulses measured by different sensors was similar at all loading conditions with only small differences in peak pressure values of about  $\pm 2\%$ . As an example, results at 90 % engine load are shown in Figure 12 and a close-up of peak pressures correspondingly in Figure 13. The observed deviations in peak pressure readings are similar to cylinder-to-cylinder pressure variations of this type of engine.

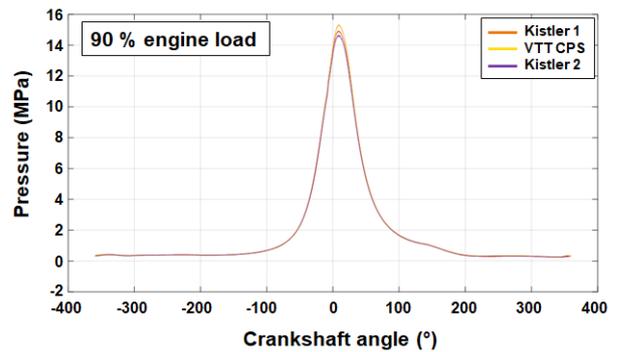


Figure 12: Cylinder pressure at 90 % load averaged over 99 cycles for VTT CPS and Kistler sensors (K1 and K2) as a function of crankshaft rotation angle.

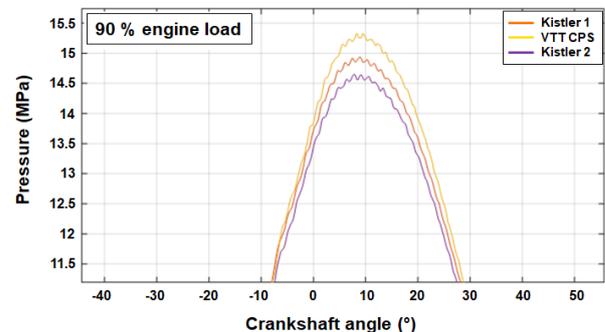


Figure 13: Peak pressure at 90 % load averaged over 99 cycles for VTT CPS and Kistler sensors (K1 and K2) as a function of crankshaft rotation angle.

Results of engine tests are summarised in Table 4.

Table 4: Summary of engine test results.

Engine load	Peak pressure (MPa)		
	Kistler 1	Kistler 2	VTT CPS
90 %	14.9	14.7	15.3
75 %	13.4	13.1	13.7
50 %	10.5	10.3	10.4
25 %	6.6	6.5	6.5
17 %	5.1	5.1	4.8

Moreover, no drift in sensor response was observed during engine testing (Figure 14). Slightly higher scattering of the VTT CPS results is caused by the electronics limiting the resolution of the sensor.

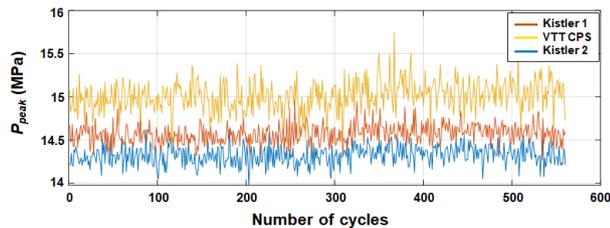


Figure 14: Peak pressures at 90 % engine load during a 3.5-hour test run.

### 3.6. Conclusion and future prospects

Validation results show that the VTT sensor performance is comparable to a state-of-the-art piezoelectric sensor, with respect to accuracy, repeatability, linearity, and temperature sensitivity. The operation of the VTT sensor was successfully demonstrated in real engine environment. An agreement of  $\pm 2\%$  was achieved when compared to VTT MIKES primary standard and when comparing against a piezoelectric sensor, which is considered an industry standard. Moreover, it was shown that a static calibration provides similar results as a dynamic calibration for the VTT sensor. Consequently, an initial adjustment and linearisation of the sensor output can be performed using existing (static) pressure standards, which gives VTT technology a significant cost advantage compared to commercial piezoelectric sensors, which need to be calibrated by means of dynamic methods. In conclusion, test results for the VTT CPS are very encouraging and indicate that the developed technology has great potential of

providing reliable and accurate on-line monitoring of engine performance in the most extreme case of large marine engines. Further long-term engine testing is needed to verify that the lifetime requirement of the sensor is fulfilled.

## 4. SUMMARY

To improve the reliability and accuracy of cylinder pressure measurements, VTT has developed a dynamic pressure calibrator to enable cost-effective and SI traceable calibrations of dynamic pressure sensors at conditions that resemble actual use. Moreover, a novel sensor for dynamic pressure measurements at harsh conditions have been developed and validated in real engine environments. VTT is now offering these new technologies to customers interesting in improving their dynamic pressure measurements.

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