EUROPEAN PARTNERSHIP Co-funded by the European Union METROLOGY PARTNERSHIP EURAMET

MaritimeMET

Metrology for Green Maritime Shipping:
Emission control through traceable measurements and machine learning approaches

MaritimeMET Workshop: Role of Metrology for Greener Shipping

Date: 16th April 2026

Venue: Wärtsilä Sustainable Technology Hub, Vaasa Finland (it is also possible to attend online)

VTT

Dynamic pressure primary standards for calibrating cylinder pressure sensors

Dr. Richard Högström, VTT MIKES, Finland
Dr. Yasin Durgut, TUBITAK-UME, Turkey

22/04/2026 **VTT – beyond the obvious**

WHY MEASURE CYLINDER PRESSURE?

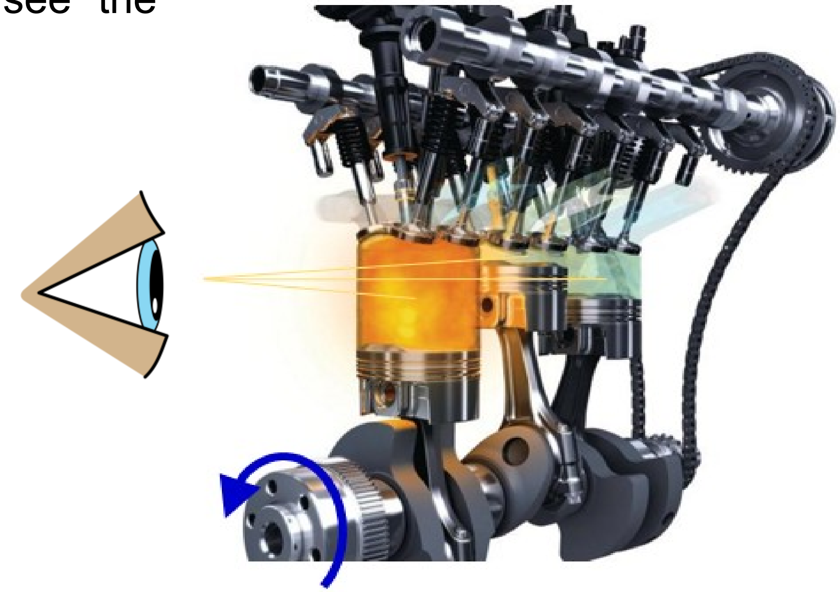
Imagine adjusting your process blindly – without ”seeing” what has changed when adjusting essential parameters

BENEFIT OF PRESSURE MEASUREMENTS?

- Pressure measurement is the ONLY way to ”see” the combustion process!

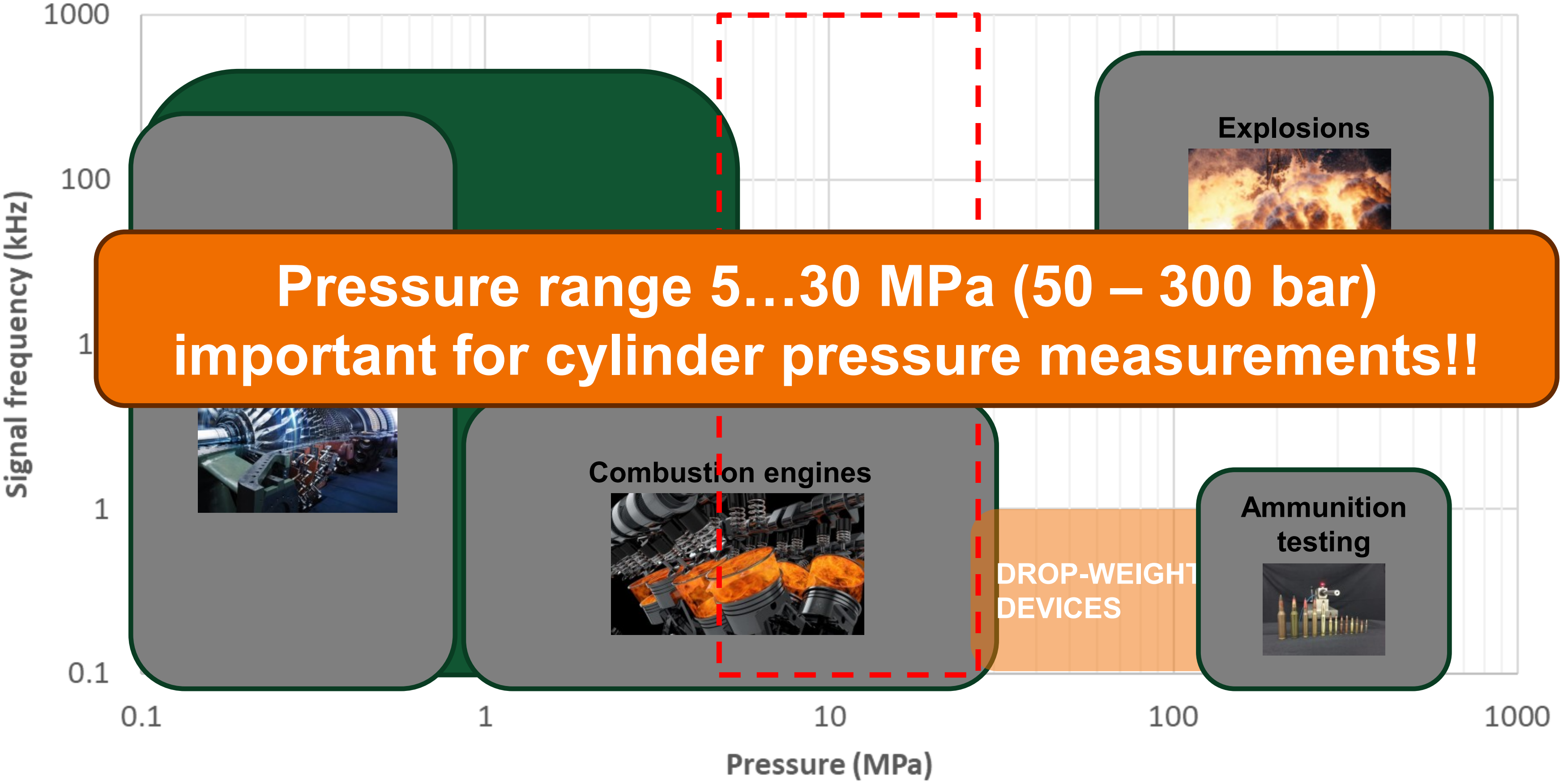
- Pressure data is used for:
  - Friction analysis
  - Combustion stability
  - Cylinder balancing
  - Irregular combustion and knocking
  - Combustion noise
  - Gas exchange analysis

→ **opimised engine performance!**



THE CHALLENGE

Primary method missing!



Pressure range 5…30 MPa (50 – 300 bar) important for cylinder pressure measurements!!

TÜBİTAK UME

Dr. Yasin DURGUT
Head of Pressure

Dropping mass system principle

INTERFEROMETRIC METHOD

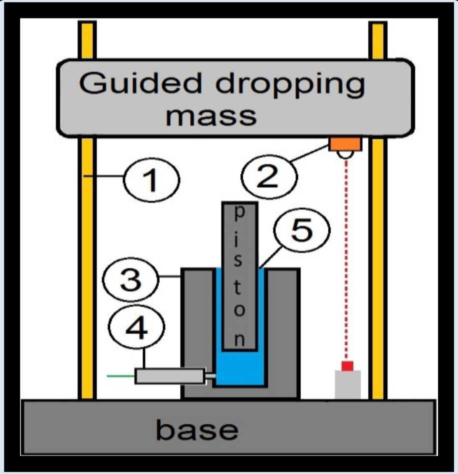
Acceleration of drop-mass

↓

pressure

↓

$$P = \frac{F}{A} = \frac{ma}{A}$$

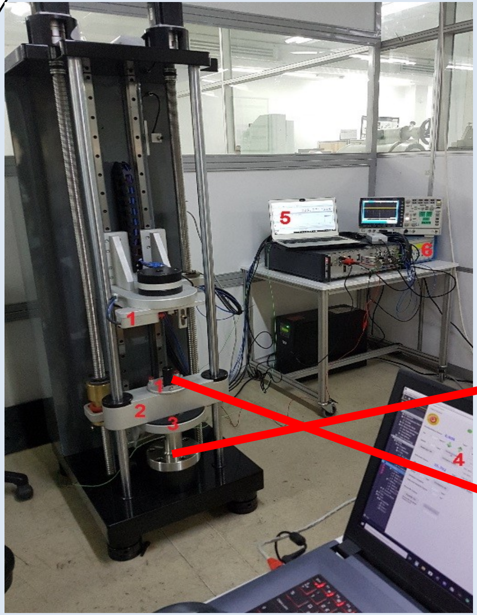


Measuring head and working principle

1-Guiding rods
2-Laser interferometer
3-Piston-cylinder
4-Sensor under calibratrion
5-Pressure transmitting liquid

Working pressure range : 0.5 MPa to 50 MPa
Expanded uncertainty : Around 1%
Working media : Liquid
Impact signal shape : Half-sine with (3-5) ms width

Dropping mass system principle



1-Laser head and laser retroreflector

2-Dropping mass

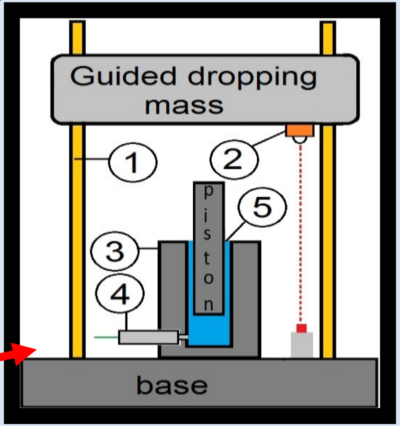
3-Measuring head

4-Controlling software for developed dynamic pressure sysem

5-Controlling system for laser interferometer

6-Amplifier for dynamic test sensors

Developed dynamic pressure calibration system



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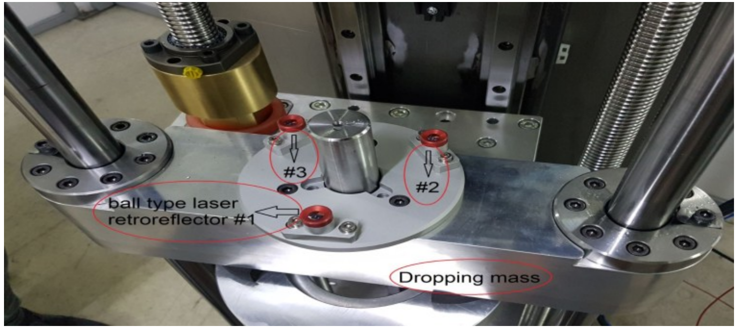
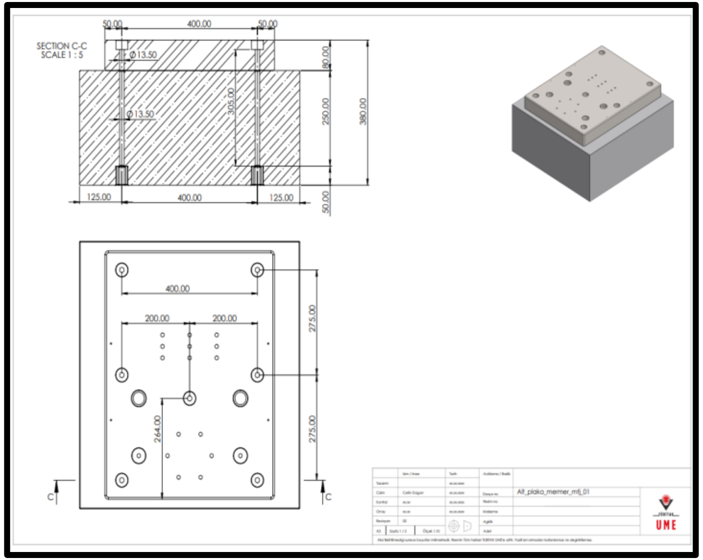
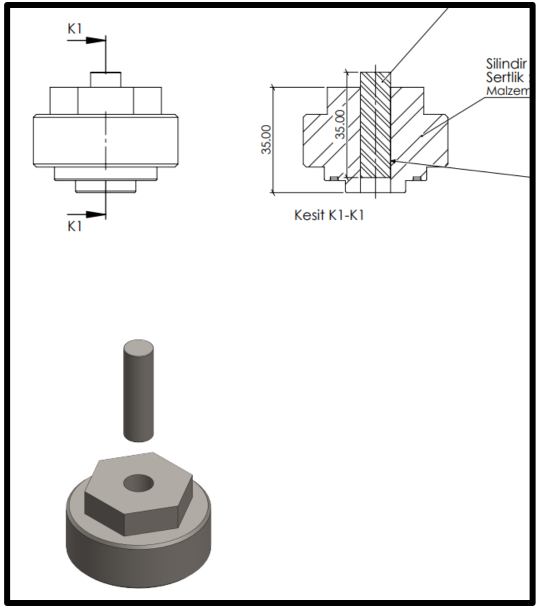


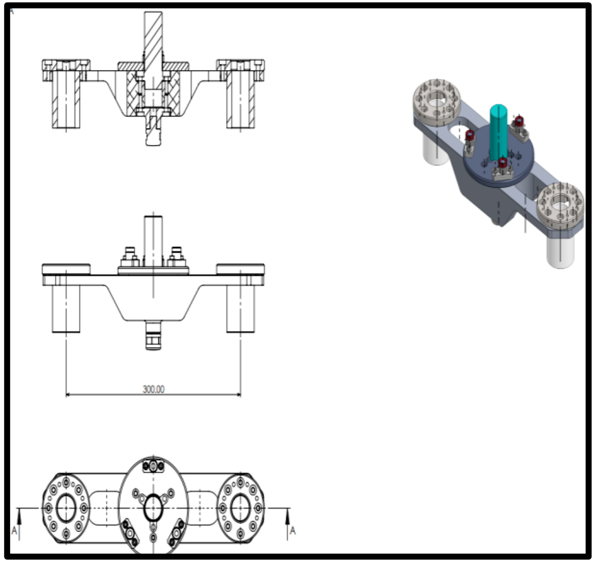
Developments in the dropping mass system



Improvements in Base Plate



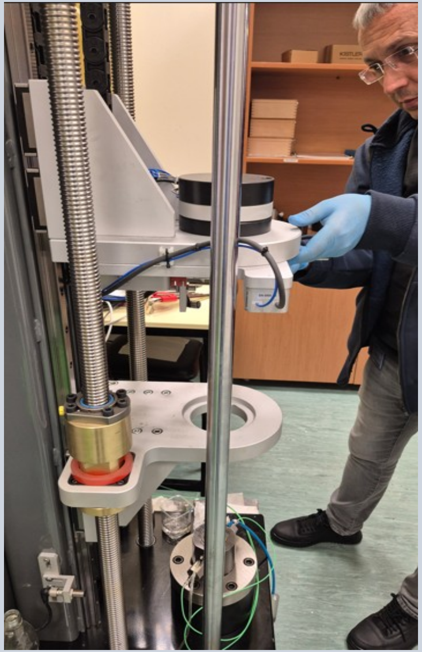
Improvements in Piston-Cylinder Tolerences



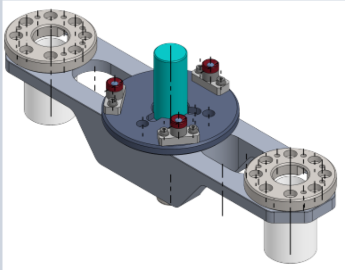
Improvements in Dropping Mass

Developments in the dropping mass system

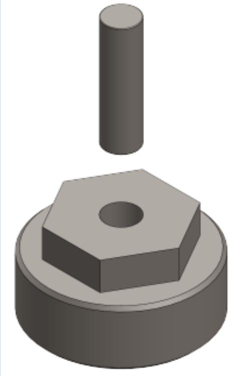
Impact mass dynamic pressure system was revised to improve the accuracy and reliability in the pressure range between 5 MPa and 50 MPa to enable in-cylinder pressure sensor calibrations with signal rise times in the millisecond range at an uncertainty level of 1 %.



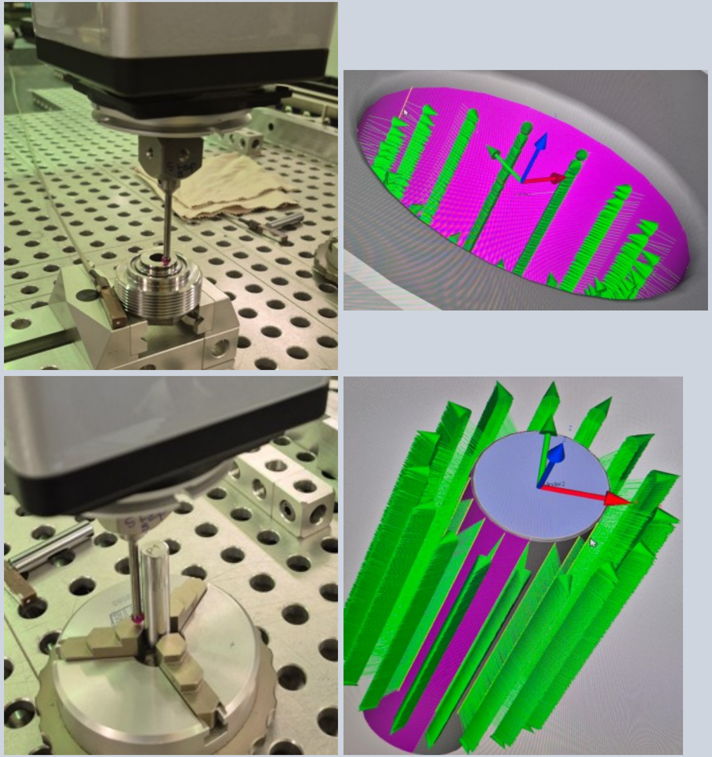
Impact mass dynamic pressure system



2 kg dropping mass with laser reflectors

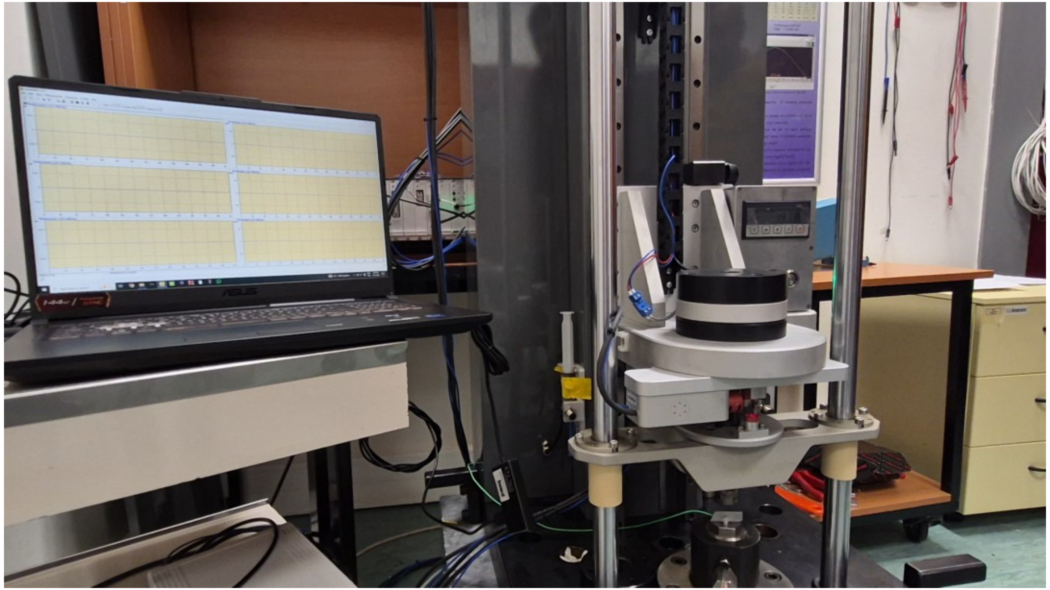


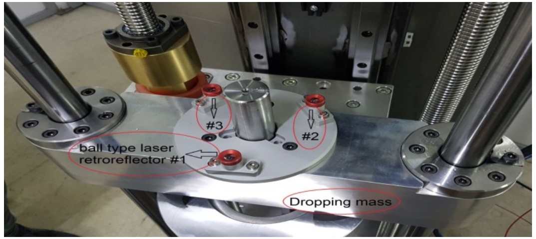
10 mm diameter Piston-cylinder unit design with lower tolerences



Dimensional measurements of the Piston-cylinder unit

Developments in the dropping mass system



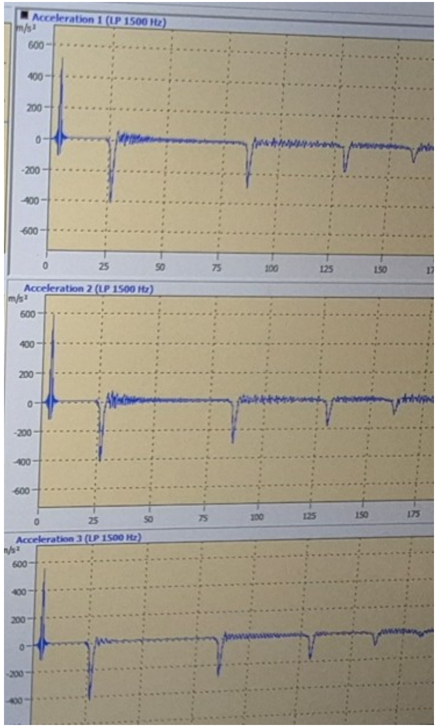


$$p = \frac{F}{A}$$

Where; p:pressure [Pa], F:Force [N], A:Area [m^2]

$$p \cong \frac{[m_{total} \cdot (m_{a,maximum} + g)]}{A}$$

Where; m_{total}:Total mass [kg], $m_{a,maximum}$: Acceleration value from 3 different beams [m·s^{-2}], g:Local gravity [[m·s^{-2}], A:Area [m^2]



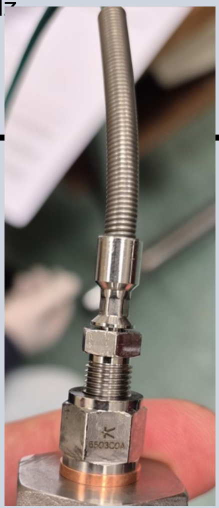
Acceleration signal from three different laser channels

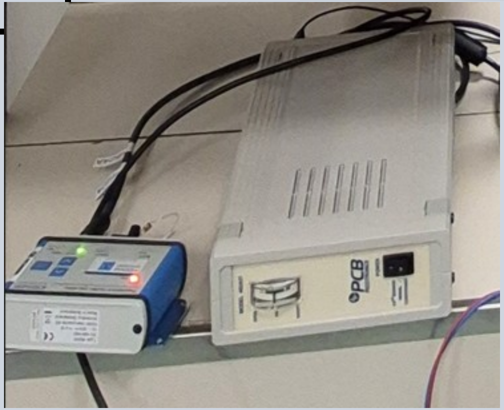
Calibration results

Reference system	Pressure medium	Pressure range (MPa)	Calibration points (MPa)	Frequency range (kHz)	Ambient temperature °C
Impact mass	Glycerol	5 – 30	6, 12, 18, 24, 30	< 1	20 ± 1

1st sensor
Piezoresistive system (sensor and amplifier)
Sensor
Manufacturer: Kistler
Model: 4065B
Pressure range: 0 MPa – 50 MPa (gauge)
Natural frequency: > 40 kHz
Amplifier
Manufacturer: Kistler
Model: 4624A

2nd sensor
Piezoelectric system (sensor and signal conditioner) Sensor
Manufacturer: PCB
Model: M102B
Pressure range: 0 MPa – 34.5 MPa (gauge)
Natural frequency: >= 500 kHz
Signal conditioner
Manufacturer: PCB
Model: 482A21





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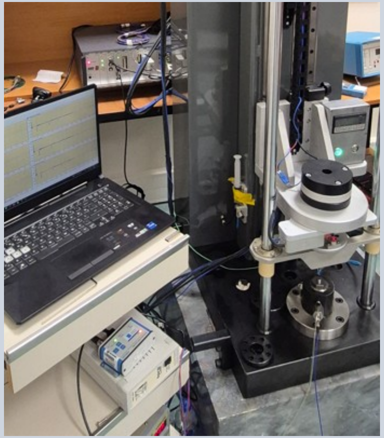
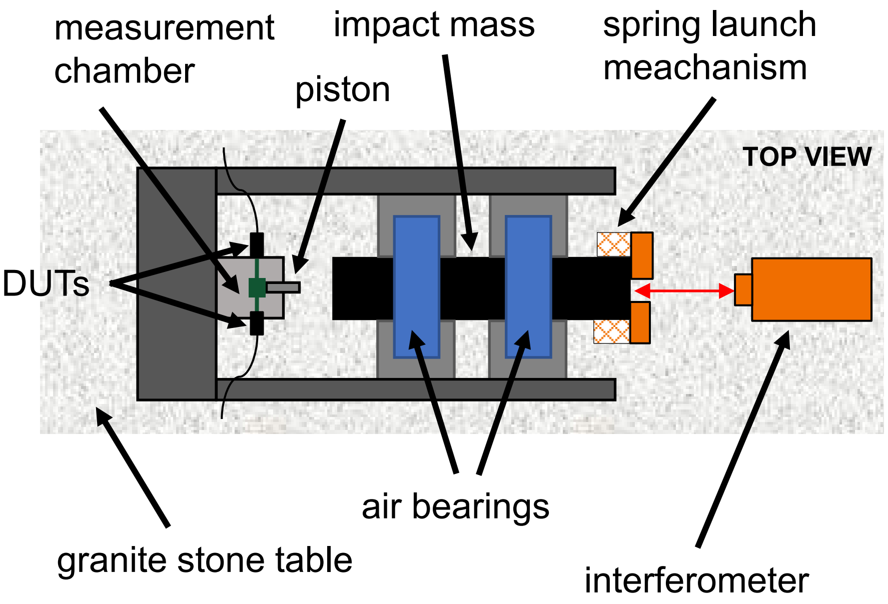


Nominal Basınç (bar)	Output signal/V (single shot)	Sensitivty/(mV/kPa) (average of 5 shots)
60	1,172606	0,1918489
60	1,248951	
60	1,181489	
60	1,202888	
60	1,287250	
120	2,392454	0,1979868
120	2,367871	
120	2,490469	
120	2,476139	
120	2,383574	
180	3,436067	0,1994350
180	3,411242	
180	3,385067	
180	3,424272	
180	3,324128	
240	4,632242	0,2000469
240	4,733309	
240	4,715298	
240	4,690983	
240	4,661371	
300	5,965691	0,1985340
300	5,867927	
300	6,009807	
300	5,845437	
300	5,893601	

Nominal Basınç (bar)	Output signal/V (single shot)	Sensitivty/(mV/kPa) (average of 5 shots)
60	0,937071	0,1471138
60	0,948911	
60	0,953656	
60	0,933885	
60	1,023503	
120	1,810988	0,1454552
120	1,668344	
120	1,845142	
120	1,852876	
120	1,846642	
180	2,710895	0,1457556
180	2,753758	
180	2,738370	
180	2,716400	
180	2,713403	
240	3,415344	0,1454417
240	3,466035	
240	3,491754	
240	3,493300	
240	3,499931	
300	4,453566	0,1459886
300	4,455621	
300	4,705504	
300	4,548935	
300	4,275962	

VTT MIKES novel primary dynamic pressure standard

Horizontal impact device



- Novel design:
  - Horizontal configuration with spring launch mechanism
    -> easier to generate low impact velocities
    -> good control of generated pressure
  - Smaller impact mass (21 kg -> 4 kg)
    -> smaller impact force (smaller generated pressure)
  - Smaller piston diameter (10 mm -> 6 mm)
    -> to minimize frictional forces
    -> optimize pulse length for large bore maritime engines
  - Air bearings for guiding the impact mass
    -> practically frictionless motion
    -> less vibrations and tilt -> better laser signal quality

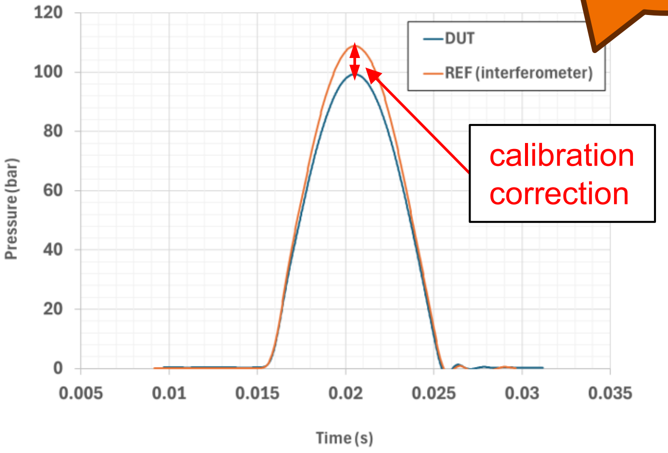
Primary standard for calibrating cylinder pressure sensors

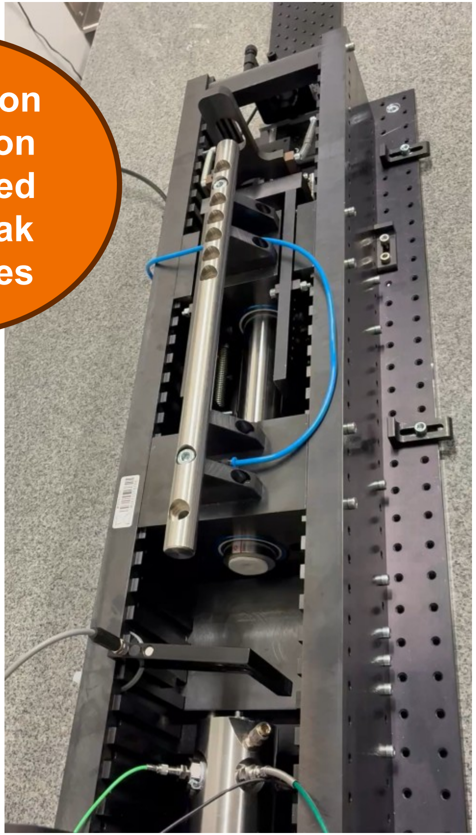
$$p = \frac{F}{A} = \frac{m \cdot a}{A}$$

m = mass of the impact mass
a = acceleration of impact mass
A = piston area

Traceability to SI is established through interferometric measurement of the acceleration of the impact mass

Calibration correction calculated from peak pressures





Uncertainty estimation

Uncertainty component	Contribution to overall uncertainty
Acceleration	???
Piston mechanical friction	???
Deformation of impact mass	0.02 %
Deformation of piston	< 0.01 %
Effective area of the PCU	0.11 %
Piston friction of eccentric impact	0.05 %
Mass of impact mass and piston	< 0.01 %
Experimental deviation	???

Vibration noise in the acceleration signal

Piston friction becomes relevant at small impact forces (low pressures)

Type B uncertainties with minimal contribution

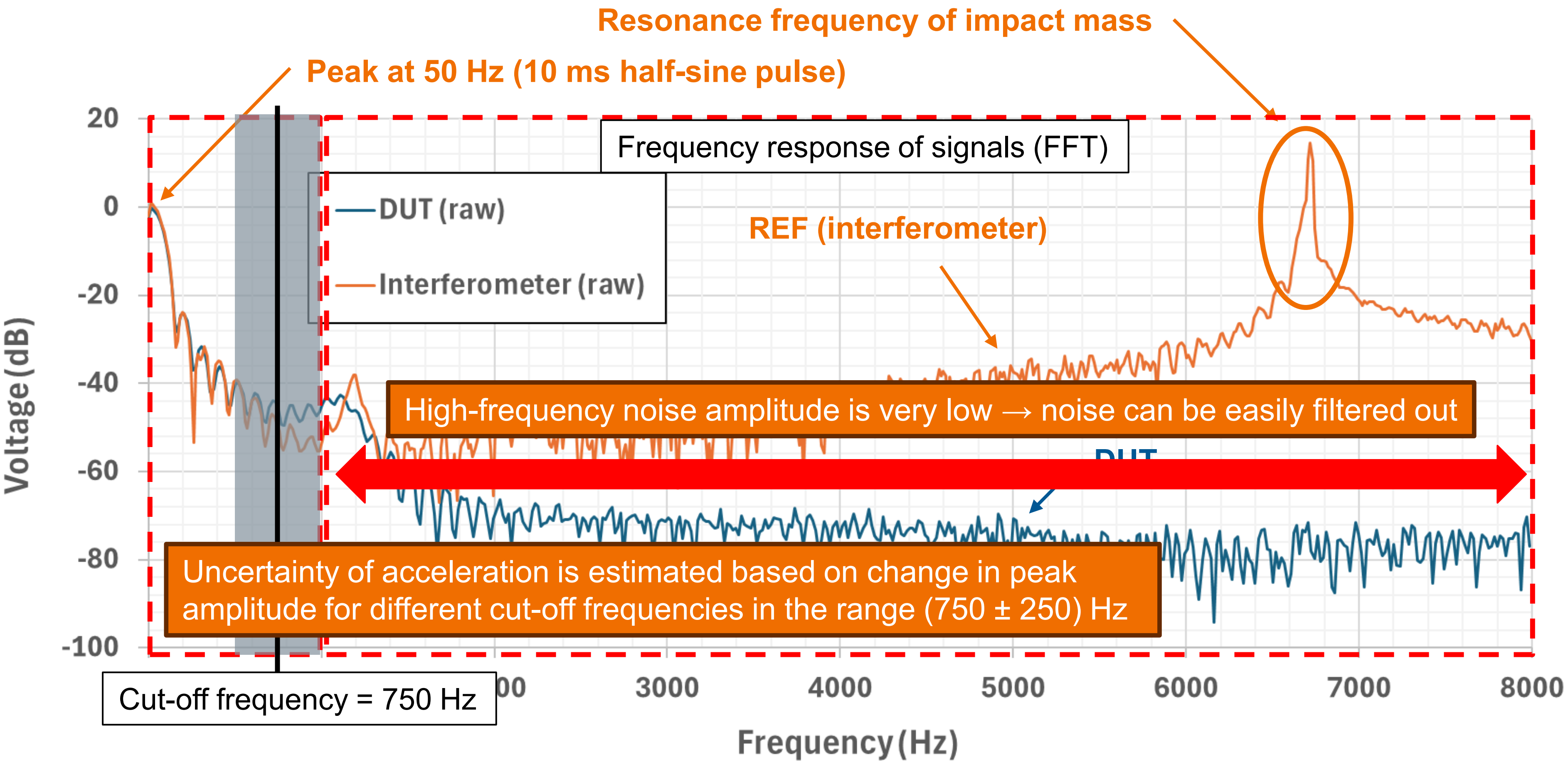
Type A uncertainty from test calibration

ELSEVIER
Measurement: Sensors
Volume 38, Supplement, May 2025, 101686

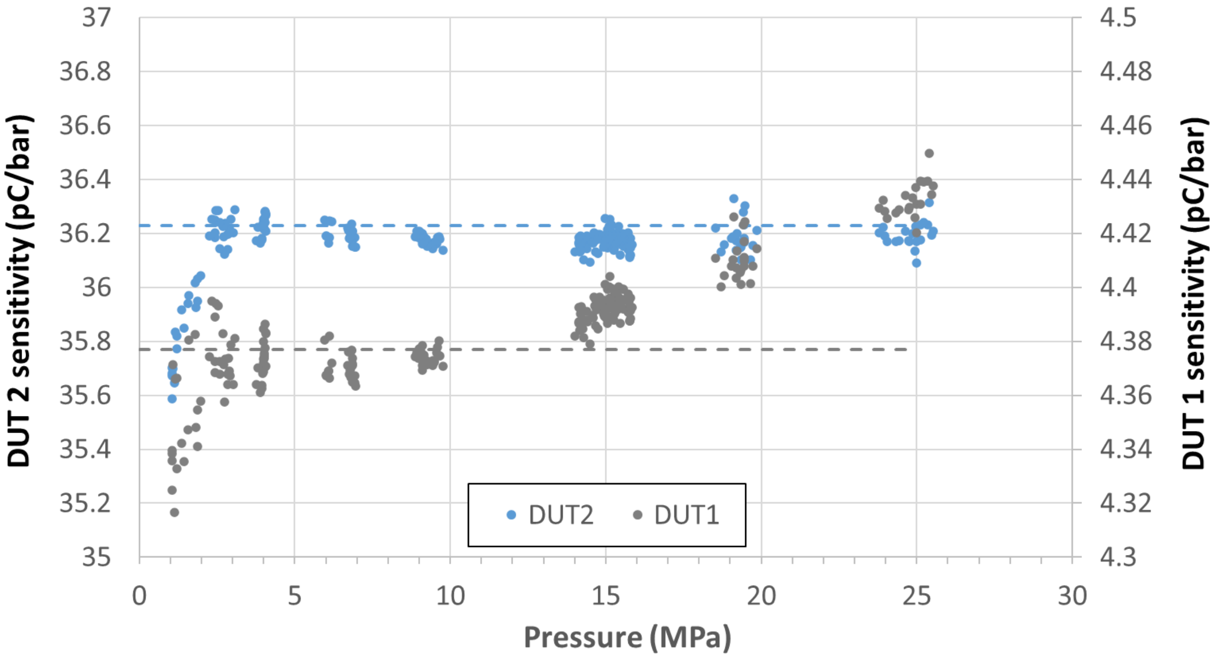
Novel primary standard for dynamic pressure up to 500 MPa

Richard Högström [a], Antti Lakka [a], Jussi Hämäläinen [a], Leevi Salonen [a], Adam Brzozowski [b]

Uncertainty of acceleration

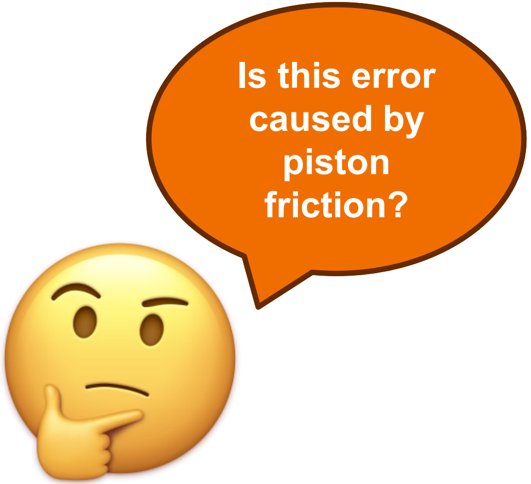


Test calibration

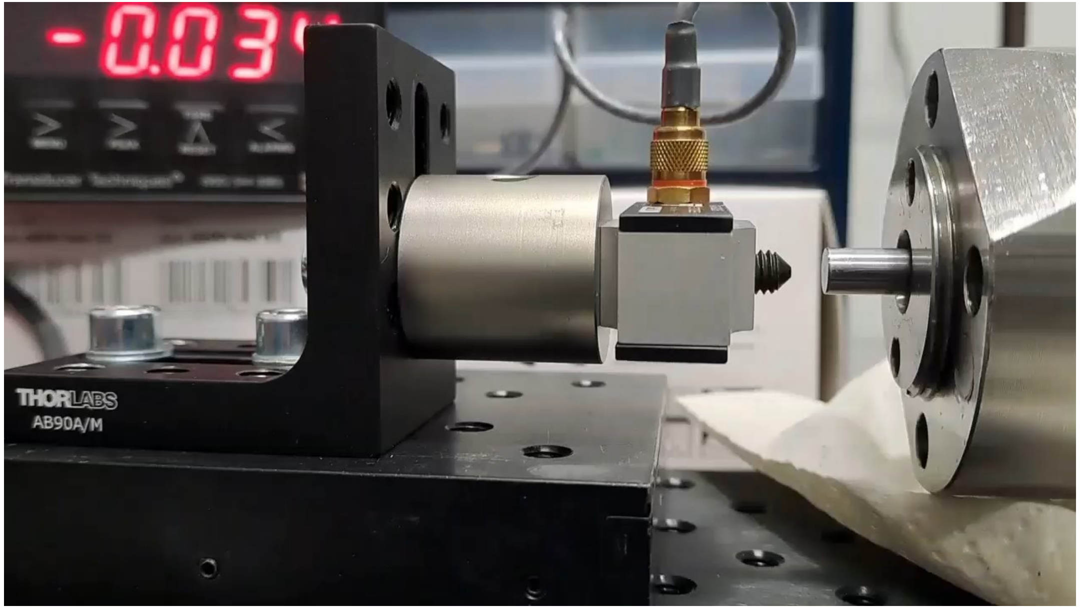


Manufacturer sensitivity shown as dashed lines

- Two piezoelectric sensors:
  - **DUT 2:** new sensor
  - **DUT 1:** old sensor



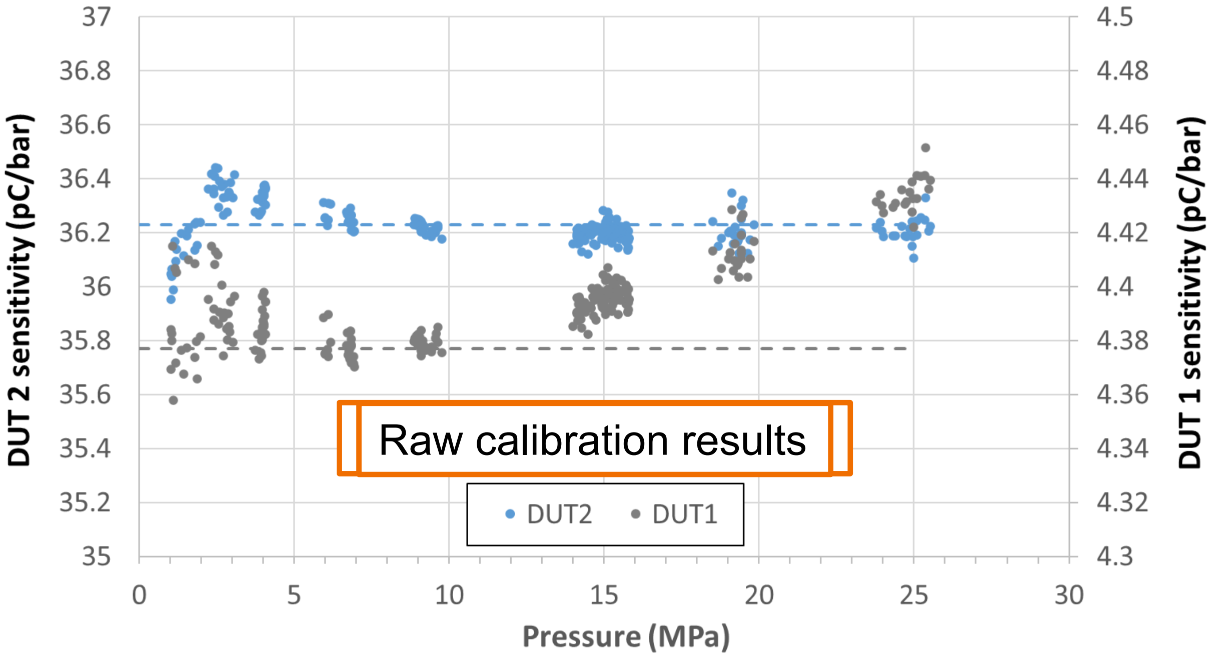
Uncertainty due to friction of piston



- Average frictional force:
  - static friction: ~0.4 N
  - kinetic friction: ~0.3 N
- Kinetic friction is assumed to prevail during dynamic impact event

Friction correction of (0.3 ± 0.1) N was applied

Test calibration



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- Two piezoelectric sensors:
  - **DUT 2:** new sensor
  - **DUT 1:** old sensor

Calibrated sensitivity of the new sensor (DUT 2) was within 0.1 % of manufacturer sensitivity!

Uncertainty budget

Table. Uncertainty budget at 2 MPa

Uncertainty component	**Contribution to overall uncertainty**
Acceleration	0.17 %
Piston mechanical friction	0.18 %
Deformation of impact mass	0.02 %
Deformation of piston	< 0.01 %
Effective area of the PCU	0.11 %
Piston friction of eccentric impact	0.05 %
Mass of impact mass and piston	< 0.01 %
Experimental deviation	0.21 %
combined standard uncertainty	0.35 %
expanded uncertainty (*k* = 2)	**0.70 %**

In the pressure range 5…30 MPa uncertainties (*k* = 2) as low as 0.5 % is achieved!

Conclusions

- New and improved primary standards based on impact mass method have been developed to realise SI traceable calibrations of cylinder pressure sensors
- Based on validation studies an overall uncertainty of less than **1 %** (k = 2) is achieved, which fulfills the strict requirements in engine applications
- Next, the validity of results and equivalence to other primary standards will be studied in an intercomparison within the MaritimeMet project

Thank you for your attention!