Protocol for pilot study - Comparison of dynamic pressure measurements

EURAMET project 1601

Summary

Traceable dynamic pressure calibration is presently lacking globally, no internationally accepted calibration methods (CMCs) exist for dynamic pressure. Due to this lack of traceable dynamic calibration, dynamic pressure measurement systems are currently calibrated using static or quasi-static methods, reporting sensitivity only with respect to pressure. Quasi-static approaches assume that the pressure measurement system responds in the same way for time-varying pressures as for static pressures, resulting in large uncertainties for the end users.

In this study, the shock tubes developed at RISE and PTB will be validated by an inter-laboratory comparison using two transfer standards. The shock tube can generate step pressure at the end-wall plate of the driven section where the device under test is flush mounted. The generated reference step pressure is assumed to have the shape of a Heaviside step function. The amplitude of the step pressure can be calculated from the shock tube model by measuring the speed of the generated shock wave and the initial parameters of the pressure medium (its initial pressure, initial temperature and the specific heat ratio). In this case, the shock tube is considered as a primary standard. On the other hand, one can consider a shock tube as a generator of repeatable reference pressure steps and calculate its amplitude by other primary methods, such as absorption spectroscopy. RISE will use the shock tube as a primary standard (using the shock tube theory to calculate the pressure amplitude). On the other hand, PTB will use the shock tube as a practical device to generate the dynamic pressure and use the absorption spectroscopy method to assess the pressure. This comparison will pave the road to apply for the first CMCs in dynamic pressure calibration.

Pressure range: 100 kPa – 400 kPa

Frequency range: 0.5 kHz – 100 kHz

The report will be written by PTB and agreed with RISE to get approved by the EURAMET TC-M sub-committee: Pressure.

Participants

The Pilot study has two participating laboratories. Contact details for the responsible person at the respective laboratory are listed below.

RISE Research Institutes of Sweden AB (RISE)
Eynas Amer
Phone: +46 105-166280
E-mail: eynas.amer@ri.se
RISE
P.O. Box 857
SE-501 15 Borås
SWEDEN

Physikalisch-Technische Bundesanstalt (PTB) - pilot laboratory
Zhechao Qu
Phone: +49 531 592 3112
E-mail: zhechao.qu@ptb.de
PTB
Bundesallee 100
38116 Braunschweig
GERMANY

Purpose and scope

This pilot study between Physikalisch-Technische Bundesanstalt (PTB) and RISE Research Institutes of Sweden AB (RISE) will provide a comparison of standards and capabilities for the measurement of dynamic pressure in Shock Tube (ST). The participants will characterize dynamic pressure measurement systems using their facilities in terms of frequency-dependent sensitivity and phase at nominal pressure levels. The PTB will use the ST as a practical device to generate the dynamic pressure and traceable optical spectroscopy techniques to determine the absolute dynamic pressures, and RISE will use ST as a primary method. The conformity of the two methods will be confirmed by this comparison and diversify standards for validating dynamic pressure sensors.

The study will be registered as a comparison pilot study in the EURAMET project database.

Measurand, quantities and units

The measurand is the gas phase dynamic pressure, with measurement results expressed in Pa and s (or any of their multiples, e.g., kPa and ms). The measurements will be compared by exchanging the two sensors from RISE and PTB. The generalized frequency-dependent response of the sensors can be determined through the response of a sensor to the dynamic pressure in the system. The sensor response is defined in terms of sensitivity and phase as a function of frequency where sensitivity is expressed in, e.g., mV/kPa, phase in radian, and frequency in kHz.

Laboratory standards (Reference method and equipment)

Both laboratories use shock tubes as signal generators (pressure step generators). As the primary method, RISE uses shock tube theory to determine the pressure step, including amplitude and phase, while PTB uses the spectroscopic method. The two different standards are described below.

RISE

Reference equipment at RISE comprises the shock tube described in recent publications [1, 2]. The shock-tube generates pressure steps with amplitudes between 0.1 MPa and 25 MPa. The working range in frequency is limited to the range between 0.5 kHz and 500 kHz. In this study, Argon will be used as a pressure medium.

The pressure steps are near ideal Heaviside steps with analogous pressure distribution in the frequency domain. The shock tube theory employs the Rankine-Hugoinot step relations to evaluate pressure step amplitude with the knowledge of the Mach number of the incoming shock front and the initial static pressure of the driven gas, a detailed description of the model can be found in references [1, 2]. The validity of the method is determined by comparisons like the present. Traceable measurement of the latency of dynamic pressure measurement systems described in [2] will be applied for phase calculation. Traceability to the SI is obtained through traceable measurements of the model input parameters.

PTB

PTB high-pressure shock tube [3] consists of a 3.5-meter driver section and a 4.5-meter driven section with an overall inner diameter of 7 cm. Five pressure sensors (603CAB, Kistler) are utilized for pressure measurements. For the laser spectroscopy measurements, two CaF2 windows are installed in the same plane as the fourth side wall pressure sensor. The CO laser beam passes through the optical windows with a path length of 7 cm via two concave mirrors and is focused onto a photodetector. A narrow bandpass filter is placed before the detector to discriminate the signal against the background emission.

Laser absorption spectroscopy will be used as the reference method for measuring dynamic pressure. This relies on the same traceability principle of the Optical Gas Standard proposed by PTB [4], i.e. using the unique quantum mechanical characteristics of the molecules as the reference value.

Transfer standards

Two transfer standards will be used, one provided by each participating laboratory, TS1 by RISE and TS2 by PTB. The standards are described below:

Transfer standard 1 (TS1)

Piezoresistive sensor and amplifier

<u>Sensor</u>

Manufacturer: Kistler
Model: 4017A
Pressure range: 0 – 0.5 MPa (absolute)
Natural frequency: > 7 kHz
<u>Amplifier</u>

Manufacturer: Kistler
Model: 4624A

Transfer standard 2 (TS2)

Piezoresistive sensor and amplifier

<u>Sensor</u>

Manufacturer: Kistler Group
Model: PiezoStar® Pressure Sensor Type 603CAB
Pressure range: 0 – 1 MPa
Natural frequency: > 500 kHz

<u>Amplifier</u>

Manufacturer: Kistler
Model: 5018A1000

Preparation of transfer standards

Preparation and handling of sensors are done according to manufacturer recommendations. Suitable adaptors for the respective sensors must be manufactured for each laboratory standard. Each laboratory is responsible for producing adaptors that fit their laboratory standard. Time will be allocated for this purpose after the reception of the other laboratory's transfer standard and before measurements are commenced. Each laboratory is also responsible for supplying the other laboratory with accessories and drawings needed for this purpose.

Transport of transfer standards

Transporting the transfer standards safely between the laboratories is the responsibility of the respective owner#, including costs. (# owner here is defined as the laboratory where the sensor is currently used for experiments)

Measurement schedule

The comparison is planned for 18 months, including finalizing the report and discussing results. PTB will organize the comparison study by following the tentative schedule below:

M1 – M3 First analysis of RISE sensor at RISE

M1 – M5 Coupling optical technique into PTB shock tube for absolute dynamic pressure studies

M4 Shipment of RISE sensor from RISE to PTB

M6 – M9 Analysis of both RISE and PTB sensors at PTB

M10 Shipment of RISE and PTB sensors from PTB to RISE

M11 – M12 Second analysis of RISE and PTB sensors at RISE

M13 RISE results submitted to PTB and vice versa,

M14 – M15 PTB to prepare draft A report, discussion on results with RISE

M16 – M18 Finalizing report and discussing results with TC-M SC Pressure and vacuum

Measurement

Pressure amplitude (differential pressure) ranges from 100 kPa to 400 kPa in steps 100, 200, 300, and 400 kPa.

Pressure medium: Argon (RISE) and 1% CO/79% Ar/20%He (PTB)

Five measurements will be taken at every nominal pressure level.

The ambient temperature is 23°C ± 2°C.

Each dataset should be collected with the same test gas on the same day.

Reporting of measurement results

The PTB is responsible for the preparation of the comparison report. The report shall include the following information where participants are to provide feedback:

- A detailed description of the facilities at RISE and PTB. Each participant will describe its facility.
- A description of the reference method used in both RISE and PTB. RISE will describe the shock tube theory, and PTB will describe the absorption spectroscopy method.
- Uncertainty evaluation: GUM-compliant uncertainty budget based on a model equation (influence quantities, distribution). Each participant will evaluate the uncertainty budget corresponding to its measurements and calculations.
- Information about sampling rate, filters used, A/D resolution, and similar information about signal conditioning and acquisition.
- PTB will send the following data to RISE:
    - The recorded pressure signals by TS1 and TS2 at different nominal pressure levels in the time domain. The calculated reference pressure amplitudes generated by the shock tube and calculated by absorption spectroscopy.
    - The calculated latency of TS1 and TS2.
- RISE will calculate the sensitivity and phase response of TS1 and TS2 as a function of frequency.

Evaluation of results

The results of the two participants will be evaluated with respect to the difference in the respective transfer standard response in terms of sensitivity and phase over the frequency range. This difference will be compared to the stated uncertainty, also over the frequency range.

Reference value: this study will consider mutual validation of shock tube theory and absorption spectroscopy for dynamic pressure measurement.

Final report

A final report based on the evaluation outcome will be prepared by PTB in collaboration with RISE after completion. This report will be published in a peer-reviewed journal like Metrologia.

How far the light shines statement

This comparison will not be linked to any key comparison due to the lack of such. This Pilot study aims to develop a method to conduct a key comparison in dynamic pressure and introduce the results and the uncertainties.

References

1. E. Amer, M. Wozniak, G. Jönsson and F. Arrhén, "Evaluation of Shock Tube Retrofitted with Fast-Opening Valve for Dynamic Pressure Calibration" *Sensors* 21(13) 4470 (2021).
2. E. Amer, G. Jönsson and F. Arrhén, “Toward traceable dynamic pressure calibration using a shock tube with an optical probe for accurate phase determination” *Metrologia*, 59 035001 (2022).
3. Zhu, D., Z. Qu, M. Li, S. Agarwal, R. Fernandes, and Bo Shu, "Investigation on the NO formation of ammonia oxidation in a shock tube applying tunable diode laser absorption spectroscopy." *Combustion and Flame* 246 112389 (2022).
4. Nwaboh, J. A., Z. Qu, O. Werhahn, and V. Ebert, "Interband cascade laser-based optical transfer standard for atmospheric carbon monoxide measurements." *Applied Optics* 56(11) (2017).