Towards traceable dynamic pressure calibration using shock tube method

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Contents

- Dynamic pressure.
- Development of the shock tube.
- Validation of the developed shock tube.
- Conclusion.

Dynamic (time-varying) pressure

Pressure signal varies significantly over time.

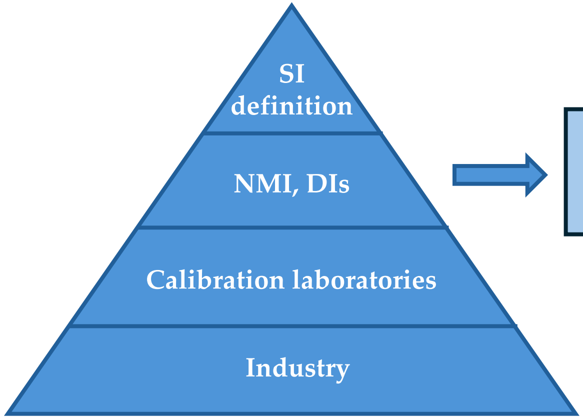
Some of the application areas:

Application	Pressure amplitude	Pressure frequency
Combustion engine	$10^2 – 10^4$ kPa	Up to tens of kHz
Pneumatic systems	$10 – 10^3$ kPa	Up to 1 kHz
Hydraulic systems	$10^2 – 10^4$ kPa	Up to 1 kHz
Gas turbines	Up to tens of MPa	Up to tens of kHz
Medical (blood pressure)	10 kPa – 100 kPa	~ 100 Hz
Blast waves	Tens of MPa	Hundreds of kHz
Ballistics industry	Hundreds of MPa	Hundreds of kHz

Dynamic calibration

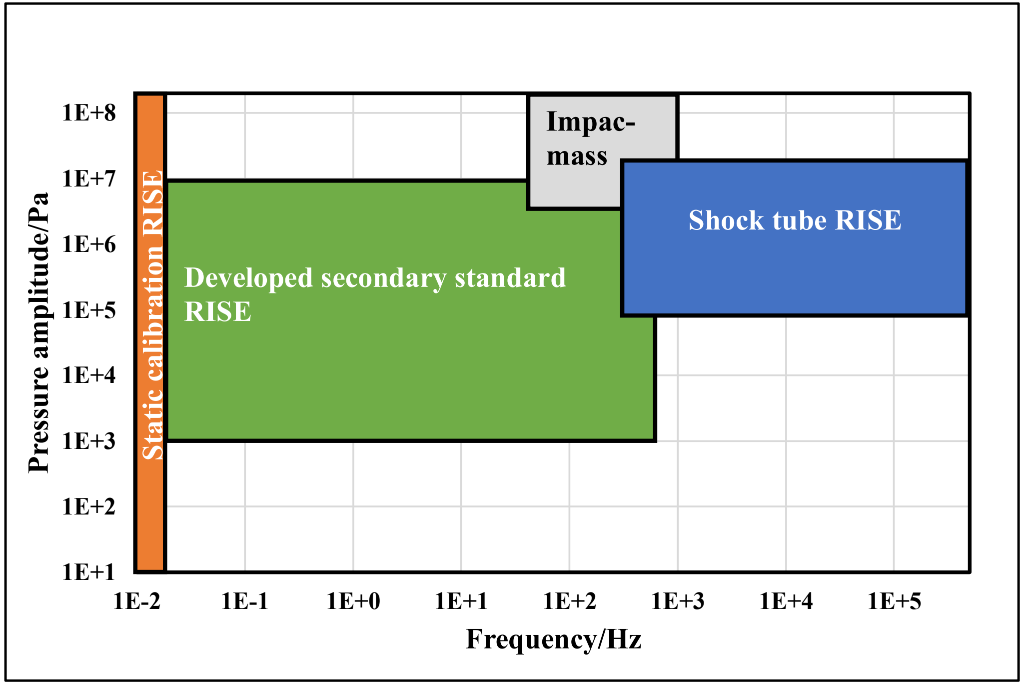
- Sensitivity (mV/kPa) versus frequency.
- Phase shift (radian) versus frequency.
- Resonant frequency.
- Rise time.
- Damping ratio.
- Overshoot.

Calibration chain



No internationally accepted method exists for dynamic pressure calibration.

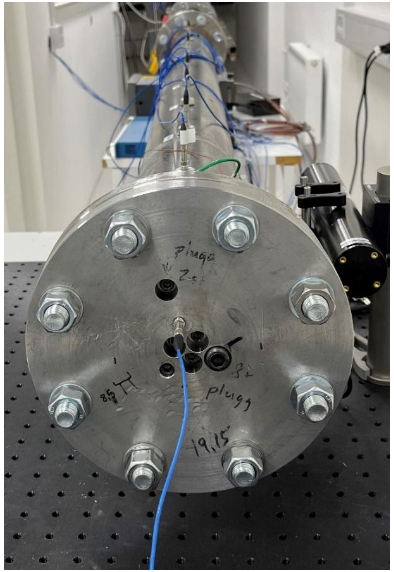
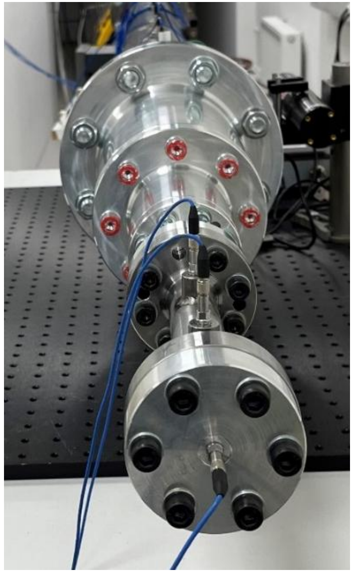
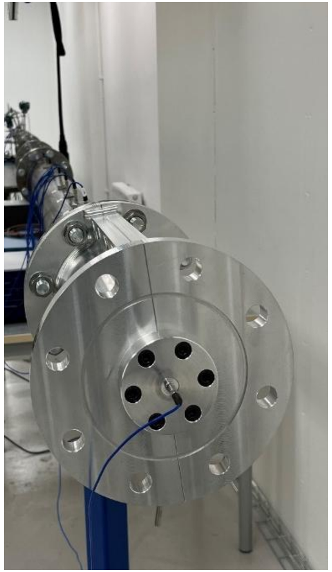
- Development of measurement methods and standards.
- Validation of the developed methods and standards.



Different pressure regimes covered by different standards.

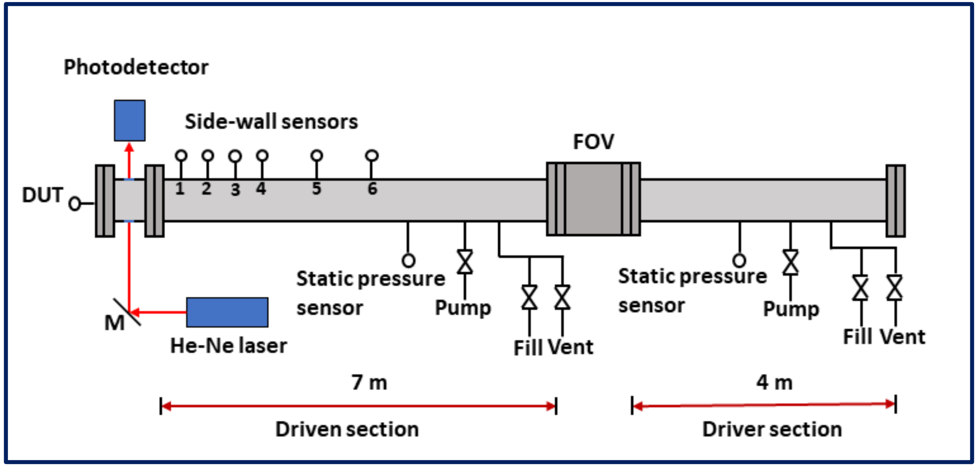
Shock tube development

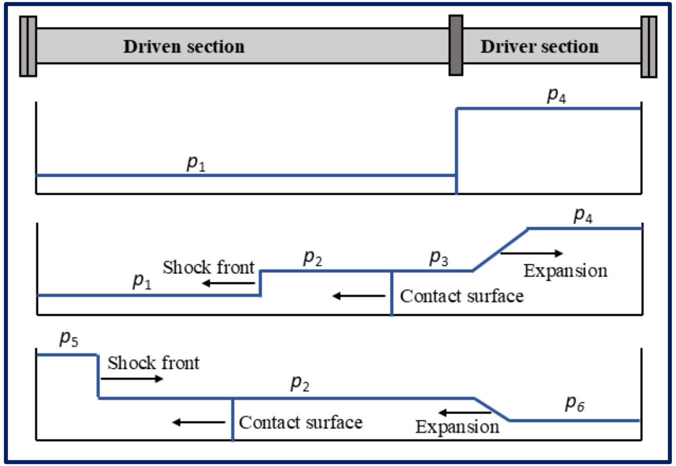
Shock tube at RISE

- Conventional: 0.1 MPa to 1.5 MPa.
- Amplification system: 1 MPa to 7 MPa.
- Converging cone: 5 MPa to 25 MPa.
- Frequency: < 0.5 kHz – 500 kHz.
- Expanded uncertainty in reference pressure ($k = 2$) < 2%.

Conventional configuration

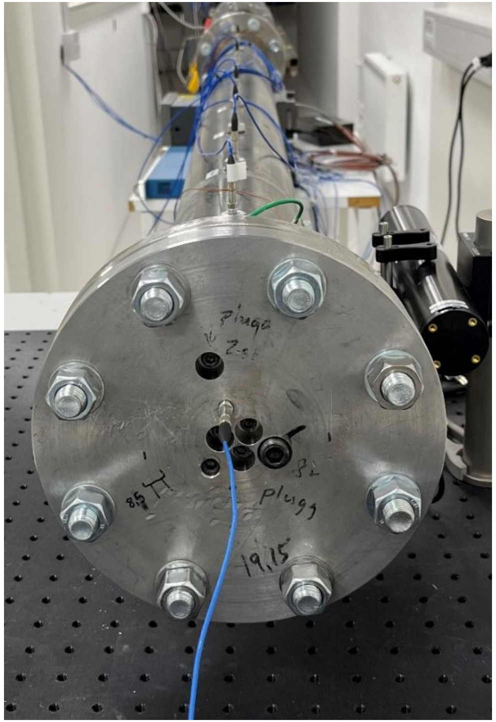


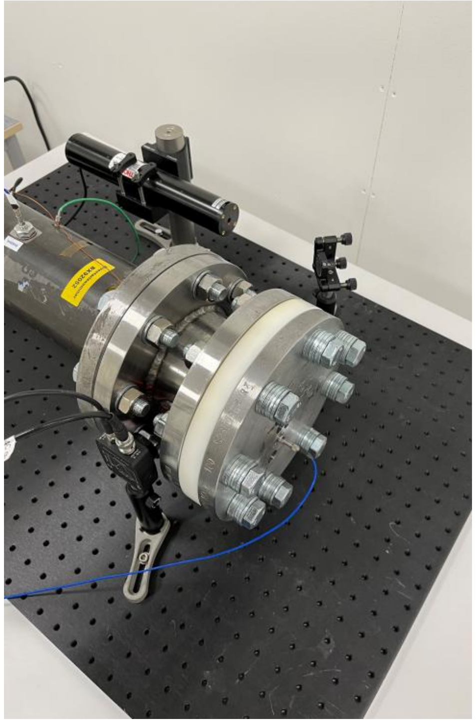


$$\Delta p = 2p_1 \frac{\gamma_1}{(\gamma_1^2 - 1)}(M^2 - 1)\left(\frac{M^2(3\gamma_1 - 1) + 3 - \gamma_1}{M^2 + \frac{2}{(\gamma_1 - 1)}}\right)$$

$$M = \frac{v}{\sqrt{\gamma_1 R_1 T_1}}$$

Conventional configuration

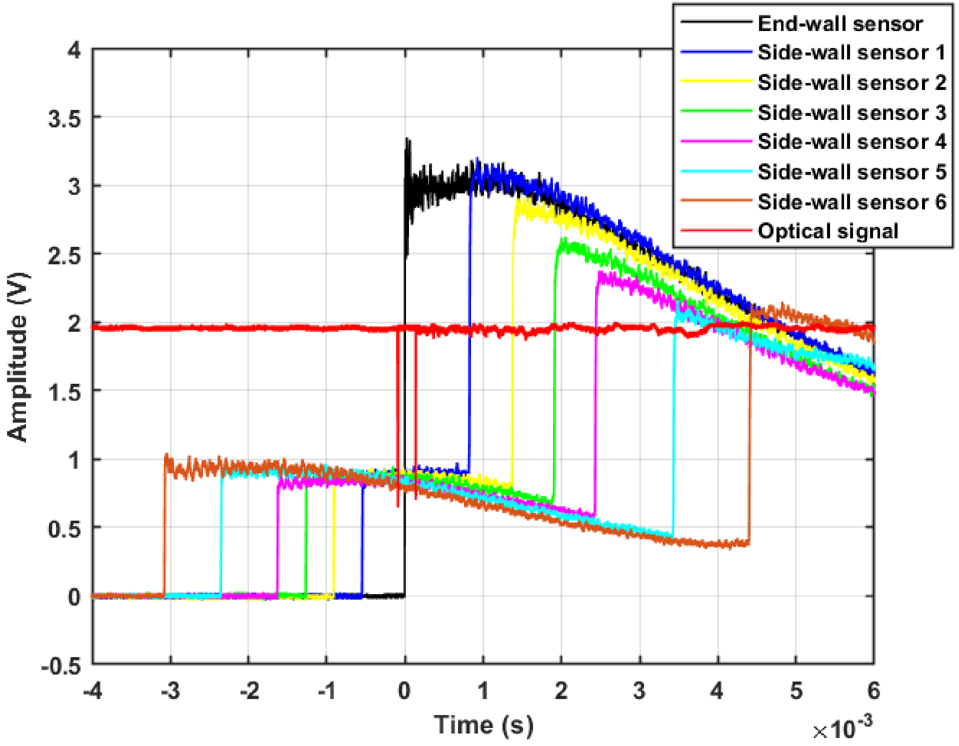




Amplitude: 0.1 MPa to 1.5 MPa.

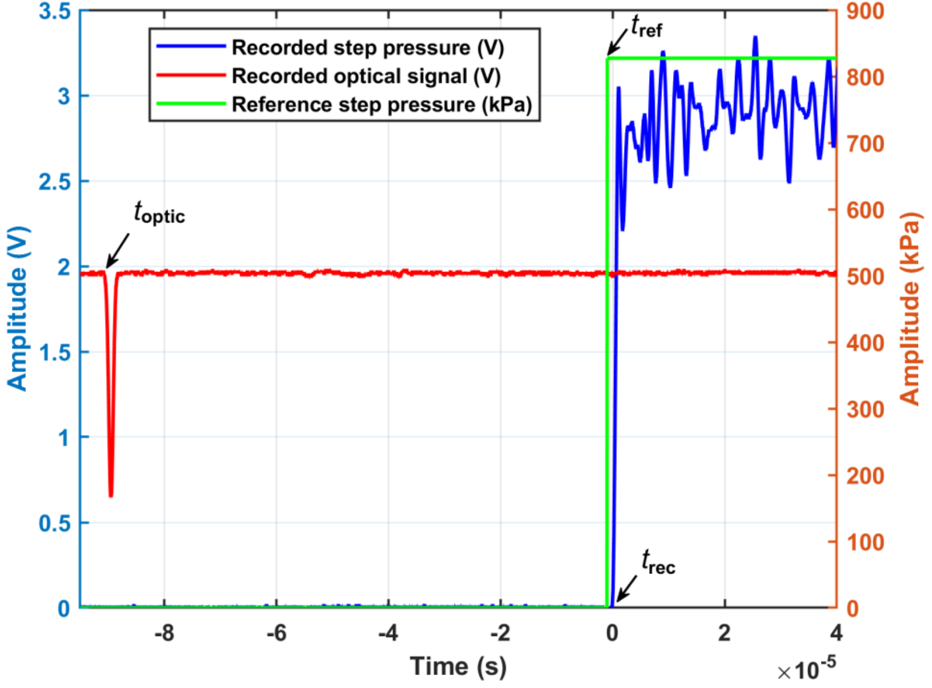
Frequency: < 0.5 kHz to 500 kHz.

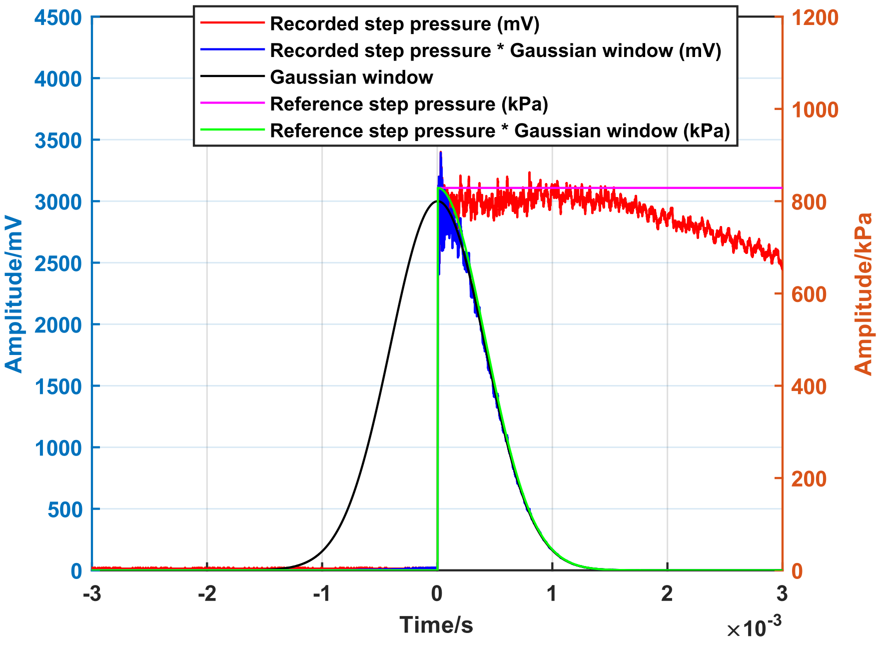
Conventional configuration



Typical recorded signals: DUT, optical signal, and the 6 side-wall sensors.

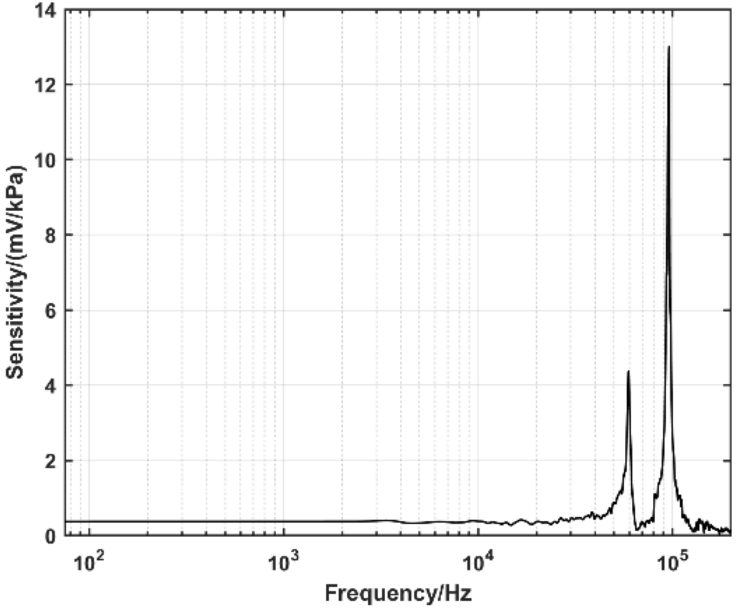
Conventional configuration



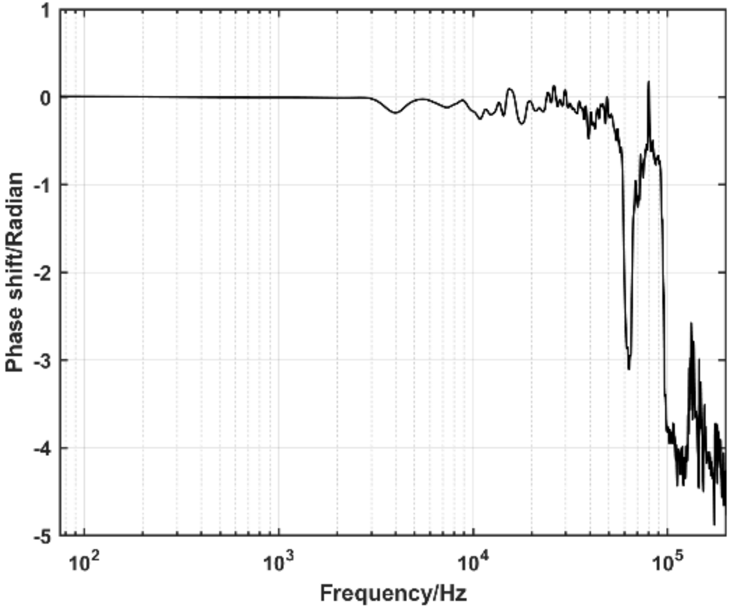


Typical example of dynamic response calculation of a device under test.

Conventional configuration



Sensitivity



Phase shift

Typical example of dynamic response of a device under test.

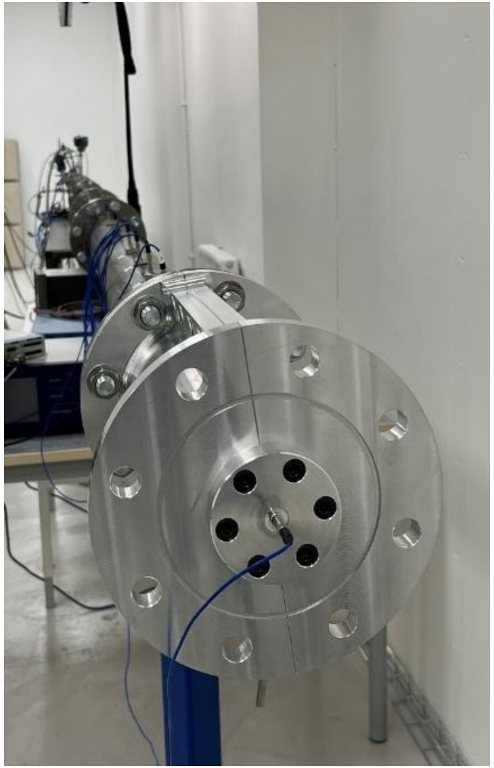
Conventional configuration

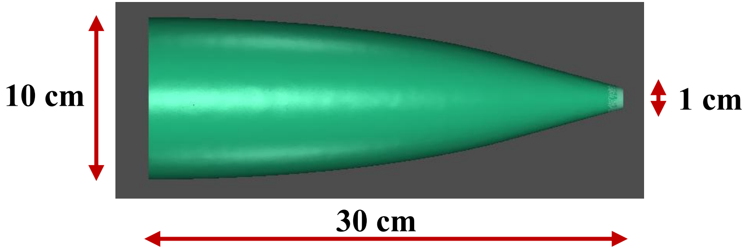
Uncertainty budget

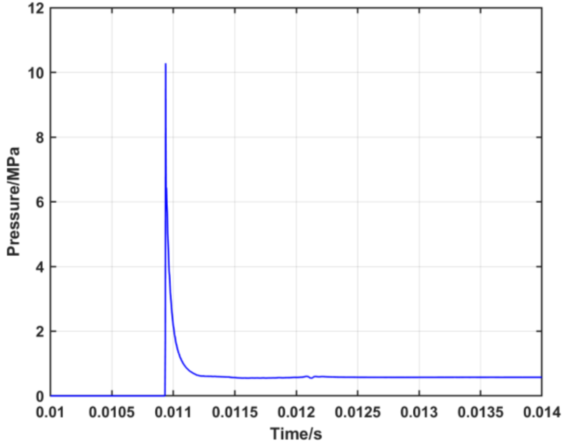
Parameter	Standard uncertainty, k = 1	Distribution
T_1 (K)	0.45: the maximum variance between the three thermocouples readings along the driven section.	Normal
	0.05: the standard uncertainty from the temperature measuring system.	Normal
γ_1	10^{-3}	Rectangular
t (s)	0.34×10^{-6}: time resolution of the measurements (sampling rate of 3 MHz).	Rectangular
	Residual from the curve fitting.	Normal
d (m)	10^{-4}: the standard uncertainty from sensors positions measurements	Normal
p_1 (Pa)	60: the standard uncertainty from transmitter calibration	Normal
	6: transmitter resolution	Rectangular
	63: temperature effect	Rectangular
	116: drift	Rectangular

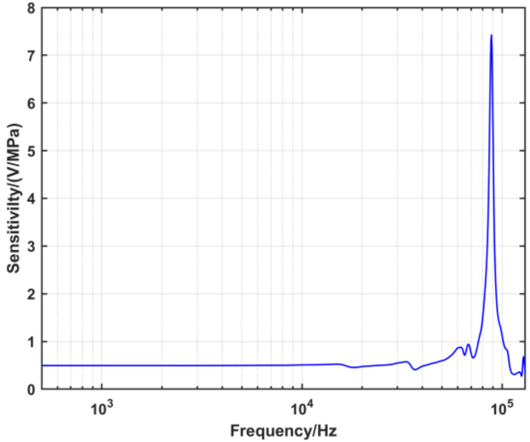
Expanded uncertainty in reference pressure ($k = 2$) < 2%.

Shock tube with converging cone





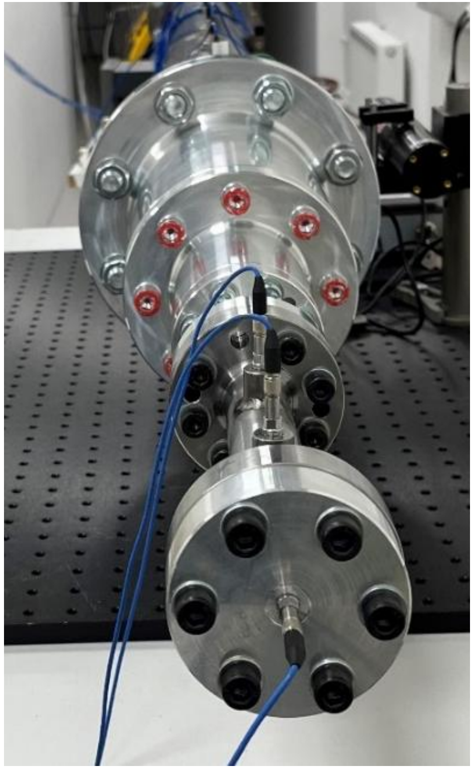


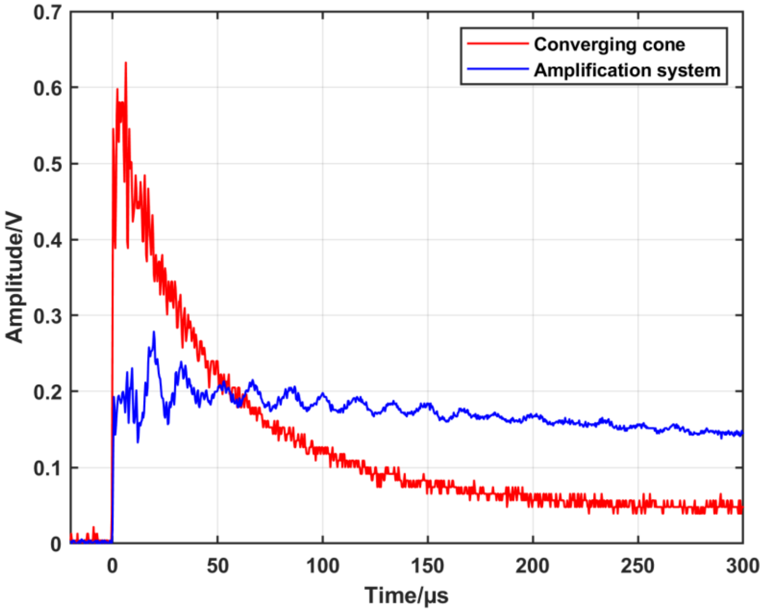


Amplitude: 5 MPa to 25 MPa.

Frequency: < 0.5 kHz to 500 kHz.

Shock tube with an amplification system

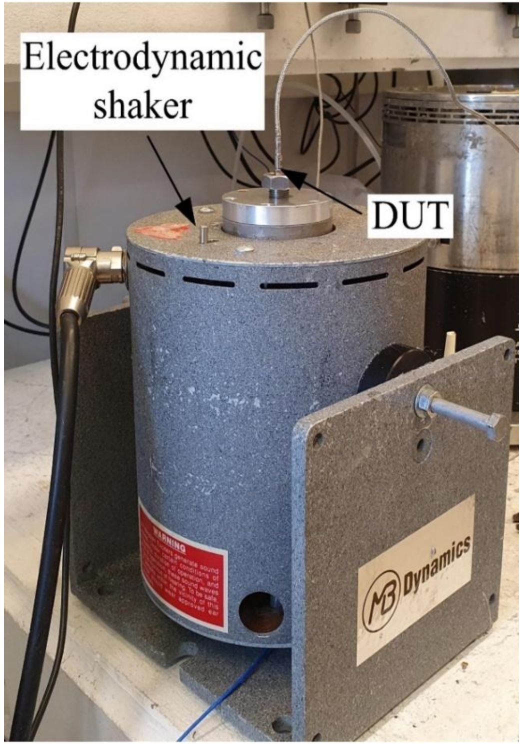


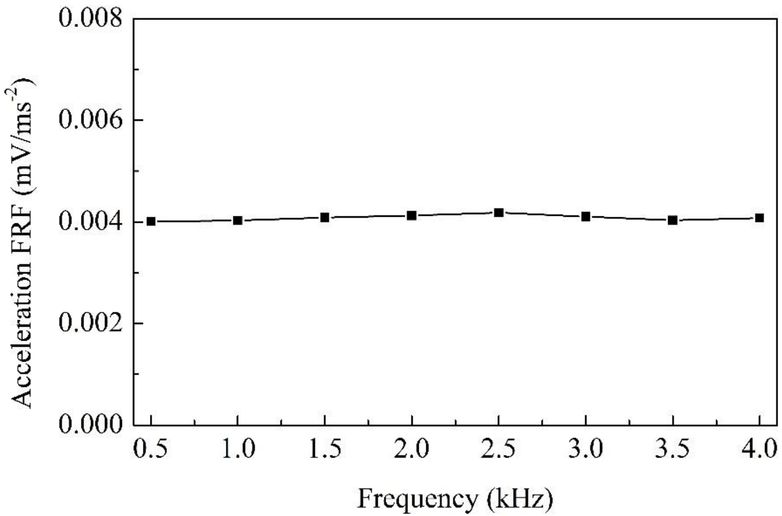


Amplitude: 1 MPa to 7 MPa.

Frequency: 1 kHz to 500 kHz.

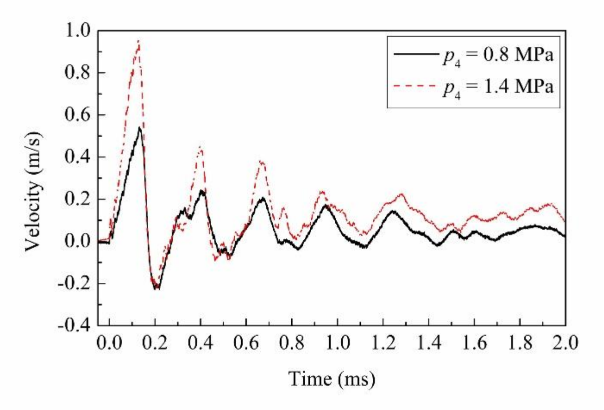
Vibration effect measurement

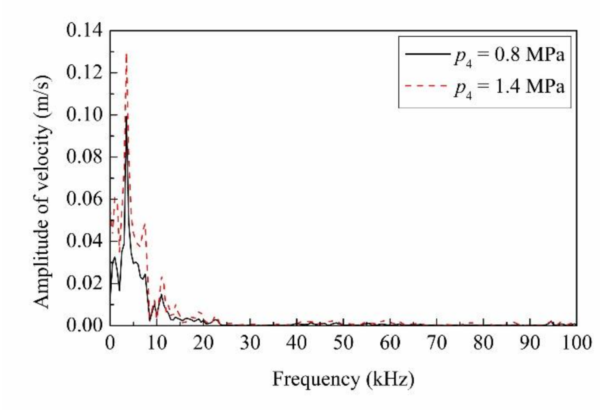




Calibration of the DUT for acceleration.

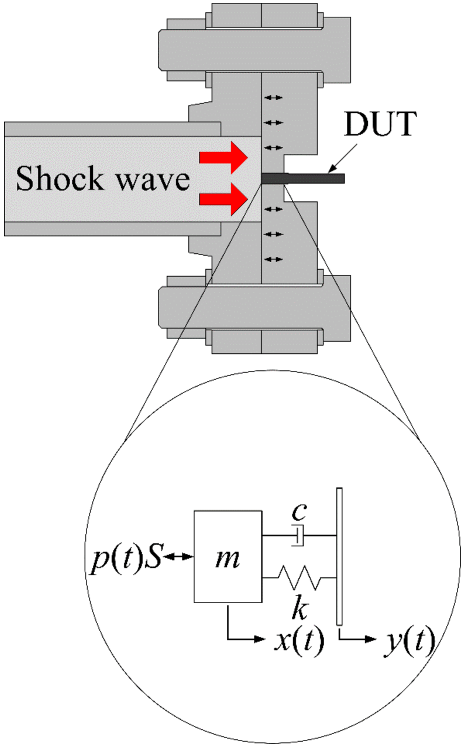
Vibration effect measurement



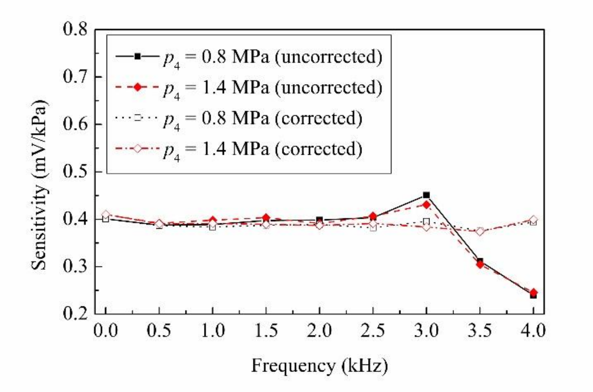


The back-plate velocity recorded by Laser Doppler Vibrometer (LDV).

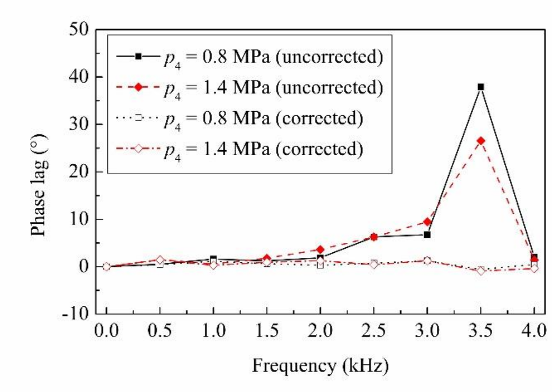
Vibration effect measurement



Mechanical model

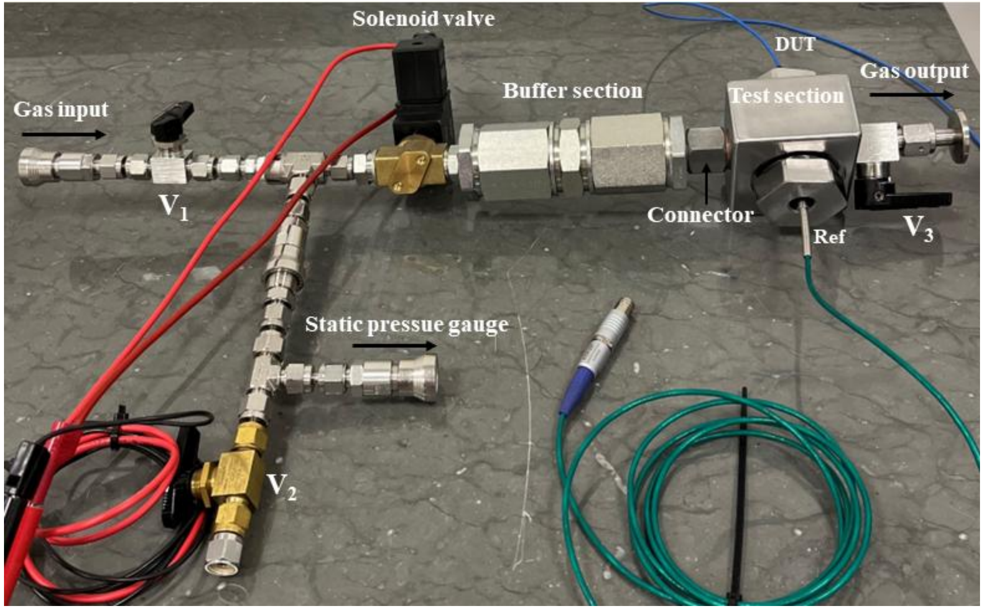


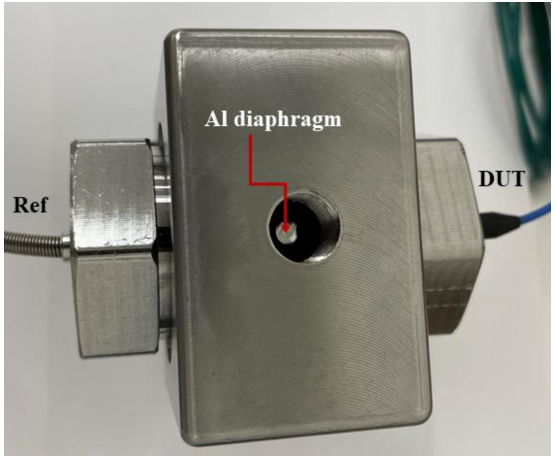
Sensitivity



Phase lag

Secondary standard



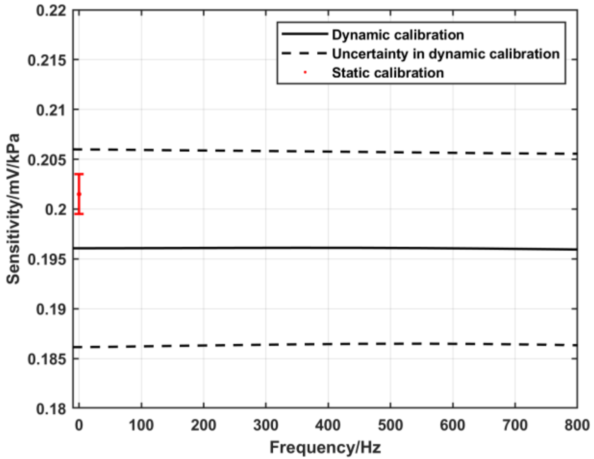


Amplitudes from 1 kPa to 10 MPa.

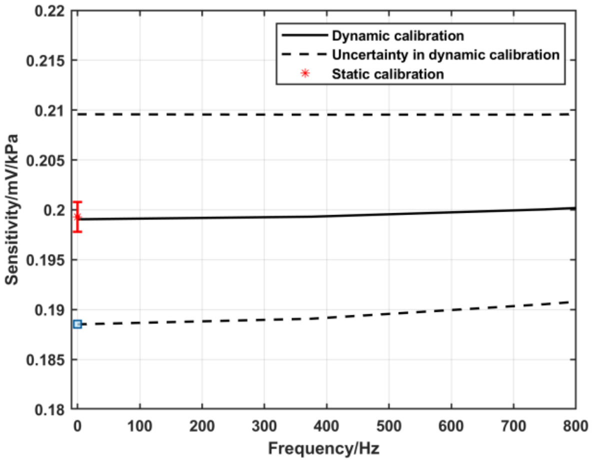
Frequency from 10^{-2} Hz to 800 Hz.

Secondary standard

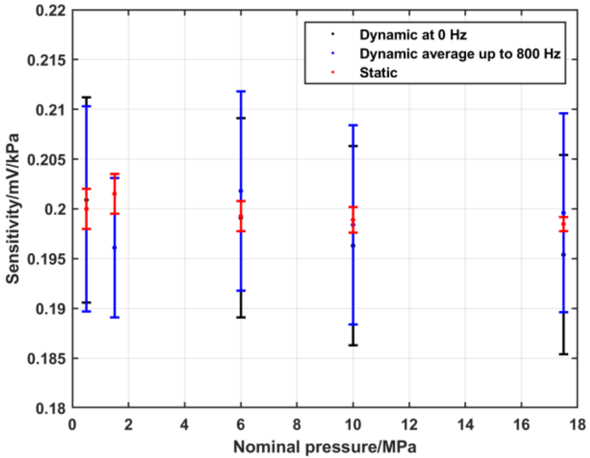
A comparison of static and dynamic calibrations of the reference sensor.



at 1.5 MPa



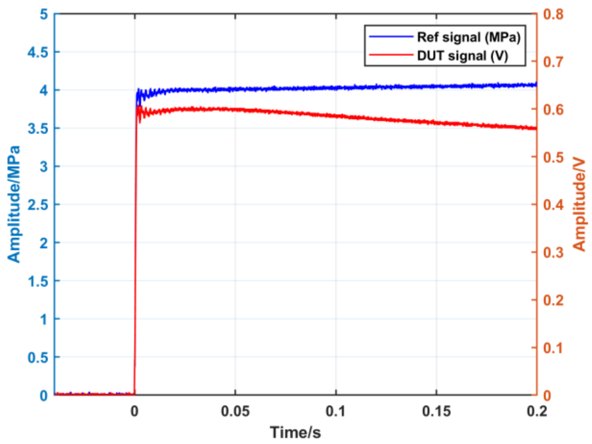
at 6 MPa



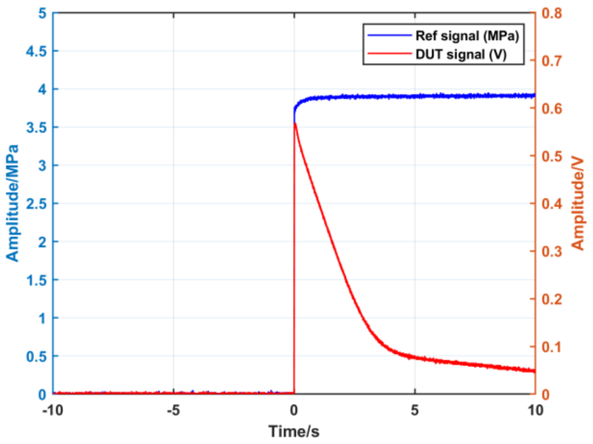
at different nominal pressure amplitudes

Secondary standard

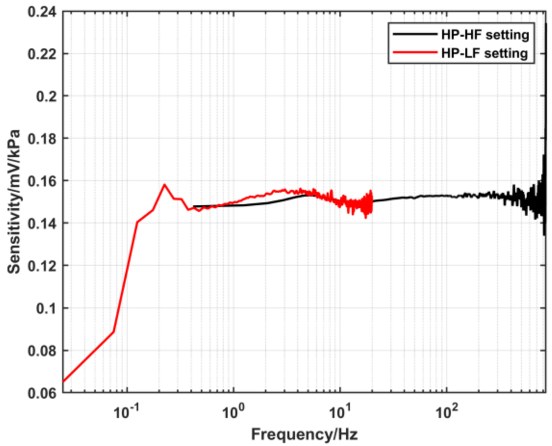
Calibration results of a device under test (DUT).



High frequency setting at nominal pressure of 4 MPa.



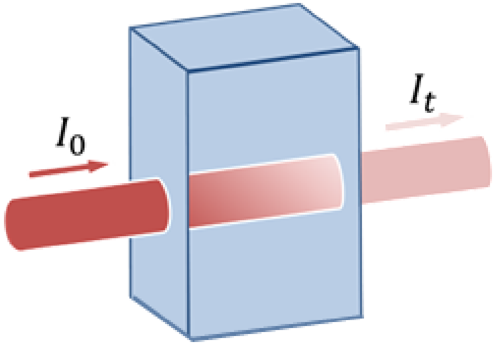
Low frequency setting at nominal pressure of 4 MPa.

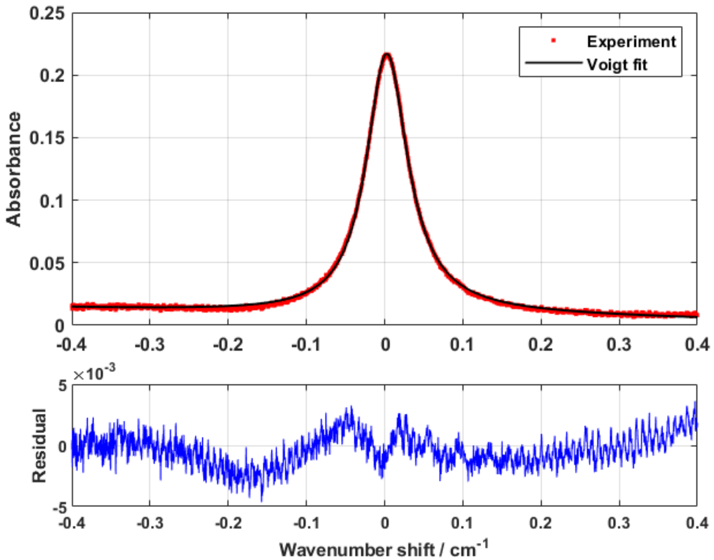


The corresponding dynamic response of the DUT.

Shock tube validation

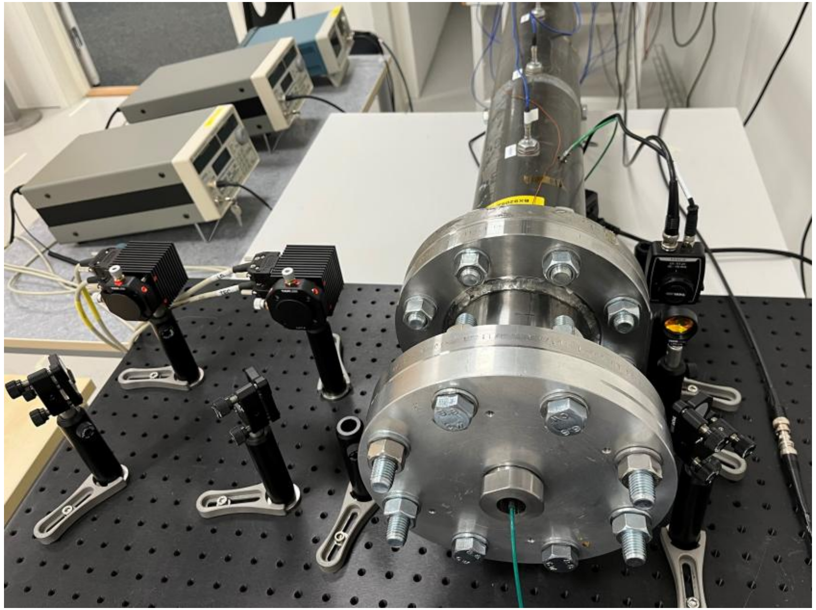
Validation of shock tube model using laser absorption spectroscopy





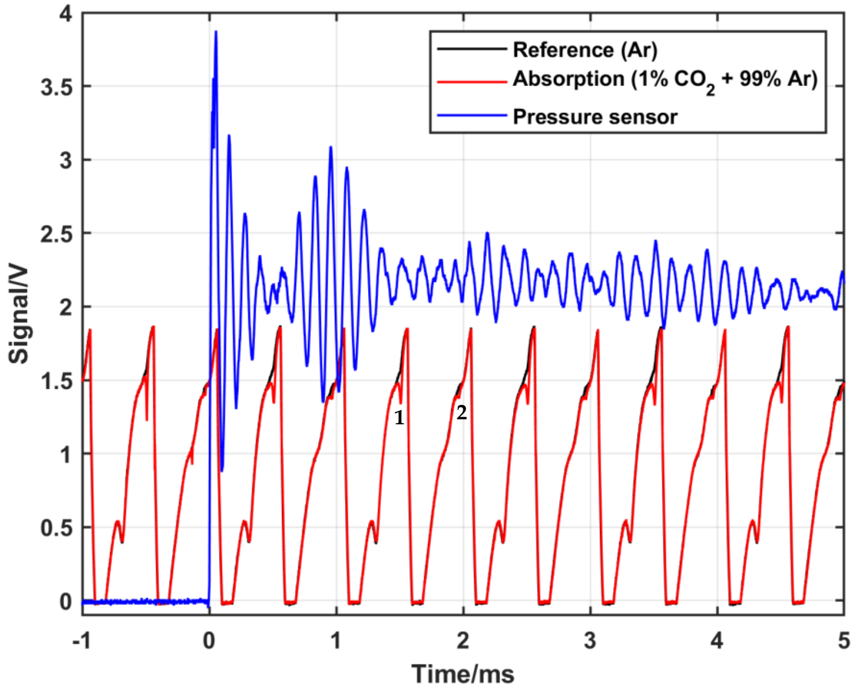
$$I_t(v) = I_0(v) \cdot \exp[-\alpha(v)]$$ Beer-Lambert law

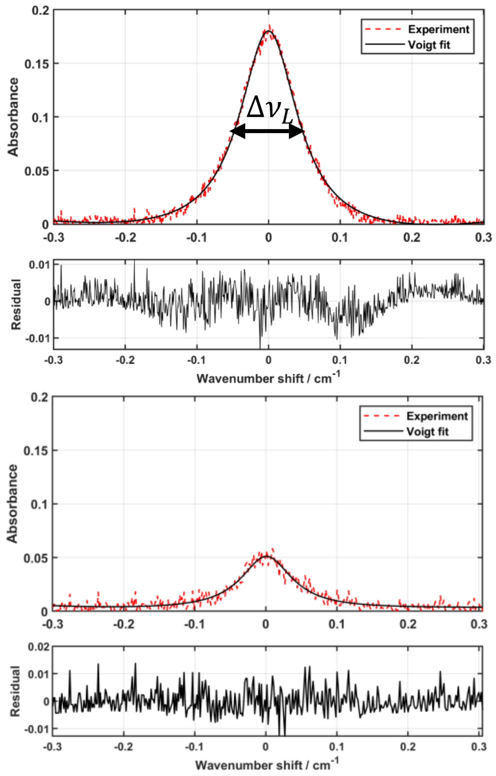
Validation of shock tube model using laser absorption spectroscopy



Laser absorption spectroscopy setup coupled to the shock tube, CO_2 transition of R(28) centred at 3633.08 cm^{-1} and R(50) centred at 3645.20 cm^{-1} were selected.

Validation of shock tube model using laser absorption spectroscopy





Laser 1: 3633.08 cm^{-1}
Laser 2: 3645.20 cm^{-1}

Validation of shock tube model using laser absorption spectroscopy

$$T = \frac{\frac{hc}{k}\left(E_2^{"} - E_1^{"}\right)}{ln(R) + ln\left(\frac{S_2(T_0)}{S_1(T_0)}\right) + \frac{hc}{k}\frac{\left(E_2^{"} - E_1^{"}\right)}{T_0}}$$

h : Planck’s constant (J.s).

c : speed of light (cm/s).

k : Boltzmann’s constant (J/K).

$E_2^{"}$: the lower-state energy for transition 2 (cm^{-1}).

$E_1^{"}$: the lower-state energy for transition 1 (cm^{-1}).

R : line strengths ratio of the two transitions.

$S_2(T_0)$: line strength of transition 2 at reference temperature of 296 K (cm^{-2}/atm).

$S_1(T_0)$: line strength of transition 1 at reference temperature of 296 K (cm^{-2}/atm).

T_0 : reference temperature 296 K.

Validation of shock tube model using laser absorption spectroscopy

$$p = \frac{\Delta v_L}{2\gamma_s \times x \times \left(\frac{T_0}{T}\right)^{n_s} + 2\gamma_f \times (1-x) \times \left(\frac{T_0}{T}\right)^{n_f}}$$

Δv_L: the collisional-broadening FWHM (cm^{-1}).

γ_s: the self broadening coefficient at reference temperature of 296 K (cm^{-1}/atm).

x: the mole fraction of the absorbing species.

n_s: the temperature dependence coefficient of self broadening coefficient.

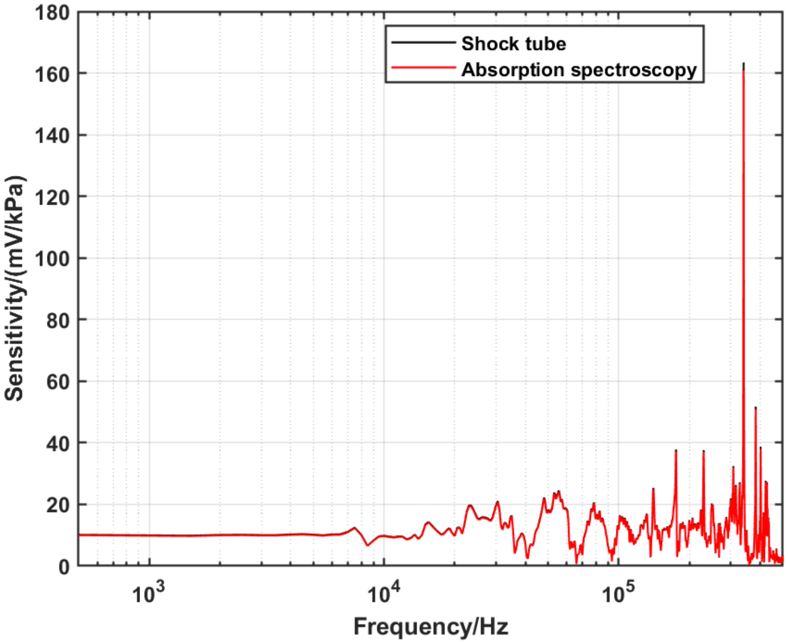
γ_f: the foreign broadening coefficient at reference temperature of 296 K (cm^{-1}/atm).

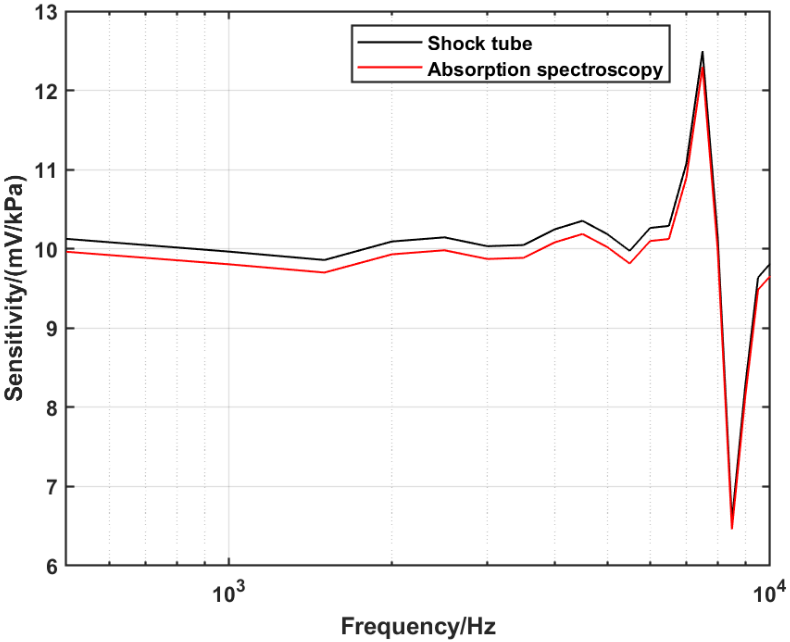
n_f: the temperature dependence coefficient of foreign broadening coefficient.

T_0: reference temperature of 296 K.

T: the gas temperature (K).

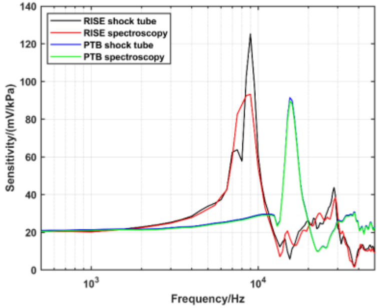
Validation of shock tube model using laser absorption spectroscopy



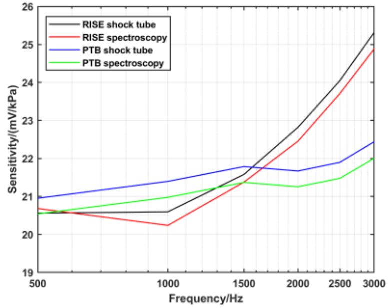


Deviation < 1.5 %

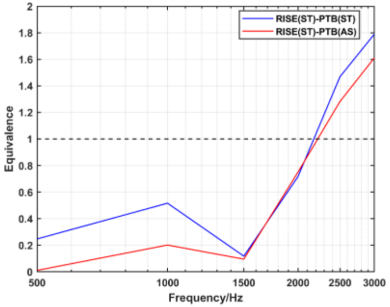
Validation of shock tube at low pressure range, inter-laboratory comparison RISE – PTB



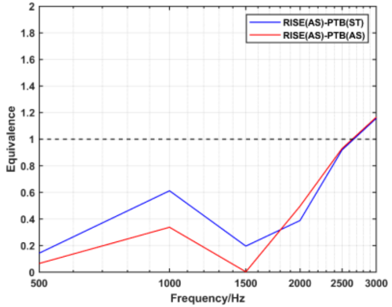
The sensitivity at Δp of 100 kPa of TS1.



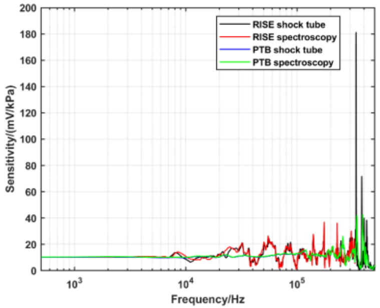
Zoom in up to 3 kHz.



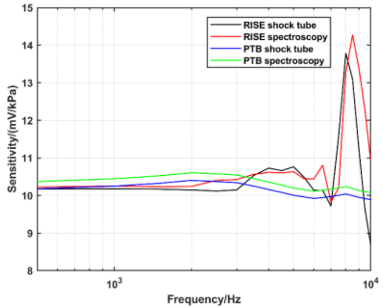
The equivalence between RISE (ST) and PTB (ST, AS).



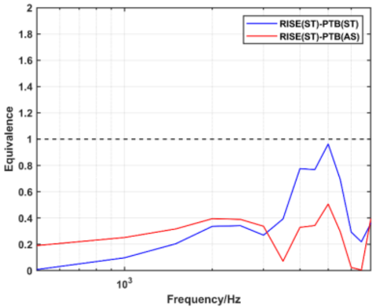
The equivalence between RISE (AS) and PTB (ST, AS).



The sensitivity at Δp of 135 kPa of TS2.



Zoom in up to 10 kHz.



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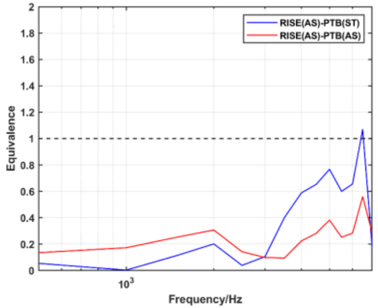

The equivalence between RISE (AS) and PTB (ST, AS).

Validation of shock tube in pressure range of 0.5 MPa – 30 MPa, inter-laboratory comparison

Nominal pressure (MPa)	0.5	1	1.5	6	12	18	24	30
RISE (ST)								
LNE-ENSAM (ST)								
UME (IMD)								
MIKES (IMD)								
PCB (IMD)								

Transfer standard system 1
Piezoresistive system (sensor and amplifier).

Transfer standard system 2
Piezoelectric system (sensor and signal conditioner).

Conclusion

- Shock tube has proven to be a potential primary standard for dynamic pressure calibration.
- It has a large bandwidth, up to 500 kHz.
- Its working amplitudes extending from 0.1 MPa to 25 MPa.
- It can provide a complete characterization of pressure measurement systems.

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EUROPEAN PARTNERSHIP

Co-funded by the European Union

METROLOGY PARTNERSHIP

Thank you
for your attention