Measuring Dynamic Pressure by Laser Doppler Vibrometry

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Abstract

The primary calibration of pressure transducers is at present realized by static procedures only. Subsequent dynamic calibrations in this field are realized by comparison measurements with a statically calibrated reference sensor. This paper describes a route to gain traceability for dynamic calibration by means of laser interferometry. As an instantaneous inertia-free measurement, the described procedure has the potential to measure the so far unknown dynamic response of pressure transducers directly with far higher bandwidth than available by the use of a classical reference transducer. This article describes the general principle employed to gain traceability, the experimental set-ups which are used for the realization, some thermophysical and interferometric background of the measurements, and the first measurement results acquired with the new set-up.

1 Introduction

Traceability of pressure measurements for static as well as dynamic applications is nowadays exclusively provided in terms of a chain of static comparison calibrations to reference standard transducers with typically a deadweight pressure balance at the top end as primary realization of pressure in terms of force per cross-sectional area.

While this is an effective procedure for static measurements, in the case of dynamic measurements this process leaves the user blind to inertia effects compromising his measurement data. That means, the transducer itself may react to a dynamic input signal with a specific response that originates from the mechanical design as much as from the original pressure input. Parts of the mechanical components of the transducer, like the sensitive membrane, are accelerated under pressure load. Since those parts have a certain mass and are coupled to the housing with a certain stiffness, they form a mechanical oscillator that may respond with its eigenmodes.

An additional influence arises from the coupled electronics in terms of a conditioning amplifier, which may even be embedded into the transducer and therefore inaccessible. These components of the measuring chain have a limited bandwidth and often high-pass characteristics, which may lead to distortions of the output in comparison to the input.

As a consequence, the metrology of dynamic pressure signals is currently affected by several imponderabilities which lead to a certain uneasiness concerning the reliability of such measurements in many industrial areas.

Therefore it is desirable to establish a calibration method that provides a proper representation of the dynamic pressure input signal devoid of inertia effects and independent of a classical reference transducer.

If inertia is an issue, usually optical methods using light as a means of measuring are the answer. Accordingly, PTB followed an approach to measure the dynamic pressure in a calibration device by using laser interferometric means.

2 The Interferometric Principle

The laser Doppler vibrometer (LDV), which is used in the proposed device, is by principle a modified Mach-Zehnder interferometer (cf. figure 1), where the reference beam is shifted in its optical frequency due to Bragg refraction in an acousto-optical modulator (AOM or Bragg cell). In the case of the device used in our application, the frequency shift is 40 MHz. This has the consequence that the photodiode detects an interferogram intensity-modulated with 40 MHz if the object beam is reflected from a non-moving target, or more precisely, when the object beam passes a constant optical path length before it is superposed to the reference beam. Any dynamic change of the optical path length results in an additional frequency shift to frequencies higher or lower than 40 MHz depending on the direction.

A measurement of a dynamically changing optical path length results in a frequency-modulated (FM) signal output of the photodetector (PD) that can be analysed by any FM demodulation technique.

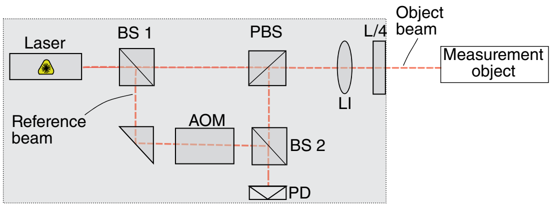

Figure 1:
Internal set-up of the heterodyne laser Doppler interferometer (BS = beam splitter, PBS = polarizing BS, L/4 = quarter wave plate, LI = lens, AOM = acousto-optical modulator (Bragg cell), PD = photodetector).

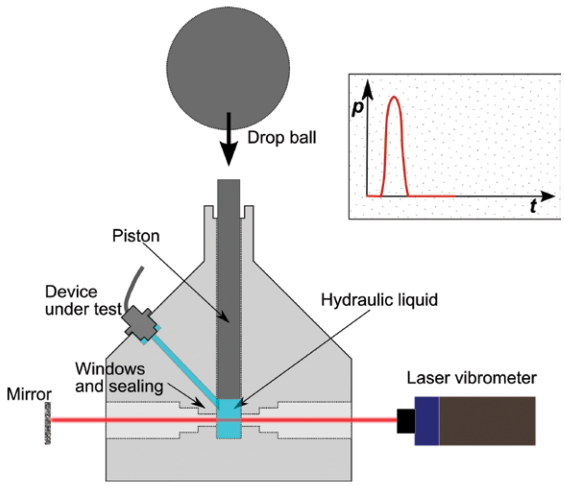

Figure 2:
Drawing of the interferometric measurement set-up used with PTB's drop weight pressure calibration device.

This principle makes these devices very sensitive even to small changes in the optical path length. Since no mechanical parts are included in the measurement, these systems provide a high bandwidth of measurement, in our case in the megahertz range, which is roughly an order of magnitude more than the classical electro-mechanical transducer systems are able to provide.
In addition, the frequency response is rather flat if proper care is taken into account and a so-called digital demodulation is applied. A flat frequency response means that the dynamic output from the device can be considered (simply) proportional to the input measurand over a wide range of frequencies.

3 The Device Set-Up

In the calibration system described here, a hydraulic medium is used to generate and transmit the pressure. The medium is compressed by means of a cylindrical piston that is forced into the medium and therefore reduces the available volume. Accordingly, the pressure and density of the medium increase while the volume decreases. The dynamic force that drives the piston into the medium is generated by an impacting steel ball which hits the top end of the piston (cf. figure 2)

The object beam of the LDV described in the previous section is transmitted through the volume of the transparent hydraulic medium and, after passing it, is reflected by a mirror or retroreflector.

The device under test (DUT) or pressure sensor to be calibrated is mounted in a drilled hole on the side of the pressure vessel. Its sensitive front has direct contact with the pressurized medium. A catcher mechanism (not drawn in figure 2) prevents the steel ball from bouncing on the piston. With drop heights of up to 1500 mm, pressure intensities up to 800 MPa (8000 bar) are achievable.

4 Physics of Compression

When the medium is compressed, the mass density increases and, in conjunction, the optical index of diffraction changes. This change of index of diffraction is the fundamental effect facilitated in the device. It is generally described by the Clausius-Mossotti relation

$$\frac{n^2-1}{n^2+2} = pk \quad \text{or} \quad n^2 = \frac{1+2pk}{1-pk} \;, \tag{1}$$

where n is the index of diffraction, ρ is the mass density, and k is a material-dependent constant factor.

For the measuring laser beam, the change in refractive index is an effective change in the optical path length between the exit aperture of the LDV and the retroreflector. The optical path length is given as the product of the index of diffraction n and the geometric path length s_{geo} *as*

$$s_{opt}(t) = n(t) \cdot s_{geo} \;. \tag{2}$$

As the index of diffraction changes with time, the optical path length becomes a time-dependent quantity, too.

The dynamic change accordingly generates a dynamic frequency shift of the FM signal of the LDV's photodiode. The frequency shift is a measure of the pressure change over time. However, due to the non-linearity of the governing equation (1), the relation between the two is not simply proportional.

5 The Link to Static Pressure

With the equations above, material properties (k) as well as geometric design properties of the device (s_{geo}) enter into the evaluation of pressure. While the first are largely unknown, especially for high pressure, the latter are not easy to determine. This holds specifically for the geometric path length of the laser beam within the pressure vessel. There is, however, a solution to this problem which works without explicit measurement of those quantities. This solution involves a static calibration of the system consisting of LDV, pressure vessel and retroreflector in relation to static pressure. If the pressure-input-to-voltage-output characteristics of the system are determined statically, these can be applied to dynamic measurements subsequently due to the fact that the LDV employs a principle unaffected by inertia, and provides a by far higher bandwidth than the electro-mechanical system under test.

For the purpose of the static calibration, the mounting hole for the DUT is sealed and a pressure balance is connected to the tube where otherwise the piston is guided. The pressure balance provides a highly precise reference pressure to the vessel that is increased stepwise by the sequence of applied deadweights. During the whole sequence the displacement output of the LDV is acquired by the data acquisition system. The step-like sequence of pressure steps is converted into a step-like sequence of LDV output voltages (cf. figure 3).

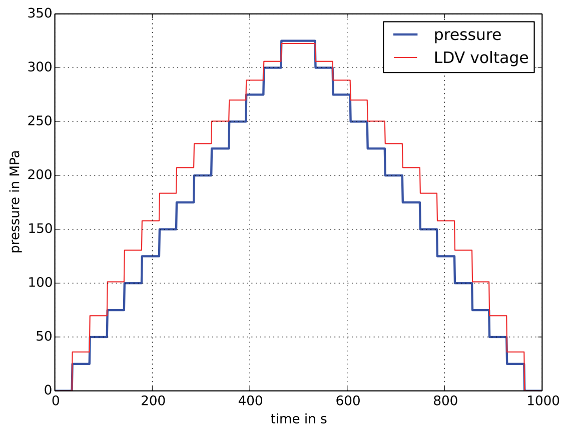

Figure 3:
Example of a step-like sequence of applied pressure levels in the process of static calibration of the laser interferometric measurement set-up
(so far hypothetical).

For this static calibration the transitions from pressure level to pressure level are ignored and only the stationary signals of each level are evaluated. Unfortunately, due to the form of the Clausius-Mossotti relation, the shape of the resulting calibration curve is non-linear but can be approximated with low deviations by a polynomial of third order (cf. figure 4). It is currently not completely clear what implications arise from the non-linearity for the dynamic calibration in terms of, e.g., harmonic distortion.

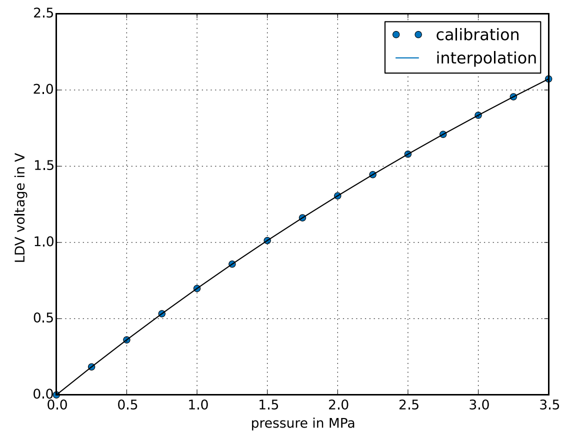

Figure 4:
Characteristic curve of the dependence of the LDV output voltage on the applied pressure derived by fitting from the stepwise calibration points at discrete pressure levels.

6 Challenges

On closer inspection one has to realize that there are further systematic differences between the pressurization during an impulse load by an impacting ball and the static calibration.

When a medium is compressed, energy is introduced into the medium. As a consequence, the medium heats up if a finite compression takes place in a finite time. Therefore, the medium encounters an increase in density due to loss of volume and an increase in temperature due to the energy deposited during the compression work. Since pressure, on the microscopic scale, is related to the momentum transferred by the molecules of the medium to the walls of the vessel while moving in Brownian motion, it is dependent on the effective frequency of momentum transfer and thus the density, but also on the effective speed of those molecules and thus the temperature.

According to the previously described mechanism, the hydraulic medium in the pressure vessel heats up shortly during compression, when the steel ball hits the piston, and cools down again during the subsequent expansion or relaxation, when the ball bounces back and the piston returns to its original position. The time scale of this process is a few milliseconds. In this short time the energy deposited in the hydraulic medium has no time to become dissipated by heat conduction. Accordingly, this process can be considered adiabatic.

The compression process during the static calibration, however, performs on a time scale of hundreds of seconds. There is plenty of time for heat dissipation towards thermal equilibrium at all pressure levels. Accordingly, this process can be considered isothermal.

The relationship between pressure and density for a hydraulic medium is different for isothermal and adiabatic processes. Since the LDV method is in fact sensitive to density changes, and ignorant of the temperature of the medium, the consequence is a systematic deviation of the static calibration characteristics from the dynamic measurement situation.

Based on the available material data, the amount of this systematic effect can be estimated and either be considered as a measurement uncertainty or (possibly) corrected for [1].

Another effect that has to be considered in terms of a disturbance or measurement uncertainty component is the inevitable geometric expansion of the pressure vessel during loading. This effect generates a superposed change of the geometric path length, where fractions of the geometric path initially propagating through air in the unloaded case will then propagate through the compressed medium in the loaded case (the sealing glass windows are considered as incompressible). This is in fact a superposition of two disturbing effects, the first is the geometric expansion and the second is the media change for parts of the path length. The first effect can only be minimized by the choice of the material and technical design of the sealing, which has to be as stiff as possible. The latter effect can be avoided by a modification of the pressure vessel, which adds some volume of the hydraulic media at ambient pressure to the pressurized chamber. Thus, the parts of the ambient pressure volume will be replaced by the high pressure volume without a change of the media [2]. However, this modification is future work and has not yet been implemented in the current test set-up.

7 First Measurements

Despite the further optimizations already described, first measurements were performed with a test set-up depicted in the photograph of figure 5. These were supposed to answer several questions, among which the general feasibility of the method was not the least important. Other practical questions are related to leakage effects of the piston guide way, signal quality and intensity of the LDV, achievable pressure intensities in relation to drop height, and the possible optical disturbances generated by the inevitable mechanical vibration due to the impact of the drop ball.

The hydraulic medium of choice was bis(2-ethylhexyl) sebacate. The pressure reference for these tests was a calibrated piezoelectric pressure transducer, since the linking of the LDV to static pressure was not yet available.

Figure 6 presents the measurement signals for two drops from different heights. The pressure is according to the reference sensor's indication, the LDV voltage is sampled from the analogue displacement output of the LDV controller. The effect of the previously described non-linearity is clearly detectable in the different pulse shapes of the sensor signal compared to the corresponding LDV voltage signal. Apparently the relationship is beyond simple scaling of the signals.

A plot of the LDV output voltage versus the reference pressure, like in figure 7, shows, however, that both measurements follow the same characteristic sensitivity curve.

8 Summary and Outlook

Within the joint research project *Traceable Dynamic Measurement of Mechanical Quantities*, a JRP of the European Metrology Research Program, PTB has set up a new kind of dynamic pressure calibration device for high hydraulic pressures up to several 100 MPa. In order to prevent inertia effects from influencing the measurements, an

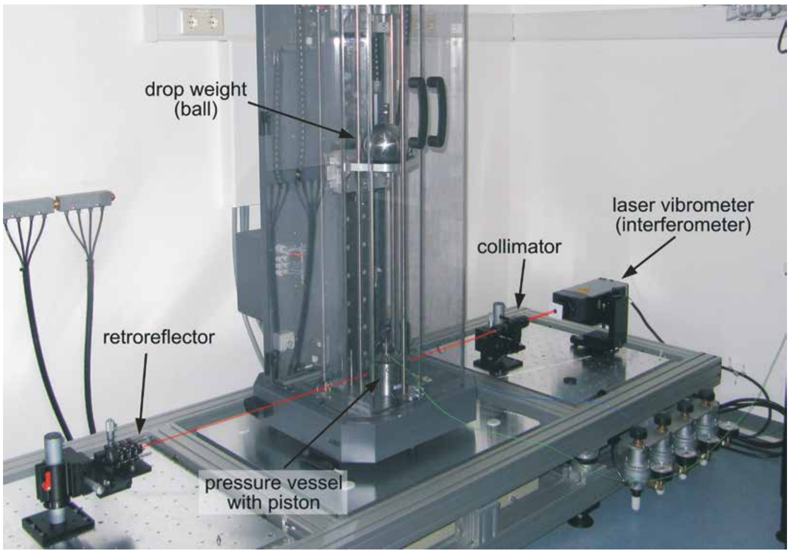

Figure 5:
Photography of the current interferometric drop weight pressure calibration set-up with the main components labeled.

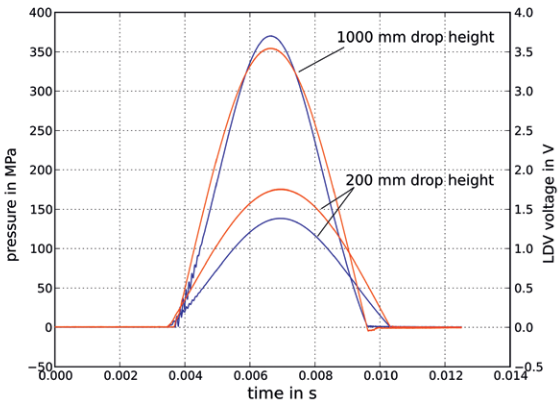

Figure 6:
Pressure pulse measurements from two different drop heights. Red curves are the reference pressure sensor signals, blue curves are LDV displacement signals.

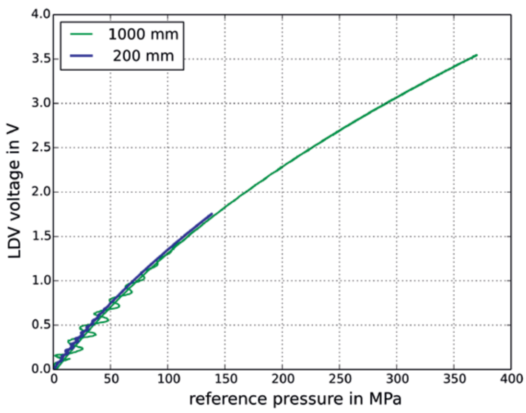

Figure 7:
LDV voltage in dependence on reference pressure for the time series data of figure 6.

interferometric principle is implemented. A heterodyne Mach-Zehnder Interferometer is used to measure the change of the index of diffraction in the pressurized hydraulic medium while a dynamic pressure signal is generated by a drop weight hitting a piston.

While first measurements provided promising signals with good general quality, there are still further investigations necessary to make this new method a national standard. Among other aspects, the non-linearity of the underlying physics has to be investigated and the major sources of measurement uncertainty need to be identified.

Acknowledgements

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References

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