

UNCERTAINTY CONTRIBUTIONS OF THE IMPACT FORCE MACHINE AT PTB

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Abstract: This paper gives a comprehensive overview about the contributions to the measurement uncertainty of the 20 kN Impact Force Machine at PTB. Various influences resulting from interferometric velocity measurements, data analyses, mass determinations and parasitic forces are described and estimated by theoretical or experimental data if possible.

Keywords: impulse force calibration, laser-Doppler interferometer, air bearing.

1. INTRODUCTION

In response to the increasing importance of dynamic force measurements, a facility for impulse force calibrations up to 20 kN peak value has been developed at PTB. Figure 1 depicts its basic components and explains the measurement principle. Figure 2 shows a photograph of the facility. Design, technical realization and first experiences have been already presented in [1-4].

Force pulses are generated by the collinear collision of two air-guided steel bodies (impacting mass m_1 and reaction mass m_2) which act on the force transducer under test mounted in between. The force amplitude is varied via the impact velocity v_0 of the impacting mass m_1 , the pulse duration by elastic pulse shapers applied at the contact surface. Traceability of force is realized by means of laser-Doppler interferometers (LDI) which measure the velocities of the involved mass bodies during time of impact. The corresponding accelerations are calculated by differentiation and the acting inertia forces are obtained according to Newton's law.

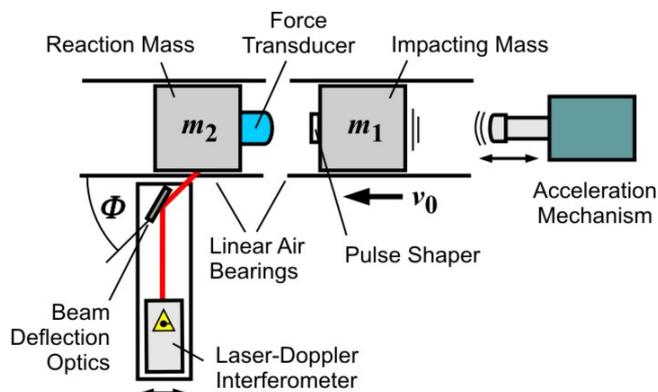


Fig. 1. Components of the 20 kN Impact Force Machine



Fig. 2. 20 kN Impact Force Machine

2. SOURCES OF MEASUREMENT UNCERTAINTY

Traceability of the generated impulse force is based upon measurements of inertia forces. The knowledge about the acting accelerations as well as of the effective inertia masses is the key to impulse force calibrations of high precision. In this context, some small corrections due to superposed parasitic forces from various sources might be applied. Further influences from the force transducer under test and its measuring chain have to be considered for calibration purposes.

A basic overview about various influences on the impulse force calibration and thus its possible sources for measurement uncertainty is illustrated in the following fishbone diagrams. The relationships are presented in two diagrams for more clarity. Figure 3 describes the influences on the acceleration measurement, Fig. 4 the influences on the higher-ranking impulse force calibration. The items are arranged in a suitable manner in order to express the relationships between causes and effects. The level of detail is chosen according to importance, clarity and descriptions presented in this paper. If necessary, further detail might be added in future for a closer look. The items are grouped into characteristic categories, e.g. acceleration measurement, inertia mass, parasitic forces and force measurement in case of the impulse force calibration. Influences and effects will be discussed in the following subsections.

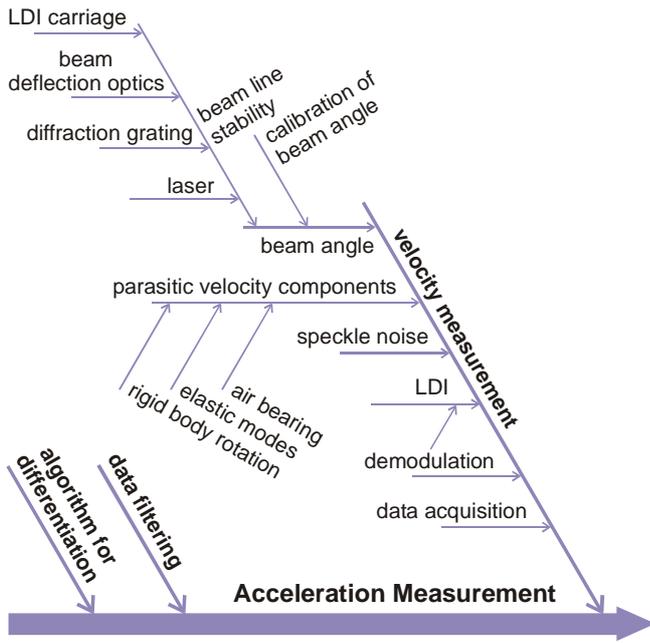


Fig. 3. Fishbone diagram of the influences on the acceleration measurement

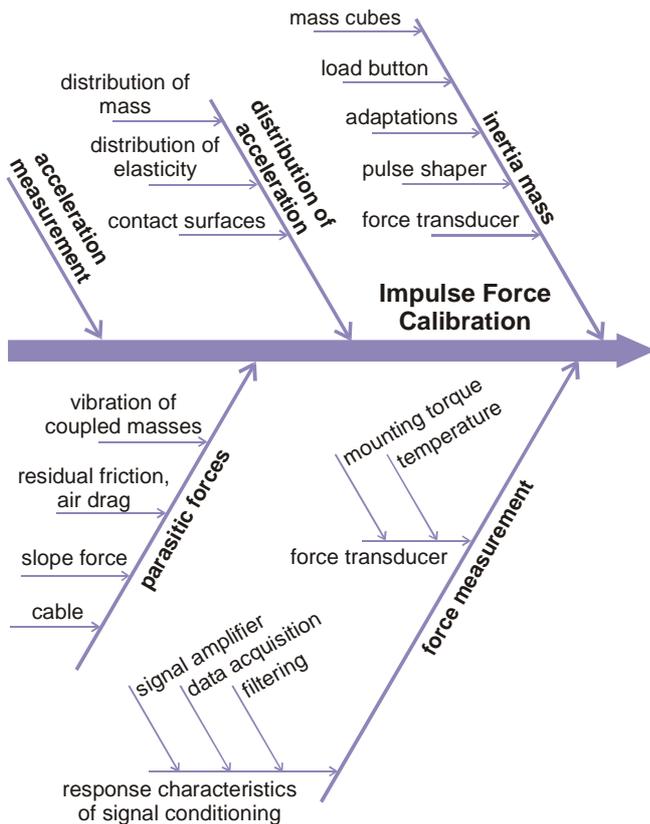


Fig. 4. Fishbone diagram of the influences on an impulse force calibration

The diagrams give a first impression of the complex relationship of various influences which contribute to the measurement uncertainty. Due to this complexity, the main objective of this paper is to provide a comprehend overview about the sources rather than to analyze all contributions in detail nor to provide a full uncertainty budget. This is to be done in future when all relevant contributions have been

analyzed and evaluated. In this context, some theoretical estimations and example measurements for some influences were already presented [1-5]. Therefore, the following will emphasize on those items not covered so far.

2.1. Acceleration measurement

The time series of acceleration during time of impact is derived from the recorded LDI velocity signal by numerical differentiation, a process which runs offline. The transient recorder either digitizes the analogue velocity output of the LDI (single-point vibrometer Polytec OFV 353) or its raw interferometer signals for a subsequent digital demodulation. For the latter, the velocity-modulated 40 MHz carrier – or a down-mixed carrier – will be sampled. Thus the required sample rate depends on the chosen LDI output type, i.e. analogue or digital. The external digital demodulation is strongly preferred and will be used in future exclusively as it provides direct traceability of velocity and smallest uncertainties. For the other method, the utilization of the analogue output would require an extra calibration of the LDI instrument.

The following subsections discuss the three main categories of influencing factors according to Fig. 3. In this context, the focus is on the interferometric measurement of velocity.

2.1.1 Algorithm for differentiation

Different algorithms of numerical differentiation were analyzed in [5]. It was shown that the digital quadrature demodulation performs by far best regarding the criteria accuracy and proliferation of disturbances like noise. In general, the differentiation process itself is prone to strong amplifications of signal noise and thus an adequate low pass filtering is mandatory.

2.1.2 Data filtering

Low pass filtering is intended to eliminate the parasitic noise components of the acquired acceleration signal as far as possible. This includes artificial components due to the differentiation process as well as natural components due to laser speckles or elastic modes for example. In principle, the transient frequency of the low pass filter has to be adapted to the frequency content of the analyzed force pulse. It should pass all wanted spectral components without any amplitude loss or phase shift and should completely block all noise. A trade-off between these conflictive requirements has to be found normally. As a consequence, the frequency response of the low pass filter has to be considered in the measurement process. The effects of data filtering can be strongly reduced for calibrations if both signals to be compared, i.e. acceleration signal and transducer signal, could pass through identical filters.

2.1.3 Velocity measurement

Various influences on the interferometric velocity measurement are depicted in Fig. 3. The uncertainty in velocity depends on many factors, namely LDI instrument and the internal or external demodulation method, data

acquisition, speckle noise, beam angle and parasitic velocity components.

Instrumental influences are laser wavelength, modulation frequency of the Bragg cell and the internal demodulation electronics for analogue output. In case of an external demodulation, the frequency mixer and the demodulation scheme have to be considered. It is suspected that only the analogue LDI output – which won't be used in future - will contribute significantly to the instrumental measurement uncertainty budget.

Effects from amplitude and phase variations of the reflected LDI beam caused by speckle noise have been drastically reduced by the use of optical gratings for retro-reflection [3]. Nevertheless, residual effects due to an inhomogeneity or a contamination of the optical grating might exist and would have an influence especially on measurements of short force pulses where the noise filtering is less effective.

2.1.3.1 Beam angle

The velocity of the colliding bodies is measured by an LDI aimed at the lateral surface under oblique observation angles. Therefore, only the line-of-sight velocity component is detected and the beam angle has to be known precisely. As retro reflection of the measuring laser beam is achieved by plane diffraction gratings in Littrow configuration, the beam angle is well defined. Specific beam angles corresponding to different gratings or to different orders of refraction, respectively, are selected by means of a beam deflection optics. This optics utilizes small mirrors mounted on a movable linear rail and a tiltable glass plate for vertical beam adjustment. Specifications about the available beam parameters including velocity transmission ratios are given in Table 1.

Table 1. Available LDI beam specifications

	order of refraction		
Grating # 1 (1000 lines per mm)	-1	-2	-3
beam angle Φ	71,554°	50,743°	18,341°
velocity transmission ratio	0,3164	0,6328	0,9492
Grating # 2 (1250 lines per mm)	-1	-2	n/a
beam angle Φ	66,703°	37,721°	
velocity transmission ratio	0,3955	0,7910	

It was shown before [3] that LDI beam angles are precisely measured by means of a second interferometer directed at the moving mass body under perpendicular incidence. This angle measurement yields the effective beam angle of the considered optical geometry. Besides the inherent uncertainty of this measurement method, the beam line might have small instabilities which would affect the effective beam angle. Possible causes could be mechanical instabilities when re-positioning the linear ball bearings of the LDI carriage or when adjusting the beam deflection optics, respectively. Furthermore, whereas local deviations of the grating's line density might lead to a small influence

on the effective beam angle and should be checked therefore, the following influences are likely to be too small for a significant contribution to the measurement uncertainty: angular stability of the LDI laser beam, temperature influence to the optical grating, deviations from flatness respectively straightness of the grating as well as of the ball bearings of the LDI carriage or mirror rail, respectively.

2.1.3.2 Parasitic velocity components

Parasitic velocity components are superposed true components which will be measured by the LDI at the observed surface spot, but which do not contribute to the inertia force affecting the force transducer. Possible causes for these disturbances are non-uniform transverse force components inside the linear air bearing, surface vibrations from excited elastic modes or a rigid body rotation of the reaction mass exited at impact.

Because of the fact that the LDI beam is off-set and oblique with respect to the central axis of body motion, the interferometer is susceptible to possibly superposed transverse velocity components. They would appear if rotational or transverse vibrations of the air-guided mass cubes are excited. This is the case for a violation of the collinear impact condition, e.g. due to a misalignment or an asymmetry inside the force transducer, respectively, which would exert a parasitic torque on the mass body under observation.

Impact experiments proved the existence of a superposed rotational vibration of low frequency. They were identified by simultaneous measurements with two single point LDIs and measurements with a 3-dimensional-LDI, respectively. Figure 5 shows an experimental setup using two LDIs directed at the reaction mass m_2 which carries the adapted force transducer. Both instruments measure at the centres of opposing lateral sides. Thus a rotational vibration results in parasitic velocity components of opposite sign. In order to discern this vibration from a possible lateral vibration, an additional measurement at normal incidence ($\Phi = 90^\circ$) was made.

Figure 6 gives an example for an impact-excited rotational vibration. The measurement was obtained with a 10 kN strain gauge transducer at 10 kN peak amplitude. The pulse duration was about 0,6 ms. The presented velocity signals of two opposing LDIs show a post-impact oscillation of opposite phase and a frequency of about 225 Hz. It is further shown that the oscillation disappears in the averaged signal. And of course, it is not found in the signal of the force transducer.

Compared to the velocity signal, the relative amplitude of the rotational vibration is less pronounced in the acceleration signal. This is due to differing spectral ranges of impact pulse and rotational vibration, respectively. The differentiation process for the calculation of acceleration generally emphasizes high frequencies whereas this vibration has a comparably low frequency. The corresponding differentiated LDI signals of the previous example are displayed in Fig. 7. But the stretched diagram (inlet) reveals

that the opposing interferometers measured slightly different pulse amplitudes and durations. The pulse peak values differ by about 3 %, the pulse durations by about 4 %.

The small amplitude oscillations visible in the stretched inlet may represent surface vibrations due to elastic modes. Further investigations on this problem have to be made.

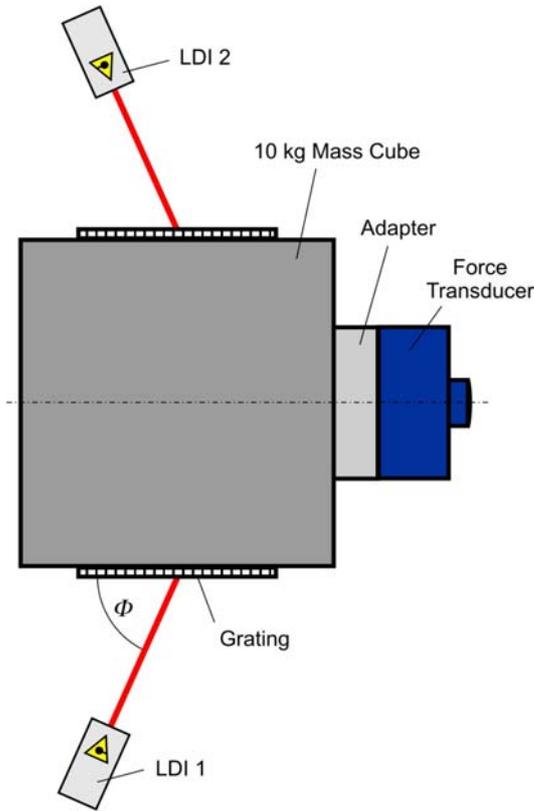


Fig. 5. Identification of rotational vibrations by a simultaneous measurement with two interferometers

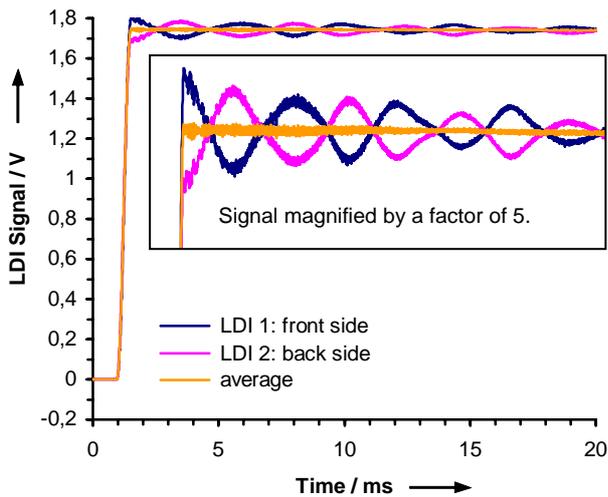


Fig. 6. Simultaneous measurements with two LDIs prove a rotational vibration

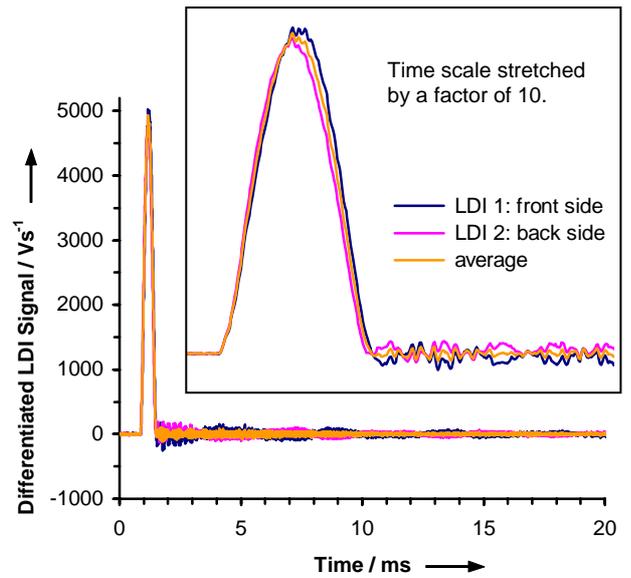


Fig. 7. Acceleration signals of the simultaneous measurements with two LDIs

It has been further experimentally tested that the susceptibility to a rigid body rotation can be strongly reduced by using a measuring beam directed towards the pivot point of rotation. This special geometry is depicted in Fig. 8. In case of a rotation of the mass cube, the observed spot at the surface of the diffraction grating would show no parasitic velocity component towards line-of-sight. It would only have a lateral component, the tangential velocity v_{tan} , for which the LDI is insensitive. Measurements with this optical arrangement are limited to beam angles greater than 60° due to diffraction gratings of 63 mm length.

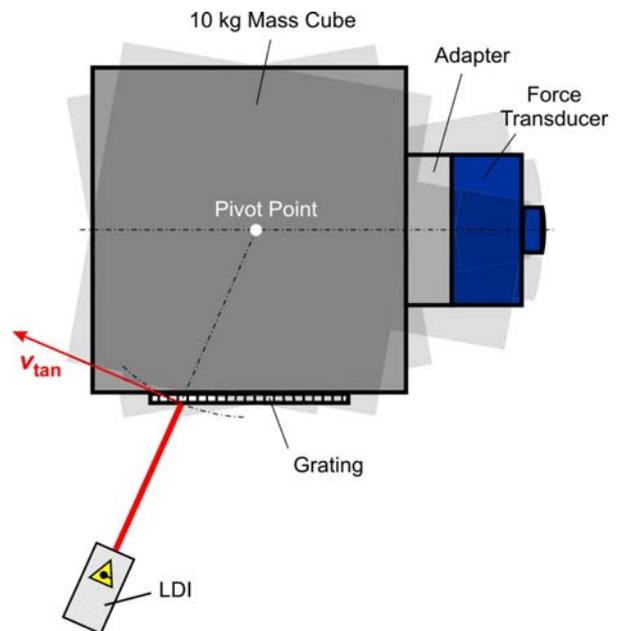


Fig. 8. Measurement geometry for insensitivity to rotational vibrations

2.2. Distribution of acceleration

A single-point LDI provides measurement data for just one observed surface point. Starting with the approximation of rigid bodies and their uniform distribution of motion quantities, a single-point measurement would supply all necessary information. But in reality, the elasticity of matter is the reason for a more or less non-uniform velocity distribution of a body which is subjected to external forces. The evaluation of the true inertia force therefore requires volume integration over all connected accelerated mass elements [1].

The spatial distribution of acceleration depends on the distribution of elasticity and that of the associated mass or density, respectively. Furthermore, the accelerated mass bodies are connected over contact surfaces which behave as non-linear compliances. In this context, the impact surfaces of the colliding bodies as well as the mounting surfaces of mass cube, adaptations, force transducer, load button and pulse shaper should be considered.

Since LDI measurements supply surface data, the effect of a non-uniform distribution of acceleration can only be estimated by modelling, preferably by finite element (FE) modelling. This modelling could also handle complex mechanical structures including the force transducer under test. First investigations showed that this influence might have no big importance [1]. Investigations on this topic will be continued in future.

2.3. Inertia mass

The mass values of the accelerated bodies have to be known precisely in order to evaluate the corresponding inertia forces. Whereas the mass values of the two cubic-shaped steel bodies of about 10 kg and most of the attached bodies like load button, adaptations and pulse shaper can be calibrated in the mass laboratory, where mass is accurately determined by means of weighing, the contributing fractional masses of the force transducer are not well known. Here, information from the manufacturer about the mechanical design of the force transducer would be of great interest in order to describe the influence on the impulse force calibration. A first approximation may be given by a separation into two mass components, i.e. base mass and top mass [4]. In addition, mass components resulting from the transducer's cable are quite ill-defined and vary according to the applied clamping conditions.

2.4. Parasitic forces

Parasitic forces produce superposed acceleration components which affect the impulse force calibration. Possible causes are inertia forces from coupled masses, e.g. from the transducer's top mass and cable, respectively, residual friction and aerodynamic drag from the linear air bearing, slope forces due to an inclination of the air bearings and bending forces of the transducer's cable.

The effect from parasitic vibrations may be measured by additional LDI if specific surface spots of interest can be assessed. A different approach for the estimation of this influence might be offered by a dynamic FE analysis.

The air bearings are slightly inclined in order to assure a defined rest position. Doing so, this inclination generates a small slope force resulting in a superposed uniform acceleration which has to be considered. For a slope angle of $0,07^\circ$, the resulting horizontal acceleration is about $0,01 \text{ m/s}^2$. Accordingly, the parasitic slope force can be estimated to be in the order of 0,1 N, which is $5 \cdot 10^{-5}$ of the capacity of the investigated facility.

Residual friction forces and air drag exert a small braking force on the air-guided mass cubes. These forces can be determined by analyzing gravity-induced slope accelerations for different inclinations of the air bearing. Investigations on frictional forces of a similar measurement setup have been presented in [6].

A comparably strong parasitic force is suspected to be contributed by the electric cable of the force transducer. The cable is fixed at the fundament at some radial distance and causes a reaction force due to bending when the air-guided reaction mass starts moving. At the resting position before impact, the summed parasitic forces of the bended cable, the slope force of the inclined air bearing and the frictional forces are approximately balanced as the air-guided mass is hold at its position.

2.5. Force measurement

An impulse force calibration of a force transducer compares the generated reference force with the output of the force transducer. Therefore, influences belonging to the force measurement chain have to be considered. Possible factors that affect the measurement behaviour of force transducers are temperature and mounting torque. Offset signal as well as sensitivity, linearity or dynamic response behaviour might be more or less affected by these factors. In general, the transducer's susceptibility will depend on its type and technical design.

The influence of the dynamic response characteristic of the data conditioning chain, which consists of the electronic components signal amplifier, data acquisition and filtering has to be further considered accordingly.

3. CONCLUSION AND OUTLOOK

This paper gives an overview about the sources of uncertainty for impulse force calibrations performed at the 20 kN impact force machine at PTB. Various influences were systematically categorized by means of fishbone diagrams and discussed. New experimental measurements could be presented that prove the existence of rotational vibrations which considerably contribute to the overall measurement uncertainty. However, these vibrations might be avoided or their influences might be eliminated by a special optical arrangement.

Whereas numerical data have been collected for some significant contributions to measurement uncertainty so far, several influences still need further investigations. Future activities will compile missing information and will elaborate general schemes for an impulse force calibration before a generally accepted budget of measurement uncertainty can be presented.

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