XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22–27, 2003, Dubrovnik, Croatia

INVESTIGATION OF INTERFEROMETRIC METHODS FOR DYNAMIC FORCE MEASUREMENT

Li Zhang[1] *and Rolf Kumme*[2]

[1]Changcheng Institute of Metrology & Measurement (CIMM), Beijing, China
[2]Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany

Abstract – Dynamic forces realised by accelerated load masses are traceable to acceleration and mass according to the force definition. For the reduction of the measurement uncertainty, the acceleration distribution of the acting mass has to be determined with higher accuracy. This is possible by using laser interferometer and suitable methods for signal processing and data analysis. In particular a method of using heterodyne laser interferometer for dynamic force calibration is investigated. Different signal processing and data analysing methods are compared. A force transducer is investigated with interferometric procedures and it is demonstrated that improvements are possible in dynamic force calibration by laser interferometer.

Keywords: Dynamic force; Laser interferometer; Calibration.

1. INTRODUCTION

Since the demand for the dynamic calibration of force transducers has been increasing, dynamic force calibrating procedures have been developed several years before at PTB force lab [1]. The force transducer to be calibrated is mounted on an electrodynamic shaker, and a load mass is screwed on the top of force transducer (see Fig. 1). According to Newton's law, the dynamic force acting on the force transducer is traceable to mass and acceleration by

$$F=m\cdot a \qquad (1)$$

where m is the total mass acting on the sensing element of the force transducer and a is the time and spatial-dependent acceleration of the mass. Different methods are used to reduce systematic influences caused by non-axial and relative motions of the load mass [1]. In the past, the acceleration was measured by acceleration transducers that are calibrated by interferometric procedures. Due to the high precision of today's mass standards with relative uncertainties of less than 10^{-6}, the mass contribute to the measurement uncertainty can be neglected, therefore, improve the measurement accuracy of acceleration is very important.

Using laser interferometer instead of acceleration transducer to measure acceleration has several advantages. First, it is an absolute measuring method, which is used in national acceleration standards with the best accuracy [2]. Second, it is an noncontact measuring method which eliminate the mass of acceleration transducer from the total mass, therefore, the system acceleration distribution is simplified. At last, compared with acceleration transducers, the interferometric measurement of the distribution of acceleration in a dynamic force calibration facility is more convenient and accurate. The selection of appropriate interferometric measurement procedures is very important. Therefore, different interferometric measurement procedures that were developed in the past in the field of acceleration measurement are investigated specially under the aspect of dynamic force measurement.

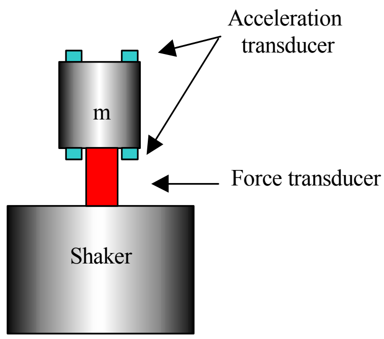

Fig.1. Typical setup for dynamic force calibration using acceleration transducer

2. PRINCIPLES OF USING LASER INTERFEROMETER IN DYNAMIC FORCE CALIBRATION

2.1. System setup

The interferometric calibration facility for dynamic force measurement is shown in Fig.2. A commercial heterodyne laser interferometer is used for dynamic force calibration [3]. Different possibilities of signal processing and evaluations of the measurement data are investigated with this facility. If the output of laser interferometer's velocity or displacement decoder is direct connected to the signal analyser as shown in Fig.2, the measurement uncertainty is limited by the accuracy of the decoder, which has to be calibrated and investigated in detail. Instead of using the output signal of displacement or velocity provided by the interferometer, original measurement signal is processed using a special signal processing system. Software is programmed based on the platform of LABVIEW to control the system and analyse data.

The interferometer is a heterodyne laser vibrometer with fibre optics [3]. Both beams travel down respective fibre optic cables each terminated with 10mm diameter front lenses. The lenses are mounted on a position control device, which can scan a 150mm x 150mm plane, therefore, acceleration distribution can be measured. Instead of the signal analyser, an ADC card is used to measure different output signals of the interferometer and the optical signal processing system. An analogue output channel of ADC card is used to control the shaker. To improve the accuracy, HP3458A digital multimeter is used to measure the output of force transducer synchronously with the measurement of ADC card.

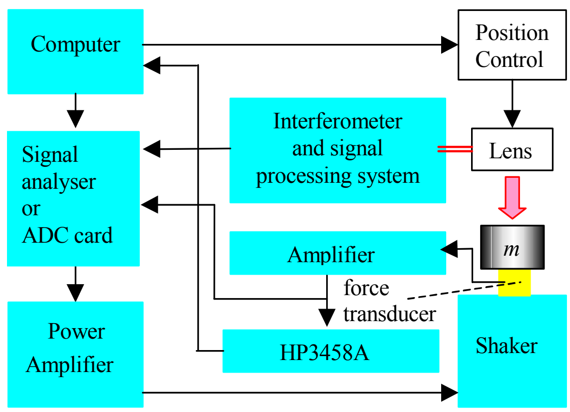

Fig.2. Set-up for dynamic force calibration using laser interferometer

The optical signal processing system is based on the developments in the acceleration section of PTB [2]. When the laser vibrometer works at single lens mode (not in differential mode), the optical and signal-processing system can be simplified as Fig.3. The heterodyne interferometer uses an acoustic-optical modulator (Bragg cell) to generate frequency shift of f_B=40 MHz in one arm of the interferometer [3]. This generates a frequency modulated carrier signal in the RF region, whose centre frequency is identical to that of the acousto-optical modulator drive signal (40 MHz). The directionally sensitive Doppler information is thus contained in the RF carrier. The signed object velocity of mass determines sign and amount of frequency deviation with respect to the centre frequency $f_B \pm \Delta f$. The vibrometer output signal f_B and $f_B \pm \Delta f$ then mixed with signal generator output signal f_s , after mixing and low-pass filtering the output signal turn to $f_s - f_B \pm \Delta f$ named as U_m and $f_s - f_B$ named as U_{ref}. If f_s is 41MHz, then the output signal frequency after mixing is from around 40MHz down to around 1MHz, therefore, they can be sampled by ADC card and needn't using a very high sample frequency [4].

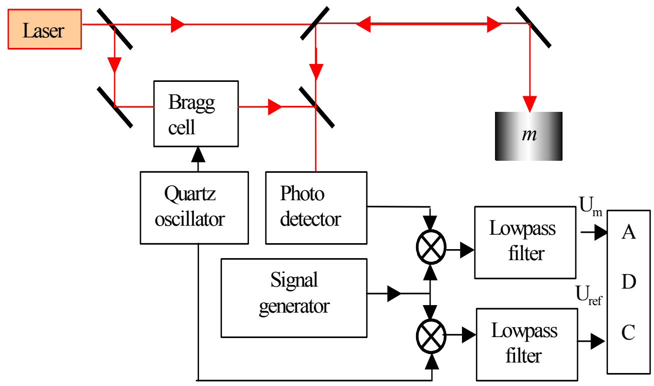

Fig.3. Interferometer and signal processing system

2.2. Data analysing

The digitized signals of laser vibrometer and force transducer are processed, which are showed in Fig 4. $U_m[n]$, $U_{ref}[n]$ and $U_t[n]$ are discrete-time signals which are sampled by ADC card and digital multimeter. U_m and U_{ref} are output signals of interferometer system, which are sampled by 12bit ADC card. The ADC card has four input channels and can sample four channel signals with maxim frequency 5MHz synchronously. U_t is the output signal of

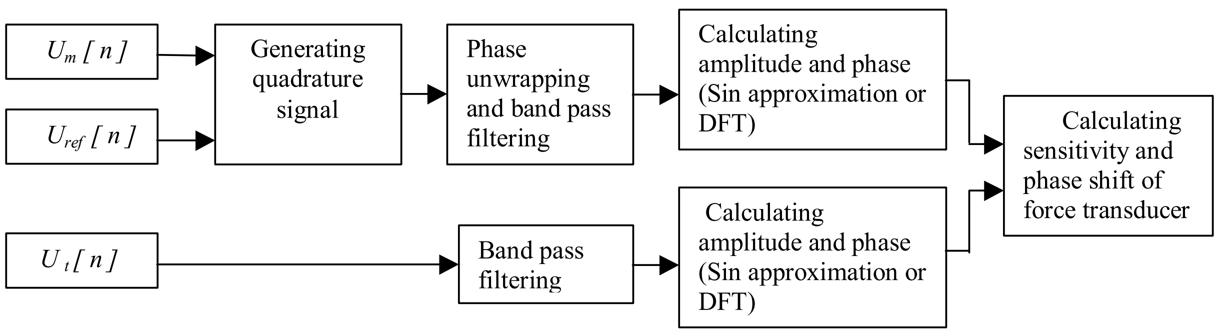

Fig.4. Data analysing procedure

force transducer that is sampled by Hewlett Packard 3458A digital multimeter, which is synchronised in time domain with ADC card.

$U_m\ [n]$ and $U_{ref}\ [n]$ are processed with delaying, multiplying and lowpass filtering procedures to generate quadrature signal $U_1\ [n]$ and $U_2\ [n]$, which have phase shift of 90 degree. Then the displacement $s[n]$ can be calculated by phase unwrapping procedure (2).

$$s[n] = \lambda / 4\pi \left(\arctan \frac{U_2[n]}{U_1[n]} + k\pi\right) \qquad (2)$$

where λ is wave length of laser and k is integer. The displacement amplitude and phase angle s_{Amp} and s_{Pha} can be calculated from $s[n]$, then the acceleration amplitude and phase a_{Amp} and a_{Pha} can be obtained by

$$a_{Amp} = 4\pi^2 f^2 s_{Amp}$$
$$a_{Pha} = \pi + s_{Pha}$$

(3)

f — calibration frequency

The force transducer output amplitude and phase angle U_{tAmp} and U_{tPha} can be calculated from $U_t[n]$. From U_{tAmp} , U_{tPha} , a_{Amp} and a_{Pha} ,the sensitivity and phase shift of force transducer can be calculated using the method introduced in section 3.

It is very important using discrete time sinusoidal sequences $s[n]$ and $U_t[n]$ to calculating the amplitude and phase of them. At every calibration frequency f, only the amplitude and phase of this frequency need to be calculated, so band pass filter can be used to reduce the level of noise. The type and parameter of the filter should be selected carefully to reduce the different kinds of noise. Improperly using filter will result in amplitude and phase error.

There are two methods used to calculate the amplitude and the phase from discrete time sinusoidal data series. One method is called sine-approximation [5], which uses least square method calculate the amplitude and phase of displacement. Another method is called DFT, which uses the discrete-time Fourier transform method calculate the amplitude and phase according to the calibration frequency. Digital simulation and experiment showed that the first method could gain good result if the vibration harmonic distortion and noise are in low level; otherwise, DFT method can attain better result. When using sine-approximation method, one should pay attention to another problem. If the signal frequency is not very accurate, the result of sine-approximation will have large deviation, but the error of DFT method is less obvious in this case.

Experiments were made using different signal analyse methods. Fig.5 is one of the results, which shows the relative deviation between the result of DFT and sine-approximation. Axis Y represents the relative deviation of displacement amplitude. The displacement amplitude is from 500000ηm at 20Hz decrease to 100ηm at 5kHz, at the same time, the signal noise ratio decreases at high frequency. This is the reason why the relative deviation increasing when the calibration frequency over 1,6kHz. It should be point out that at each calibration frequency, the deviation distributed randomly every times, which could be reduced by average.

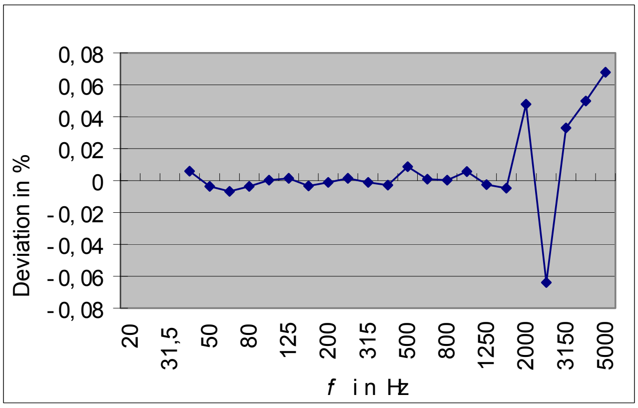

Fig. 5. Relative deviation between the result of DFT and sine-approximation

2.3. Comparison of acceleration measurement with PTB acceleration lab

The uncertainty of acceleration measurement can be evaluated in the way introduced in [5]. To get more information of the accuracy of this system, inter comparison was made between PTB force lab and acceleration lab, which has the Germany national acceleration standards. The comparison is made in different mode.

Mode 0, calibration of charge amplifier. During the comparison, charge amplifier is calibrated several times by both labs using respective calibration system;

Mode 1, comparison of acceleration measurement using laser vibrometer. Both labs using respective laser vibrometer and calibration system take measurement of acceleration at the same time. The measuring point of two vibrometers is nearly same, which located at the top of shaker.

Mode 2, comparison of interferometric signal processing system and software. Two laser vibrometer's output signal are parallel taken by both measurement system of two labs. Therefore, the signal processing systems have the same interferometric signal to processing.

Mode3, Calibrating B&K 8305 standard acceleration transducer at the high frequency shaker of acceleration lab. At first, using acceleration lab calibration system calibrates acceleration transducer, then using force lab calibration system control the shaker and calibrate the same transducer. There are two laser vibrometer used in the whole procedure, and the both acceleration and force lab using the same laser vibrometer.

Mode 4, Calibrating B&K 8305 standard acceleration transducer at force lab. Heterodyne laser vibrometer with fibre optics and different shakers used for dynamic force calibration are used to calibrate acceleration transducer. The calibration system of acceleration lab doesn't attend this mode work.

The detailed results of this inter comparison will be present in other paper. Only the most important conclusions are reported at here. The results of mode 1 show that from

20Hz to 5kHz, the deviation of acceleration between the calibration system of force lab and acceleration lab is within 0.1%. This means that using laser vibrometer the acceleration measuring deviation of both lab is within 0.1%. Mode 3 and mode 4 use different system to calibrate accelerometer. Compared with mode 1 , the measurement of the output of accelerometer is added in this case. The relative deviation of accelerometer sensitivity that is calibrated by both labs using different shaker is within 0.2%, which is perfect result nowadays [6]. The detailed results of the whole comparison will be published in future.

3. RESULT OF CALIBTATION OF PIZEOELECTRIC FORCE TRANSDUCER

Equation (1) is an ideal formula that can only be used in the low frequency range. Due to the finite elasticity of the material used for the masses, the continuum vibration must be taken into account. The dynamic force should be determined from acceleration distribution $a(x,t)$ and the mass distribution with density $\rho(x)$ (where x is the location in space) according to

$$F = \int_V \rho(x).a(x,t)dV \tag{4}$$

The distribution of acceleration on the mass surface can be measured by the dynamic force calibration system by scanning the laser measuring point on the surface of the load mass with the position control system. Therefore, the distribution of acceleration at any location can be calculated by FEM or by analytical approximation [1]. The mass of adapter to mount transducer and end mass of transducer must be taken into account. The end mass means the part of the transducer mass situated between the sensing element of force transducer and the point of force introduction.

A piezoelectric force transducer is calibrated using the system introduced in this paper. Different mass block are used to calibrate the transducer and calculate the end mass of transducer. The acceleration is measured at the top surface of mass block. Analytical approximation formula introduced in [1] is used to compensate acceleration distribution.

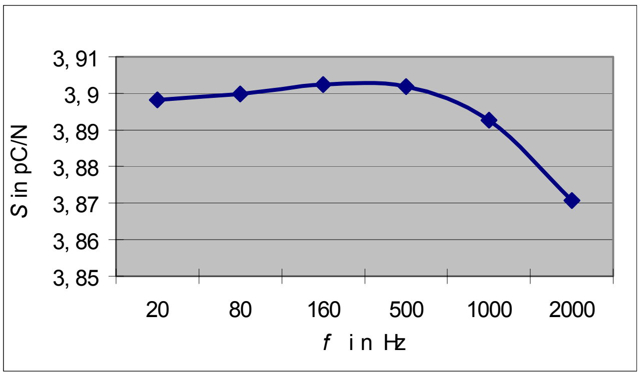

Fig. 6. Calibration result of force transducer

The final result of the dynamic sensitivity is plotted in Fig. 6 for a few frequency points to demonstrate that the interferometric procedure can be used for dynamic force calibration.

4. CONCLUSION

Dynamic force calibration can be improved by using laser interferometer. The results of this investigation have shown that the selection of an appropriate optical and signal processing system is very important. Methods like developed for national acceleration standards are used to determine the acceleration distribution and the acting dynamic force.

Acknowledgments

The authors would like to thank Mrs. A. Täubner, Mr. W. Wabinski and Dr. H.-J.v.Martens from the acceleration lab of PTB for advice and support in the field of interferometric acceleration measurments.

REFERENCES

[1] R. Kumme, Untersuchung eines direkten Verfahrens zur dynamischen Kalibrierung von Kraftmeßgeräten — ein Beitrag zur Verringerung der Meßunsicherheit, PTB-Bericht MA-48. 1996

[2] H.-J.v.Martens, A.Täubner, W. Wabinski, A. Link, H.-J. Schlaak, "Traceability of vibration and shock measurments by laser interferometry", Measurement, 28 (2000), pp.3-20.

[3] A.Lewin, H. Selbach, F.Mohr, Heterodyn-Interferometer zur Vibrationsanalyse, Technisches Messen 57 (9) (1990) pp.335-345.

[4] W. Wabinski, H.-J.v.Martens, Time interval analysis of interferometer signals for measuring amplitude and phase of vibrations, Proceedings 2nd International Conference on Vibration Measurements by Laser Techniques, Ancona, Italy, 1996, pp.166-177.

[5] International Standard ISO 16063-11, Methods for the calibration of vibration and shock transducers- part11:Primary vibration calibration by laser interferometry,1999.

[6] H.-J.v.Martens, A. Link, H.-J. Schlaak, A.Täubner, W. Wabinski, Christof Weissenborn, Investigations to assess the best accuracy attainable in accelerometer calibrations. Proceedings of SPIE Vol. 4827 (2002) , pp.258-276.

Authors:
Li Zhang, Changcheng Institute of Metrology & Measurement, P.O. Box 1066, Beijing 100095, China, Tel +86 13901322086, Fax +86 1062456138, Email: Zhangli@bj163.com
Rolf Kumme, Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany, Tel. +49 5315921121, Fax. +49 5315921205, Email: Rolf.Kumme@ptb.de