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LASER VIBROMETER CALIBRATION AT HIGH FREQUENCIES USING CONVENTIONAL CALIBRATION EQUIPMENT

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Abstract − The calibration of Laser vibrometer is an increasing demand in industry and research. The equipment suggested for use in particular for high frequency calibration, however, is typically of prototype stage and not commercially available. This is due to the demand of the employed homodyne quadrature method for a certain minimum displacement, typically a quarter of a wavelength, of the vibrating object. The authors demonstrate that this is not necessarily a compulsory condition. With conventional, commercially available components it is possible to set-up a system for Laser vibrometer calibration up to 90 kHz. This could be achieved by employing a distinctive optical set-up combined with an unusual (dual frequency) excitation and an improved or extended signal processing.

Keywords Laser vibrometer, calibration, multisine

1. INTRODUCTION

Laser vibrometer as non contact measuring devices without inertia effects on the measured object are ideal instruments to measure high frequency mechanical vibrations, e.g., in the field of MEMS technology. Accordingly the technical specification of current commercial devices state a applicable frequency range from DC to several MHz. In order to support such technical specification a calibration is necessary, which in the optimal case is an overall measurement on a system which provides a well defined motion quantity like acceleration, velocity or displacement. However, for frequencies beyond 20 kHz it becomes increasingly difficult to provide such a well defined motion with sufficient amplitude, due to limitations in the performance of the electrodynamic motion exciters. For the application of the so called “arctan-method” in combination with a homodyne quadrature interferometer a displacement amplitude of approximately 160 nm is required. At 50 kHz this is equivalent to an acceleration of approx. 15,8 km/s² and at 100 kHz an acceleration of approx. 63 km/s² would be necessary. This is not feasible with any commercial electrodynamic exciter. The reason for the displacement requirement is the need for at least one full interference fringe included in the signal to apply the non-linearity correction [1, 2].

In fact this requirement is essential for the evaluation of the interference signal [3], however, it is not essential to fulfil it at the nominal, high frequency. Starting from this observation the authors developed a Laser vibrometer calibration set-up, where the excitation was provided with a dual frequency signal, including a low frequency component providing the necessary displacement and a high frequency component used as nominal calibration frequency.

In order to cope with this type of signal in the data analysis the usually applied sine-approximation method was extended.

2. THE TECHNICAL SET-UP

2.1. The optical arrangement

The optical set-up makes use of a kind of beam recycling, i. e. the Laser beam of the device under test (DUT), a commercial heterodyne Laser vibrometer (Polytec. OFV 503), is re-used as the Laser source for a modified Michelson interferometer (MMI), which is the reference. The general scheme is depicted in fig. 1. The light emitted from the DUT is circular polarized (“circ.” in Fig. 1). In order to adjust the polarization in the beam line of the MMI the quarter waveplate L/4 is included in the reference beam. It was the experience of the authors that the rotational position of L/4 needs to be adjusted individually in order to get maximum quadrature in the I and Q signal.

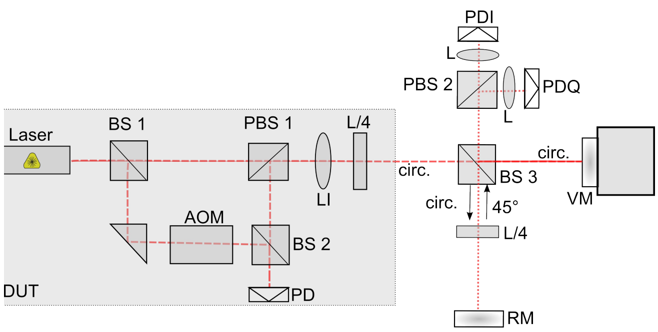


Fig. 1: Optical arrangement for the Laser vibrometer calibration combining a heterodyne and a homodyne-quadrature set-up using the DUT as the single Laser source.

2.2. The vibration excitation part

The vibration exciter used, was a Brüel & Kjær type 4809, which has a membrane borne armature of 60 g. Mounted on top of the armature was a solid piece of steel of a mass of 10 g, with a polished surface acting as the vibrating mirror (VM in Fig. 1, Photograph in Fig. 2).

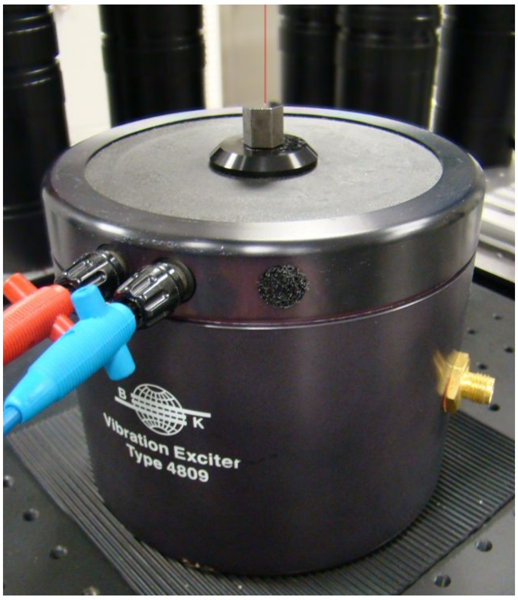


Fig. 2: Commercial vibration exciter with mounted steel reflector

The electrodynamic exciter was driven via a BEAK BA 500 power amplifier, which in turn was connected to an arbitrary waveform generator (AWG, Agilent 33220A). The above mentioned dual frequency signal was stored in the user memory of the AWG before measurement. Fig. 3 shows typical waveforms for a frequency ratio of 1:10 and an amplitude ratio of 1:4 in voltage.

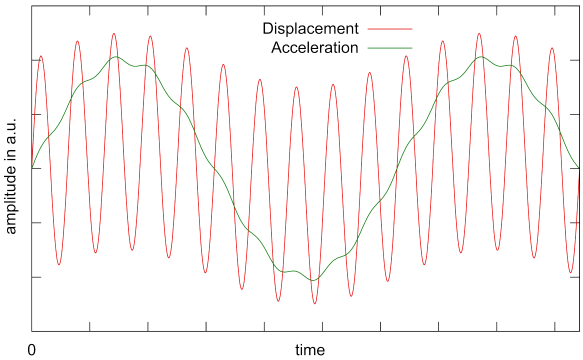


Fig. 2 Calculated signals of displacement and acceleration from the dual frequency excitation for the ratios mentioned in the text.

Considering that the force and therefore the acceleration is roughly proportional to the applied voltage the given ratios result in a displacement ratio of 25:1. Thus in combination with the technically required 160 nm low frequency displacement amplitude a high frequency amplitude of 6,4 nm could be realized.

2.3. The Data acquisition

Four data channels were synchronously acquired for the measurement, the I and Q signals of the MMI as reference, generated by the photo diodes PDI and PDQ, respectively, the frequency modulated output (FM) of the DUT and the velocity proportional analogue output (VEL) of the DUT. Note, that the FM is a modification of the commercially available device, provided for the specific use at PTB. All channels were sampled with 50 MS/s at 12 Bit resolution.

Synchronization is achieved by employing a common clock line running at 10 MHz which is connected to all components but the transient recorder. The ADC cards used here could only be driven by a 20 MHz clock. Therefore it was necessary to provide this clock rate with the help of a supplementary frequency generator (G2) which was in turn synchronized with the common 10 MHz clock signal. The common clock signal was retrieved from the internal clock of generator G1.

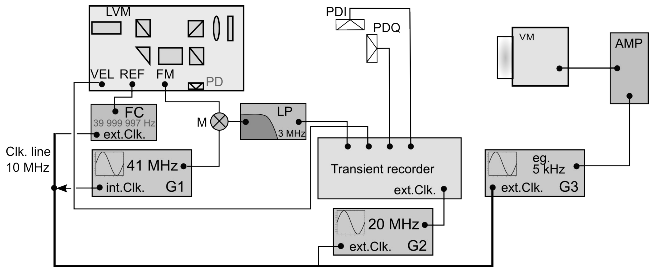


Fig. 3 Diagram of the data acquisition and vibration excitation set-up including the synchronization.

Note that the frequency counter FC was synchronized, too, in order to have the measurement of the carrier frequency of the DUT, i.e. the carrier frequency of FM, on the same time scale.

3.2. The data processing

The digital demodulation of I-Q-data from MMI set-ups has been described extensively in literature and should not be discussed in detail here. However, it is worth to mention, that the non-linearities were treated with the Heydeman-correction [1].

The demodulation of the FM is done by first down mixing the provided 40 MHz carrier frequency of the signal to 1 MHz. With this convenient carrier frequency the signal is sampled and subsequently synthetic I and Q signals are generated by digital mixing with sine and cosine time series. The method is described in some more detail in [4]

After the respective demodulation the two channels of the MMI resulted in a displacement timeseries as did the single FM channel of the DUT. This two derived displacement signals were subsequently differentiated in order to derive velocity. This was done with the intention to diminish the influence of low frequency disturbances. A second differentiation would have increased the amplitude of the high frequency part, however it would increase the disturbances due to noise as well. Therefore, the evaluation as velocity (as in contrast to displacement or acceleration) turned out to be best suited in an overall sense.

The velocity signal, VEL did not need any processing in terms of demodulation. For this output, which is typically used in industrial applications, the demodulation is done internally in the DUT and a velocity proportional voltage output is supplied. Note, however, that this paper focuses on the comparison of the MMI and the FM. The processing of the VEL channel would be straight forward and almost identical. For the internal use at PTB, however, it is of little concern.

3.2. The data analysis

The established method to analyse calibration data based on sinusoidal excitation is the "sine-approximation method" defined in ISO 16063-11. For this method a function of the form

$$v(t) = a \cdot \sin(\omega t) + b \cdot \cos(\omega t) + c \tag{1}$$

with known angular frequency $\omega = 2\pi \cdot f$ is fitted by linear least squares to the sampled data of a sinusoidal signal.

This scheme can be easily extended to the case of the dual frequency excitation. For this case two more component amplitudes a_2 and b_2 are introduced to fit the amplitude components of the second angular frequency $\omega_2 = 2\pi \cdot f_2$. Thus the fit-function becomes

$$\begin{aligned} v(t) \quad = \quad & a_1 \cdot \sin(\omega_1 t) + b_1 \cdot \cos(\omega_1 t) \\ & + a_2 \cdot \sin(\omega_2 t) + b_2 \cdot \cos(\omega_2 t) + c \end{aligned} \tag{2}$$

The knowledge of the frequency is crucial to the performance of the fit, i.e. the precision of the resulting magnitudes

$$\hat{v}_1 = \sqrt{a_1^2 + b_1^2} \quad \text{and} \quad \hat{v}_2 = \sqrt{a_2^2 + b_2^2} \tag{3}$$

and initial phase values

$$\varphi_1 = \tan^{-1}(a_1 / b_1) \quad \text{and} \quad \varphi_2 = \tan^{-1}(a_2 / b_2) \tag{3}$$

which is one reason for the extensive synchronisation effort. Fig. (5) gives an impression of the result of the fitting procedure. The plot depicts a set of samples representing one of the velocity channels (FM after the data processing) together with the approximated low frequency vibration velocity (at 10 kHz) and the respective high frequency vibration velocity at (80 kHz).

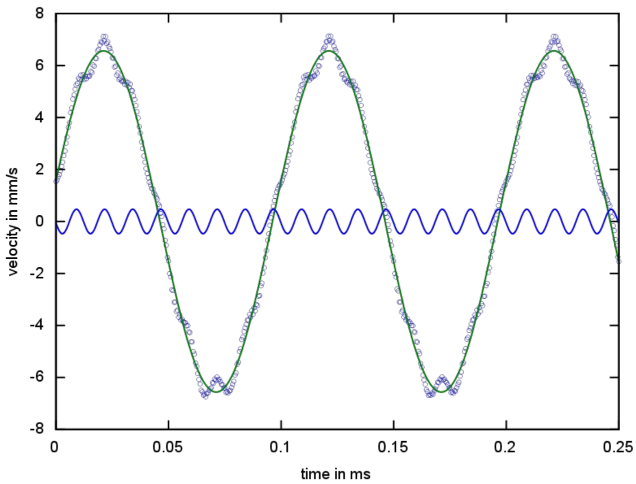


Fig. 5: Plot of the digitized and processed velocity data of the FM channel (circles) together with the approximated low frequency and high frequency vibration functions.

After fitting the two different data channels (MMI and FM) the results were compared in terms of relative magnitude deviation to the reference (MMI) and absolute phase deviation to the reference. The preliminary quantitative results are given in the next section.

4. PRELIMINARY RESULTS

As described above, the results were taken as comparison values of the DUT (FM output) vs. the MMI as reference. The magnitude deviation between MMI and MMI and DUT is given as a relative root mean squared deviation RMSD with

$$RMSD = \frac{\sqrt{\sum_k (\hat{x}_{\mathrm{FM}} - \hat{x}_{\mathrm{MMI}})^2}}{\sum_k \hat{x}_{\mathrm{MMI}}} \quad ,$$

while the phase $\Delta\varphi$ deviation is given in absolute terms in degree and as the standard deviation $\sigma_{\Delta\varphi}$ of repeated measurements. Frequencies combined in one measurement, *I.e.* in one dual frequency excitation, are reported in subsequent lines of table 1.

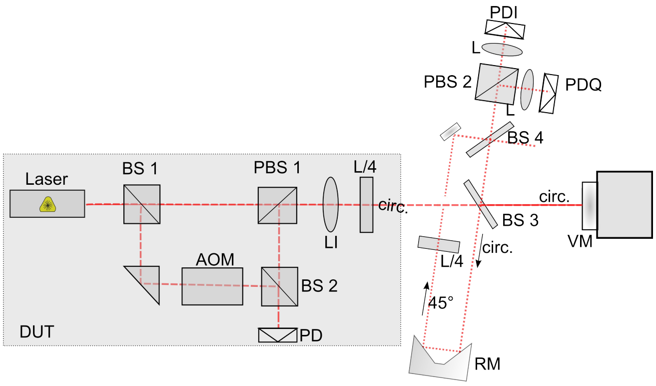
table 1: preliminary results of the Laser vibrometer calibration with dual frequency excitation

Low/high frequency in kHz	**Magn. $\hat{x}_{\mathrm{DUT}}$ in nm**	**Magn. Dev. RMSD in %**	**Phase dev. $\Delta\varphi$ in °**	**Std. Dev. $\sigma_{\Delta\varphi}$ in °**
10	159,9	0,07	2,5012	0,0022
50	4,3	0,27	12,04	0,37
10	545,5	0,01	2,4658	0,0036
80	8,2	0,46	19,94	0,5
10	419,9	0,03	2,4660	0,014
90	3,1	1,26	22,41	2,2

5. OUTLOOK

The combination of two interferometric set-ups with one common coherent light source poses some complications due to three wave interference effects, which generate some crosstalk between the distinctive interferometers and might even disturb the laser emission. This was particularly encountered with the orthogonally aligned set-up depicted in Fig. 1. A small intentional misalignment, which reduced the retro-reflection of the reference beam into the DUT, reduced the effect to an extent which enabled the reported measurement results. In order to eliminate these problems, the set-up was recently modified as depicted in Fig. 6. This modification guides the reference beam in an optical loop such, that it does not pass BS 3 a second time after reflection at RM. Thus, there is no re-introduction of the reference beam into the DUT. First measurements at standard frequencies exhibited an improvement in the signal to noise ratio of the MMI channels of a factor of three. This substantial improvement make us confident, that even higher frequencies (than 90 kHz), i.e. lower amplitudes can be measured and evaluated with this new arrangement.

Another optimization which is in preparation is concerned with the vibration generation. Due to its electromechanical properties the amplitude of the utilised commercial exciter converges rapidly to zero for the high frequency component. However, the two-frequency excitation can as well be generated with two distinct exciters which are either mechanically coupled or subsequently introduced into the measurement beam. The latter could be accomplished by a folding of the beam.



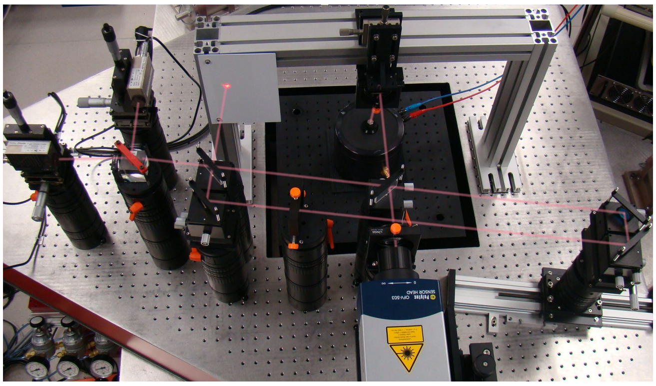


Fig. 6: Optimized set up of the MMI which avoids spurious reflections of the reference beam MMI into the DUT by guiding the beam in a loop .

An exciter which is, according to preliminary investigations well suited to provide the necessary displacement is an electrostatic speaker as it is used for ultra sound generation. This devices are available with a mass of about 20 g, which makes them suitable for mounting on the armature of the B&K exciter which was utilised so far. In preliminary measurements using a Laser-Doppler-vibrometer such a device produced a displacement amplitude of 60 nm at 100 kHz, which is very promising.

6. CONCLUSION

The described method employing a dual frequency excitation for Laser vibrometer calibration using a MMI as reference proofed its validity. Using this method a Laser vibrometer can be calibrated up to 90 kHz (probably even beyond) with conventional equipment. The particular interferometric set-up with “beam recycling” greatly reduces the effort usually necessary for proper optical alignment, in addition it removes the disturbances from relative motion completely. With a modification of the Michelson interferometer reference which avoids re-introduction of the reference beam into the DUT an additional significant performance gain is possible.

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