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PRECISE FORCE MEASUREMENTS BY PHOTO-ELASTIC LASER CRYSTALS IN THE TIME /FREQUENCY DOMAIN

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Abstract: Mechanical forces can be sensed over a very broad input range (10 nN up to 100 kN) with high resolution and linearity by applying the photo-elastic effect in small solid-state lasers (diode-pumped Nd:YAG crystals). The input force vector modulates the optical frequency of the laser crystal. In our experiments sinusoidal, pulse, and transient forces are generated by a PCT drive in a special dynamic test set up. By simple autodyne detection of the laser beam and concurrent signal processing of the electrical beat signal, we can measure sinusoidal forces from DC up to 100 kHz modulation frequency. Frequency counter measurement of pulse forces can be performed within few microseconds. By digital filtering, the final value of structure-induced transient forces can be predicted with high precision in milliseconds.

Keywords: force measurement, force-to-frequency conversion, photo-elastic effect

1. INTRODUCTION

If measurement of static and dynamic forces in mechanic-cal structures is of interest tactile, force sensors must be integrated in the system. These sensors should be very stiff and must have low mass and low internal damping to keep disturbing influences on system dynamics low. And the sensor bandwidth must be broad enough to get static loads as well as the highest mechanical resonances of the structure.

A novel way in high-precision force measurement is detecting frequency detuning and modulation in lasers applying the photo-elastic effect [1-5]. Laser crystals have high mechanical stiffness due to their mono-crystalline structure and no creeping and hysteresis are observed in force measurements. Their frequency output offers a high signal to noise ratio and high measurement resolution. Thus, it is of interest to check the performance of photoelastic laser crystals in detecting very short pulse forces and monitoring of structure-induced vibrations, respectively. Our interest is in precise detection of the Fourier components in the force signal as well as in a fast prediction of the final value of transient forces.

2. MEASUREMENT PRINCIPLE AND MODELING

The minimal configuration of the novel force sensor applies a cylindrical laser crystal (Nd:YAG, 1064 nm) on a stiff support (Fig. 1). If the crystal is optically pumped by a laser diode and subjected to an external force F_x to be measured, it serves simultaneously as an active laser as well as a photo-elastic converter. Due to the force input, a frequency split $\nu_1 - \nu_2$ of the orthogonally polarized modes in the laser beam occurs which can be easily observed as the beat frequency f_{Beat} in the electrical detector output signal. The linear beam polarization indicates the orientation of the input force vector, which –due to the polarization-dependent transfer function of the device [6]– has to be parallel with one of the main axes of the laser crystal.

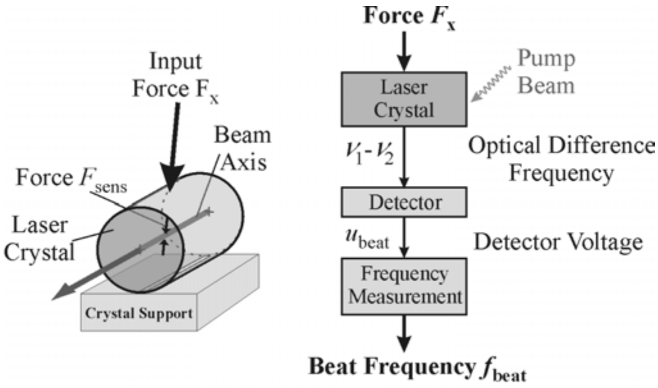

Fig. 1: Minimal configuration of the laser force sensor (left) and signal conversion (right)

Our mathematical modeling of the minimal configuration [4, 6] gains the transfer function of the force-to-frequency conversion (FFC) in the laser sensor:

$$f_{\mathrm{Beat}}(s) = E \cdot F_{\mathrm{sens}}(s) = E \cdot G(s) \cdot F_x(s) \tag{1}$$

Here F_{sens} is the sensed force in the beam axis and E is the static sensitivity of the laser converter. The complex function $G(s)$ describes dynamic response of the minimal configuration. E and $G(s)$ depend on size and material constants of crystal und support [3, 4]. We conclude from the detailed analysis that measurement sensitivity E of the laser converter is independent of measurement bandwidth. This is contrary to other force sensors (for instance strain gauge cells). Furthermore, our detailed theory says miniaturizing of the laser crystal should increase significantly its measurement sensitivity E.

Additionally, we perform a mathematical modeling of our dynamic test set up (see Fig. 2, Chapter 3) to compare experimental data with our sensor model [4]. This model applies a 5-mass system assuming the minimal configuration as a subsystem with very low mass, low internal damping and high stiffness. By the model we can calculate and experimentally check the overall frequency response of the complete test set.

3. EXPERIMENTAL SET UPS AND TEST RESULTS

In our experiments, the laser crystal and a PCT drive are integrated in a special test set up (Fig. 2). For generating time-depending forces F_x acting on the crystal, this test set up can be excited with sinusoidal input voltages as well as with step and transient voltages. The crystal can be subjected additionally to offset forces by mechanical adjustment of the test set up.

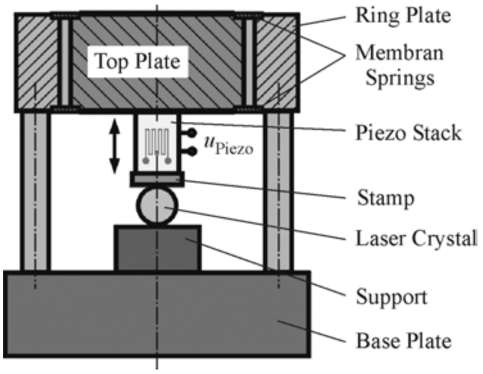

Fig. 2: Test set up configuration

Applying a DC-voltage of 1 V generates 0.1 N static force in the test set up. To get the vibration forces we measure frequency response of our set up by applying sinusoidal driver voltages and spectral analysis as well as by time-domain monitoring of the FM-beat signal [4]. Measured and calculated frequency responses of the test set up are in very good accordance within a frequency range from DC up to app. 100 kHz modulation frequency of the generated force (Fig. 3). On the basis of this accordance we conclude that the dynamic sensor response function $G(s)$ does not depend on modulation frequency, i. e. $G = 1$ in this frequency range. Furthermore our static and dynamic load experiments demonstrate over app. nine decades of the input force that the frequency output (i. e. beat frequency change) of the laser crystal is highly proportional to the applied force. For a typical crystal (size: 3 x 5 mm^2) the smallest detectable forces are in the order of only 10 nN [4].

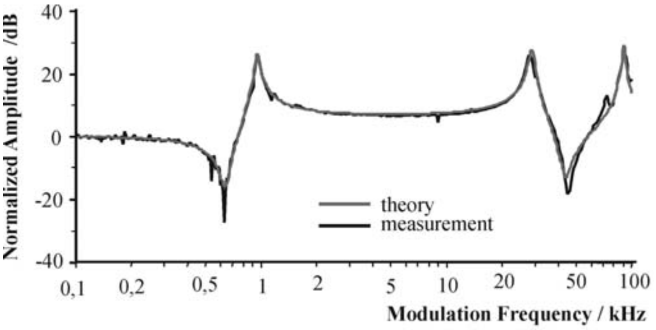

Fig. 3: Amplitude response of the test set up

We can induce damped eigenoscillations in the mechanical structure of the test set up by applying step- and pulse-voltages on the input side and by high-speed frequency counting the beat frequency output. As an example, by applying a high sample rate (333 kHz) the step response of the beat frequency as well as the calculated Fourier spectrum can be observed with high resolution (Fig. 4). Each frequency measurement is performed within a few microseconds up to 12-bit-resolution. The observed mechanical resonance frequencies including the 112 kHz peak are in good accordance with our mathematical model of the test set up [4, 5].

We can get a fast and precise prediction of the static force magnitude (which is equivalent with the DC component in the Fourier spectrum and the final value in the time domain, respectively) by digital low-pass filtering the data of the impulse response at the beginning of the eigenoscillation. Filtering can be done via time domain averaging or FIR-filtering.

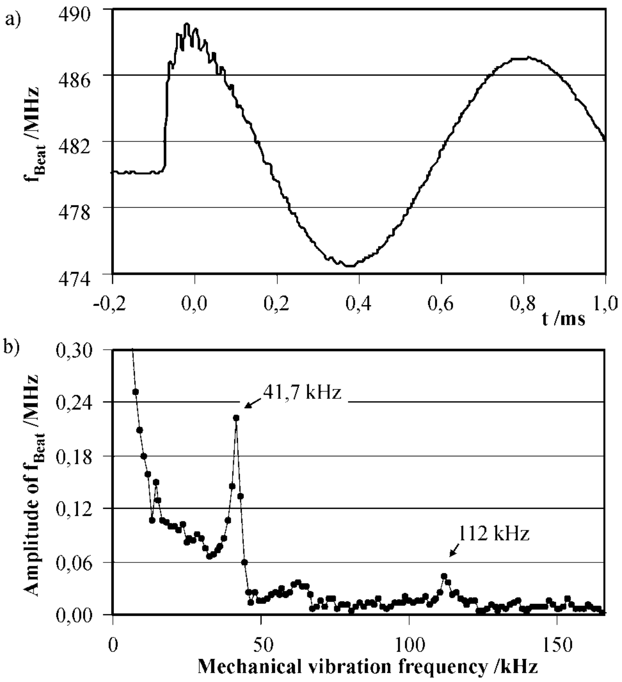

Fig. 4: a) Measured step response of beat frequency f_{Beat} in the time domain (f_{sample} = 333 kHz), b) Spectral distribution of the beat frequency amplitude after Fourier transformation

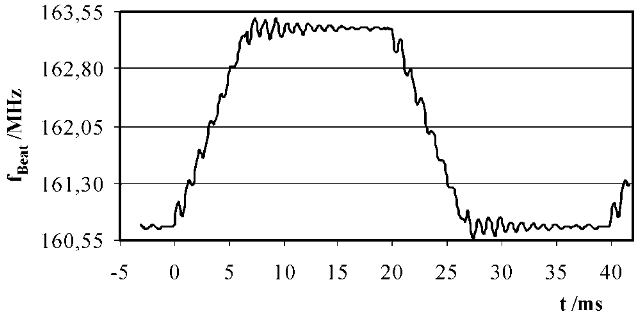

Fig. 5: Response of the test set up to a trapezoid force pulse

Take for example the dominating low frequency eigenoscillation at 1050 Hz in the step response (Fig. 4a). The eigenoscillation is also present after a pulse excitation of the structure. In Fig. 5 the response of the test set up to an input pulse force (trapezoid shape, overall impulse length: 26 ms) is displayed. Due to the low damping in the test set up the duration of this eigenoscillation (approximately 100 ms) exceeds the input force pulse length significantly.

Our experiments demonstrate that the final value of the eigenoscillation can be estimated with accuracies of approximately some 10^{-3} within the first few milliseconds of the oscillation (Fig 6). Step inputs yield higher prediction errors than trapezoid pulses. Increasing the filter-averaging time up to 40 ms has only weak influence on the observed prediction errors. This is true for both applied signal processing procedures (time averager, FIR).

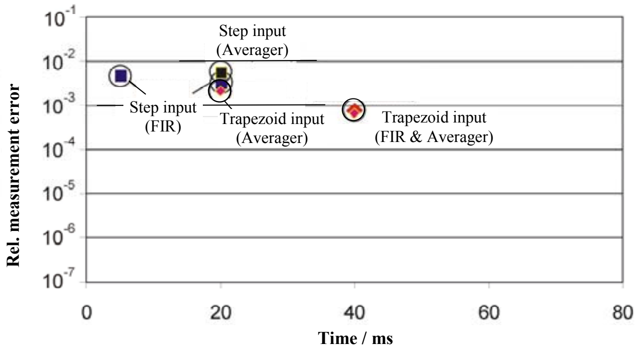

Fig. 6 Relative prediction error versus measurement time (experiment)

4. CONCLUSIONS

The experiments confirm a high performance of the photoelastic sensor in dynamic force measurement. In the sampling mode each individual frequency measurement of the force sensor output can be carried out within few microseconds and modulating forces can be detected free of dynamic distortion within the bandwidth from DC up to 100 kHz. Thus, detection of very short force pulses as well as monitoring of structure-induced low damped vibrations is feasible with high precision and time resolution. By applying digital filters to the frequency output of the sensor, the prediction of the DC-component in the modulating force can be performed in few milliseconds with accuracies in the order of 10^{-3}, i. e. within the first periods of the 1 kHz-eigenoscillation. To our knowledge, this observed performance in combined static/dynamic sensing is superior to competing force sensor principles like strain gauge force meters or piezoelectric transducers.

In our experiments, there could be unused potential of much higher measurement/prediction accuracy of the photoelastic sensor. To explain the uniform accuracy limit of app. 10^{-3} we have performed extended mathematical modeling of digital filtering the FM-signals of the structure induced vibration. Contrary to the experimental facts in Fig. 6, our simulations yield that the prediction error should clearly depend on the digital filter type and measurement time, too (Fig. 7). Accuracy of FIR filters should be more than one

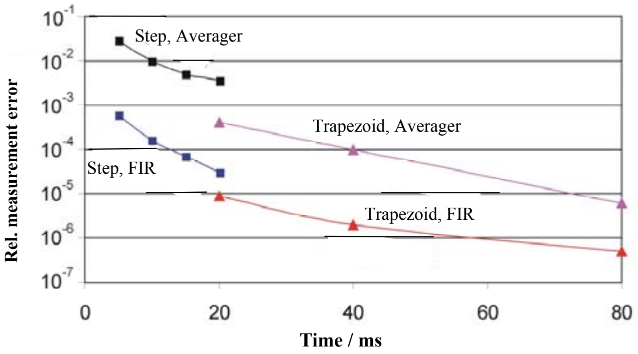

Fig. 7: Relative prediction error versus measurement time (simulation)

magnitude higher than of time averagers and would increase with longer measurement times up to 10^{-6} (FIR, trapezoid pulse). Thus, our experiments and simulations indicate that experimental accuracy in the dynamic experiments could be limited primarily by residual non-reproducibility of the dynamic test set up and not by instabilities in the force sensor itself. This is reasonable to assume because the observed reproducibility and linearity of the characteristics in the static test of the sensor crystals are two magnitudes higher [3, 4, 6].

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