FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA

REMOTE VIBROMETRY FOR CHARACTERISATION OF MATERIALS AND PROCESSES

Ch. Döttinger1), J. Stanullo1), M.L. Lyamshev2), G. Busse1)

1)Institut für Kunststoffprüfung und Kunststoffkunde, Universität Stuttgart,
Pfaffenwaldring 32, 70569 Stuttgart, Germany
2)General Physics Institute, Russian Academy of Sciences,
Vavilovstr. 38, 117942 Moscow, Russia

ABSTRACT

Vibrometry is basically an old technique for defect detection in an empirical way. The use of piezosensors combined with fast data processing have made this technique even more efficient in terms of quantification and frequency range.

However, mechanical excitation of vibration in combination with piezoelectric detection are not always applicable: Samples may be wet or sticky, hot or cold, or just too small to attach even a small sensor to them. In any case, every attached sensor affects the dynamic behaviour (stiffness, mass, losses) of the inspected sample. The only rigorous solution to this problem is remote generation and remote detection of vibration.

We report results of experiments performed with tunable monofrequent excitation which were performed optically by an intensity modulated laser beam. In this case the absorption of periodically deposited energy results in periodical thermal expansion which drives the mechanical excitation. Detection was performed with an interferometric laser vibrometer coupled to a lockin amplifier. The resolution achieved in these measurements was up to 10^{-6}. With this kind of remote mechanical spectroscopy we were able to characterize processes, e.g. drying of paint on polymers and wood, diffusion of humidity into these materials and sintering of ceramics.

INTRODUCTION

Nondestructive characterization of materials in the manufacturing process is a challenging and promising task. The characterization of product quality at different production stages enables the operator to immediately adjust process parameters. However, the difficulty in this approch is associated with the state of the materials, which may be soft, hot or sticky during processing. From this point of view it is important to develop techniques that are capable of characterizing materials in a nonideal state.

Vibration analysis is a well established technique for assessing the quality of processed parts. But the majority of available methods require a mechanical contact between a sensor and the part under test. Optical methods and laser photoacoustic methods specifically allowing to generate and detect mechanical oscillations remotely are more prospective in this regard [1]. Several laser based techniques for materials characterization including photoacoustic methods were reported previously. A laser photoacoustic method for the determination of elastic constants involving an electroagnetic acoustic transducer (EMAT) for the detection of the acoustic signal was reported by Idris et al. [2]. Bayon et al. [3] determined eigenfrequencies of a cylindrical rod using a mechanical impact and interferometric detection. Philp et al. [4] were able to excite resonances of a suspended truck-wheel of mass 57 kg using a pulsed laser and an optical proximity sensor. Despite the large structure under test the excitation energy of the pulsed laser was kept below the ablation threshold. Hane et al. [5], in contrast, tested very small structures using a modulated laser diode for excitation and a beam deflection or interferometric method for detection. With this setup they sensed thickness, attachment, tension and adhesion of samples with geometrical dimensions as small as 1×0.2×0.005 mm^3.

This paper reports the application of a laser photoacoustic vibrometry technique with laser interferometric detection for monitoring of processes such as drying of varnish on polymers and wood and the diffusion of humidity into these materials. This technique has been used previously for the in situ characterization of ceramics during the sintering process [6]. With a modified setup (feed back mechanism) we were able to reduce the time between successive measurements to about one second. Therefore it is now applicable to a variety of short time processes.

EXPERIMENTAL SETUP

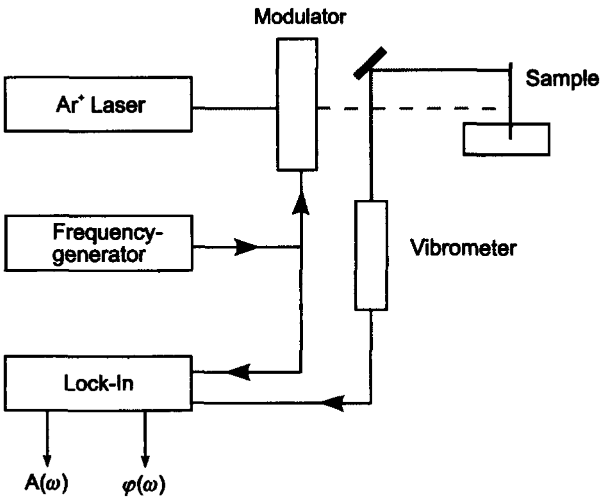

Fig. 1: *Experimental setup for remote excitation and detection of mechanical vibrations*

The scheme of the experimental setup is given in Fig. 1. The CW-radiation of an Ar^+-laser (1.5 W at 514 nm) is modulated by a Bragg-cell coupled to a sine-wave generator. The radiation is absorbed and mechanical oscillations are generated due to periodical thermal expansion. The detection of the mechanical vibrations is performed with a Polytec OFV 3000/OFV 302 laser interferometric vibrometer. The signal from the vibrometer is fed into a lock-in analyzer which uses the signal from the sine-wave generator for reference. The signals for phase and magnitude of the detected mechanical vibrations are directed to a computer and then presented as plots of amplitude and phase vs. frequency. This

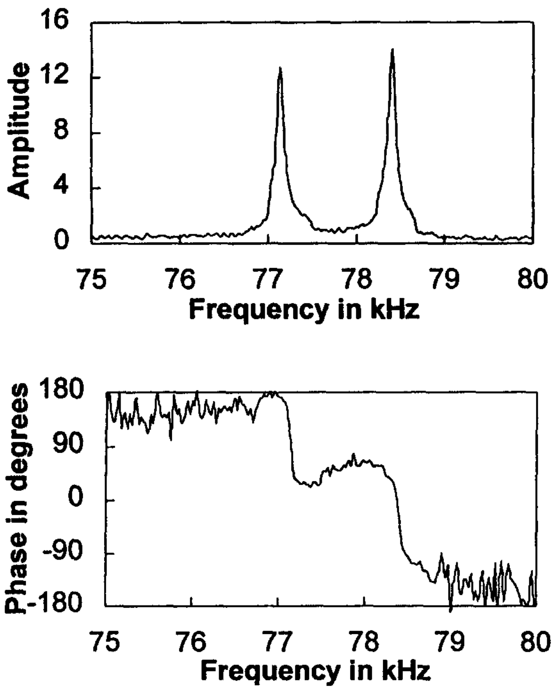

Fig. 2: *Amplitude (top) and phase (bottom) of resonance curve of a ceramic disk. Note that the frequency is above 70 kHz and the presence of the double peak.*

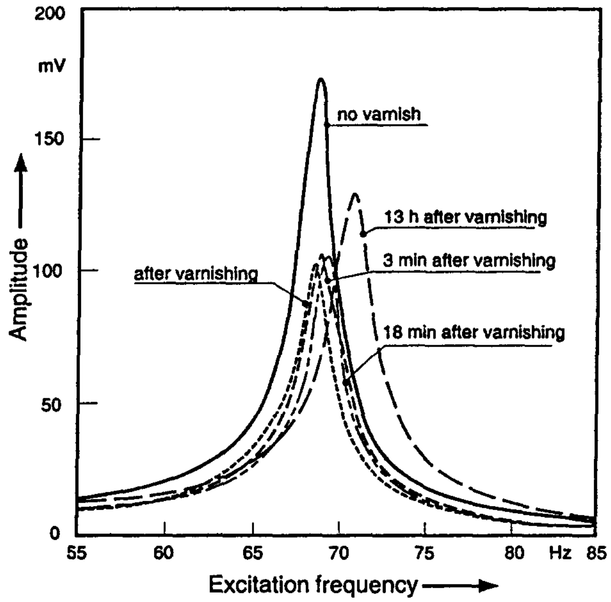

Fig. 3: *Shift of resonance curve during the drying of varnish*

arrangement allows the generation and detection of frequencies ranging from 5 Hz to several MHz. In order to demonstrate the opportunities given by this method, a characteristic resonance curve produced by a ceramic disk with a diameter of 11 mm and a thickness of 5 mm is given in Fig. 2. The resonances shown here are above 70 kHz, well beyond the typical acoustical limit of 20 kHz. Any piezosensor attached to this small sample would seriously affect the boundary conditions and thus probably not resolve the double peak.

A problem occuring frequently in industry is the determination of the instant of time when paint, lacquer or varnish are dried. With photoacoustic vibrometry we were able to to monitor the drying process of varnish on a thin polymer strip (Fig. 3). After varnishing the amplitude drops, because the liquid varnish attenuates the vibration. The amplitude recovers and the resonance frequency increases with time due to a stiffness contribution of the drying varnish.

The setup shown in Fig. 1 requires a time consuming frequency sweep (about two to ten minutes depending on the number of frequencies) for the acquisition of each resonance curve. For monitoring of the drying process it is sufficient to continuously measure the resonance frequency. With this in mind a feedback loop is introduced into the experimental arrangement (Fig. 4) thus forcing the sample to vibrate at the frequency with the highest amplitude - the resonance

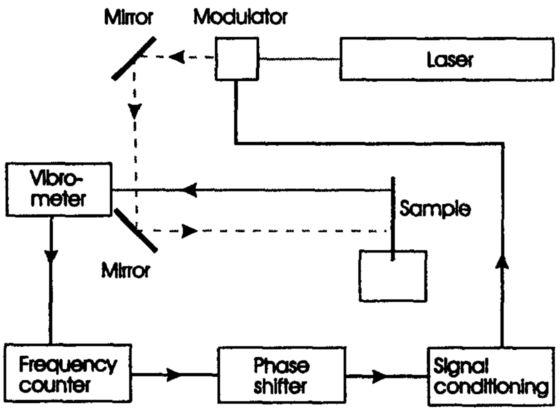

Fig. 4: *Experimental setup with feed back loop*

frequency. A precise frequency counter reads out the current frequency every second. A phase shifter delays the received signal such as to satisfy the resonance condition, i.e. a phase shift of 90° between driving force and resulting vibration. Subsequently the signal conditioning adapts the signal for the acousto-optical modulator, which in turn determines the excitation frequency. The only drawback of this setup is that the information about the width of the resonance curve is lost. This information could be regained by phase shifting the excitation signal by ± 45° and noting the frequency difference, but this way the high data acquisition speed would be lost.

RESULTS

The drying process of lacquer on oak veneer (400 μm thick) as monitored with the modified setup (Fig. 4) is shown in Fig. 5. After the application of lacquer the resonance frequency drops immediately by more than 10%. It shows a steady rise with decreasing slope as the drying proceeds. After 70 minutes the data acquisition was interrupted and resumed four hours later. The final resonance frequency is approximately 27% higher than the original one. Its absolute and relative shift depends on the relative thicknesses of lacquer and veneer, respectively.

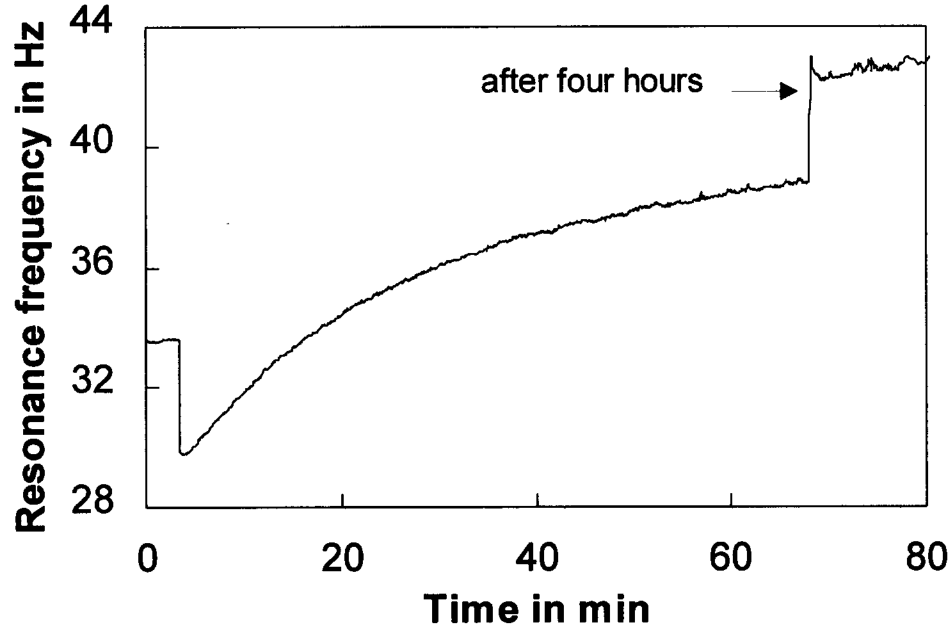

Fig. 5: *Drying of lacquer on oak veneer*

Fig. 6 shows the change in resonance frequency of oak veneer that was dried in an exsiccator prior to exposure to a laboratory environment with 60% humidity. The increasing water contents has three effects that contribute to the observed decrease in resonance frequency:

- a mass increase
- a loss of stiffness
- an increase in damping

As the water contents approaches its saturation the resonance frequency decreases to its asymptotic limit. The discontinuities in the experimental data are due to an occasional break down of the feedback loop.

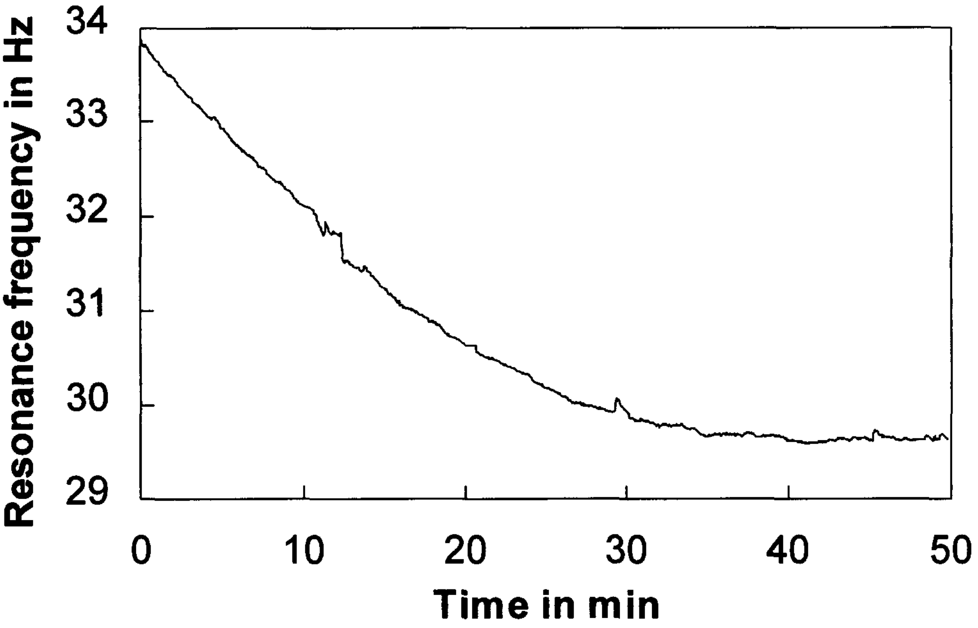

Fig. 6: *Water diffusion into dried oak veneer*

A similar behaviour is observed for water diffusion into polyamide 6 (Fig. 7). The experimental procedure was the same as described above. In contrast to the slow decrease of the resonance frequency of oak veneer, the resonance frequency of polyamide 6 shows a steep decrease immediately after exposure to humidity. This is probably due to a quick diffusion of water through the surface of the hygroscopic polyamide 6, which is slower in the case of veneer. The higher noise level in the data can be attributed to a smaller signal to noise ratio for the polymer, which is a consequence of its high mechanical loss factor and therefore less pronounced resonance amplitude.

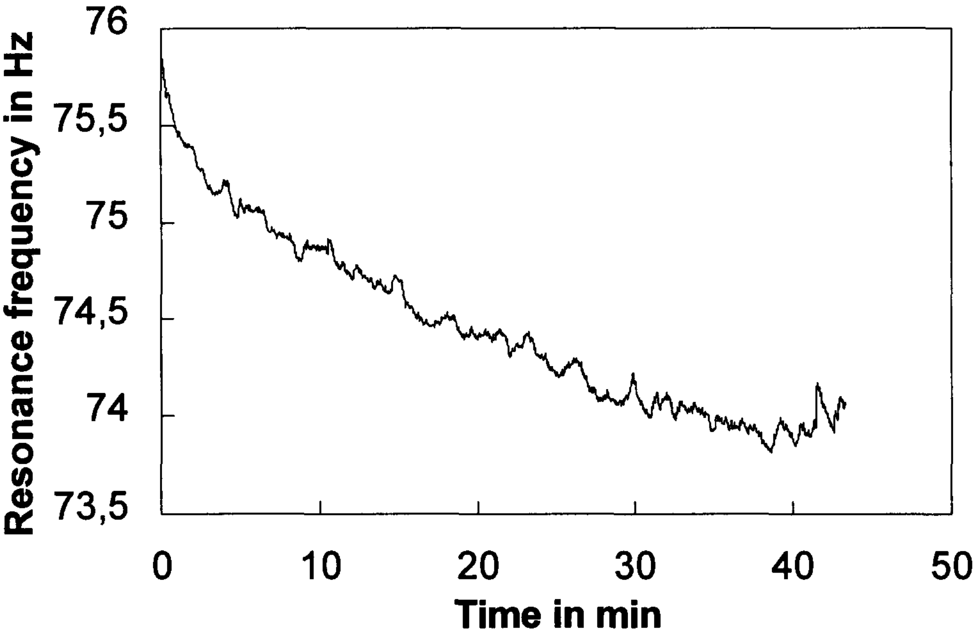

Fig. 7: *Water diffusion into dried polyamide 6*

CONCLUSION

We have demonstrated the potential of remote vibrometry based on laser excitation and interferometric detection for monitoring of processes such as drying of varnish on polymers and wood and the diffusion of humidity into these materials. The key to quick successive measurements — a necessity for monitoring short time processes — was the introduction of a feed back mechanism into the experimental setup.

Potential difficulties of this technique for use in an industrial environment are related to the employment of a powerful laser for the generation of vibrations:

- The sample must absorb at least 10 to 20% of the laser radiation (glass or transparent polymers require blackening).
- For strongly damped samples the high energy needed to excite the vibrations may heat or damage the sample.
- There are some safety regulations that must be obeyed when operating a powerful laser.

A possible solution to these drawbacks is the use of a different method (e.g. acoustical waves) for the excitation of vibrations. We have obtained promising first results with this approach which will be published later.

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