Depth-resolved slow velocity field measurement using wavelength scanning interferometry

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Abstract. This paper presents an approach to measure time resolved out-of-plane displacement of interfaces in multi-layered structures. It is based on wavelength scanning interferometry to provide simultaneous depth-resolved localization and phase sensitive tracking of various interfaces. The average (through the thickness) refractive index and thickness of the different layers can also be established and measured as a function of time. The technique is suitable for the measurement of slow deformation fields such as those induced by mass transport through diffusion (e.g. hygroscopic swelling).

Introduction

Wavelength scanning interferometry, based in low coherence interferometry, provides a convenient way to perform depth-resolved interferometry in multi-layered structures or scattering materials [1-4]. In general, a sequence of smooth-wavefront or speckle interferograms is recorded of a test sample while linearly tuning the laser wavenumber $k=2\pi/\lambda$. Depth-selectivity arises as the frequency of the interference signal is proportional to the optical path difference $\Lambda=2nz$ between the reference wavefront and a point in the object at a roundtrip distance $2z$ from it (out-of-plane sensitivity), through a medium with refractive index n, i.e.

$$f = \frac{\delta k \Lambda}{2\pi} \tag{1}$$

with δk the interframe wavenumber increment. Fourier transformation of the interference signal reveals peaks at frequencies which correspond to interfaces through the thickness of the sample. Depth-resolved phase detection is thus possible to measure depth-resolved displacements. Usually this is done by performing a laser scan with the object in a reference, static condition; a load is then applied and a second scan is performed. Phase changes between scans are then evaluated at all frequencies. This requires high stability during the scans, a well-known limitation in phase shifting interferometry.

Time-resolved phase tracking of multiple interfaces. The tunable laser in fact provides carrier frequencies that are depth dependent and which can be exploited to detect very slow time-resolved changes in the object configuration during the scan. In the case of a stable object, the frequency peaks that correspond to its depth profile remain stable with no frequency (or phase) changes. A linear phase change with constant slope is obtained. However, if the object dimensions or the refractive index change during the scan, the peaks frequencies reflect those changes, which can be tracked by measuring the phase drift from an otherwise linear behaviour. In the Fourier transform frequency domain, this is observed as a broadening of the frequency peaks. Given that the object interfaces are far enough so that the broadened peaks do not overlap in the spectrum, they can be separated by filtering and their time-resolved phase variation (linked to the displacement of each interface) can finally be established. In this way, different interfaces at multiple depths can be tracked independently with high sensitivity.

Maximum velocity. The optical path difference between consecutive interfaces in the object imposes a limit to how fast they can move during the wavenumber scan, so that their spectral responses do not overlap. It can be shown that the maximum relative speed between 2 interfaces separated by a distance z in a medium of refractive index n is given by

$$\dot{z} = -z\delta k\left(\frac{1}{n}\frac{dn}{dk} + \frac{1}{k}\right) \tag{2}$$

In the case of constant refractive index this reduces to

$$\dot{z} = \frac{z\delta\lambda N}{\lambda_c T} \tag{3}$$

where $\delta\lambda$ is the interframe wavelength change when the wavelength is equal to the central wavelength λ_c, and N/T is the framing rate. Notice the independence of Eqn.(3) with respect to the refractive index. As an example, we can take the following characteristic values which correspond to a layer of a (semi-transparent) material onto a rigid substrate and near infrared tunable laser: z=10^{-3}m, $\delta\lambda$=10^{-10}m, λ_c=10^{-6}m and N/T=$10s^{-1}$. In this case, the depth resolution $\delta z \sim \lambda^2/2n\Delta\lambda$ would be approximately 10^{-5}m and the relative velocity between the air/layer and layer/substrate interfaces should not exceed 10^{-6} m/s.

If the time-resolved phase variation is evaluated by spectral filtering in the Fourier domain, then the bandwidth and shape of the filter will determine the maximum measurable velocity.

Conclusion

This paper presents an approach to measure depth-resolved velocity fields using wavelength scanning interferometry. In an imaging interferometer, this approach can be applied in a pixel by pixel basis, thus leading to a spatially resolved (axially and transversally) velocity field to study slow mechanical responses. This makes the technique suitable for the measurement of slow deformation fields such as those induced by mass transport through diffusion (e.g. hygroscopic swelling) or the determination of the associated strain.

References

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