DOI 10.5162/SMSI2020/D1.3

Increasing the sensitivity in the determination of material parameters by using arbitrary loads in ultrasonic transmission measurements

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Summary

Due to the increased use of polymers in research and industry, the non-destructive determination of material parameters is gaining importance. In order to determine the material parameters of a polymer, transmission measurements through waveguide specimens can be evaluated. However, sensitivity analyses show a high uncertainty in the determination of the mechanical shear parameters. As a means to increase the sensitivity to these parameters, different excitations are investigated.

Keywords: ultrasound transducer, sensitivity optimisation, material characterisation, polymers, scaled boundary finite element method

Motivation

The development of measurement systems based on ultrasound becomes increasingly reliant on modelling and numerical simulations, which in turn require a good knowledge of the material's mechanical and acoustic properties. There are several waveguide-based approaches of non-destructive material characterisation, which in general differ not only in the measurement principle chosen but also in the specimen's geometry, e.g. plate-like or cylindrical. This contribution is focused on a measurement setup which applies ultrasound transmission through a hollow cylindrical specimen, and has previously shown low sensitivity to the material parameters that describe the shear behaviour [1]. One approach to increase this sensitivity is to replace the currently applied full-surface excitation of the measuring system by a locally segmented excitation.

Figure 1 shows a schematic of the measurement setup, consisting of a transmitting and receiving transducer and the cylindrical specimen. The material parameters are determined in an inverse procedure, i.e. by minimising the deviation between the measured signal and a simulation result [2].

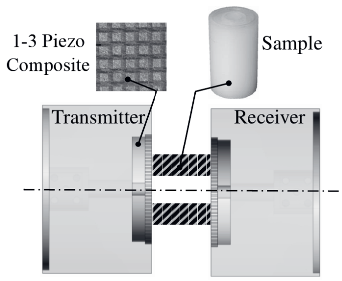


Fig. 1. Measurement system for the characterisation of polymer materials using transmission measurements of a hollow cylindrical waveguide [1].

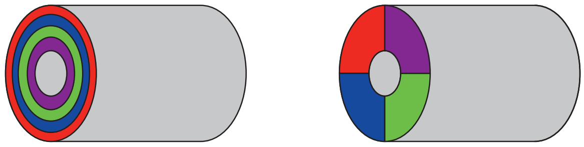
Simulation model

Cylindrical samples are advantageous in that the measurement setup can be kept relatively simple and the forward simulation model for the inverse procedure can be assumed axially symmetrical. The elasticity matrix C describing the material in Voigt's notation, assuming transversely isotropic material behaviour, depends on five independent constants $E_\mathrm{L}, E_\mathrm{T}, \nu_\mathrm{L}, \nu_\mathrm{T}$ and μ_L and is given by

$$C = S^{-1} = \begin{bmatrix} 1/E_\mathrm{T} & -\nu_\mathrm{T}/E_\mathrm{T} & -\nu_\mathrm{L}/E_\mathrm{L} & 0 & 0 & 0 \\ -\nu_\mathrm{T}/E_\mathrm{T} & 1/E_\mathrm{T} & -\nu_\mathrm{L}/E_\mathrm{L} & 0 & 0 & 0 \\ -\nu_\mathrm{L}/E_\mathrm{L} & -\nu_\mathrm{L}/E_\mathrm{L} & 1/E_\mathrm{L} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/\mu_\mathrm{L} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/\mu_\mathrm{L} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/\mu_\mathrm{T} \end{bmatrix}^{-1}.$$

Here, E is Young's modulus, ν Poisson's ratio and μ the shear modulus. As a transversely isotropic material is assumed, a directional dependence of the material parameters is given, indicated by the subscript L for longitudinal and T for transversal direction. The parameter μ_T is given by $\mu_\mathrm{T} = \frac{E_\mathrm{T}}{2(1+\nu_\mathrm{T})}$.

Since segmented loads, e.g. circumferential segments, have to be considered for increased sensit-



(a) Ring segmentation. (b) Sector segmentation.

Fig. 2. Schematic of different segmented excitations.

ivity, a three-dimensional simulation model is necessary. As the transmission pulses have a centre frequency of 1 MHz and above, a standard 3D finite element simulation is not feasible especially for an inverse procedure, as it would require a high spatial discretisation made necessary because of the small wavelength of the acoustic waves. Due to the given axially symmetric shape of the test specimens, the application of the Scaled Boundary Finite Element Method (SBFEM) is particularly suitable [3]. The fact that one direction is solved analytically (in this case the axial direction) leads to improved computation efficiency. SBFEM can be extended to make those segmented loads applicable and provide a sufficiently accurate approximation of the output signal in an acceptable time.

Sensitivity analysis

The dimensionless scaled sensitivity $\Upsilon_{p_i}(t)$ is defined as the scaled sensitivity of the cause p_i to an observation $y(t)$ at an operation point p_i^* [4]:

$$\Upsilon_{p_i}(t) = \left(\frac{\delta y(t)}{\delta p_i} \bigg|_{p^*} \right) p_i^*,$$

In this case, the cause p_i is any of the five independent parameters of the matrix C, and the observation is a result of the simulation, i.e. the mechanical displacement on the back of the hollow cylinder. The sensitivities are determined using the central difference quotient by varying each parameter by $\pm 1\,\%$. Appropriate material parameters similar to polyamide 6 $(E_\mathrm{L} = E_\mathrm{T} = 3.76\,\mathrm{GPa}, \nu_\mathrm{L} = \nu_\mathrm{T} = 0.3157, \mu_\mathrm{L} = 1.36\,\mathrm{GPa}, \rho = 1150\,\frac{\mathrm{kg}}{\mathrm{m}^3})$ are used as the operating point. As an approximation to the transmission signals used in the measurement setup, a Gaussian modulated sine with a centre frequency of 1 MHz is used as an input signal. In both cases of segmented excitation, see figure 2, the signal is phase-shifted by $90°$ between neighbouring segments (Indicated by colour).
Due to the different orders of magnitude, normalisation is useful when quantifying the sensitivities of the material parameters. Figure 3 shows Υ with respect to μ_L with comparable results to Bause et al. [1]. A difference between the full surface excitation compared to one with four radial segments (rings) and four circumferential segments (sectors) becomes apparent. Especially excitation with four rings shows a significant increase in sensitivity. In order to compare the different types of excitation, the composite scaled sensitivity [4] can be calculated:

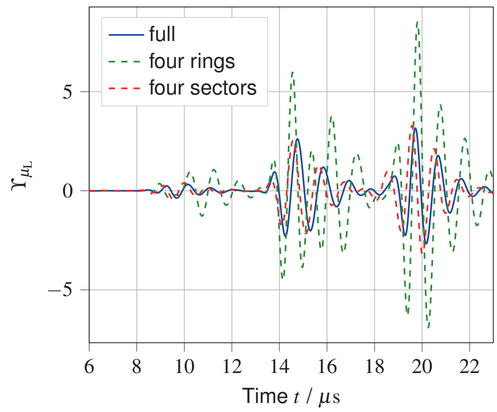


Fig. 3. Dimensionless scaled sensitivity of μ_L with full surface, four rings and four sectors excitation.

$$\overline{\Upsilon}_{p_i} = \sqrt{\frac{1}{T}\int_0^T \left(\Upsilon_{p_i}(t)\right)^2 dt}$$

For an full surface excitation the composite sensitivity is $\overline{\Upsilon}_{\mu_L,\mathrm{full}} = 0.68$. At four circumferential segments depicted in figure 3 is $\overline{\Upsilon}_{\mu_L,\mathrm{sect}} = 0.73$, thus the sensitivity is increased by 7 % with regard to the full surface excitation. Excitation with radial segments (rings) shows $\overline{\Upsilon}_{\mu_L,\mathrm{ring}} = 1.79$, a significant increase by about 150 %.

Conclusion

The SBFEM was successfully used to provide accurate results with circumferential loads. It has been demonstrated that an increase in sensitivity to the shear modulus μ_L can be achieved by a locally segmented excitation. Thereby Υ_{μ_L} increases significantly, especially using a ring segmentation.

Literature

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