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].

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 \( E_L, E_T, \nu_L, \nu_T \) and \( \mu_L \) and is given by

\[
C = S^{-1} = \begin{bmatrix}
\frac{1}{E_T} & -\nu_T/E_T & -\nu_L/E_L & 0 & 0 & 0 \\
-\nu_T/E_T & \frac{1}{E_T} & -\nu_T/E_T & 0 & 0 & 0 \\
-\nu_L/E_L & -\nu_T/E_T & \frac{1}{E_L} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1/\mu_L & 0 \\
0 & 0 & 0 & 0 & 0 & 1/\mu_L \\
0 & 0 & 0 & 0 & 0 & 1/\mu_T \\
\end{bmatrix}^{-1}
\]

Here, \( E \) is Young’s modulus, \( \nu \) Poisson’s ratio and \( \mu \) 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 \( \mu_T \) is given by \( \mu_T = \frac{E_T}{2(1+\nu_T)} \).

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

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

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 ($E_L = E_T = 3.76$ GPa, $Y_L = Y_T = 0.3157$, $\mu_L = 1.36$ GPa, $\rho = 1150 \frac{kg}{m^3}$) 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 $90\degree$ 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 $\Upsilon$ with respect to $\mu_L$ 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:

$$\Upsilon_{p_i} = \sqrt{\frac{1}{T} \int_0^T (Y_{p_i}(t))^2 dt}.$$

For an full surface excitation the composite sensitivity is $\Upsilon_{\mu_L, \text{full}} = 0.68$. At four circumferential segments depicted in figure 3 is $\Upsilon_{\mu_L, \text{sect}} = 0.73$, thus the sensitivity is increased by $7\%$ with regard to the full surface excitation. Excitation with radial segments (rings) shows $\Upsilon_{\mu_L, \text{ring}} = 1.79$, 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 $\mu_L$ can be achieved by a locally segmented excitation. Thereby $\Upsilon_{\mu_L}$ increases significantly, especially using a ring segmentation.

Literature


