An Image Based Inertial Impact Test for the Characterization of Viscoelastic Materials

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Abstract. Polymers often exhibit a strong viscoelastic behaviour that describes the time and rate dependence of their mechanical properties in the elastic regime. These materials are often modelled as a system of springs and dashpots using the generalized Maxwell constitutive model. However, identifying the model parameters on the short time scales associated with high strain rate using common techniques has proven challenging. Here we present a framework for a novel application of the Image Based Inertial Impact test that allows for identification of both the shear and bulk constitutive parameters with associated relaxation time constants on the order of tens of microseconds. We verify the technique with finite element simulations and simulate systematic experimental error on synthetically generated images deformed according to the simulations. Constitutive parameters obtained from synthetic images are found to compare favourably with those obtained directly from the finite element simulations.

Introduction

Polymers typically exhibit a strong viscoelastic behaviour that governs the time and strain rate dependence of their elastic stress response. These viscoelastic materials are often modelled using the generalized Maxwell model which approximates the material as a system of elastic springs and viscous dashpots [1]**.** The incremental stress response of the generalized Maxwell model can be calculated with the algorithm presented in [2].

Identifying the elemental stiffness parameters, C_{ijkl_m} and relaxation time constants, τ_m, using standard high-rate testing techniques has proven challenging. For example, Kolsky bars are generally unsuitable for the characterization of the elastic behaviour of materials due to the requirement that force equilibrium be maintained during the valid portion of the test. Additionally, Kolsky bars typically only probe one stress component at one strain rate per experiment necessitating a large test matrix to fully characterize a material [3,4]. To address these shortcomings, the Image Based Inertial Impact (IBII) Test has been developed. Here, we propose a theoretical expansion of the IBII test method towards the characterization of viscoelastic materials.

The IBII Test

Building upon the framework proposed by Pierron et al [4], the IBII test method has been used to identify the orthotropic high-rate elastic [5] and interlaminar properties of composites [6] as well as to characterize rate dependent plasticity in a titanium alloy [7]. An IBII experiment involves an edge on impact on a thin plate of material generating a plane stress wave that propagates through the specimen. The specimen is instrumented with an ultra-high-speed camera and a quantitative full-field imaging pattern, such as a regular grid. Displacement fields are then obtained from the images and differentiated in time and space to obtain acceleration and strain fields respectively. The constitutive parameters can then be obtained using the stress gauge implementation of the virtual fields method (VFM). The full equations and derivations of the stress gauge implementation of VFM have been omitted for brevity but can be found for a linear elastic material in [6]. Constitutive parameters are extracted through the minimization of a cost function consisting of the square of the difference between stresses calculated from the generalized Maxwell model and those calculated from the stress gauge equations.

Finite Element Verification

To validate using the proposed IBII test method to extract viscoelastic constitutive parameters, an IBII experiment was simulated using Abaqus/Explicit finite element software. The specimen was modelled as a $70\ \mathrm{mm} \times 44\ \mathrm{mm} \times 4\ \mathrm{mm}$ viscoelastic plate and meshed using 4 node quadrilateral plane stress elements. The material was loosely based on polymethyl methacrylate [8], with a single time constant and the properties listed in Table 1. In the table, the subscript ∞ indicates a quasistatic property, and the bulk modulus, K_1, and shear modulus, G_1, are calculated from C_{ijkl_1} using the standard relations between isotropic elastic constants. The impact was simulated with a parametric sweep of uniform pressure impulses applied over half of one 44 mm edge. To investigate the effects of pulse shape on identification accuracy, both smooth symmetrical triangle pulses, and smooth symmetrical trapezoidal pulses, with a rise time of $1\ \mu s$, were simulated. Finally, displacement, acceleration, and in-plane strain fields were extracted at a simulated frame rate of 1Mfps for 128 frames.

$\rho\ (\mathrm{kg/m^3})$	E_∞ (GPa)	ν_∞	K_1 (GPa)	G_1 (GPa)	τ_1 (μs)
1185	2.98	0.26	1.53	0.877	10.0

Table 1 Constitutive parameters used in the finite element simulation of an IBII test

Fig 1 presents a comparison of the errors in constitutive parameter identification for triangular and trapezoidal pulses in a simulated IBII experiment. Identification error increases as asymptotically as pulse duration approaches interframe time and converges below 1% after approximately 20 μs for triangular pulses and 10 μs for trapezoidal. At short durations, parameters are identified more accurately for trapezoidal pulses, but after 25 μs symmetrical triangular pulses result in less error. To probe the systematic errors introduced by the camera resolution and quantitative imaging method, a synthetic image of a regular grid with a resolution of $400\ \mathrm{px} \times 250\ \mathrm{px}$ and 5 px per grid pitch of 0.9 mm was generated and deformed according to the finite element kinematic fields. A grid method algorithm [9] was then used to extract the kinematic fields, and the stress gauge VFM identification errors were found to compare favourably with those obtained directly from the finite element kinematic fields. For a symmetrical trapezoidal pulse with a rise time of 10 μs and total duration of 30 μs, the identification errors were found to be 1.46% for K_1, 3.00% for G_1, and 3.02% for τ_1 compared to 0.28%, 0.78%, and 1.38% respectively for pure finite element data. This agreement indicates that despite the errors introduced by the imaging system, viscoelastic constitutive parameters remain reasonably identifiable in experimental conditions.

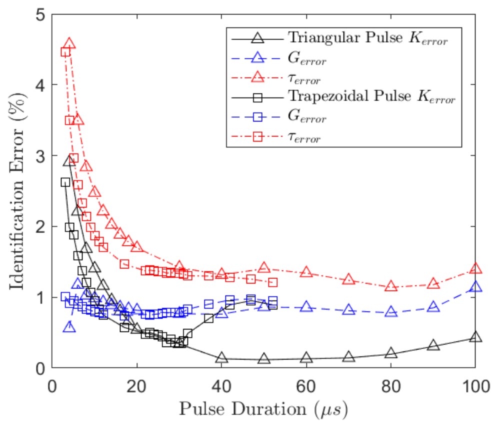

Fig 1 Identification error as a function of pulse duration for viscoelastic material with $\tau_1 = 10$ μs and a simulation duration of 128 μs at 1 Mfps

Conclusion

This study presents a framework for applying the Image Based Inertial Impact test to the characterization of viscoelastic materials under impact loading. We validate the technique with finite simulations and the addition of experimental sources of error including temporal and spatial resolution. Constitutive parameters with time constants on the order of 10 μs are found to be identifiable across a range of loading pulses both from pure finite element data, and data obtained from quantitative full-field imaging. These findings show the promise of the IBII test for the characterization of viscoelastic materials and can be used to inform the design of physical experiments.

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