Nonlinear material modelling of an airsoft pellet applied for impulse excitation

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Summary. This contribution presents the material characterization of an airsoft pellet, which is applied for the excitation of machine tools in order to reduce the multi-hitting effect during the impact. The material behavior of the pellet shows nonlinear elastic, plastic and viscous properties. Consequently, to obtain the exciting force during the impact a complex visco-elasto-plastic material model should be applied in the finite element simulations. The commercial finite element software ABAQUS offers the two-layer viscoplastic model to capture such a complex material behavior. Based on the fitted material model the results of the numerical simulations can be compared with measurement results obtained using high-speed camera.

Introduction

In the field of machine tool vibrations, the transfer function of cutting tools with large L/D ratio and blade-type workpieces plays significant role. In modal testing the transfer function can be measured as the response for hammer excitation. However, during the hammer impact the so-called multiple-hitting phenomena might occur (see Figure 1.), which should be avoided. The natural frequencies of the machine tool are usually high, which yields that the time of impact (T) should be decreased to ensure wider relevant frequency range. Thus, smaller hammers should be applied, which makes the measurement difficult. Additionally, the hammer excitation of high-speed rotating tools also poses safety risks.

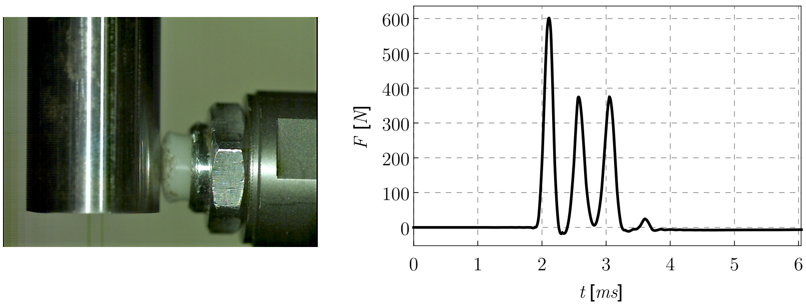

Figure 1: The phenomena of multiple-hitting during the hammer excitation of a dummy tool

In this approach, the impulse excitation of the machine tool is provided using an airsoft pallet. In order to estimate the relevant frequency range, the process of excitation is recorded using high-speed camera, thus the impact time could be determined. Since the force signal of the excitation could not be measured, it can be computed based on finite element (FE) simulations, which requires the complete understanding of the material behavior of the pellet during the impact.

Mechanical behavior of the airsoft pellet

The investigated samples of the commercial airsoft pellet are spherical balls with diameter $d = 5.95 \pm 0.01$ mm, while the average mass is $m = 0.43$ g. Due to the lack of the raw material, the behavior of the pellet can be investigated by compression mechanical test, which are performed on the balls itself. The preliminary tests (including e.g. uniaxial compression tests, ramps tests, high-speed camera tests) showed that the pellet undergoes deformation showing not only elastic but also viscous and plastic properties as well. Consequently, in the applied material model the viscoelastic and yielding properties should also be included. The number of available material models for this complex behavior is limited. The only available model in the commercial FE software Abaqus [1] is the so-called two-layer viscoplastic model [2, 3].

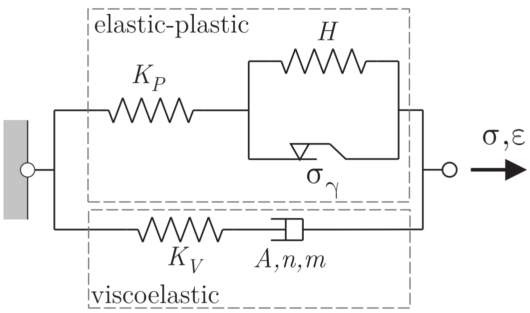

Figure 2: The one-dimensional representation of the two-layer viscoplastic model

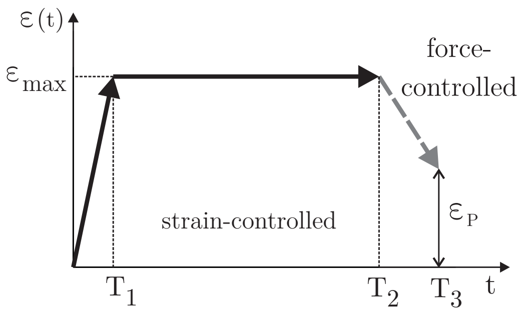

Figure 3: The load input of the uniaxial cyclic relaxation test applied in the parameter-fitting process

The 1D representation of the two-layer viscoplastic model is comprised of a viscoelastic branch in parallel with an elastic-plastic network as it is presented in Figure 2. [2, 3]. This yields that the total stress can be obtained additively as $\sigma = \sigma_P + \sigma_V$, where σ_P and σ_V are the stresses in the elastic-plastic and the viscoelastic branches, respectively. The elastic behavior of the material model is described using linear isotropic elasticity. The corresponding Poission's ratios are identical in both branches, namely $\nu = \nu_P = \nu_V$, while the total elastic modulus can be expressed as $E = K_P + K_V$, where K_P and K_V are the elastic modulus in the elastic-plastic and in the viscous branches. In Abaqus [1] the corresponding elastic parameters are the total elastic modulus E, and the elastic ratio f, which is defined as $f = K_V/E$. For the dashpot in the viscoelastic branch the nonlinear strain-hardening power-law model has been applied. The characteristic differential equation of the model can be expressed as

$$\frac{d}{dt}\varepsilon^{\bar{cr}} = \left(A\tilde{q}\left((m+1)\,\varepsilon^{cr}\right)^m\right)^{\frac{1}{m+1}}\,, \tag{1}$$

where $\varepsilon^{\bar{cr}}$ is the equivalent creep strain, $\tilde{q}$ the equivalent deviatoric uniaxial stress, while A, n, m are material parameters. The plastic behavior is modelled by linear isotropic hardening, which can be characterized by the initial yield stress σ_{Y0} and the hardening modulus H. Altogether the model contains eight parameters, namely $E, \nu, f, A, n, m, \sigma_{Y0}$ and H.

Material modell fitting

The material parameters of this complex behavior can be obtained using parameter fitting based on the uniaxial cyclic relaxation test performed on the pellets. The applied load (see Figure 3.) consists of three parts: strain-controlled uploading ($\varepsilon_{\text{max}} = 0.04$, $T_1 = 14.3$ s), holding the strain ($T_2 = 314.3$ s) and force controlled unloading ($T_3 = 318.3$ s).
Since the mechanical test were performed on the balls and the closed-form solution of the model is not available, the parameters could be fitted by minimizing the error between the measurement data and the FE simulations. This implies, that in each iteration step of the fitting process a complete FE simulation of the cyclic compression of the pellet should be performed [4, 5]. This method can be performed by linking Abaqus [1] and the external optimization software Isight [6].

Results

The result of the fitted model is presented in Figure 4. Additionally, the FE simulation of the impact has also been performed, which has been compared with high-speed camera recordings. Figure 5. shows the comparison of the deformed shapes after the impact. It can be concluded that the nonlinear behavior of the airsoft pellet can be adequately modelled by the two-layer viscoplastic model, therefore the force signal of the impulse excitation can be accurately approximated.

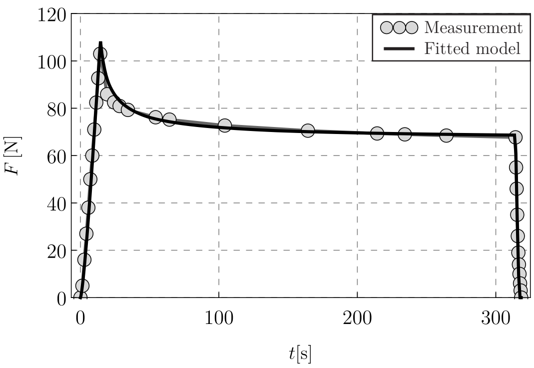

Figure 4: Comparison of the $F(t) - t$ curves of the fitted model and the experimental results of the pellet

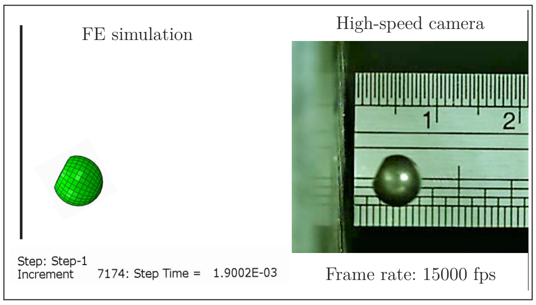

Figure 5: Comparison of the deformed shape of the pellet after the impact to rigid wall in case of FE simulation and high-speed camera measurement with input velocity $v = 36$ m/s

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