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Quantitative analysis of impact measurements using dynamic load cells

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ABSTRACT

A mathematical model is used to estimate material properties from a short duration transient impact force measured by dropping spheres onto rectangular coupons fixed to a dynamic load cell. The contact stress between the dynamic load cell surface and the projectile are modeled using Hertzian contact mechanics. Due to the short impact time relative to the load cell dynamics, an additional Kelvin–Voigt element is included in the model to account for the finite response time of the piezoelectric crystal. Calculations with and without the Kelvin–Voigt element are compared to experimental data collected from combinations of polymeric spheres and polymeric and metallic surfaces. The results illustrate that the inclusion of the Kelvin–Voigt element qualitatively captures the post impact resonance and non-linear behavior of the load cell signal and quantitatively improves the estimation of the Young's elastic modulus and Poisson's ratio. Mathematically, the additional KV element couples one additional differential equation to the Hertzian spring-dashpot equation. The model can be numerically integrated in seconds using standard numerical techniques allowing for its use as a rapid technique for the estimation of material properties.

1. Introduction

Load cells are transducers that produce an electrical signal when subjected to a force and are commonly used in laboratory instruments to measure static and dynamic forces. Of particular interest in this paper are load cells that utilize a piezoelectric material to generate the electrical signal. Due to the rigidity of many piezoelectric materials, piezoelectric type load cells provide rapid response to dynamically varying forces, and have been used in numerous studies to quickly characterize, or sort materials from impact experiments [1–4].

For many experiments, empirical analysis of dynamic load cell (DLC) measurement data is sufficient for qualitative material characterization. However, the transient impact force data measured by a DLC can be used to quantitatively estimate material properties given a model for the impact collision, and a constitutive equation for the materials properties [5,6]. Due to the stiffness of the common load cell strike surface (typically a steel alloy) relative to the test material, the deformation of the load cell can often be neglected when modeling the impact collision. Moreover, the response time of dynamic load cells is often sufficiently fast that the output signal can be assumed to be directly proportional to the instantaneous contact force. Consequently, the impact dynamics can be approximated as a collision between the test material and an elastic half space with an infinite modulus. This approximation, however, may not be valid for materials with a high modulus, or for collisions with very short duration.

The minimum impact duration (maximum frequency) accurately measured by a dynamic load cell is due to the small but finite deflection of the piezoelectric material necessary to generate the electric field. For measurements that occur at time scales substantially longer than the natural resonant frequency of the crystal, the crystal load can be approximated as quasi static. For a quasi static load, the crystal deformation and electrical signal are directly proportional to the normal force, and the crystal inertia can be ignored, as in the assumption of an elastic half space. However, for transient loads that have characteristic time scales comparable to the crystal resonance time scale, the inertia of the crystal may not be negligible, and could give rise to a non-linear response between the dynamic load and the output signal [6].

Ideally, the load cell used in an experiment should have a natural frequency that is substantially greater than the highest Fourier frequency being measured. However, due to limitations in real-life load cell designs, it may not be possible to utilize a load cell that fulfills the resonant frequency requirement. In such cases, it would be beneficial to have a model that incorporates the load cell dynamics into an impact model that can improve the measurement accuracy. The goal of this paper is to derive a model for the transient response of the piezoelectric crystal in a dynamic load cell, and compare experimental impact force measurements to predictions with and without explicit modeling of the crystal dynamics.

2. Material and methods

The impact measurement instrument consists of a custom built aluminum stand (MDC Associates) that holds a vacuum tube stationary

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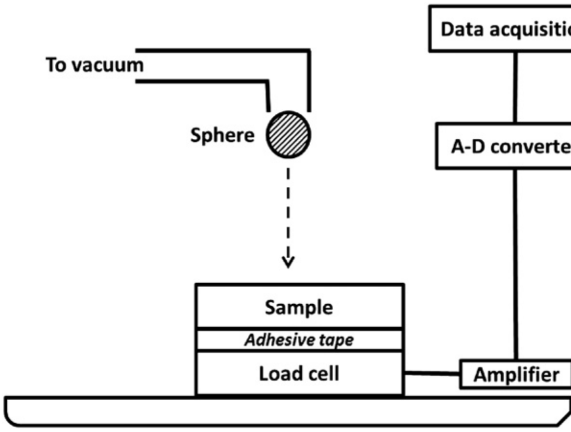

Fig. 1. Schematic of the impact measurement setup.

above a dynamic load cell (Omega DLC101-10) (see Fig. 1). The amplified (Omega ACC-PS3A) analog voltage of the load cell is digitized at a sampling rate of 1 MHz with an analog digital converter (Omega OMB-DAQ-3500) that is triggered and controlled by custom software [7,8].

Rectangular samples are attached to the load cell strike cap using double sided adhesive tape. It is necessary that the compact be rigidly secured to the load cell strike cap, such that entire impact force on the compact surface is transmitted to the load cell. Next, a sphere is attached to the end of the vacuum tube at a set height above the compact. Disengaging the vacuum releases the sphere to impact the surface of the compact. The impact produces a transient voltage signal, which is digitized and stored onto a computer for subsequent analysis. The mechanical properties of the compact and sphere are extracted from the experimental data by iteratively adjusting the compact Young's modulus of elasticity, Poisson's ratio and coefficient of restitution to fit the theory.

The load cell parameters are estimated by dropping spheres of known mechanical properties (Table 1) onto surfaces with known mechanical properties (Table 2) and fitting the transient voltage signal to the theory. The coefficient of restitution for each sphere and surface pair is determined by measuring the sphere rebound height from slow playback of videos recorded during the impact.

Table 1
Sphere properties.

Material	Property	Value
Steel	Radius	0.299
	Modulus (GPa)	194
	Poisson's ratio	0.33
	Mass (g)	.8780
Acetal resin	Radius	0.476
	Modulus (GPa)	3.0–3.3
	Poisson's ratio	0.35
	Mass (g)	0.6116
Polypropylene	Radius	0.476
	Modulus (GPa)	2.8–3.5
	Poisson's ratio	0.38
	Mass (g)	0.4024
HDPE	Radius	0.476
	Modulus (GPa)	1.08
	Poisson's ratio	0.35
	Mass (g)	0.4232
PTFE	Radius	0.476
	Modulus (GPa)	0.5
	Poisson's ratio	0.46
	Mass (g)	0.9692
Neoprene	Radius	0.318
	Modulus (GPa	0.082
	Poisson's ratio	0.499
	Mass (g)	0.1981

Table 2
Properties of rectangular samples.

Material	Property	Range
Aluminum	Modulus (GPa)	69
	Poisson's ratio	0.33
PVC	Modulus (GPa)	2.5–4.0
	Poisson's ratio	0.38–4.1
Polycarbonate	Modulus (GPa)	2.0–2.4
	Poisson's ratio	0.37

3. Theory

Following the analysis by Maranzano et al. [6], the trajectory of a sphere during impact with a load cell is described by Newton's second law of motion (Eq. (1)), where the forces exerted on the sphere include, the gravitational force, F_{grav}, an elastic deformation force, F_{el}, and a dissipative deformation force, F_{dis}.

$$\frac{d}{dt}(mv)_{\text{sph}} = F_{el}(\delta) + F_{\text{dis}}\left(\dot{\delta}\right) - F_{\text{grav}} \tag{1}$$

Here, m is the sphere mass and v is sphere velocity. The Hertzian spring-dashpot model provides expressions for the elastic force as a function of the deformation, δ (Eq. (2)), and the dissipative force as a function of the deformation rate, $\dot{\delta}$. (Eq. (3)).

$$F_{\text{el}} = K\delta^{32} \tag{2}$$

$$F_{\text{dis}} = \alpha(\epsilon)\sqrt{mK}\delta^{1/4}\dot{\delta} \tag{3}$$

The material constant, K, in Eqs. (2) and (3), is related to the modulus of the compact, E_1, the modulus of the planar surface, E_2, the Poisson ratio of the compact, ν_1, and the Poisson ratio of the planar surface, ν_2, by:

$$K = \frac{\frac{4\sqrt{R}}{3}}{\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}} \tag{4}$$

The expression for a dissipative force constant, α, in Eq. (3) is a function of the coefficient of restitution, ϵ 5[9,10].

$$\alpha(\epsilon) = \frac{-\sqrt{5}\ln\epsilon}{\sqrt{\ln^2\epsilon + \pi^2}} \tag{5}$$

And the coefficient of restitution is defined in terms of compact deformation as:

$$\epsilon \equiv -\frac{\dot{\delta}(\tau)}{\dot{\delta}(0)} \tag{6}$$

where, τ is defined as the duration of the impact, which begins at time zero.

Experimentally the signal generated by the load cell is caused by the deflection of an internal piezoelectric crystal, which generates an electric field when deformed. Due to the rigidity of the crystal and the load cell design, the crystal deflection is usually very small relative to the deformation of the impacting body. Furthermore the dynamics of the crystal (which is proportional to the square-root of the crystal stiffness divided by the crystal mass) are typically much faster than the impact transients. Thus, for many applications the crystal deflection is in a quasistatic equilibrium with the instantaneous load cell contact forces.