Chapter 1
When Mass Matters: Basics of Dynamic Mechanical Testing, Kolsky Bar, and More

Evan L. Breedlove

Abstract Dynamic mechanical tests pose unique challenges with short duration, rapid-events, but the most defining feature is the importance of mass. Mass acceleration requires force imbalance, which complicates for measurement. Moreover, during short durations, elastic wave propagation can become an important issue, and the wave speed depends on the mass of the accelerating body. Accounting for mass is imperative in dynamic testing. This short introduction discusses the issues caused by inertia, gives a quick overview of wave propagation, and finally applies these concepts to force sensor selection and the theory underpinning the Kolsky bar.

Keyword Dynamic behaviour · Rate sensitivity · Basics of · Elastic waves · Kolsky bar

Introduction

Experimental mechanics generally consists of measuring forces and displacements or some related analogue. Under quasistatic conditions (i.e., relatively slow), force sensors can be placed at the boundary of test specimens and displacements can be measured using a range of different contact, optical, and/or imaging-based techniques. However, with increasing strain rates, new challenges emerge, even if the material is not strictly rate-sensitive. At strain rates in excess of O(10)/s, inertia becomes a central issue in the design of any experiment. We know from Newton's third law that

$$\sum F = ma \tag{1}$$

the vector sum of the forces equals the mass times the acceleration. When the acceleration is close to zero, this reduces to stating that forces will be equal and opposite. This simplification is commonly used in quasistatic speed testing means that forces acting on a test specimen balance with the forces acting on the instrument, and the force measured by the force sensor is the same as the force acting on the specimen. This equal-and-opposite logic can be chained together, meaning that fixtures holding a specimen to the force sensor do not affect the measurement. The validity of approximating $a = 0$ is the essence of what quasistatic means.

So what does it mean if the acceleration is not zero? Even before considering deformable body mechanics, this guarantees that the forces acting on a test specimen cannot be in balance. A common scenario is the effect of a massive fixture, like a grip, placed between the specimen and the force sensor. If the fixture is accelerating, then the forces acting on it cannot be in equilibrium. In other words, it is impossible that the force acting on the force sensor is the same as the force acting on the specimen. This highlights the first challenge in dynamic mechanical testing: ensuring inertia of fixtures and/or the specimen does not ruin the measurement.

The second major issue becomes apparent when you consider that everything is deformable. Taking the conservation of linear momentum for a deformable body, we get

$$\rho \frac{Dv}{Dt} = \nabla \cdot \sigma + b \tag{2}$$

Evan L. Breedlove, Ph.D.
3M Center, Maplewood, MN 55144
e-mail: elbreedlove@mmm.com

© The Author(s), under exclusive license to River Publishers 2026

Paul Allison et al. (eds.), *Dynamic Behavior of Materials, Volume 1, 2026*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.13052/rp-9788743816249

where ρ is the density, Dv/Dt is the total derivative of the velocity with respect to time (i.e., the acceleration), $\nabla \cdot \sigma$ is the divergence of the stress, and b are body forces such as gravity. Often gravity can be neglected at the continuum-scale, and when acceleration is approximately zero, (3) gives the well-known result that "the divergence of the stress is zero", which is the deformable body analogue of (1). But when the acceleration is not zero, (3) is in the form of a wave equation. The implication is that stress has a wave speed. In other words, under dynamic conditions, when a stress is applied at one part of a body, it takes time for the stress to travel to the other side. Depending on the size of the specimen and the duration of the test, this delay may be inconsequential. But in dynamic testing, it should never be ignored. For conventional test methods stretched to higher speeds, like servohydraulic loadframes, this reality can be a significant challenge. But wave propagation can also be leveraged as a tool, as in Kolsky bar testing, allowing for test methods that are not feasible under quasistatic conditions.

These two effects of inertia—force imbalance and wave propagation delay—are the reasons that mass matters in dynamic mechanical experiments. This poses unique challenges that lead to unique test methods; however, when properly managed, accurate and reliable measurements are possible. In this brief overview, we briefly discuss elastic wave propagation. Next, we describe some of the challenges inertia poses to force sensing. Finally, we describe how inertia can be used as a tool in the design of Kolsky bar experiments.

Elastic Wave Propagation

Elastic wave propagation has been extensively studied and described in other works [1]. The French mechanician Jean-Baptiste d'Alembert first described the elastic wave equation for a vibrating string [2], deriving the classical wave equation

$$\frac{\partial^2 u}{\partial t^2} = C \frac{\partial^2 u}{\partial x^2} \tag{3}$$

where C is the wave speed, u is the displacement, t is time, and x is position. This is an example of a hyperbolic PDE, and d'Alembert identified that the solution to this and all related problems consists of two pulses called "characteristics" which travel in opposite directions. Characteristics are essentially the initial condition of the wave that is applied to the system translated along the path of wave propagation. In idealized non-dispersive systems without damping, these waves travel along the body unaltered at the wave velocity. Cauchy and Navier later connected this wave speed with the elastic modulus, yielding

$$C = \sqrt{\frac{E}{\rho}} \tag{4}$$

where E is Young's modulus. The problem of dispersion often arises in practical problems if the wave path is particularly long, such as in Kolsky bar testing. Dispersion is an inertial phenomenon, occurring because of the motion of motion of a body perpendicular to the wave path because of the Poisson effect, effectively making the wave speed frequency dependent. Imagining a Fourier decomposition of the characteristics, these Fourier components travel unaltered but at different speeds, causing the relative phase to change as the wave travels and leading to a distortion of the overall wave. Pochhammer [3] and Chree [4] both studied the dispersion problem for waves traveling in slender rods and derived exact solutions, making it possible to correct for the dispersion which occurs between a point of interest and the point of measurement; however, the exact solutions are often difficult to use in practice. Instead, it is common to either use tabulated results [5] or an approximation function [6].

One notable feature of wave propagation is how a wave behaves when encountering a discontinuity in the body. It is useful to first define the wave impedance, which is the proportionality constant between applied force (expressed in the frequency domain) and the local velocity. For waves in a slender rod, this is given by

$$Z = \rho C A \tag{5}$$

where A is the cross-sectional area of the rod. When a wave encounters an impedance discontinuity, a portion of the wave reflects and a portion is transmitted. If the transition is from high impedance to low impedance, then the wave will propagate into the next section with the same sign and a reflecting wave with the same sign will also be generated, with the transmitted strain amplitude such that the force balances across the discontinuity. However, if the wave travels from low to high-impedance, the reflected wave will flip sign, meaning a compressive wave will reflect as a tensile wave. The amplitude of the reflection depends on the magnitude of the impedance change, and the incident, reflected, and transmitted waves will obey the equilibrium constraint

$$\epsilon_i + \epsilon_r = \epsilon_t \tag{6}$$

the amplitude of the reflected wave will be scaled by

$$R = \frac{Z_2 - Z_1}{Z_1 + Z_2} \tag{7}$$

and the amplitude of the transmitted wave will be scaled by

$$T = \frac{2Z_2}{Z_1 + Z_2} \tag{8}$$

In the case of a wave encountering a wave boundary, ignoring any acoustic transmission, a wave will fully reflect with equal amplitude and flipped sign.

Finally, it should be noted how wave characteristics relate to vibration. Vibration occurs when waves reflect and interfere, creating wave patterns that evolve in time but do no travel in space (i.e., standing waves). The unique patterns that appear for specific boundary conditions lead to the well-known mode shapes in deformable body vibrations. This fact is useful in designing dynamic experiments, since stress waves must make multiple transits for vibrations to occur. If the duration of a test is less than the time required for multiple transits, it is impossible for the experiment to vibrate. This is another strategy employed in Kolsky bar testing.

There are three key takeaways from this discussion. First, the solutions to wave equations are complex and often require numerical simulation; therefore, it is preferrable to select simple geometries for which analytical solutions have been derived. Second, even in simple geometries, wave dispersion is a real and confounding effect of inertia. Designing the test to minimize dispersion improves data quality and avoids spurious conclusions. Finally, impedance mismatches can be a challenge but also a feature. Be careful about wave reflections, and be mindful that a measurement on the other side of a high-to-low impedance boundary will necessarily be scaled down due to the reflected wave.

Force Sensors

Most commercial force sensors function by deforming a spring of known stiffness and measuring the displacement. This principle works for strain gauge sensors used on load frames, piezoelectric load cells, as well as capacitive gauges [7]. A simplified model for such a sensor is shown in Figure 1 (damping is typically minimal, but a technically more accurate model would include a damper). The sensor consists of a mass attached to a spring with known stiffness k, and the applied force is determined by measuring the displacement x. Evaluation of the equation of motion for this force sensor in the frequency domain reveals that the spring stiffness is the proportionality constant up until a point. At larger frequencies (and by extension strain rates), the measured displacement suddenly spikes and then plummets. The spike is the resonant frequency of the force sensor, given by

$$\omega_c = \sqrt{\frac{k}{m}} \tag{9}$$

and at frequencies beyond the resonance, the displacement rapidly drops with increasing frequency, asymptotically approaching zero. Because commercial force sensor are typically small in size, wave transit times are short, and they are essentially guaranteed to vibrate during use.

The resonant frequency is typically listed for force sensors. Common strain gauge based sensors such as s-beam force sensors as well as shear beam force sensors have very steady force measurements ideal for long-duration measurements; however, the mass which moves is quite large compared with the stiffness, meaning that the resonant frequency is comparatively low. The mass inside the sensor will generate a spurious force if the sensor is rapidly accelerated; but even if the sensor is held fixed, these sensors cannot accurately measure dynamic events. Piezoelectric force sensors typically involve a much smaller mass and larger stiffness, setting their resonant frequency higher. Piezoelectric sensors suffer from voltage leakage that causes the signal to drift over time, but this issue is negligible over short duration tests, making them ideal for dynamic testing. Many commercial sensor manufacturers have published helpful white papers further explaining the limiting use cases and appropriate applications.

Finally, strain gauges on their own are very responsive under dynamic loads having low mass and electrical characteristics that work for both quasistatic and dynamic events. It is common to transform a component of a dynamic test into a force sensor by applying a strain gauge rather than using a commercial force sensor, as we will see for the Kolsky bar.

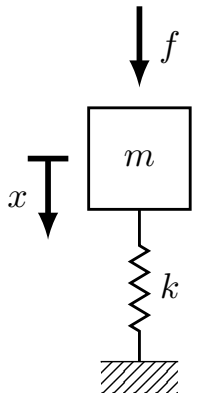

Fig. 1 Mass-spring model of a force sensor.

Kolsky Bar

The Kolsky bar, also known as a split-Hopkinson bar, is an apparatus for high strain rate characterization of materials that beautifully illustrates management and even creative harnessing of inertia for dynamic measurements. A typical apparatus (Figure 2) consists of a gas gun which fires a striker bar, an incident bar, and a transmission bar. The incident and transmission bars can be several meters long or longer. The gas gun propels the striker into the incident bar, creating a stress pulse. The pulse travels down the incident bar, eventually interacting with the sample, with a portion of the wave reflected back along the incident bar and another portion transmitted down the transmission bar. Both bars are instrumented with strain gauges. The output of the measurement is a stress-strain curve.

So how does this leverage inertia to make the measurement? First, rather than trying to avoid the problem of wave propagation, it embraces it. Why? Vibrations are a major issue in dynamic tests, but the Kolsky bar is intentionally too long for standing waves to develop over the duration of the test, meaning the instrument cannot vibrate during the time period of interest. Second, it is designed to take advantage of the reflections caused by impedance boundaries. Unlike quasistatic testing, where the instrument is much stiffer than the specimen, Kolsky bar testing is designed so that bar impedance is close to the sample, but slightly larger. This means that the incident wave will reflect at the sample boundary, but the reflection will ideally only be a small (but measurable) portion of the incident wave. By making the bar so long, the incident and reflected waves can pass by the incident strain gauge without overlapping, allowing for a clean measurement of both waves. Furthermore, because the bars are slender, dispersion is minimized, meaning the measured strain is an accurate representation of the wave interacting with the sample at the interface. (Note: dispersion can be a very big issue if bars are not chosen carefully, and dispersion corrections are sometimes made when processing Kolsky bar data)

The wave that passes into the sample reflects multiple times within the sample and establishes stress equilibrium. It then passes out of the sample into the transmission bar is going through a low-to-high impedance transition, meaning there is effectively no loss. Finally, since the transmission bar strain gauge is measuring the force directly acting on the bar rather than a force acting on an attached mass, the strain in the bar is a direct consequence of the force the sample applies to it. In other words, the transmission bar is a giant force sensor that is too long to vibrate.

Kolsky bar data processing is based on evaluating stress equilibrium at the bar faces. By considering the incident, reflected, and transmitted waves, both the stress and strain can be computed as a function of time [8]. The long bars become wave guides that are too long to vibrate and allow for separate measurement of each of the wave components. In short, the Kolsky bar takes wave propagation, impedance-boundary reflections, and the physics of vibration and harnesses them to perform high speed testing. There are many elegant ways to employ this principle for high speed testing, and the Kolsky bar

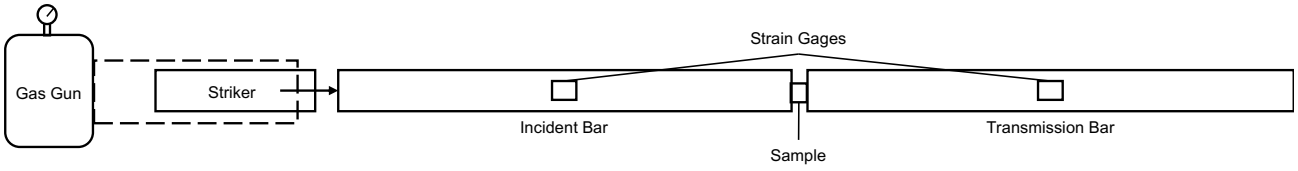

Fig. 2 Schematic of a typical Kolsky bar configured for compression testing.

literature is rich with ingenious arrangements of different ways of applying pulses or introducing additional bars to control pulse propagation. The excellent book by Chen and Song provides a comprehensive overview of Kolsky bar design, theory, and application [8], and it is also provides a good foundation for entering the world of dynamic testing. Breedlove et al. also reviewed the Kolsky bar in the context of polymer testing as well as other common dynamic test methods such as drop towers and high-rate load frames [9].

Conclusion

One of the defining features of dynamic mechanical experiments is the importance of inertia. Accelerating masses cause force imbalance, and propagating stress waves require consideration of not only where a force is applied but also when. Reflecting stress waves can lead to spurious measurements or set up into vibration patterns. Despite these challenges, careful management of inertia can also become a tool in dynamic measurements, as with Kolsky bar testing. Many other dynamic measurement techniques are commonly used—such as gas guns, shock tubes, drop towers, and more—but in all of these tests, mass matters. A final word of advice to researchers beginning to work in dynamic testing: as with most experimental fields, there are many tricks and tactics for effective high-rate measurement which are not clearly documented in the literature. This knowledge is often passed through hands-on training and experience. When in doubt, collaborate.

References

1. K. F. Graff, *Wave motion in elastic solids*. Courier Corporation, 2012.
2. J. le R. D'Alembert, "Recherches sur la Courbe que Forme une Corde Tenduë Mise en Vibration," *Hist. Académie R. Sci. B.-lett. Berl.*, vol. 3, pp. 214–219, 1747.
3. L. Pochhammer, "On the propagation velocities of small oscillations in an unlimited isotropic circular cylinder," *J Reine Angew. Math.*, vol. 81, pp. 324–326, 1876.
4. C. Chree, "The equations of an isotropic elastic solid in polar and cylindrical coordinates, their solutions and applications," *Trans Camb. Phil. Soc.*, vol. 14, pp. 250–369, 1889.
5. P. S. Follansbee and C. Frantz, "Wave Propagation in the Split Hopkinson Pressure Bar," *J. Eng. Mater. Technol.*, vol. 105, no. 1, pp. 61–66, Jan. 1983.
6. J. C. Gong, L. E. Malvern, and D. A. Jenkins, "Dispersion investigation in the split hopkinson pressure bar," *J. Eng. Mater. Technol. Trans. ASME*, vol. 112, no. 3, pp. 309–314, 1990, doi: 10.1115/1.2903329.
7. D. M. Ştefănescu, "General Classification of the Electrical Methods and Principles for Measuring Mechanical Quantities," in *Handbook of Force Transducers: Characteristics and Applications*, D. M. Ştefănescu, Ed., Cham: Springer International Publishing, 2020, pp. 29–40. doi: 10.1007/978-3-030-35322-3_3.
8. W. Chen and B. Song, *Split Hopkinson (Kolsky) Bar*. New York: Springer Science, 2011.
9. E. L. Breedlove, C. Li, C. Chen, and L. Trimiño, "High-rate Testing of Structural Adhesives," in *Advances in Structural Adhesive Bonding*, Second Edition., Elsevier.