STRAIN MEASUREMENTS USING HIGH-SPEED DATA ACQUISITION SYSTEMS AT THE EXAMPLE OF A SPLIT-HOPKINSON BAR

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Abstract: Material testing machines are used to determine material characteristics such as Young's modulus and Poisson's ratio. Young's modulus is the proportionality constant of strain and stress and thus an important material characteristic for many applications. A force-strain curve for the specimen to be tested is taken to determine Young's modulus. This is in general done on a quasi-static basis.
In addition to temperature-dependent behavior, materials, however, also show different responses to varying loading rates. So-called Split-Hopkinson bar tests have been used to determine the dynamic stress-strain response of materials for many decades. In this application it is important to make sure that the right strain gauges are used as well as adequate cabling and data acquisition systems.
The article is to provide an overview of the use of extremely fast measurement technology taking HBM's Genesis High Speed measurement system as an example.
Key words: Split-Hopkinson Bar, Strain Gauges, Oscilloscope, Delta-Sigma-Converter, Flash Converter, SAR Converter.

1. INTRODUCTION

Material constants like Young's modulus and Poisson's ratio are important characteristic quantities of materials that are used in components, designs and structures. Depending on the design, it is absolutely essential to exactly know the respective parameters valid for the materials used, since they provide information, for example, about how much a component is deformed when a force is applied to it. The values specified in standard works and tables have usually been measured in testing machines under quasi-static conditions. However, other methods are required to determine material behavior under dynamic conditions, [4].

2. SPLIT-HOPKINSON BAR

A so-called Split-Hopkinson bar is often used to determine material behavior under dynamic conditions. In general, a Split-Hopkinson bar comprises two long, thin-diameter, high-strength steel bars that are mounted on bearings to enable easy axial sliding of the bars while resisting bending in other directions. These are called the *Incident Bar* and the *Transmission Bar*. In addition there is a third bar – called the *Striker* – made of the same steel as the two main bars. It is much shorter, however, it has the same diameter as the two main bars and can move easily, [1].
When conducting experiments, a cylindrical sample of the material under test is fitted between the two bars and carefully aligned for axial symmetry. This means that, ignoring radial effects, any data gathered can be analyzed using one-dimensional wave theory. An air gun is then fired at various high speeds to launch the striker against the incident bar.
The impact of the striker sends a compressive stress wave traveling through the incident bar and the sample. Using this approach means that the sample is rapidly impacted by the compressive stress wave. When the compressive stress wave arrives at the sample, the impedance difference between the bar and the sample splits the input wave into two parts.
One part is a tensile wave that is reflected back along the incident bar. The second part continues as a compressive wave that – rapidly and permanently – plastically deforms the sample. The compressive wave then propagates into the transmission bar.
Some prerequisites need to be met to be able to infer the required material characteristics from the acquired signals. Both the incident bar and the transmission bar need to be made of the same material and need to have a great length in comparison to their diameter. In addition, it is essential to know the speed of sound C_0 at which the pressure waves run through the bars. Provided that the bars' diameter is small, as described above, the speed of sound can easily be calculated from Young's modulus E and the density ρ:

$$C_0 = \sqrt{\frac{E}{\rho}} \tag{1}$$

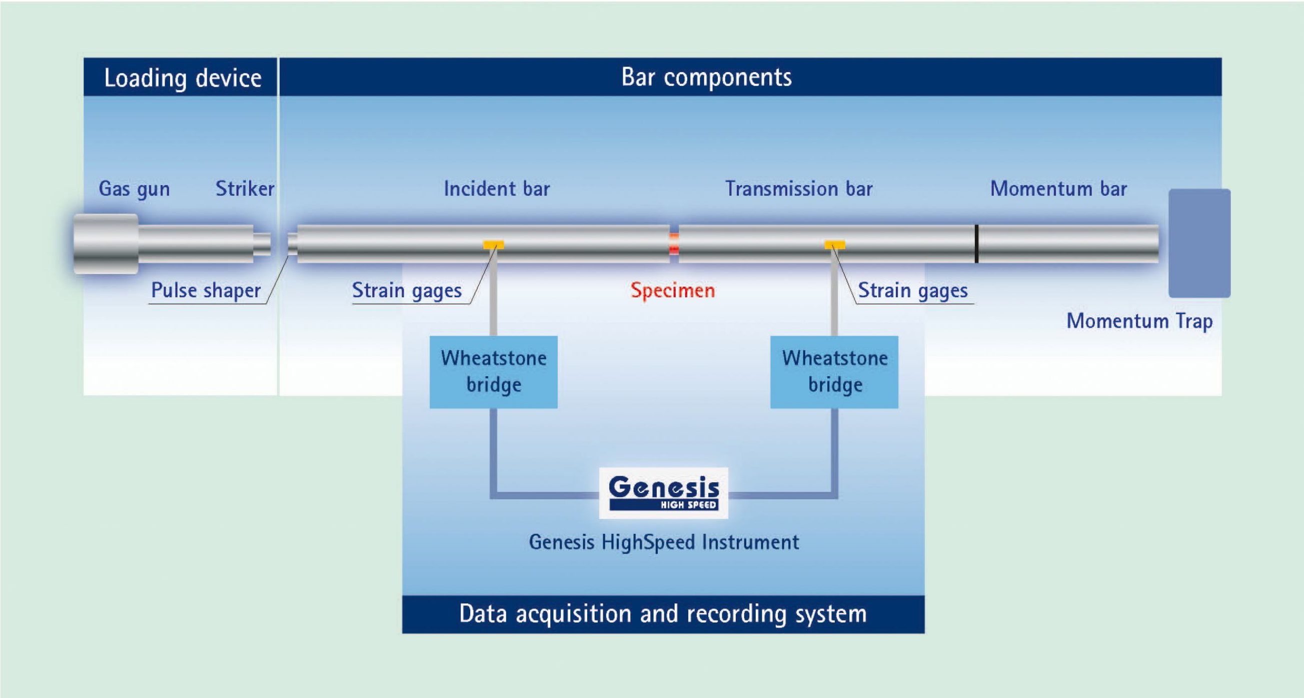

Fig.1. Illustration of a Split-Hopkinson Bar

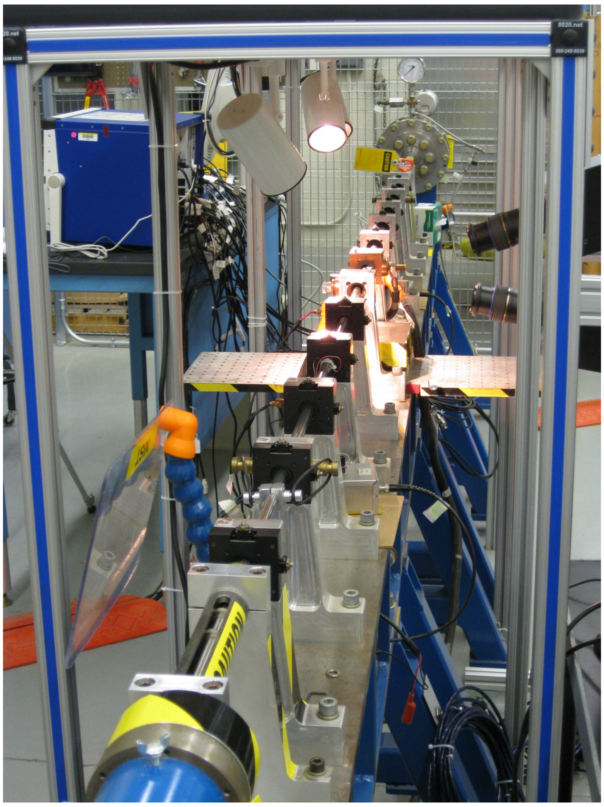

Fig. 2. Split-Hopkinson Bar at NIST, [5]

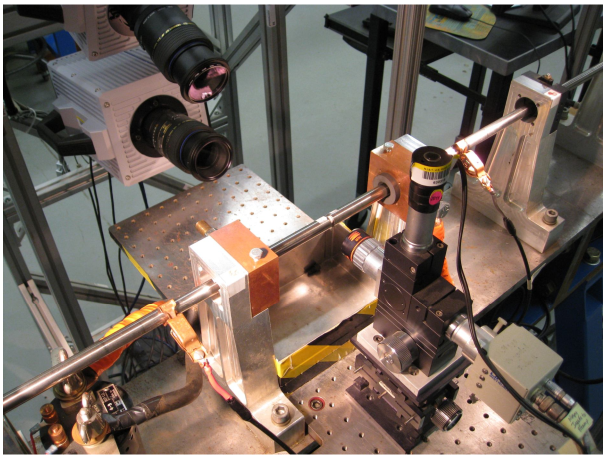

Fig. 3. Detailed section of the Split-Hopkinson Bar and the device under test; high-speed camera above

The above-described strain signals of the pressure wave applied to the incident bar ε_I, of the reflected pressure wave ε_R and of the transmitted pressure wave ε_T are measured. The resulting material stress is:

$$\sigma_S = E\frac{A_0}{A}\varepsilon_T(t) \qquad (2)$$

with E being Young's modulus for the transmission bar and A_0 the transmission bar's cross-section and A the material sample's cross-section. The strain rate of the material sample under test together with the original length L of the material sample is:

$$\frac{d\varepsilon_S(t)}{dt} = -\frac{2C_0}{L}\varepsilon_R(t)\,. \tag{3}$$

Forming the integral, the resulting strain is:

$$\varepsilon_S(t) = -\frac{2C_0}{L}\int_0^T \varepsilon_R(t)dt \tag{4}$$

Using the measured and calculated results σ_s and ε_s and Hooke's Law

$$\sigma = \varepsilon \cdot E \tag{5}$$

Young's modulus of the test specimen can be calculated easily, [2].

3. STRAIN GAUGES

A strain gauge converts mechanical strain into a change in resistance of the strain gauge. Due to the fact that the change in resistance is very small, strain gauges will be always used in a Wheatstone bridge circuit. In most cases, strain gauges are installed on the surface of the object under test using an adhesive. Welding is another method used to install strain gauges. However, it is more time-consuming and expensive; therefore gluing strain gauges to an object under test rather is the standard installation method.
When selecting and installing the strain gauges it is essential to choose a small measuring grid length ($\leq$ 3mm) and a suitable installation point. The strain gauge on the transmission bar must not be installed too close to the bar end, because otherwise the applied wave and the reflected wave are superimposed. The strain gauge resistance too is of critical importance, since strain gauge and measuring leads form an RC element that shows a frequency response. For this reason, 120 ohm strain gauges are usually used, [2].

4. DATA ACQUISITION

Measuring and acquiring transient processes in a Split-Hopkinson bar requires test and measurement equipment that provides the appropriate sampling rates and bandwidths for recording these processes. Modern measurement systems primarily use delta-sigma converters, flash converters, and SAR converters today. However, not every analog-to-digital converter (ADC) is equally well suited for acquiring transient processes.

Fig. 4. Typical layouts of strain gauges

5. OSCILLOSCOPES

Oscilloscopes were used for test evaluation in the past. Analyzing the measurement and computing the material constants was time-consuming and required a lot of calculation, since this technology required graphical analysis of measurement results. Modern digital test and measurement technology significantly facilitates measurement acquisition and subsequent computation of material characteristics.

6. SIGMA-DELTA ADC

Sigma-Delta converters offer a high resolution of 24 bit and would be the perfect choice for frequency domain applications like tests on shakers, [3]. However, they should not be used for time domain applications and, in particular, for transient tests. One of the negative impacts of using a Sigma-Delta converter is the so-called "overshoot" effect of the measured signal. Due to the operation of the Sigma-Delta converter the measured amplitude of the signal can be too high (Fig. 5).

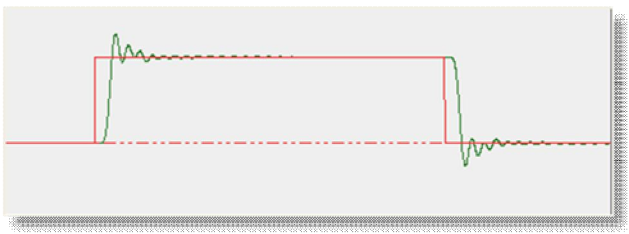

Fig. 5. Potential step response of a Sigma-Delta ADC with "overshoot" effect

A digital filter (decimation filter) follows the analog-to-digital converter (ADC) reducing the (usable) sampling rate, filtering off unwanted noise signals and increasing the resolution of the output. Typically, the maximum sample rate of a Sigma-Delta converter is 250 kS/s in standard data acquisition systems and therefore it is not suited for transient applications.

7. SAR ADC (SUCCESSIVE APPROXIMATION ADC) AND FLASH ADC

From the application point of view, SAR and Flash ADC offer almost the same behavior for transient tests. The differences between both ADC types are marginal for the user of data acquisition systems equipped with either one or the other ADC.
SAR and Flash converters offer way higher sample rates compared to Sigma-Delta converters. Furthermore, the typical bandwidth of an SAR converter meets the requirements for transient applications. There are no errors resulting from the impulse response nor are there any built-in filters which might have an effect on the measured signal.
The only disadvantage of SAR and Flash converters compared to Sigma-Delta converters is their limited resolution. However, the typical resolution (16 bit for an SAR converter; approx. 12 bit for a Flash converter) is not a real drawback, especially when taking into account other effects such as cabling effects, the accuracy of the strain gauge which is given by the gauge factor, and bandwidth limitations.
It is important to note that the bandwidth refers to a so-called corner frequency. However, reaching this corner frequency, which is really not a problem for impulse tests like the Split-Hopkinson Bar test, means that a the amplitude will be reduced. For example, if a -3dB value is listed in the specifications of a data acquisition system the amplitude is reduced by -30%.

8. HBM'S OFFER

Hottinger Baldwin Messtechnik GmbH (HBM) offers high-speed data acquisition systems with high sample rates of up to 100 MS/s per channel. This is more than the required 1 MS/s as mentioned in the book *Split-Hopkinson (Kolsky) Bar* from *Weinong Chen, Bo Song*, page 9 [1].
Furthermore, data acquisition cards with direct connections of strain gauge bridges are available, too. SAR converters are used for transient measurements like the Split-Hopkinson Bar test.
Figure 6 shows a GEN5i system from HBM in the Split-Hopkinson Bar test at NIST in Washington, D.C.

9. CONCLUSION

Measuring and acquiring transient signals in a Split-Hopkinson bar requires test and measurement equipment that provides the appropriate sampling rates and bandwidths for recording these processes. In this context, both the resolution and the accuracy of the acquired signals are key to subsequent analysis of measurement results.

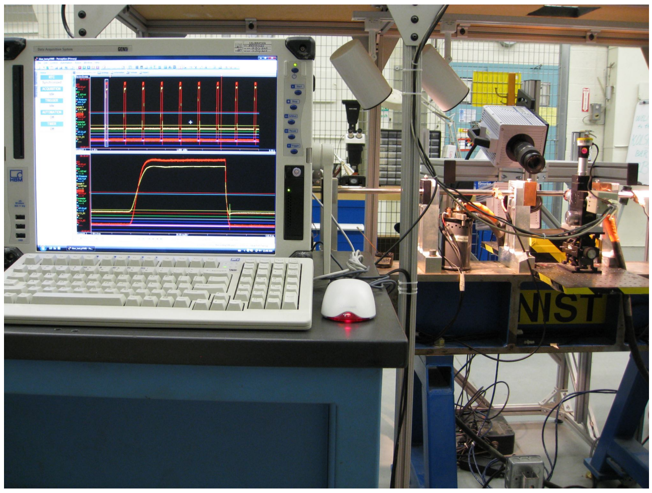

Fig. 6. HBM's GEN5i data acquisition system in the Split-Hopkinson Bar at NIST; the measured strain signal of the transmission bar can be seen on screen

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