

The NIST Kolsky Bar Data Processing System

Eric Whilenton, National Institute of Standards and Technology (NIST)
Mail Stop 8223, Gaithersburg MD 20899-8223
Eric.Whilenton@Nist.Gov

ABSTRACT

A new dynamic testing apparatus has been built at the National Institute of Standards and Technology (NIST) to measure dynamic material properties for machining simulation and other applications. This apparatus—the NIST Pulse Heated Kolsky Bar—is based on the traditional Split Hopkinson Pressure Bar, or Kolsky Bar, design with an added unique feature of rapid electrical resistance heating of the sample. To quickly reduce and archive the strain gage records, as well as document all other aspects of the tests, software for data management and processing has been implemented. Called the Kolsky Bar Data PADS (Processing And Distribution System), the software interactively re-computes stress-strain and other curves as the user examines various assumptions. The Data PADS also includes a database containing strain gage data, visible high speed videos, thermal camera videos, high speed pyrometer data, sensor data measuring the velocity of the projectile, as well as technical papers and associated information. Multiple users may use and add data to the system, allowing for sharing of data maintenance tasks. This paper shows important features of the program, data analysis procedures unique to the software, and examples of its use.

1 INTRODUCTION

Kolsky Bars, also known as Split Hopkinson Pressure Bars (SHPB), have long been used for high strain rate materials testing. A sample to be tested is placed between two bars. A projectile strikes the end of the first bar, called the incident bar, causing a stress wave to travel through the bar and the sample. A portion of the stress wave is reflected back into the incident bar and a portion travels through the sample and on to the second bar, called the transmitted bar. Strain gauges mounted on both bars measure data relevant to the stress wave. A stress-strain curve for the sample is calculated from this strain gauge data. A simplified schematic of the NIST SHPB is shown in Figure 1. It combines the traditional SHPB with rapid pulse heating, high speed visible light imaging, high speed thermal spectrum imaging, as well as data acquisition and electronics to control the system [1-4].

In addition to the normal one-dimensional data such as calibration constants and test conditions, the NIST SHPB produces a wide range of both two-dimensional data (current, temperature, projectile position and strain gauge data vs. time) and three-dimensional data (thermal image and visible light image vs. time). Additionally, there are multiple users of the facility, each performing different types of tests with the system in various configurations, heated versus room temperature tests for example. Thus, other data must be managed such as system configurations, testing schedules, specimen tracking, calibrations, photos of experiments and samples, and published reports resulting from SHPB experiments. This volume of data must be managed effectively so that it may be accessed easily when desired.

Another situation which arises is that individual users often process the data in different ways. This makes the comparison of results difficult. Thus, some level of standardization in the data processing is desirable.

2 THE NIST KOLSKY BAR DATA PADS

Responding to this need, a software program called the NIST Kolsky Bar Data PADS (Processing And Distribution System) was developed. It is used to store, process, manage, and share SHPB data among multiple researchers. All test data are stored in the unprocessed form and processed live in an interactive environment, allowing users to control the processing. Default processing parameters are stored in the database so that users are not required to set any parameters.

Historically, researchers have analyzed SHPB data using static, procedural scripts in languages such as Fortran or Matlab. In recent years, however, the tools for developing software with a graphical user interface (GUI) have proliferated. This challenges both researchers and software developers to utilize these new tools in such a way that the GUI actually adds to the usefulness of the software, and is not just an attempt to make the old software look modern.

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Also, researchers have generally performed experiments, analyzed the data, and then made only the processed data available. However, most modern software languages have extensive relational database facilities built into them. The modern PC has processing speeds and data storage capabilities unheard of in the past. This enables the researcher to store the original data, along with processing parameters, and reprocess the data in real time as needed, which is useful when producing stress-strain curves from the SHPB strain gauge data. There is no single, universally-accepted procedure for determining the starting times, or time zeros, for the incident, transmitted and reflected waves. This is also true for the baseline voltages, or voltage zeros. The placement of these zeros can have an impact on the values in the processed stress-strain curves. Enabling a researcher to change these zeros and immediately see the effects on the stress-strain curves facilitates the assessment of the sensitivity of the final results on the placement of the zeros. Also, different strategies for placing the zeros may be compared. Later in this paper, the issue of modifying the zeros will be discussed further.

The current version of the software is designed to be used in two different ways: it may be accessed over a network via a file server, or it may be installed on a laptop PC and used in stand-alone mode. Web server/browser based solutions were not used because they have the disadvantage of being cumbersome to install on stand-alone PCs. While there are many adequate programming environments available, the Data PADS program was written using Microsoft Visual Basic and National Instruments Measurement Studio. Data are stored in two ways. Relational databases keep track of one-dimensional data such as test conditions and calibrations. Other data such as two-dimensional data, three-dimensional data, and published documents are stored as separate files, the locations of which are contained in the relational database along with the one-dimensional data.

This paper will give examples of a few of the program's capabilities. Section 3 briefly discusses how the user accesses the wide variety of data and functionality offered by the program. Section 4 discusses analysis of projectile velocity, temperature, and stress-strain data. Finally, Section 5 looks at two specific examples of analyzing stress-strain data.

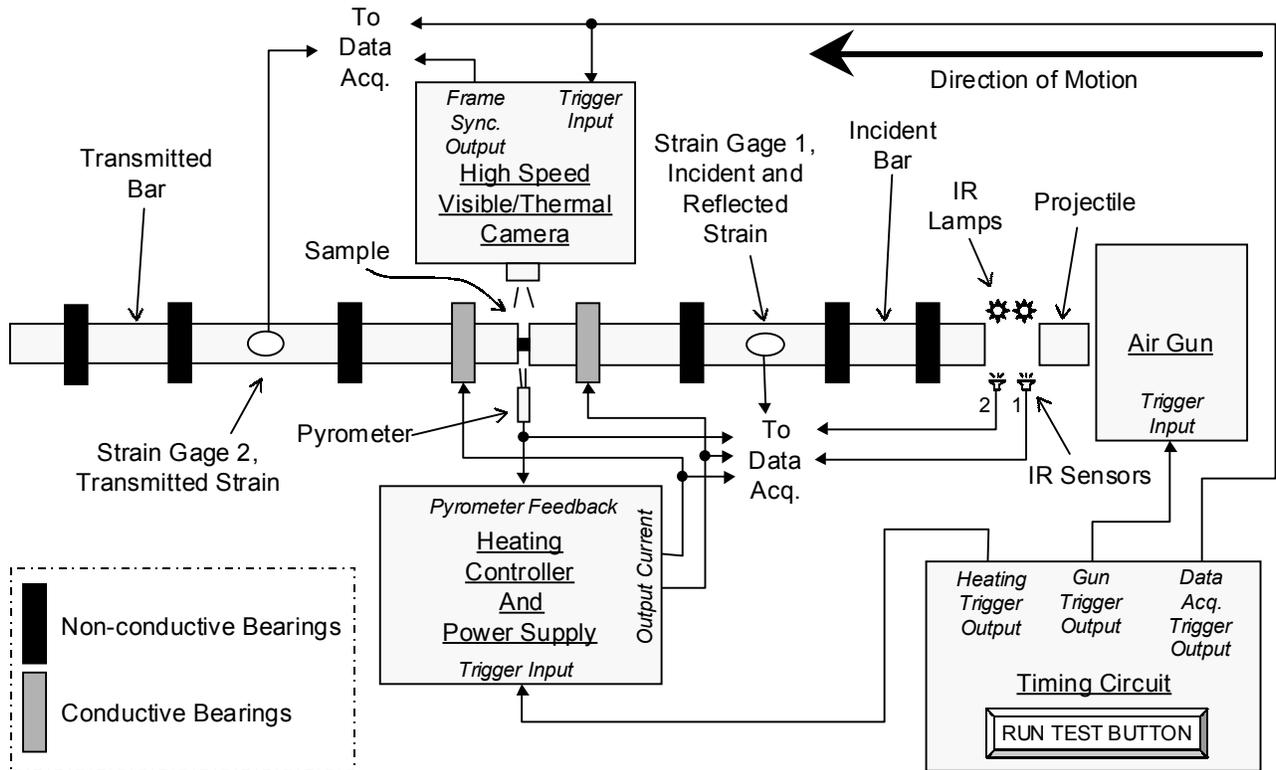


Figure 1. Simplified schematic of the pulse heated NIST SHPB.

3 BRIEF SOFTWARE OVERVIEW

PADS is a software package intended to both archive all aspects of SHPB test data, and allow interactive reduction of the data. The strength of Data PADS is the ability to readily meet the needs of a variety of users. Built into Data PADS are a variety of useful analytical relations. The data may be reduced in either a standard or non-standard manner. The complete record of a test may be readily retrieved, including not only the conventional strain gauge data, but also other data such as temperature data, the matching sample documentation, high-speed visual and thermal images, and references and finished reports.

The capabilities of Data PADS are clearly displayed across the top of the main screen. Shown in Figure 2, the controls may be combined into several groups:

- I) The user may quickly select the name and date of a test to be analyzed. Once a test is selected, information on the test is displayed in the test details display box.
- II) When the user elects to either view or edit the relational database, a new screen appears showing the data in a spreadsheet style environment. When viewing the database, a test may be selected for analysis by simply double-clicking the row in the spread-sheet containing the data for the test.
- III) Once a test has been selected, simply clicking a button recalls files documenting that test, such as sample photos, sample material specification sheets, and high-speed video.
- IV) Tabs are used to select a data processing or retrieval function. The first 3 tabs; "Stress-Strain," "Projectile Velocity," and "Temperature" will be discussed in more detail later in this paper. The "Utilities" tab is a collection of utilities, such as a calendar utility for scheduling tests and a temperature calculator. The "Other Documents" tab allows individual users to maintain their own file areas for storing files such as published papers. Each file area has an associated relational database. All users may search all of the databases to find documents of interest.

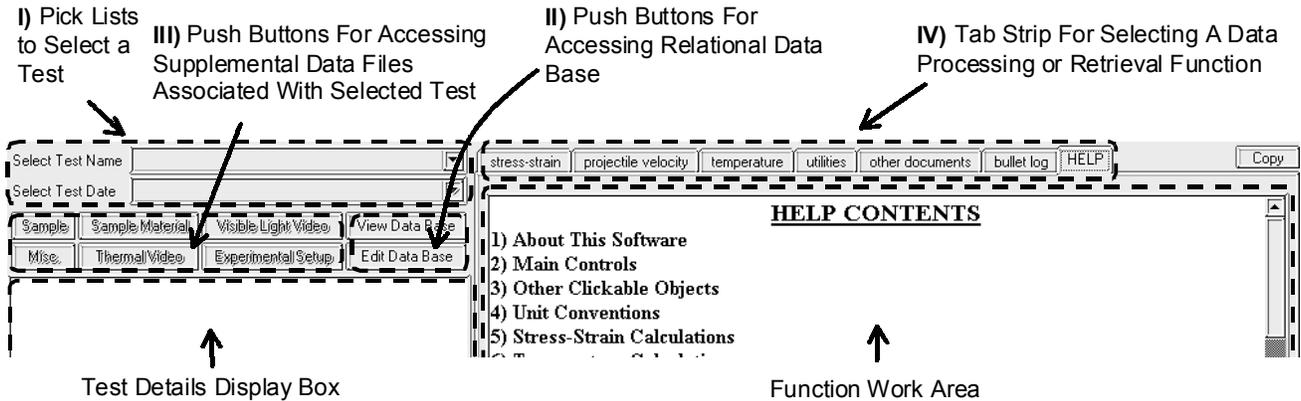


Figure 2. Top portion of the main screen.

4 IMPORTANT FEATURES OF TECHNICAL INTEREST

4.1 PROJECTILE VELOCITY ANALYSIS

As shown in Figure 1, the SHPB is instrumented with two IR (infrared) sensors which detect the point in time when the projectile has reached a given position in its travel towards the incident bar. As shown in Equations 1 and 2, two estimates of velocity, V_1 and V_2 , are possible, each at different times. The estimate of V_1 is calculated from the distance between the two sensors, 25.4 mm, and the difference between the times, t_1 and t_2 , when the projectile passes the first and second sensor, respectively. The estimate of V_2 is calculated from the distance between the second sensor and the end of the incident bar (also 25.4 mm), the start time t_3 for the incident wave, the length L_b of the incident bar, and the speed V_w of the stress wave through the bar. It is assumed that the strain gauge is mounted in the middle of the incident bar. These two estimates may be compared to see if the projectile is accelerating as it leaves the barrel of the air gun. To the author's knowledge, we are the only researchers using the incident wave data as a part of the projectile velocity analysis.

$$V_1 = \frac{25.4}{t_2 - t_1} \quad (\text{Eq. 1})$$

$$V_2 = \frac{25.4}{\left(t_3 - \frac{L_b/2}{V_w}\right) - t_2} \quad (\text{Eq. 2})$$

4.2 TEMPERATURE ANALYSIS

The program has several facilities for manipulating temperature data. The primary facility is an analysis of the temperature vs. time as measured by the pyrometer. Other relevant data such as the start time of the incident wave are also used in the analysis. The incident wave is included because, when time-shifted to compensate for wave speed, it allows the user to determine the temperature at the exact moment of impact. This is an example of how having all of the data together in an integrated environment facilitates better use of the data.

4.3 STRESS-STRAIN ANALYSIS

The controls on the screen from a typical stress-strain analysis, shown in Figure 3, may be grouped as follows:

- A) A plot of the raw strain gauge data. Voltage zeros for the strain gauge data are marked with horizontal lines. Time zeros designating the start of the incident, transmitted, and reflected waves are marked with vertical lines. These lines may be dragged by the mouse and moved to change the zeros. This causes the screen to refresh with the stress-strain plots recomputed using the revised data.
- B) The voltage and time zeros are displayed numerically in text boxes. In addition to changing their values by dragging the lines on the plots in group A, the zeros may also be changed by either typing values into their associated text boxes or clicking the up-down arrows next to each text box. Default values for the zeros for each test are stored in the relational database, thus users do not have to manipulate these controls unless they wish to. If, after trying other values, a user decides to change the default values to the new values, then the "Upload To Database" button may be clicked, and the current values will be placed into the relational database. If no default values have been set for this test, they can be set by clicking the "Guess Values" button. This sets the voltage zeros by averaging the first $N/20$ points, where N is the total number of points. The time zeros are estimated by looking for deviations of the data from the voltage zeros. There are also controls for modifying the estimates of the zeros in a semi-automated way by using equilibrium plots. This will be discussed in the examples in Section 4.

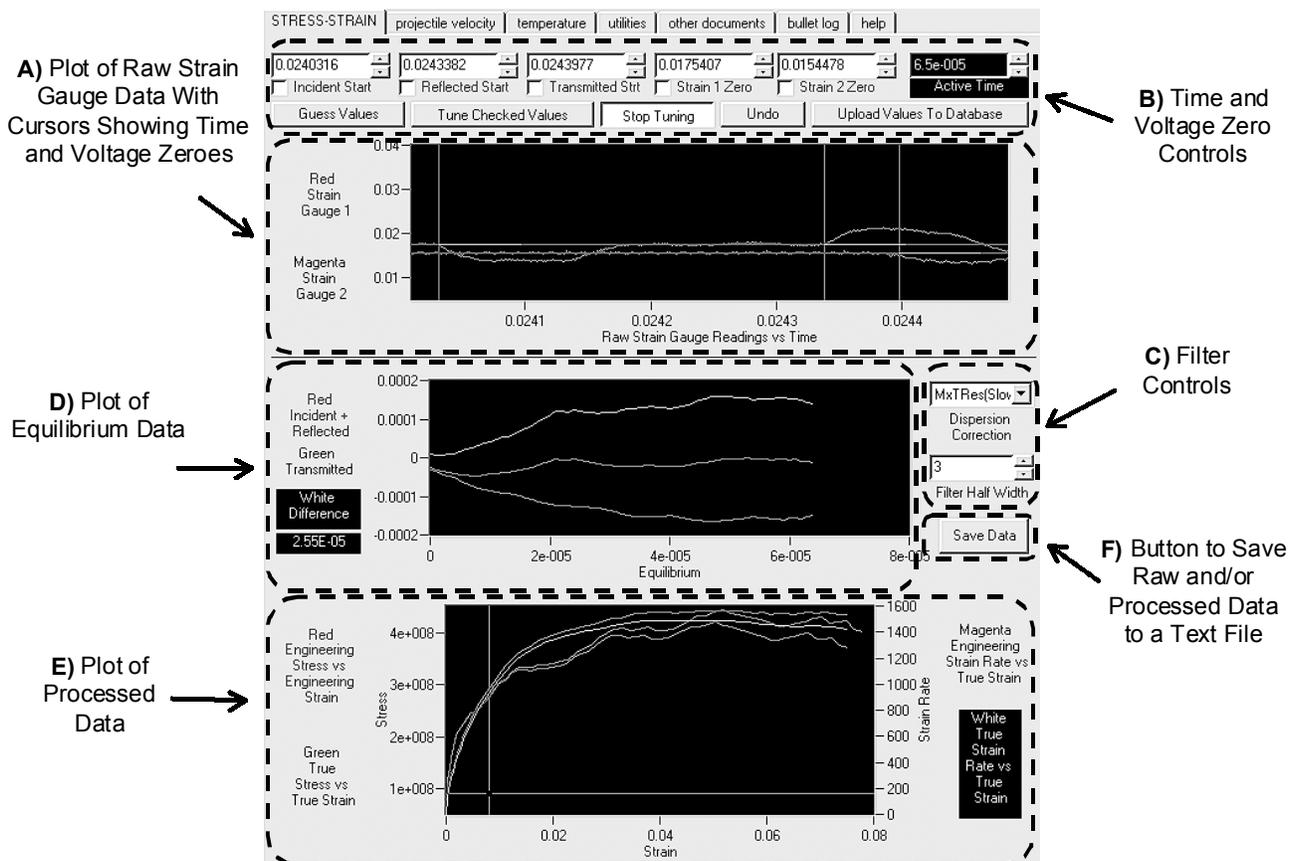


Figure 3. Stress-strain data processing function.

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- C) This group contains 2 controls affecting the filtering of the strain gauge data. Both filters affect the equilibrium plot, the processed data plot, and any data saved by the user. The first control is a pick-list allowing the user to select a dispersion correction filter [5-9]. The second control is an up-down arrow allowing the user to adjust a moving average low pass filter, which may be used to remove high frequency noise.
- D) One of the assumptions used in the stress-strain calculations is that the system reaches equilibrium during the test [9]. If this assumption is correct, then the Equation 3 should be true for the latter part of the curves:

$$(\epsilon_I + \epsilon_R) - \epsilon_T \approx 0. \quad (\text{Eq. 3})$$

ϵ_I is the strain induced in the bar by the incident wave, ϵ_R the strain induced in the bar by the reflected wave, and ϵ_T is the strain induced in the bar by the transmitted wave. In PADS, the curve obtained when the transmitted wave data is subtracted from the sum of the incident and reflected wave data is called the Difference Curve, and the RMS value for the last half of the Difference Curve is referred to as the Difference Coefficient. The last half was chosen because it is where the system presumably has reached equilibrium. An example application of this feature will be shown in Section 5.

- E) The data are now processed and plotted. Engineering stress vs. engineering strain, true stress vs. true strain, engineering strain rate vs. true strain, and true strain rate vs. true strain are plotted. The equations used to compute these curves are shown in Equation 4 through Equation 9, where ∂ is stress, ϵ is strain, $\dot{\epsilon}$ is strain rate, d is diameter, E is the elastic modulus of the bar, V is velocity, L is length, and Δt is the time between data points. The subscript e designates an engineering value, t a true value, b the bar, s the sample, T the transmitted wave, R the reflected wave, and (i) the i 'th data point. More precise versions of these equations are available. However, these were chosen because they give reasonable values and are very quick to compute. Fast computation is important in an interactive program such as Data PADS.

$$\partial_{e(i)} = \frac{d_b^2 \cdot E}{d_s^2} \cdot \epsilon_{T(i)} \quad (\text{Eq. 4})$$

$$\dot{\epsilon}_{e(i)} = \frac{2 \cdot V_R}{L_s} \cdot \epsilon_{R(i)} \quad (\text{Eq. 5})$$

$$\epsilon_{e(i)} = \epsilon_{e(i-1)} + \frac{\dot{\epsilon}_{e(i)} + \dot{\epsilon}_{e(i-1)}}{2} \cdot \Delta t \quad (\text{Eq. 6})$$

$$\partial_{t(i)} = (1 - \epsilon_{e(i)}) \cdot \partial_{e(i)} \quad (\text{Eq. 7})$$

$$\epsilon_{t(i)} = \ln(1 + \epsilon_{e(i)}) \quad (\text{Eq. 8})$$

$$\dot{\epsilon}_{t(i)} = \frac{\epsilon_{t(i)} - \epsilon_{t(i-1)}}{\Delta t} \quad (\text{Eq. 9})$$

- F) Pressing the "Save Data" button allows the user to save the data to a text file for use in other software.

5 EXAMPLES OF STRESS-STRAIN ANALYSIS

Two examples of stress-strain curve assessment will now be given. However, a full discussion of the requirements for a valid SHPB test is beyond the scope of this paper. The purpose of these examples is to show how interactive software facilitates the manipulation and validation of the data.

As discussed in Section 4.3, one of the assumptions used in the stress-strain calculations is that the system reaches equilibrium during the test, which should yield values in the latter portion of the Difference Curve that are approximately zero. Based on this assumption, a reasonable hypothesis which might be tested is that deviations of the latter portion of the Difference Curve from zero may be due to errors in the voltage and/or time zeros. These zeros may be changed manually to immediately assess the impact on the Difference Curve and the Difference Coefficient, as well as the processed stress-strain data. As a second option for testing the hypothesis, the Difference Coefficient is used as a feedback variable in an auto-tuning routine (invoked by pressing buttons in group B in Figure 3). The voltage and/or time zeros are modified to minimize the Difference Coefficient value. If, before the auto-tune button is pressed, the Difference Coefficient is already near zero, the auto-tune will have little effect. However, if the Difference Coefficient is far from zero, the voltage zeros will converge on either reasonable values or obviously incorrect values. If the latter occurs, the test data is possibly flawed.

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In the following examples, only the voltage zeros will be changed and the time zeros left constant. Both examples start with the voltage zeros set at the average of the first $N/20$ points. Shown in Figure 4, the first example is of a test on an iron sample. The Difference Curve clearly levels off with the Difference Coefficient having a value of $2.62E-5$. This indicates a potential problem with the data. After the auto-tune function was invoked, the voltage zeros settled to obviously incorrect values. Any plot may be examined more closely by double-clicking on it, which causes the plot to expand to fill the entire work area. The expanded raw strain gauge plot is shown in Figure 5. The horizontal lines representing the voltage zeros are clearly too far from the strain gauge baselines to be valid. Thus, the large Difference Coefficient can not be explained by errors in the voltage zeros. This indicates that the equilibrium conditions were not met. Thus, the calculated stress-strain curves are likely inaccurate, possibly due to friction between the sample and the bars.

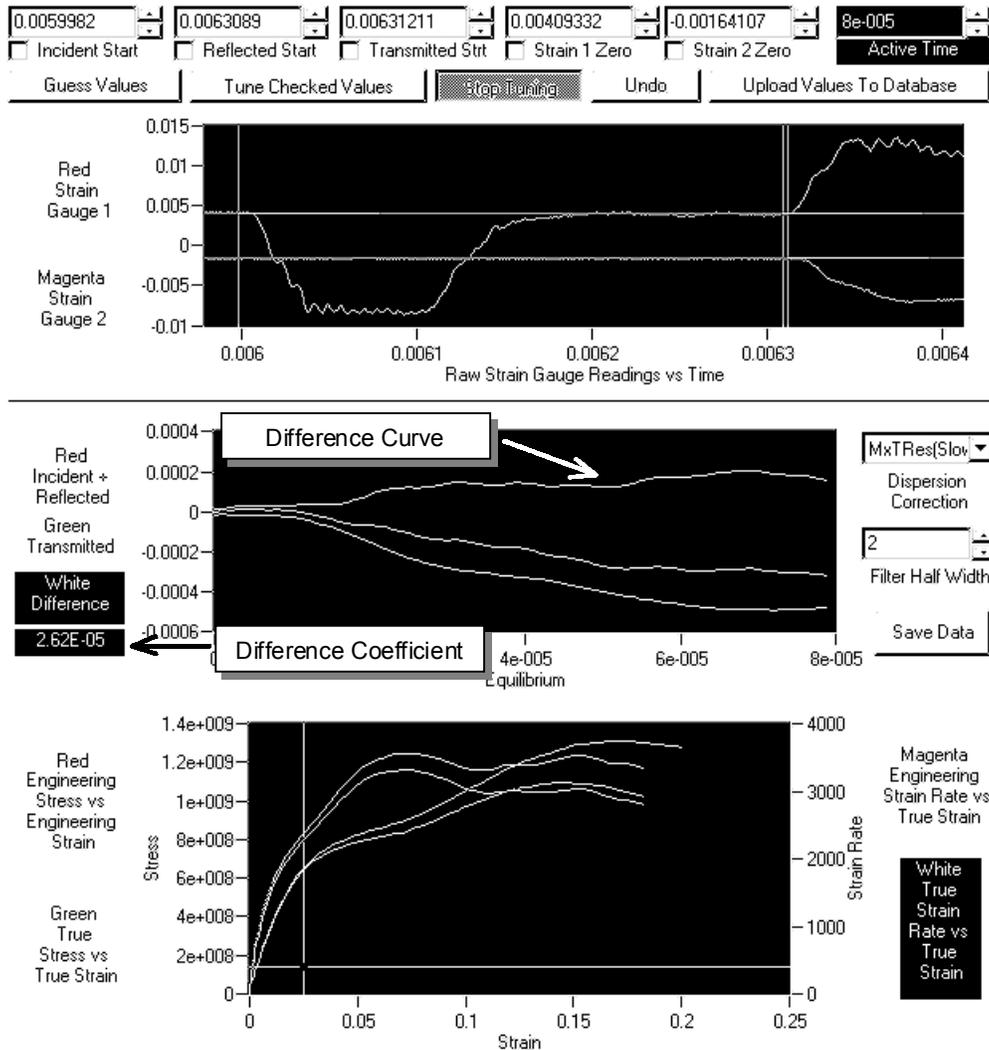


Figure 4. Questionable results from an iron sample.

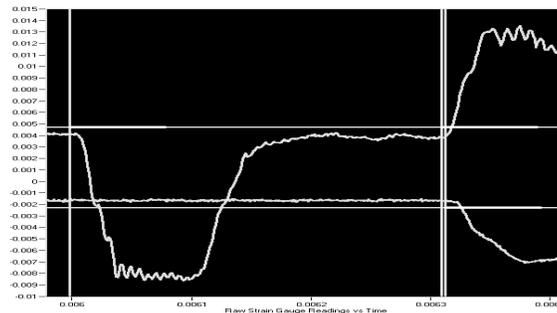


Figure 5. Placement of strain gauge voltage zeros minimizing the Difference Coefficient.

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Figure 6 shows the results from a test on a steel sample. This second example has a more favorable, or smaller Difference Coefficient of $5.36E-6$. The processed data was saved to a file for later use. Next, the auto-tune feature was invoked. The voltage zeros change very little, with the Difference Coefficient changing approximately 2%. The resulting new processed data was also saved to a file. Finally, both files were imported into a Microsoft Excel spreadsheet and the differences in the average values for the second half of the curves computed. One can see from Table 1 that the processed data changed by less than 3%. Such a table is normally not necessary, but was used to make the point that the values change very little. This simple analysis has shown the following for this test: The small magnitude of the Difference Coefficient does indeed indicate that the test reached the equilibrium condition specified in Equation 3. The small change in the Difference Coefficient as a result of using the auto-tune function shows the deviation from zero in the Difference Curve is not due to errors in the voltage zeros. This indicates that the equilibrium conditions were met, and thus the calculated stress-strain curves are likely more reliable than that of the first example.

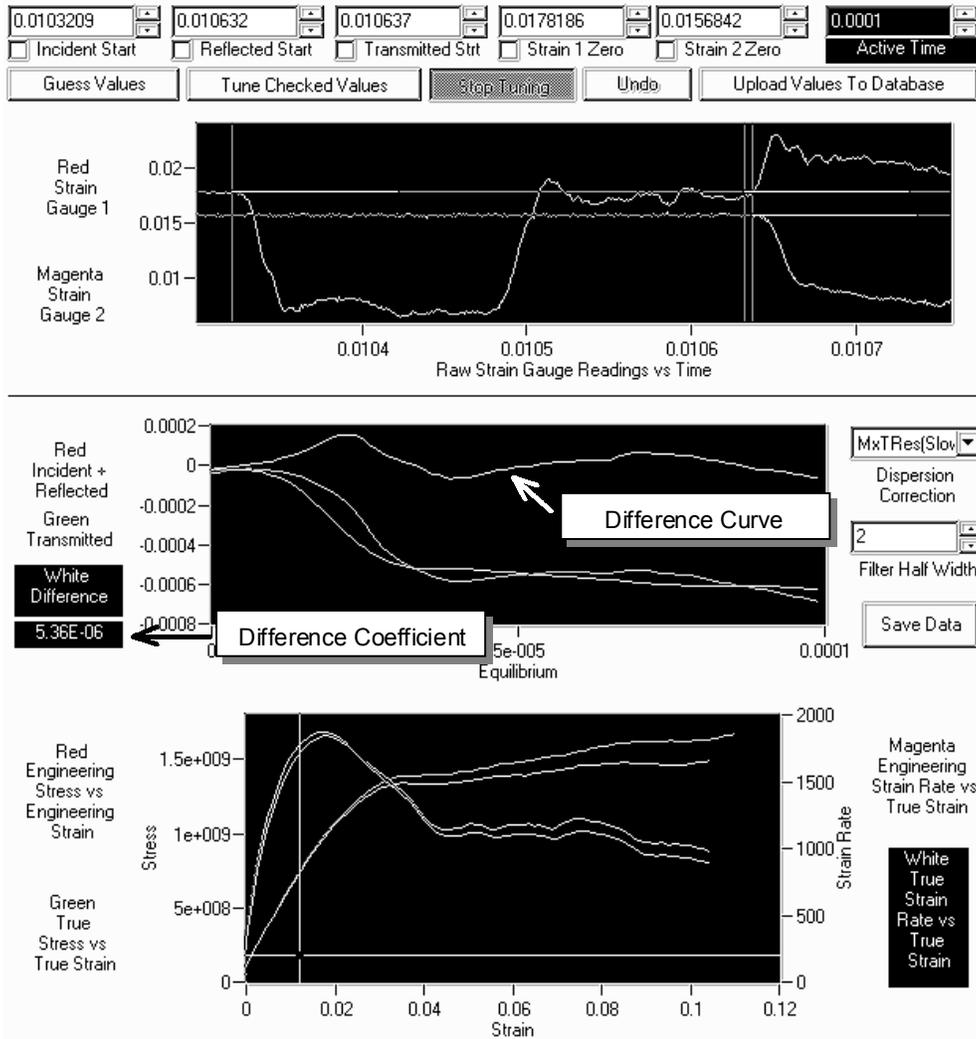


Figure 6. Results from a steel sample.

Strain Gauge 1 Zero	6.4	μstrain
Strain Gauge 2 Zero	1.7	μstrain
Difference Coefficient	2.1	%
Engineering Stress	0.3	%
Engineering Strain	2.8	%
Engineering Strain Rate	2.8	%
True Stress	0.0	%
True Strain	2.7	%
True Strain Rate	2.6	%

Table 1. Changes in values due to minimizing the Difference Coefficient.

5 CONCLUSIONS

The NIST SHPB facility presents many data processing and data management challenges. In response, a user friendly, interactive, point-and-click style software program enabling the rapid processing, verification, and sharing of SHPB and related data was developed. Some of the data processing techniques used in Data PADS appear to be unique to this software. The software has proved an invaluable tool for NIST researchers. As our experience using this software grows, we will continue to make refinements.

ACKNOWLEDGEMENTS

The author acknowledges R. Rhorer, D. Basak, T. Burns and others for their valuable input and guidance. Also, the NIST ATP Intramural Program and the Smart Machining Systems Program provided financial support. Finally, I wish to thank the users of the Data PADS software for their feedback as the program evolves and improves.

REFERENCES

- [1] "Kolsky Bar with Electrical Pulse Heating of the Sample," Rhorer, R., Basak, D., Blessing, G., Burns, T., Davies, M., Dutterer, B., Fields, R., Kennedy, M., Levine, L., Whinton, E., Yoon, H., 2003 SEM Annual Conference, Charlette, NC, June 2-4, 2003
- [2] "Temperature Control of Pulse Heated Specimens in a Kolsky Bar Apparatus Using Microsecond Time-Resolved Pyrometry," Basak, D., Yoon, H., Rhorer, R., Burns, T., Matsumoto, T., Fifteenth Symposium on Thermophysical Properties, June 22 –27, 2003, Boulder, Colorado
- [3] "Influence of Heating Rate on Flow Stress in Modeling on Machining Processes," Burns, T., Davies, M., Rhorer, R., Basak, D., Yoon, H., Fields, R., Levine, L., Whinton, E., Kennedy, M., Ivester, R., CIRP International Workshop on Modeling and Machining, Cluny, France, May 2004
- [4] "Thermal Imaging Of Metals In A Kolsky-Bar Apparatus," Yoon, H., Basak, D., Rhorer, R., Whinton, E., Burns, T., Fields, R., Levine, L., Thermosense 2004, Paper #5073-39
- [5] "A Numerical Method For The Correction Of Dispersion In Pressure Bar Signals," Gorham, D., J Phys Instrum., Vol. 16, 1983
- [6] "The Velocity of Longitudinal Waves in Cylindrical Bars," Bancroft, D., Physical Review, Volume 59, 1941
- [7] "Advancements in the Split Hopkinson Bar Test," Kaiser, M., Masters Thesis, Virginia Polytech Institute and State University, 1998
- [8] "Wave Propagation in the Split Hopkinson Pressure Bar," Follansbee, P., Frantz, C., Journal of Engineering Materials and Technology, Vol. 105, 1983
- [9] "Classic Split-Hopkinson Pressure Bar Testing," Gray, G., ASM Handbook 10th Ed, Vol. 8, pp. 462-469