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IWA: an analysis program for isentropic wave measurements

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IWA: an analysis program for isentropic wave measurements

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Abstract

IWA (Isentropic Wave Analysis) is a program for analyzing velocity profiles of isentropic compression experiments. IWA applies incremental impedance matching correction to measured velocity profiles to obtain in-situ particle velocity profiles for Lagrangian wave analysis. From the in-situ velocity profiles, material properties such as wave velocities, stress, strain, strain rate, and strength are calculated. The program can be run in any current version of MATLAB (2008a or later) or as a Windows XP executable.

Acknowledgments

The IWA program is built upon the many discussion with Jim Asay. An earlier analysis program by Tracy Vogler provided the starting point for this work. Dan Dolan compiled the program into a Windows executable, and provided MATLAB support.

Experimental data used in the analysis example was made possible by the DICE facility technicians who operate and maintain the Veloce pulsed power generator.

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Chapter 1

Introduction

This report describes the IWA (Isentropic Wave Analysis) program which was developed for efficient analysis of velocity profiles of isentropic compression experiments. The program was designed to be fairly easy to use and made readily available to users within Sandia's dynamic compression community.

1.1 Program summary

The IWA program is completely self-contained and employs a simple graphical user interface (GUI) to guide users through the analysis process. It is written in MATLAB and can operate on any platform (Mac OS X, Windows XP/Vista, and Linux) with MATLAB version 2008a or later. For non-MATLAB users, a compiled executable is also available for Windows XP. The IWA program can be obtained by contacting Tommy Ao (tao@sandia.gov).

1.2 Overview of report

Chapter 2 gives a brief theoretical background of isentropic compression experiments. Chapter 3 gives details about installing and using the IWA program. A step-by-step example of typical velocity profiles of an isentropic compression experiment is presented in chapter 4. The program's capabilities and future releases are summarized in chapter 5.

Chapter 2

Theoretical background

The high-pressure equation-of-state (EOS) of materials has been studied extensively through shock compression experiments [1, 2, 3, 4]. The data obtained from these experiments are used to determine the pressure-volume-energy states produced by a steady shock wave. Results from multiple shock experiments determine the locus of end states produced by shock compression, otherwise known as the the Hugoniot curve.

The Hugoniot is one curve in the EOS phase space. The isotherm represents the P-V response obtained by compressing a material at constant temperature, typically using a diamond-anvil cell. The Hugoniot represents an adiabatic compression process by a series of steady shock waves to different final states, but is highly irreversible and results in a higher temperature and pressure states offset from the isotherm. Yet another curve that access other areas of the EOS is the compression isentrope. The isentrope lies between the isotherm and the Hugoniot and represents the response from continuous, adiabatic and reversible compression. The temperature states achieved as a function of pressure along the Hugoniot (shock loading) are considerably higher than the along isentrope (shockless or ramp loading). Unlike a shock wave compression experiment, which yields only a single final P-V point, an isentropic compression experiment yields a continuum of points along the isentropic loading path. Combined with the isothermal and shock (Hugoniot) data of a material, isentropic compression data serve to more tightly constrain EOS models.

The need for accurate off-Hugoniot states measurements has compelled development of several experimental approaches to produce well-controlled continuous, or ramp, loading of condensed matter [5, 6, 7, 8]. The thermodynamic states produced by ramp loading of all materials, and solids in particular, generally produce thermodynamic states close to an isentrope since irreversible effects produced by visco-plastic and plastic work are usually small. This technique is often referred to as Isentropic Compression Experiments, or ICE [9].

2.1 Wave propagation

The propagation of waves within a material is governed by its dynamic material properties. In most materials, the local sound speed increases with increasing pressure. Continuous compression produces a ramp wave that will tend to steepen as it propagates into the sam-

ple, and will eventually evolve into a shock wave, which has nearly discontinuous jumps in pressure, density, energy, temperature, and entropy. Since wave evolution is governed by the local non-linear mechanical response of a material, measurement of wave evolution with propagation distance provides information on the continuous compression response at the corresponding loading strain rate [10, 11].

The governing equations for planar shock loading of a solid initially at rest are summarized as [12, 13],

$$\sigma - \sigma_0 = \rho_0 U_S u_p, \tag{2.1}$$

$$\frac{V}{V_0} = 1 - \frac{u_p}{U_S}, \tag{2.2}$$

$$E - E_0 = \frac{1}{2}\left(\sigma + \sigma_0\right)\left(V - V_0\right). \tag{2.3}$$

In these equations, σ_0 is the initial longitudinal stress in the material, which is usually zero, σ is the longitudinal stress in the shocked state, ρ_0 is the initial mass density, V_0 and V are the initial and final specific volumes $(1/\rho)$, respectively, E_0 and E are the initial and final specific internal energies, respectively, u_p is the material or particle velocity, and U_S is the shock velocity. Typically two variables such as shock velocity and particle velocity are measured in a steady shock wave experiment, allowing determination of the other three variables. Measurement of these variables produces a single point on the EOS surface. The locus of points produced by shock compression from the initial state to different final stresses is referred to as the principal Hugoniot.

Similarly, the relations for isentropic loading of a solid initially at rest can be derived from the generalized conservation equations, and are given as

$$\frac{\partial \sigma}{\partial h} = \rho_0 \frac{\partial u_p}{\partial t}, \tag{2.4}$$

$$\frac{\partial V}{\partial t} = -V_0 \frac{\partial u_p}{\partial h}, \tag{2.5}$$

$$\frac{\partial E}{\partial t} = -\sigma \frac{\partial V}{\partial t}, \tag{2.6}$$

where the derivatives are taken with respect to Lagrangian position h, and time t. In the Lagrangian reference frame, the coordinates are fixed to specific material or fluid elements which move in space. If the material response is strain-rate-independent, the motion becomes self-similar and the stress waves induced in the material are referred to as simple waves. For simple waves, the flow in an inviscid fluid, where longitudinal stress is equal to hydrostatic pressure, is isentropic ($S = S_0 = constant$) and Eqs. 2.4 - 2.6 reduce to:

$$d\sigma = \rho_0 c du_p, \tag{2.7}$$

$$dV = -V_0 du_p / c, \tag{2.8}$$

$$dE = -\sigma\left(S_0\right) dV, \tag{2.9}$$

where $c = dh/dt$ is the Lagrangian wave velocity.

Strictly speaking, isentropic flow is obtained only for an inviscid fluid, but the response for simple flow in solids is often used to approximate isentropic response [10]. The Lagrangian wave velocity is determined from the wave propagation properties of simple waves and is approximately related to the $U_S - u_p$ relation as,

$$c \approx c_0 + 2 s u_p, \tag{2.10}$$

where c_0 is the initial sound speed, and s is the parameter in the Hugoniot relation for shock speed [12],

$$U_S = c_0 + s u_p. \tag{2.11}$$

Equation 2.10 may be obtained by using the relationship between the Eulerian and Lagrangian wave velocities and substituting in Eq. 2.11, and should be a good approximation at low stresses (up to $\sim$ 30 GPa in Al) since the Hugoniot and isentrope are similar.

2.2 Lagrangian wave analysis

The Lagrangian wave analysis method [11, 14] is based on wave propagation and stress-strain response of a material in uniaxial loading and unloading [15], as shown in Fig. 2.1. In this case, the initial response is elastic until the onset of plastic yielding. This produces an initial elastic wave referred to as the elastic precursor. Subsequent plastic response is governed by the bulk response of the material and produces a plastic wave. Upon unloading from the compressed state, the response is initially elastic until the onset of reverse yielding, followed by plastic unloading.

The standard method for obtaining EOS measurements along a compression isentrope involves the planar ramp loading of at least two samples of different thicknesses in which the thickness difference Δx is known precisely, as shown in Fig. 2.2. The isentrope loading curve is reconstructed from the measured Lagrangian wave velocity histories of the rear surfaces

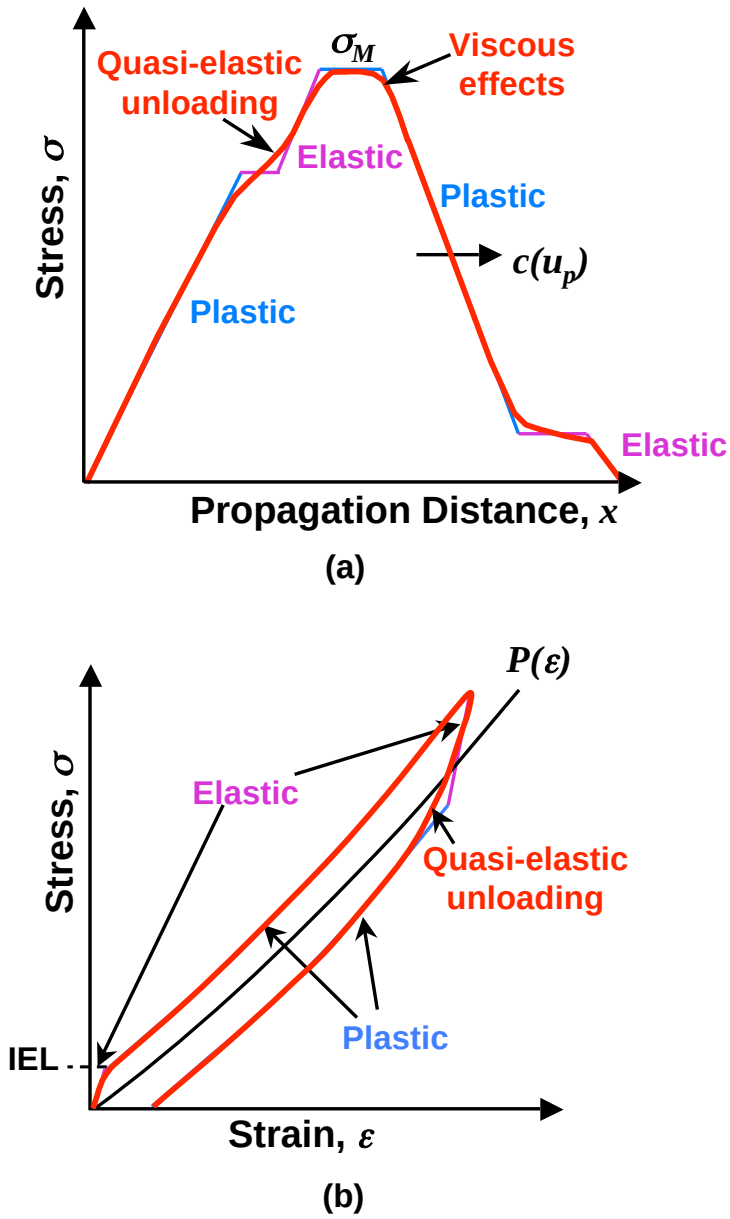

Figure 2.1. Ramp loading and unloading: (a) wave propagation, (b) stress-strain curve.

of the samples (either free surface or window interface). It is important to note that for the Lagrangian wave analysis, as long as the two sample 'EOS pairs' both experience the same pressure drive history, knowledge of actual input pressure wave profile is not required.

2.2.1 Material strength

Determination of mechanical properties such as compressive strength of materials under dynamic loading has been proven to be extremely difficult. Strength data has been obtained for a few metals and ceramics under shock loading and in limited stress ranges [15, 16, 17, 18, 19]. Typically, strength increases with shock pressure initially, but eventually it begins to soften due to thermal effects and tends to zero as the shock melt pressure is approached. However, under isentropic loading, thermal effects are minimized, so strength is expected to reach considerably higher levels than in shock loading. Strength measurements under isentropic compression are even more limited than measurements under shock loading.

The technique for estimating compressive strength at peak stress is based on the self-consistent method by Asay and Lipkin [16]. To obtain strength information for the unloading profiles, the principal assumption is that the elastic-plastic relation

$$\sigma = P + \frac{4}{3}\tau, \tag{2.12}$$

applies incrementally at all points in the measured profiles. The procedure begins by differentiation of 2.12,

$$\frac{\partial \sigma}{\partial \varepsilon} = \frac{\partial P}{\partial \varepsilon} + \frac{4}{3}\frac{\partial \tau}{\partial \varepsilon}, \tag{2.13}$$

where σ is the longitudinal stress, τ is the shear stress, P is the hydrostatic pressure and ε is the engineering strain. Using the definition of Lagrangian wave velocities,

$$\frac{\partial \sigma}{\partial \varepsilon} = \rho c^2, \tag{2.14}$$

$$\frac{\partial P}{\partial \varepsilon} = \rho c_B^2, \tag{2.15}$$

the following relation for material yield strength is obtained [16],

$$Y \approx \Delta\tau = \frac{3}{4}\rho_0 \int \left(c^2 - c_B^2\right) d\varepsilon, \tag{2.16}$$

where $\Delta\tau$ is the change in shear stress developed during unloading, ρ_0 is the initial density, c is the Lagrangian longitudinal wave velocity, and c_B is the Lagrangian bulk velocity.

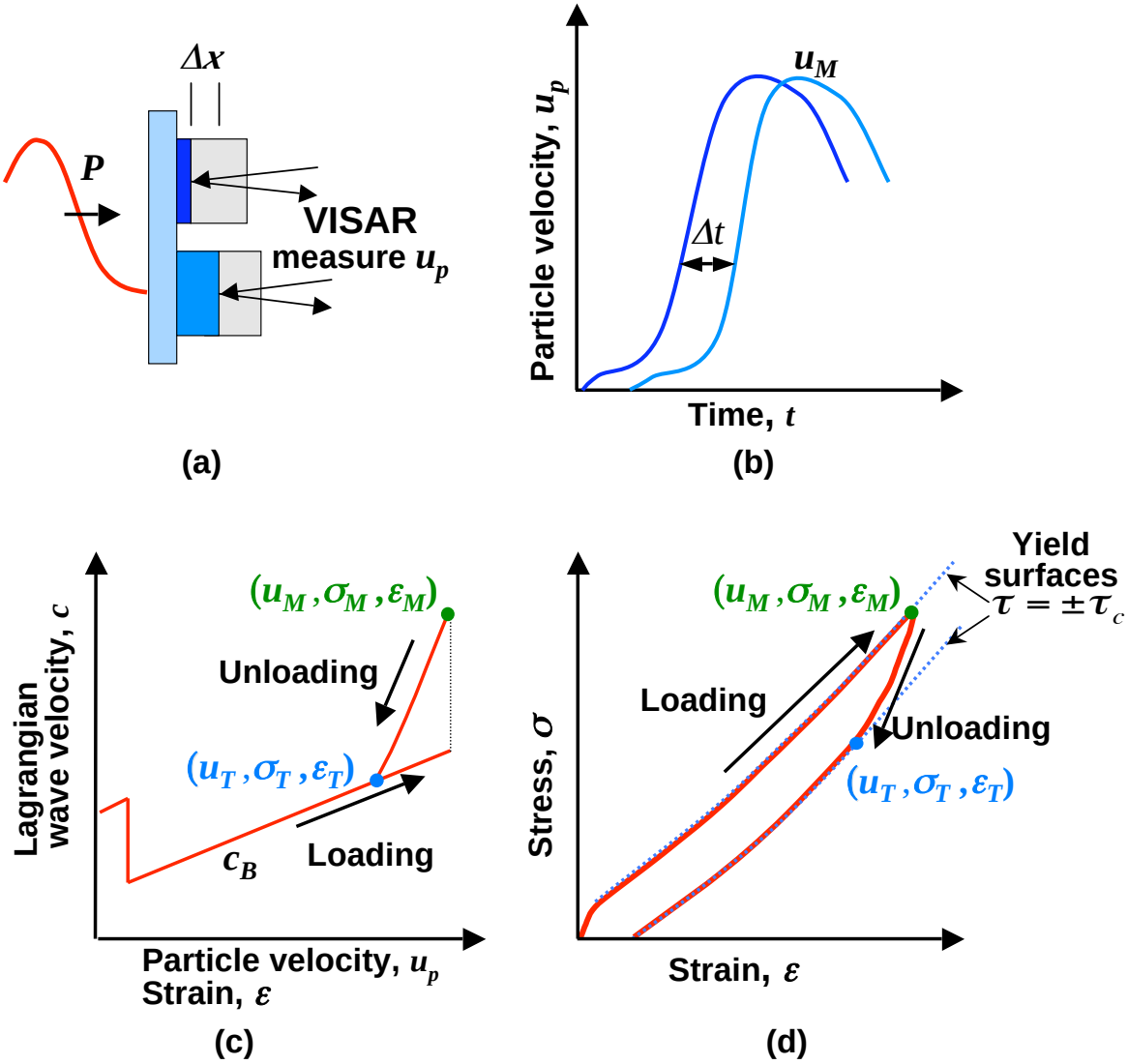

Figure 2.2. Lagrangian wave analysis: (a) experimental setup, (b) velocity profiles, (c) wave velocity, and (d) stress-strain curve.

Equation 2.16 may be also viewed as the stress difference between the loading and unloading curves [16],

$$Y \approx \frac{3}{4}\left(\sigma_L - \sigma_U\right). \tag{2.17}$$

Chapter 3

Program overview

An overview of the IWA program is presented in this chapter. First, program installation and execution instructions are given. Next, the features of the graphical user interface are presented. Finally, the program's analysis stages are defined.

3.1 Installing and running IWA

IWA exists in two formats:

1. a MATLAB version which runs within the MATLAB program,
2. a Windows executable version which may be used on Windows systems without the MATLAB program.

Installation of each version is different and are described separately in the following sections.

3.1.1 MATLAB version

The MATLAB version of IWA is intended for MATLAB 2008a or later. A valid MATLAB license (http://www.mathworks.com) is required. First, copy the folder `matlab`, which contains all files and subdirectories of the MATLAB version of IWA, to a local directory of the machine. Next, startup the MATLAB program. To install IWA, add the `matlab` directory to the MATLAB path, using either the "addpath" command or the "Set path" tool on the "File" menu. Only the main folder itself, not the `private` subdirectory, should be added to the path. After installation is complete, the program can be started by typing "IWA" at the command line.

3.1.2 Windows executable

The executable version of IWA is intended for Windows XP. The program may operate in older versions of Windows but is not supported. Also, the executable version of IWA

has not been tested on Windows Vista but should presumably work. After the contents of the `winexe` folder has been copied to a local directory of the machine, double click the `MCRInstaller2008a.exe` program and accept all default choices in the installation. This process installs necessary libraries and support functions for IWA, and needs to be performed once for each machine where the program is to be used. When the MCR installer is complete, IWA can be launched by double clicking on the `IWA.exe` executable. The initial launch of the program will be somewhat slow as the various routines are unpacked for the first time, but subsequent launches should be considerably faster.

3.2 Graphical user interface

This section describes the graphical user interface (GUI) of IWA. The IWA GUI consists of a main figure, buttons, menu, and tools, as shown in Fig. 3.1.

3.2.1 Main figure

In the center of the IWA GUI is the "main figure" where the majority of the user graphical interactions occur. As the user proceeds through the analysis stages, the main figure will display the appropriate graph where the user will be asked to select various data points needed in the analysis.

3.2.2 Buttons

The "buttons" are grouped into separate panels corresponding to the analysis stages described in the analysis overview (section 3.3). Clicking on a button will initiate the labeled analysis function. Dialog boxes will appear to guide the user through the chosen analysis routine until it's completion.

3.2.3 Menu items

At the top of the IWA GUI is the "menu" bar, which consists various actions that grouped into the headings: "Load Data", "Save Data", "Figures", and "Program". Upon clicking on a menu heading, a list of actions is revealed.

Under the Load Data menu heading, the "Set Directory" and "Import Data" actions are enabled. The first action sets the directory from which input data files will be loaded into IWA, and where output files will be saved. Upon clicking the import data action, the user is asked to load velocity profiles individually into the program.

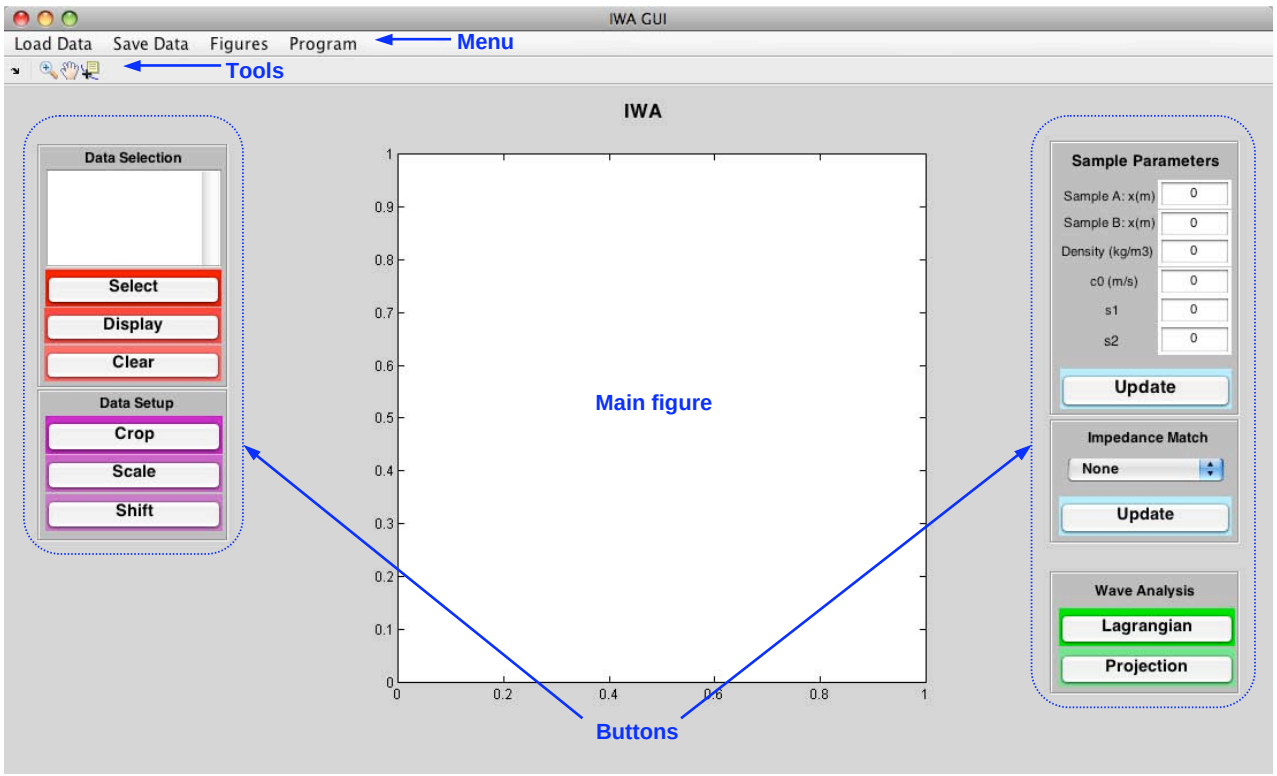

Figure 3.1. IWA GUI.

Under the Save Data menu heading, the "Store Data" and "Export Data" actions are enabled. The store data action saves the analyzed results into data matrices. The export data action takes the stored data matrices and exports them as ASCII text files into the directory that the user chooses.

Under the Figures menu heading, individual plots may be opened in separate figure windows. The figures can be saved to a file using the "Save figure" button (disk icon) of the figure window. The default format is a MATLAB figure (.fig), but other formats (.pdf, .eps, .jpg, .tif, etc.) are available.

Under the Program menu heading, the following actions are enabled: "About", "Restart", and "Exit". The about action provides general information about IWA. Restart closes and relaunches the program, clearing all parameters and returning the program to its default state. Exit closes the program.

3.2.4 Tools items

Under the Menu bar is the "Tools" bar, which contain tools to aid the user in the analysis.

1. "Zoom" - plots can be zoomed into with either a left mouse click or by clicking and dragging to create a zoom box. Shift-click zooms out and double click restores the plot to the original view. Press the right mouse button for additional options.

2. "Pan" - user can click and drag the plot around for better viewing.

3. "Data cursor" - displays the (x, y, z) values of the point that the user clicks on. Right-click for additional options.

3.3 Analysis overview

The analysis stages of the IWA program are displayed in Fig. 3.2.

3.3.1 Load data

The IWA program begins by opening the load data menu. The first step is to set the directory for importing and exporting files. Next, the data files are imported individually into the program. The first column of each file should be the time points, and the second column should be the velocity points.

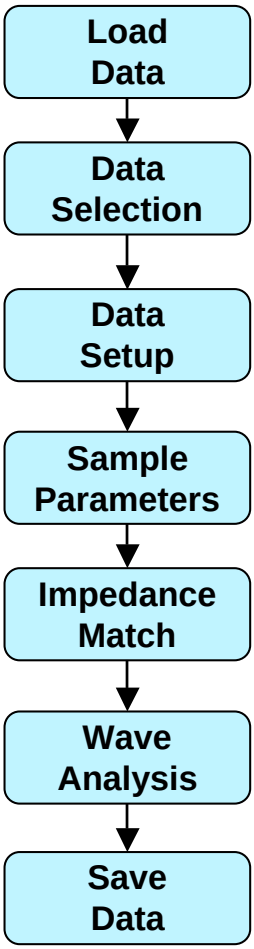

Figure 3.2. IWA layout.

3.3.2 Data selection

The "Data Selection" panel consists of a file viewer window and three action buttons: "Select", "Display", and "Clear". To begin the user clicks on the file viewer window to show the names of all loaded files. To choose a data file, the user clicks on the name of the data file and then clicks on the select button. Next, to view the data in the main figure window, the user clicks on the display button. Additional data may be chosen by subsequent clicking on file names and the select button. The velocity profiles are numerically labelled based on order of selection. Alternatively, multiple sets of data may chosen by highlighting all of the desired file names and clicking on the select button. To remove all of the selected data, the user clicks on the clear button, and new data selection can be done.

3.3.3 Data setup

The "Data Setup" panel consists of the action buttons: "Crop", "Scale", and "Shift". To begin, the user clicks on the crop button to choose the time range of interest. Since, the subsequent analysis stages are performed with SI (mks) units, the data need to be converted such that velocity is in m/s and time in s. Upon clicking the scale button, the user is asked to scale either the velocity or time values. Next, the user is asked if the scaling will be performed on all of the data at once with a single scale factor or separately with individual scale factors. In a similar manner, shifting of the velocity profiles along the time or velocity axis is performed by clicking on the shift button.

3.3.4 Sample parameters

The "Sample Parameters" panels consists of 6 input boxes and the "Update" button. The top 2 boxes are for the thicknesses (m) of the 2 samples (A and B) to be compared. The other boxes are for the sample density (kg/m^3), initial bulk wave velocity c_0 (m/s), first order wave velocity parameter s_1, and second order wave velocity parameter s_2. The Lagrangian wave velocity of the sample is assumed to be the form,

$$c \approx c_0 + s_1 u_p + s_2 u_p^2. \tag{3.1}$$

After inputing the sample parameters, the user clicks on the update button to set the values into the program.

3.3.5 Impedance match

The "Impedance Match" panel consists of a drop down list and the "Update" button. The function of this action is to convert the measured interface velocity profiles into in-situ

particle velocity profiles using an incremental impedance matching technique. Upon clicking the drop down list, the user picks the appropriate window (LiF, Sapphire, Diamond, Quartz, other) or free surface which contacts the sample. Next, the user is asked to set the window parameters. Upon clicking the update button, the user is asked to input the velocity profile number to apply the impedance matching. The new in-situ particle velocity profile is updated in the main figure. To reset the impedance matching performed on all of the velocity profiles, the user chooses "None" in the drop down list and clicks on the update button.

3.3.6 Wave analysis

The "Wave analysis" panel consists of the "Lagrangian" and "Projection" buttons. Upon clicking the Lagrangian button, user is asked to input the numbers of the velocity profiles which correspond to samples of A and B. These two velocity profiles are used to calculate the Lagrangian wave velocity of the sample.

Next, the user is asked to specify the initial particle velocity (as a percentage to the peak velocity) in which the calculation is performed. The wave velocity as a function of the particle velocity is displayed in the main figure window. The Lagrangian wave velocity versus particle velocity is displayed on the main figure. Next, the user is asked to choose on the bulk loading curve start and end particle velocity cutoffs. The program performs a fitting on the cropped curve to find c_0, s_1 and s_2. From the Lagrangian wave velocity, the stress and strain during loading and unloading is calculated. Finally, the strength of the material is obtained from the difference between the loading and unloading curves. The Lagrangian wave velocity vs. particle velocity, stress vs strain, strength vs. strain, and strain rate vs. time are displayed in separate side figures.

For a more direct comparison of the two velocity profiles, the program also performs a projection analysis which takes the first velocity profile and propagate it to the location of the second velocity profile. Upon clicking the projection button, the user is asked whether to use the c_0, s_1 and s_2 values that was given by the user or to use the fitted values from the Lagrangian wave analysis. The results are displayed in the main figure.

3.3.7 Save data

To save the analyzed data, the user goes to the "Save Data" menu and first clicks on the "Store Data" action. The user is asked to choose a number (0-9) under which the results will be stored. The user may now go back and modify the analysis (eg. scaling, shifting, sample parameters, etc.), after which the user may store the new results under a different storage number. Finally, upon clicking on the "Export Data" action, the user is asked to choose the number (0-9) of the stored data which the user wants to export. The results are saved in 5 ASCII text files with the default file names:

1. `IWA_Time_VelInsitu.txt` - time and in-situ particle velocity profiles;

2. `IWA_TimeSR_StrainRate.txt` - time and strain rate;
3. `IWA_Up_Cs_Strain_Stress.txt` - particle velocity, Lagrangian wave velocity, strain, and stress;
4. `IWA_Strain_Strength.txt` - strain upon unloading and material strength;
5. `IWA_TimeProj_VelProj.txt` - projected time and velocity profile.

Chapter 4

Using IWA

This chapter describes the practical use of the IWA program. Analysis of an example is given with step-by-step results for comparison. Also, some analysis hints are presented to aid the user.

4.1 Example

The example is taken from a experiment performed on the Veloce pulsed power generator [20, 21]. The load consisted of Al 6061-T0 and Al 6061-80 samples, each backed by 6 mm thick LiF windows, that were glued onto 20 mm wide by 1.0 mm thick Al load panels. Ramp loading up to 6.5 GPa of the samples was achieved upon discharging the 440 ns, 2.5 MA current pulse of the Veloce generator.

The 4 velocity profiles provided with the IWA package are found in the folder `IWAexample`:

1. `Al_LANL_1.4141mm.txt` - Al 6061-T0 sample (1.4141 mm thick) with LiF window;
2. `Al_LANL_2.4011mm.txt` - Al 6061-T0 sample (2.4011 mm thick) with LiF window;
3. `Al_WSU_1.5024mm.txt` - Al 6061-80 sample (1.5024 mm thick) with LiF window;
4. `Al_WSU_2.4023mm.txt` - Al 6061-80 sample (2.4023 mm thick) with LiF window.

After setting the directory to where the data files are located, load each file with the load data action. Next, in the data selection panel click on the file viewer window and highlight all of the file names. After clicking the select and display button, the velocity profiles should be displayed in the main figure, as shown in Fig. 4.1.

Under the data setup panel, click on the crop button to limit the data range from t = 900 ns to 1850 ns. Use the scale button to convert the units of the velocity (km/s) and time (ns) data points to m and s, respectively. The cropped and scaled velocity profiles should be now resemble Fig. 4.2.

The following steps correspond specifically to the analysis of the Al 6061-T0 data set, namely velocity profiles 1 and 2. Under the sample parameters panel, set the thickness of

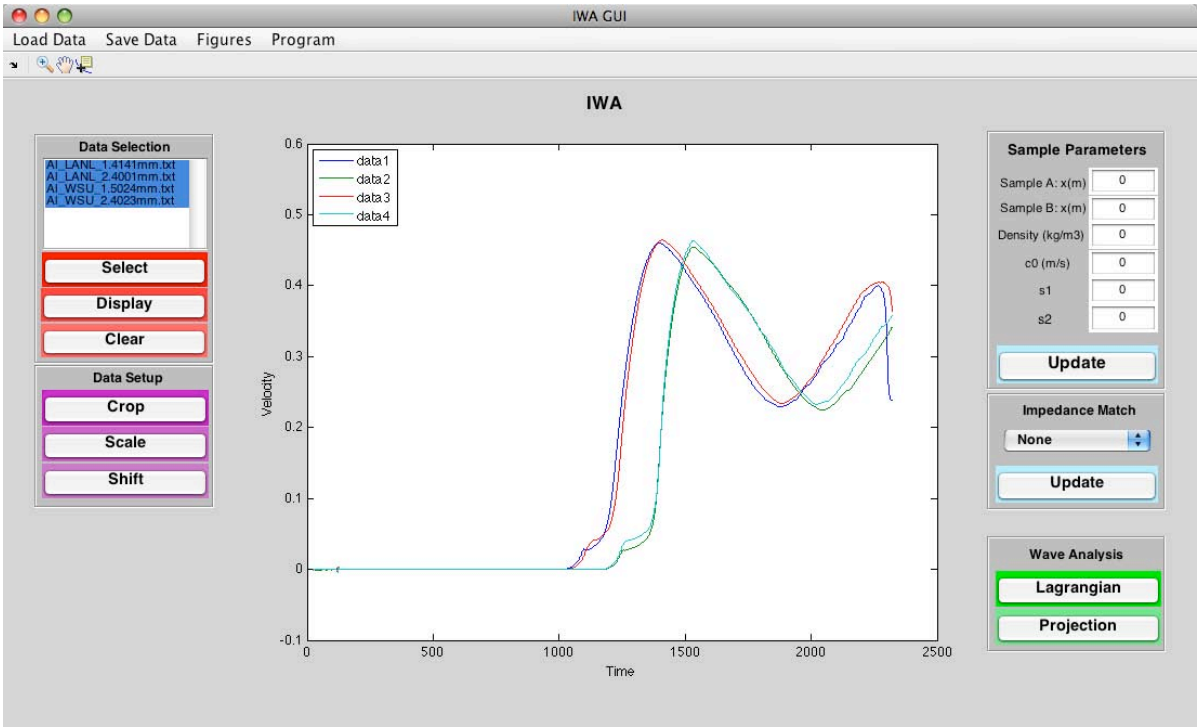

Figure 4.1. IWA example: raw velocity profiles.

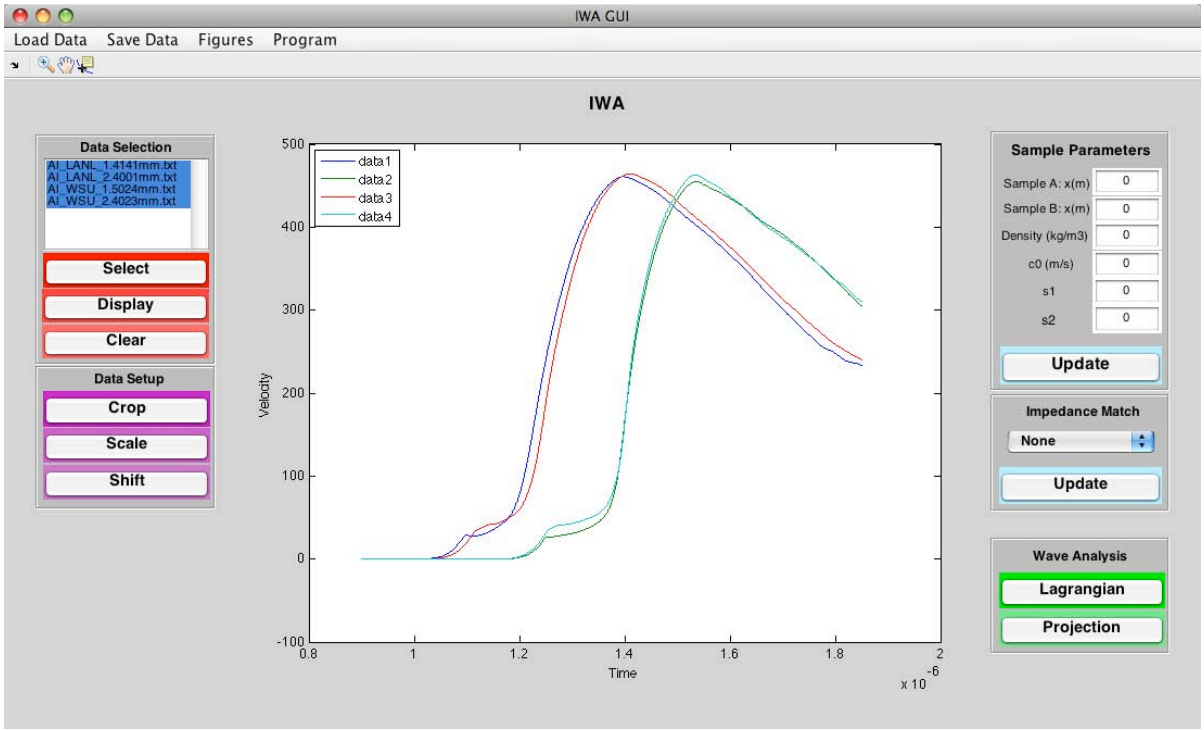

Figure 4.2. IWA example: cropped and scaled velocity profiles.

sample A and B to 1.4141e-3 m and 2.4011e-3 m, respectively. Also, set the sample density to 2.700e3 kg/m^3, c_0 = 5.288e3 m/s, s_1 = 2.752 and s_2 = 0. Click on the update button to set the values into the program.

Since these samples are backed by LiF windows, under the impedance match panel set the window material to "LiF". To perform the incremental impedance matching, click on the update button and enter number "1" to convert the first raw velocity profile to an in-situ particle velocity profile. Repeat the updating on the rest of the raw velocity profiles (i.e. 2, 3, 4) until all are converted to in-situ particle velocity profiles, which should now resemble Fig. 4.3.

Under the wave analysis panel, click on the Lagrangian button and enter velocity profile numbers "1" and "2" for the inputs of samples A and B, respectively. After the Lagrangian wave velocity plot appears in the main figure, click on start and end points on the bulk loading curve. Since these points are used define the data range in which the program fits the material's bulk response, avoid the initial elastic wave velocity and the bending section near peak loading. The fitted curve along with the linear fit parameters c_0, s_1 and s_2 are displayed in the main figure, as shown in Fig. 4.4.

From the Lagrangian wave velocity, the program calculates the loading and unloading stress-strain curves which are then used to obtain the material's strength as a function of unloading strain. Also, the strain rate as a function of time is calculated by the program. These results are displayed in separate side figures, as shown in Fig. 4.5.

To compare the velocity profile of sample A projected forward to the sample B location, click the projection button. Enter velocity profile numbers "1" and "2" for the inputs of samples A and B, respectively. The user is asked which sample parameter, the "Fit" values obtained from the analysis or the original "Given" values that the user previously inputted into the program. The projected velocity profile is shown in Fig. 4.6.

At this point, the user may want to input the new "fitted" values of c_0, s_1 and s_2 into the sample parameters boxes and update their values. Repeat the impedance matching to get a new set of in-situ velocity profiles, and the perform the Lagrangian and projection analysis again. The process may be repeated until the user is satisfied with that the input sample parameters and fitted parameters are consistent with each other.

Under the save data menu, store the analyzed results as storage number "1". The user may now export the results using the export data action. The results are saved as 5 ASCII text files in the directory chosen by the user. Alternatively, the user may perform additional analysis such as analyzing the Al 6061-80 data set (velocity profiles 3 and 4). Those results may be stored under a different storage number and exported.

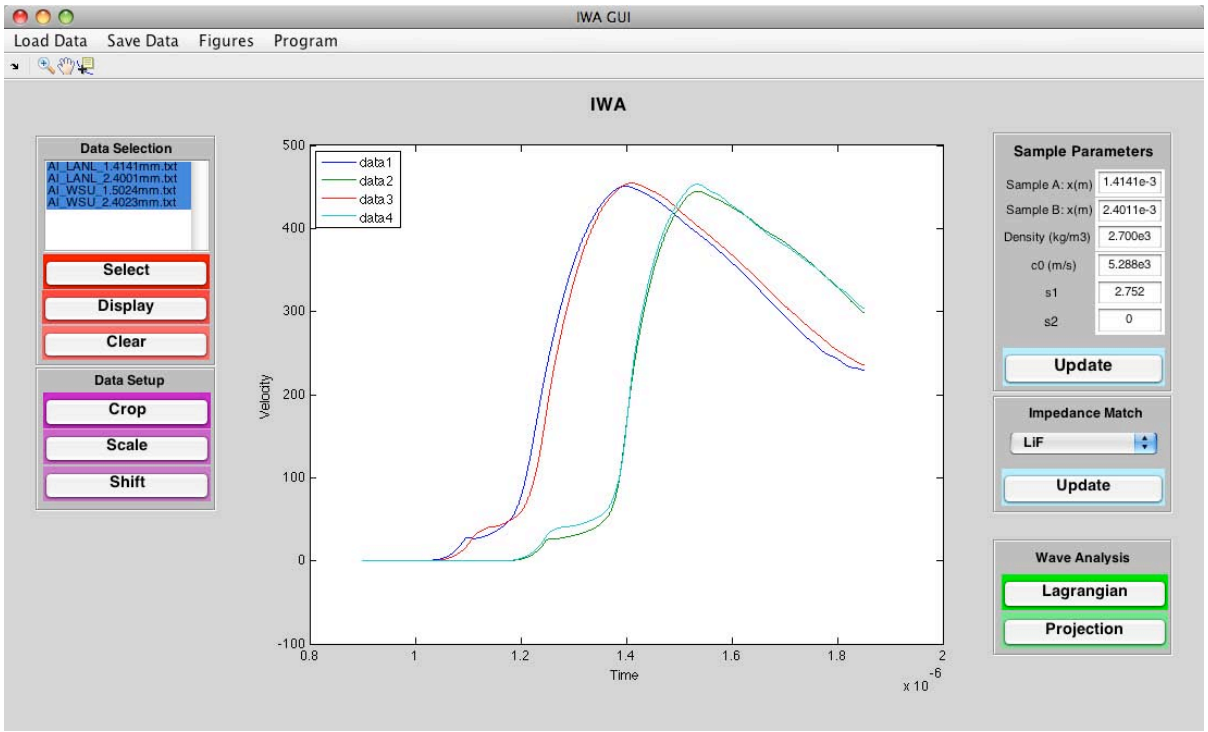

Figure 4.3. IWA example: impedance matched velocity profiles.

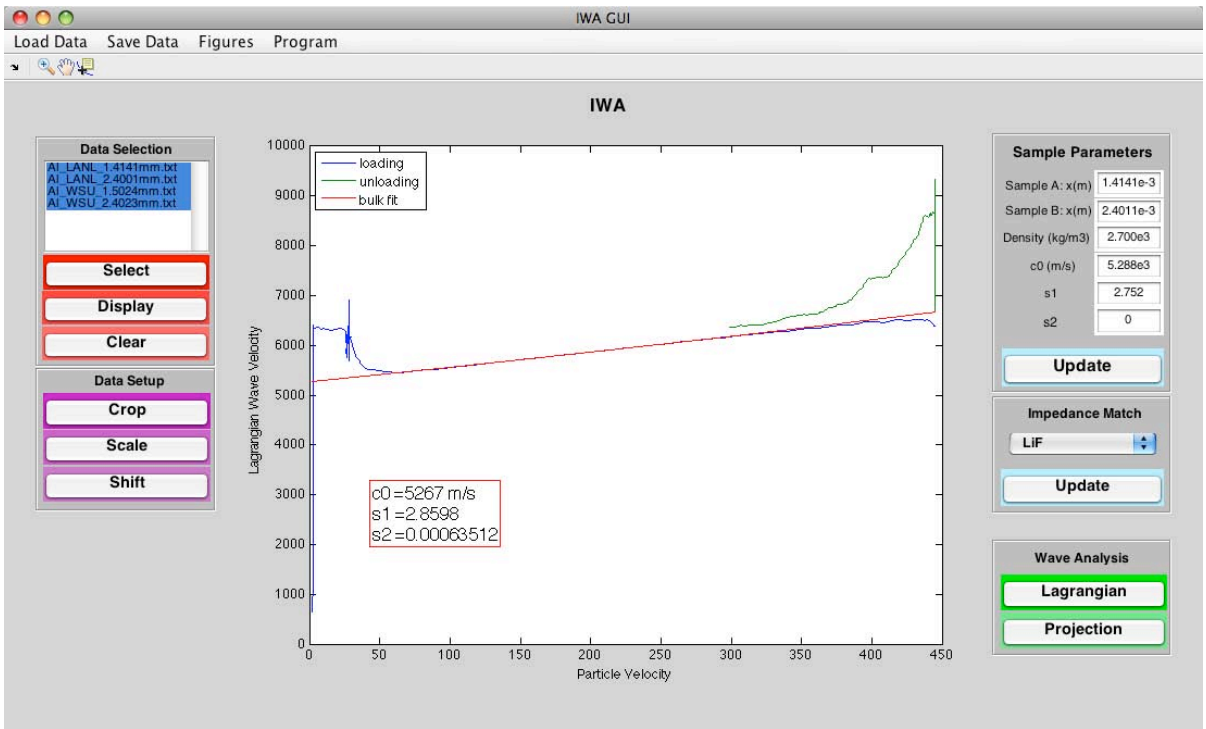

Figure 4.4. IWA example: Lagrangian wave velocity.

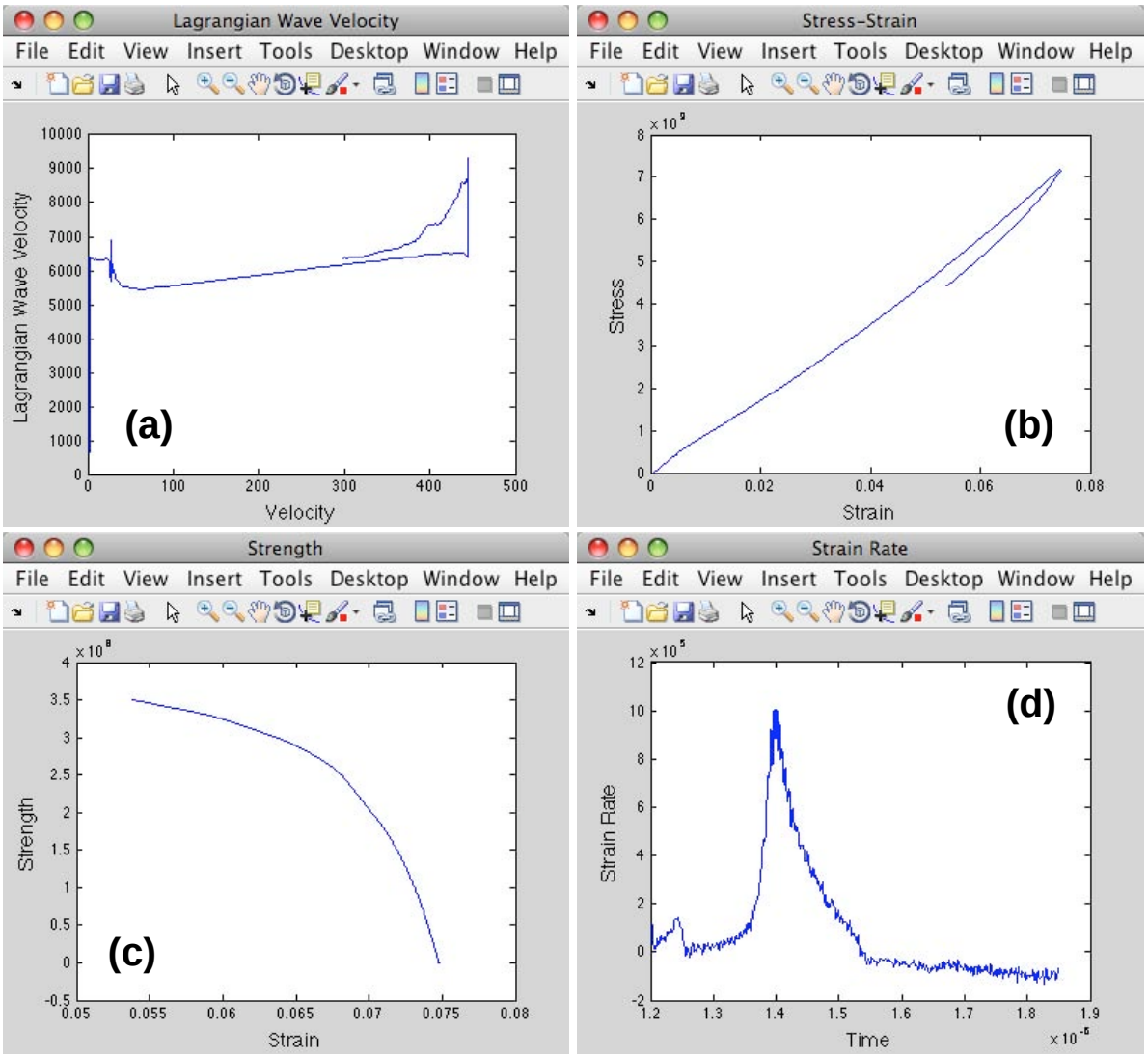

Figure 4.5. IWA example: side figures of (a) Lagrangian wave velocity vs. particle velocity, (b) stress vs. strain, and (c) strength vs. strain (d) strain rate vs. time.

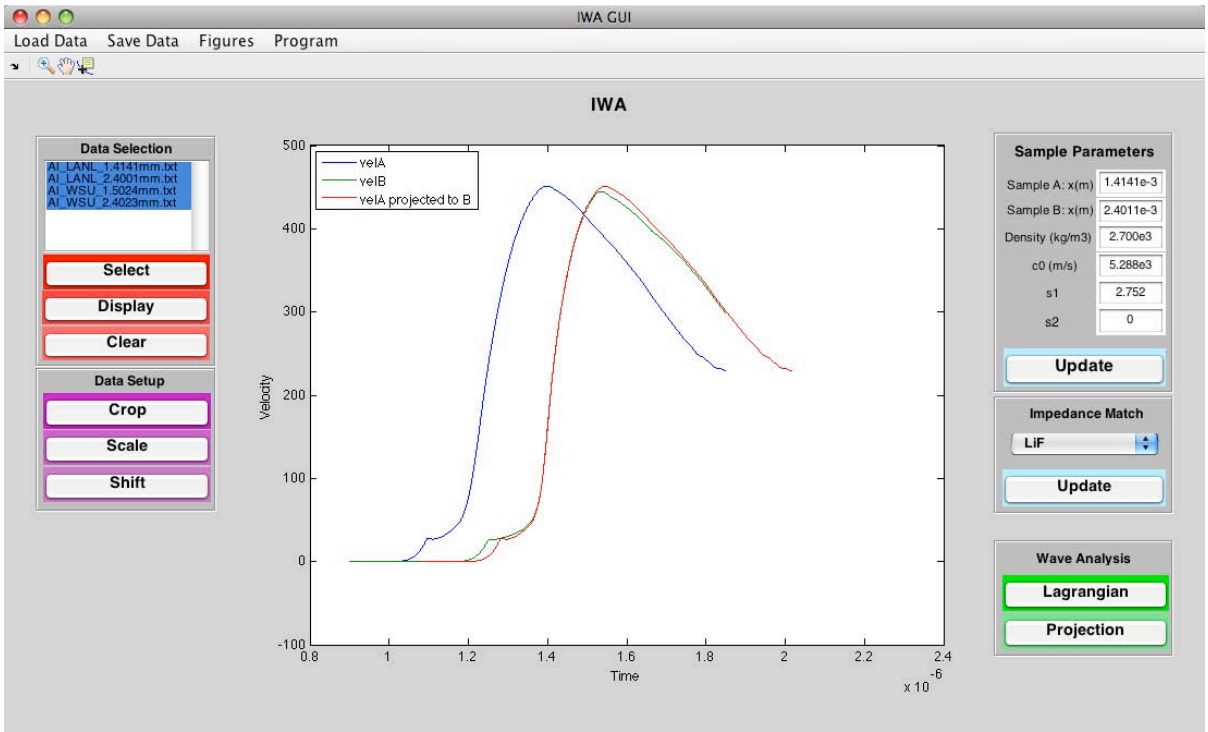

Figure 4.6. IWA example: projected velocity profile.

4.2 Analysis hints

4.2.1 Cropping

The current IWA program is not setup for reloading profiles. In the above example, after the unloading the data was cropped prior to the reloading of the upstream velocity profile. Also, at the start of the Lagrangian wave analysis, an initial velocity cutoff (% of the peak velocity) is chosen to avoid the noisy signal at the low velocities which would cause spikes in wave velocity calculations.

4.2.2 Smoothing

After the raw data is cropped to the appropriate data range, an initial smoothing parameter is selected to reduce noise effects in the analysis. The precise choice will depend on the level of signal noise, the sampling rate, and the relevant features of interest.

4.2.3 Scaling

Intuitively, the downstream velocity profile should have lower peak velocity than the upstream velocity profile. However, due to non-uniform drive along the panel the downstream peak velocity might be higher the upstream peak velocity. For that case, the downstream velocity profile should be scaled lower so its peak is the same or less than the upstream peak velocity.

Chapter 5

Summary

5.1 Program features

The IWA program accepts measured velocity profiles from isentropic compression experiments in the form of separate text files. The user may scale and shift the data, and specify the time range over which the analysis is performed. Sample parameters are entered directly into the program and may be changed during the analysis. Incremental impedance matching is performed to convert measured velocity profiles to in-situ particle velocity profiles.

Lagrangian wave analysis is performed to obtain the Lagrangian wave velocity, stress, strain, strain rate, and strength of the material. In addition, velocity profiles at upstream material positions may be projected forward and compared with downstream velocity profiles. Results generated by IWA may be exported as text files for post-processing or be saved in various graphical formats.

5.2 Future releases

Users should contact Tommy Ao (tao@sandia.gov) with questions, bug reports, and feature requests. Bug fixes will be made as necessary and will be distributed by email. Features under consideration for future versions of IWA include:

- Recall configurations of previous settings and results, and
- Single velocity profile approximate analysis.

No scheduled update to IWA is planned at this time, but new releases will be considered based on user feedback.

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