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A MATLAB GUI for the Prediction of Coefficients of Restitution

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Abstract

The motivation behind a MATLAB GUI to predict the coefficients of restitution is to enhance the fidelity of rigid body simulations. Currently, the common practice is to use the coefficient of restitution as a way to capture numerous factors of damping instead of using a coefficient true to the materials in contact. By switching to a model that predicts the coefficient of restitution as a function of velocity between any two materials, rigid body simulations will be more accurate due to higher fidelity models of the actual physics. Additionally, by packaging this software with a library of materials, all rigid body simulations can be run using consistent properties, eliminating any guesswork and “ballpark” figures. This report will therefore cover the existing code and how it delivers all of the features needed to easily estimate coefficients of restitution.

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NOMENCLATURE

CofR	Coefficient of Restitution
DOE	Department of Energy
GUI	Graphical User Interface
SNL	Sandia National Laboratories

1. INTRODUCTION

1.1. Motivation behind the GUI

The motivation and focus of this GUI is to increase the fidelity of rigid body simulations within Sandia National Laboratories. The current practice is to use the coefficient of restitution (CofR) as a way to capture other damping effects otherwise not modeled within the system. This can work well when trying to tweak a model to match experimental data, but ignores the physics critical to the fidelity of the model.

Thus comes the goal of the GUI, to accurately predict the CofR that analysts can use within their models that actually reflect the physics involved. The significance between using a CofR that captures numerous damping effects and one that captures the actual physics can be quite severe. For instance, at the time of writing this document, most rigid body simulations are being run with a CofR of around 0.4. Under the same impact velocities, both the experimental and theoretical estimates of the CofR can be as high as 0.9, with the difference of 0.5 being used to account for other, non-impact related damping. Using the GUI developed within this paper will help alleviate the practice of using these ballpark figures and instead encourage the use CofRs true to the physics at hand.

It must be recognized that in shifting to a paradigm where impact is modeled more faithfully, other sources of energy dissipation in the system (such as bearing friction, viscous losses, etc.), will need to be modeled with greater accuracy. However, recent research [1, 2] has shown that inaccurate models of energy dissipation mechanics can lead to inaccurate predictions of a system's dynamics. Incorporation of an improved model of contact dynamics is the first step in assuring that simulations make accurate predictions for the system of interest.

2. THE GUI ITSELF

The GUI is split into three main programs: the Launch Screen, the Coefficient of Restitution Modeler, and the Materials Manager. This division splits the GUI into three sections, each with distinct functions, so that each section can specialize in its function, while still working together seamlessly. Each program is contained within its own script file, and can thus be launched individually if so desired. The purpose behind this is that anyone can use the Materials Manager as a standalone program to have a consistent set of material properties to use. Additionally, as the program becomes more widespread, so will the material library and its usefulness as a material property database will increase correspondingly.

2.1 Launch Screen

The launch screen (Fig. 1) is the first screen that most users will see when opening the program. It provides brief descriptions of each of the subprograms as well as links to them. It also provides links to the help documentation. The final section is unique to the launch screen and allows the user to select default settings. These settings are saved in the file “settings.txt” in the same directory as the rest of the programs.

Figure 1 – Launch Screen

2.2. Coefficient of Restitution Modeler

The Coefficient of Restitution Modeler section of the GUI is responsible for gathering inputs for geometric and material properties, transferring these inputs into the contact model, and displaying the results in an easy to interpret manner.

Figure 2 – The Coefficient of Restitution Modeler

Figure 2 shows a view of the modeler. In the upper-left corner of the program is the geometric properties section. The lower-left contains the material properties inputs. In the upper-right, users can change the settings of the model. Finally, the lower-right corner contains all of the outputs for the program, including a graph of the data, a numerical output, and a polynomial interpolation of the data. Overall, the design of the GUI aims to be very clean and separated, with each section standing apart from the others both in layout and in function. It is also important to note that a menu bar exists at the top of the program to grant easy access to other features within the GUI.

2.2.1. Geometric Properties

The geometric properties section of the GUI is based on the elastic-plastic contact model described in [1], which assumes spherical contact. This contact requires either sphere-on-sphere or sphere-on-plate contact.

Geometric Properties

Object 1

☒ Sphere
☐ Flat Plate

Radius: ft

Object 2

☒ Sphere
☐ Flat Plate

Radius: ft

Figure 3 –The Geometric Properties Section

In Fig. 3, the options for “Sphere” and “Flat Plate” are clearly shown. Another feature not visible in this image is that upon selecting Flat Plate for either Object 1 or Object 2, the other object’s option of Flat Plate will correspondingly be disabled. This signifies that a selection of two flat plates is incompatible with the contact model. The data field in this section is an input for the radius of each object. To prevent errors occurring within the model, an error message appears if the radius entered is a negative number, a zero entry, or a complex number.

2.2.2. Material Properties

In the Material Properties section, the user is asked for the six properties that properly define the impact characteristics. These include: Young’s Modulus, Poisson’s Ratio, yield stress, Meyer’s Hardness, density, and Brinell Hardness. Once again, an invalid entry into any of these inputs will prompt the user with an error message stating that the number entered is not suitable for the model.

Material Properties

Object 1

Custom Material

Young's Modulus psi

Poisson's Ratio

Yield Stress psi

Meyer's Hardness

Density lbm/ft³

Brinell Hardness kg/mm²

Object 2

Custom Material

Young's Modulus psi

Poisson's Ratio

Yield Stress psi

Meyer's Hardness

Density lbm/ft³

Brinell Hardness kg/mm²

Figure 4 – The Material Properties Section

Fig. 4 is a detailed view of the material properties section of the program. Here users can enter in material properties manually in the text boxes, or select a material from the dropdown menu. This dropdown menu is automatically populated with materials from the currently loaded material list. Upon selection of a material, the material properties of that material will automatically be inserted into the text box, from here a user can tweak the numbers if needed or use the values listed. It is important to note that there is no limit on the combination of materials selected, and thus it is possible to model any metal on metal impact necessary.

2.2.3. Model Settings

The model settings section is responsible for managing the way the data is simulated. It is separated into two settings, the velocity resolution setting, and the interpolation setting. The velocity resolution setting determines how many velocities the CofR is calculated for and what interval is inspected, and the interpolation setting determines the type of curve fit to the data.

Figure 5 – The Model Settings

Shown in Fig. 5 are the available model settings. The three options for the velocity resolution are coarse mesh, which selects 51 points between 0.1 m/s and 5 m/s, fine mesh, which selects 491 points between 0.1 m/s and 5 m/s, and custom mesh. The custom mesh option opens a new dialog window which prompts the user for the interval and number of points to use. This way, the user can simulate impacts in an interval that is within the range of operation of the rigid body simulations. The number of points is also critical because it indicates a tradeoff between simulation time and accuracy of the interpolation. With more points, the trend is more easily visible but also takes longer, whereas the opposite is true for less data points.

The options for interpolation include a fractional polynomial fit, an exponential fit, and a hybrid fit, which combines the previous two. The fractional polynomial fit follows the form

$$p(x) = \alpha x^{\beta} + \gamma, \quad (1)$$

where β is restricted to be less than one, and α must be negative. This ensures the fit follows a general downward trend while flattening towards higher velocities. The exponential fit is

$$p(x) = \alpha e^{\beta x} + \gamma. \quad (2)$$

For the exponential fit, a downward trend is produced by forcing β to be negative. In both equations, there are three unknowns, and thus three conditions are needed to solve for these equations. The conditions used in this GUI are:

- the CofR at 0 m/s must be equal to 1,
- the CofR at the endpoint of the interval must equate to what the model predicts,
- the error in the interpolant must be minimized by optimizing the coefficients.

The hybrid method takes the previous two methods, and combines them with optimized weights as to further reduce the error. The hybrid interpolant then becomes

$$p(x) = A * \text{exponential fit} + B * \text{polynomial fit} \quad (3)$$

Using the same conditions as listed above, $A + B = 1$, which gives a range to optimize the coefficients and minimize error.

2.2.4. Model Output

This section is the main result of the GUI, where inputs are converted into graphical outputs to be interpreted by the user. The buttons at the top of this section read: “Compute,” “Export,” “Detailed View,” and “Reset.” The first button, “Compute,” calculates the CofR as a function of the user-supplied parameters, then plots the result against impact velocity. Next, the “Export” button saves the data presented in the graph, namely the velocities and corresponding CofRs. Three different data formats are available to the user: the first option is to save the data as an array, which creates a .mat file with the data in a location selected by the user. The second option both saves the data into the .mat file, and creates a function handle containing the polynomial displayed. The third option saves the data into a .csv file that can be read by programs other than MATLAB. The “Detailed View” button displays the same graph already showing, but in a new window, complete with the toolbars normally associated with a MATLAB figure. This allows the user to use MATLAB’s built in tools to examine the graph as well as displays a larger graph of the data. The final button, “Reset,” returns the graph and all of the associated fields to their initial, empty state.

Figure 6 shows how the Model Output section would look after running a simulation. At the top are the aforementioned control buttons. Below that shows the graph of the data with the blue line being the model predictions, and the red line interpolating the data using the selected method. The equation for the interpolant is listed here below the graph in MATLAB notation. The final feature of this section is that a user can input a single velocity to get a point estimate. The GUI outputs both the interpolation estimate and the model estimate for the given velocity and displays it in this section.

Figure 6 – The Model Output Section with Data

2.2.5. Menu Toolbar

The menu toolbar for this program provides easy access to other programs packaged within the GUI as well as easy access to settings and help files.

Figure 7 – The Coefficient of Restitution Modeler Menu Toolbar

Shown in Fig. 7 are the various controls included within the menu toolbar. The first dropdown, “Other Programs,” lets the user switch between the various programs packaged within the GUI including the Materials Manager and the Launch Screen. The next option, “Material Lists,” allows the user to specify the active material list. These material lists can be edited in the Materials Manager program and provide a way to sort materials within the library. For example, one list could contain all types of Aluminums and other list could contain a list of most commonly used materials. The material lists are completely customizable by the user and will be explained in more detail within the Materials Manager section.

The “Help” toolbar item contains links to help documents, both regarding the program itself and the theory behind the model. It also includes tooltips that appear within the program and give detailed directions on the function of each section, as seen in Fig. 8.

Figure 8 – The Coefficient of Restitution Modeler with Open Tooltips

The final option available via the menu toolbar, “Unit System,” allows the user to change the unit system of the program. The default unit system can be changed by using the Launch Screen, but can also be manually changed here. If any fields have data in them when the unit system is changed, those values will be changed accordingly, and all unit labels will change as well. Note that the x-axis scale on the graph will reflect these changes too.

2.3 Materials Manager

The Materials Manager program, shown in Fig. 9, is where materials can be added or removed from the material library. The Materials Manager also allows for the editing of material lists to assist in organizing materials into a meaningful way for each individual user. When not used in conjunction with the Coefficient of Restitution Modeler, the Materials Manager can still provide an easy to navigate library of material properties.

Figure 9 – The Materials Manager

The Materials Manager follows the same graphic design as the Coefficient of Restitution Modeler in that each section of the program is separated by function. In this program, the upper-left contains the material database, full of material properties, organized alphabetically. Below that, in the lower-left, is the material editor where additions and changes to the library can be made. On the right side is the list manager. A menu toolbar appears in the program to provide easy access to other programs and settings similar to the Coefficient of Restitution Modeler's toolbar.

2.3.1. Material Database

In this section, each material is displayed alphabetically in a spreadsheet containing all of the material properties. These materials are loaded from the "All_Materials.csv" file located in the same directory as the script files. This allows the library to be loaded into other programs if necessary and not contain MATLAB only formatting. Selecting any material in the database can be done by clicking on any cell within the spreadsheet. This will immediately load that material into the material editor below for quick editing.

2.3.2. Material Editor

The material editor (Fig. 10) is where edits to existing materials and additions of new materials can be made. This section also contains all of the controls for managing the material library.

Figure 10 – The Material Editor

Instead of selecting a cell in the database above, the user can also select a material from the dropdown menu. If entering in a new material, the dropdown menu should be left at “Custom.” The data fields in this section correspond to the material properties of the material selected. If Custom is selected, then the “Delete” and “Add to List” options are unavailable, and the data fields must be entered with the appropriate values before attempting any other options. Once the properties are entered, the “Add to Database” button will insert the new material into the database in alphabetical order. When editing a material, these originally disabled buttons become enabled and allow for the deletion of a material, as well as the addition of a material to a material list. The user can also edit the properties in the database for the selected material by changing any of the data fields and selecting “Save Changes.”

Although any changes made will be reflected in the database table immediately, the changes are not saved to “All_Materials.csv” until the “Write Data to File” button is pressed. This helps avoid accidental changes to the database, and saves runtime since MATLAB does not have to rewrite an entire table of data at each change. If a user tries to exit the program without saving changes first, a dialog prompt will appear asking if the user wishes to exit without saving, exit and save changes, or to cancel the action, as seen in Fig. 11.

Figure 11 – Material Manager Exit Prompt

2.3.3. List Manager

Figure 12 shows the list manager, which helps to organize materials into meaningful lists. Some common examples include making a separate list for each type of material (e.g. Aluminums, Steels, Coppers, etc.) or creating a list of the most commonly used materials. It saves each list as a .csv file with the list of each material in the list and the list name as the header of the column. It

is important to note that to save runtime and eliminate redundant operations, the material list does not include the material properties.

Figure 12 – The List Manager

At the top of the list manager is the active list. Immediately below that is the list of all materials within that list arranged alphabetically. A material from the list can be selected by clicking on it. This will enable the “Remove from List” option, which will remove the selected material from the list when clicked. Unlike the material database, changes to a list take place immediately and do not need to be saved. This section also includes options for adding and removing entire lists. A warning though, removing a list is irreversible except for creating that list again from scratch, and a warning dialog will appear upon clicking the “Delete List” button.

2.3.4. Menu Toolbar

The menu toolbar for the Material Manager is very similar to that of the Coefficient of Restitution Modeler, providing many of the same functions including easy access to other programs and help tools, as shown in Fig. 13.

Figure 13 – Menu Toolbar for Material Manager

The first dropdown, “Other Programs,” shows links to the other programs packaged with the GUI. The next option, “Unit System,” provides the same choices of unit systems as before, Metric (m/s/kg), English (in/s/lb) and English (ft/s/lb). Also similar to the Coefficient of Restitution Modeler, once a unit system is selected, it converts any data entered in the edit fields into the appropriate unit system as well. Last, the “Help” option here also redirects the user to documentation regarding the theory behind the model and help for program itself, including tooltips.

3. FUTURE WORK

3.1. Materials Library

The current materials library is far from exhaustive. In the future, a more extensive library would be beneficial, especially if material properties could be determined from Sandia National Laboratories testing. This would ensure that the material properties provided within the table are the material properties of the materials used within rigid body simulations. It would also be beneficial to include references for each material property so that these properties can be validated and kept track of in the future.

3.2. Polynomial Interpolation

An included feature in the Material Manager is the polynomial output of the interpolant. Originally this was intended so that users could copy the polynomial for future use within MATLAB. Another possible use for this output is incorporation into rigid body simulation programs. For instance, LMS Virtual Lab contains a function input for the CofR. If the polynomial output could be displayed in a compatible format for the simulation program, then that program could accurately calculate CofRs for each impact velocity within the simulation. The only thing necessary to implement this feature is to spend some time determining the correct formatting for each simulation program, and debug any compatibility issues between the GUI and simulation programs.

3.3. Theory Revision

Lastly, it is important to continually update the code behind the simulations. In the first version of the GUI, an elastic-perfectly plastic contact model is used. As this model is refined, extended to higher order effects, and as new classes of materials (such as visco-elastic-plastic) are added to the body of theory, the GUI will need to be updated as well as recompiled for the stand-alone version.

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