

KALIBOND - A TOOL FOR TEACHING BOND GRAPH MODELING

H. Peter Jörgl, Johann Kallinovsky, Peter Wurmsdobler

*Institute for Machine- and Process Automation
Vienna University of Technology, Vienna, Austria
joergl@impa.tuwien.ac.at*

Abstract: The presented software tool KaliBond makes bond graph modeling possible within MATLAB . It allows the menu driven drawing of bond graphs, the automatic causality assignment and the computation of the system state space representation in MATLAB format. Since it is the intended purpose of KaliBond to provide a system model for linear control system analysis and design, its functionality is limited to linear system models.

Keywords: Bond graphs, Modeling, Linear systems, State-space-models, Software tool

1. INTRODUCTION

MATLAB (MathWorks Inc., 1992) is a widely used tool for the analysis, design and simulation of control systems in engineering practice and for teaching purposes. On the other hand, the bond graph concept (Karnopp *et al.*; 1990, Thoma; 1990, Gawthrop and Smith, 1996) proved to be highly successful for teaching dynamic system modeling. Despite its widespread acceptance by control engineers and students, MATLAB offers no tool to directly include bond graph modeling. The purpose of KaliBond is to enable the use of bond graphs within MATLAB. KaliBond

- is a menu driven tool,
- provides a graphic interface for drawing and editing of bond graphs,
- performs an automatic causality assignment to the bond graph,
- computes the state space representation of the dynamic system modeled from the bond graph. The results are obtained in a format compatible with all other MATLAB toolboxes, thus making many further calculations possible,
- performs the simulation of the system unit-step- and unit-impulse response,

- for compatibility reasons is written entirely in the MATLAB programming language and the state space model representation is shown directly in the MATLAB workspace.

Since it is intended to use KaliBond to provide a system model for linear control system analysis and design, its functionality is limited to linearized systems without any modulated elements.

2. MENU DESCRIPTION

KaliBond is started by the command `kalibond` at the MATLAB prompt. Since the bond graph is checked for completeness before the next operation, only those menu items are enabled which make sense. The following menu items and functions are available:

File

New

Clear screen and change the name to `NoName`. If the currently displayed bond graph has changed since the last saving, a security check will be displayed.

Load

Load the bond graph for editing. If the currently displayed bond graph has changed since the last saving, a security check will be displayed.

Save

Save the bond graph.

Save As

Save the bond graph. The user is asked for a new name which will also become the name of the currently displayed bond graph.

Print

Print the graphical representation of the bond graph on the default printer.

Printer Setup

Change to one of the options for the default printer.

Export

Save the graphical representation of the bond graph. This provides the possibility to import the graphic into other documents. At the present time there are two file-formats available:

- Encapsulated PostScript
- Encapsulated Color PostScript

Exit KaliBond

Terminate KaliBond. If the currently displayed bond graph has changed since the last saving, a security check appears before exiting. KaliBond should only be exited this way, since this function provides the necessary memory clean-up.

Drawmode-on

Activate the functions needed to draw a bond graph. After "clicking" a function with the cursor its capabilities are immediately available. Only one function can be activated at a time.

bond

Drawing of bonds:

1. "Click" at the point where the bond is to begin (tail of the bond). At the tail a question mark representing a dummy element will appear.
2. "Click" at the point where the bond is to end (head of the bond). The bond will be drawn with a half arrow at its head indicating the positive power. Again, a question mark representing a dummy system element will appear.
3. This step is only necessary if a single straight line is not sufficient to draw a bond, i.e. if a bond with a knee is necessary. The procedure is the same as in step 2, only the right mouse key is used.

The steps 1,2 and 3 are repeated until the entire bond graph structure is completed. The numbering of the bonds is done automatically.

SE, SF, C, I, R, TF, GY, 0, 1

These are double purpose functions:

1. Replace the dummy system elements (generate a new element). This is accomplished by selecting the appropriate button and by "clicking" at the position (dummy element) in the graph.

2. Change the type of an element. This is accomplished by selecting the appropriate button and by "clicking" the element to be changed.

par

Parameter assignment to C-, I-, R-, TF- and GY-elements.

1. "Click" on the element to which the parameter is to be assigned. On top of the KaliBond window an edit window opens, where an eventually existing parameter value is displayed.
2. "Click" with the mouse cursor into this window and enter a non-zero value.
3. Complete the parameter assignment with **Enter**.

causa

Manual assignment of causality to a bond.

1. "Click" the bond number.
2. "Click" the system element where the causal stroke should be, or "click" the bond number again to make the bond a-causal.

move

"Click" the system element or the knee of a bond and move it to the new position with the left mouse key kept pressed down.

del

Delete an element or a bond.

1. Delete a bond by "clicking" the bond number.
2. Delete a system element by "clicking" it. After deleting an element, all bond attached to it have to be deleted as well. This is necessary because the bond-drawing function can "catch" an element, but the element-drawing function cannot "catch" a bond.

Drawmode-off

Disable all functions described in drawmode-on.

Actions

Delete Causal Strokes

Remove all causal assignments.

Assign Causality

This function assigns the causalities automatically. It always tries to assign the largest possible number of integral causalities. After completing the causality assignment, the program displays a message giving the number of energy storing elements with integral and derivative causalities. If, due to unavoidable causal conflicts, the assignment could not be completed successfully, the program displays an appropriate error message and the option show causal conflicts is turned on automatically.

Note: The program assigns causality only to those bonds which are a-causal at the moment of the program start. All already assigned causalities remain unaltered. This leads to the following consequences:

- To make sure that a correct causality assignment is obtained, all causal strokes already assigned have to be deleted.
- In bond graphs containing elements with derivative causality, the derivative causality may be assigned to different energy storing elements, still yielding a valid causality assignment. In this case, a manual assignment of the derivative causality to elements other than the default solution is possible.

State Space Matrices' Names

The state variables are the energy variables of the energy stores with integral causality. The state space matrices are stored in the variables A, B, C, D, E and F by default. This menu item is required to select other variable names. The procedure is: "Click" into the edit window, enter the variable name and complete by Enter.

Output-Vector

To be able to compute the output it is necessary to define the vector of output variables. The elements of the output vector are separated by semicolons. The entry must be completed with Enter and OK. Any power- and/or energy variables can be chosen in the output vector.

Compute

Compute the state space representation of the system in the following form:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A} \cdot \mathbf{x} + \mathbf{B} \cdot \mathbf{u} + \mathbf{E} \cdot \dot{\mathbf{u}} \\ \mathbf{y} &= \mathbf{C} \cdot \mathbf{x} + \mathbf{D} \cdot \mathbf{u} + \mathbf{F} \cdot \dot{\mathbf{u}}\end{aligned}$$

The matrices **A** through **F** will be stored in the variables declared above.

Simulate

To get a quick look at the dynamic behavior of the system under investigation, KaliBond offers the possibility to plot the unit-impulse- and unit-step-response of the system.

Options

As a help feature KaliBond offers the possibility to color the bond graph according to the following criteria.

Show the bond graph structure

- red:
- Undefined type elements,
 - Elements with no bonds attached,
 - Bonds with no element at head and/or tail,
 - One-port elements with more than one bond attached,
 - Two- or multi-port elements with only one bond attached,
 - Transformers or gyrators, when both power-half-arrows point towards or away from it.

yellow: - Elements without parameters

black: - OK

Show Integral Causalities

green: - Energy storing element with integral causality,

red: - Energy storing element with derivative causality,

black: - all other elements.

Show Causal Conflicts

green: - Bond with a causal stroke,

black: - A-causal bond,

red: - Causal conflict.

Off

Monochrome display, but higher drawing speed.

Zoom

Zoom

Enlarge a section of the bond graph.

1. Point the cursor to one corner of the section to be enlarged and press the left mouse key.
2. While holding the left mouse key pressed down, go to the opposite corner of the section to be enlarged and release the mouse key.

Un-Zoom

Inversion of the Zoom-function.

Zoom-max

Set the magnification such that the entire bond graph fills the window.

3. CAUSALITY ASSIGNMENT

The algorithm implemented in KaliBond for assigning the causality follows the procedure described in Karnopp *et al.* (1990) and consists of the following steps:

1. Choose any source (SE, SF) and assign the required causality. Immediately propagate the causal implications through the graph as far as possible, using the constraint elements (0, 1, TF and GY).
2. Repeat step 1 until all sources have been used.
3. Choose any energy storing element (C, I) and assign its preferred (integral) causality. Immediately propagate the causal implications through the graph as far as possible, using the constraint elements.
4. Repeat Step 3 until all energy storing elements have been assigned a causality.
5. Choose any unassigned R-element and assign a causality to it (basically arbitrary). Immediately propagate the causal implications through the graph as far as possible, using the constraint elements.
6. Repeat step 5 until all R-elements have been used.
7. Choose any remaining unassigned bond (attached to two constraint elements) and assign a causality to it arbitrarily. Immediately propagate the causal implica-

tions through the graph as far as possible, using the constraint elements.

8. Repeat step 7 until the assignment is completed.

This procedure, sometimes called SCAP (Sequential Causality Assignment Procedure), divides the assignment procedure into 6 layers:

1. SE (effort sources)
2. SF (flow sources)
3. C (capacitive energy stores)
4. I (inertive energy stores)
5. R (energy dissipating elements)
6. bonds connecting two constraint elements

These rules are implemented KaliBond with several extensions to avoid causal discrepancies. If it is possible to assign the causality to the bond graph without causal discrepancies, KaliBond will find the solution. If there is more than one possible solution to the causality assignment problem, KaliBond will always find the solution containing the minimal number of energy storing elements with derivative causality.

4. EXAMPLES

The physical system used in the following examples is shown schematically in figure 1a. Figure 1b shows its bond graph which will be used to demonstrate the features of KaliBond. The system consists of an ideal pressure source (P_1), a piece of pipe with fluid-resistance and -inertance properties, a piston-cylinder unit and a mass that is to be moved against a spring and velocity-dependent friction force (Examples 1 and 2). In addition, a load force is considered acting on the mass (Example 3).

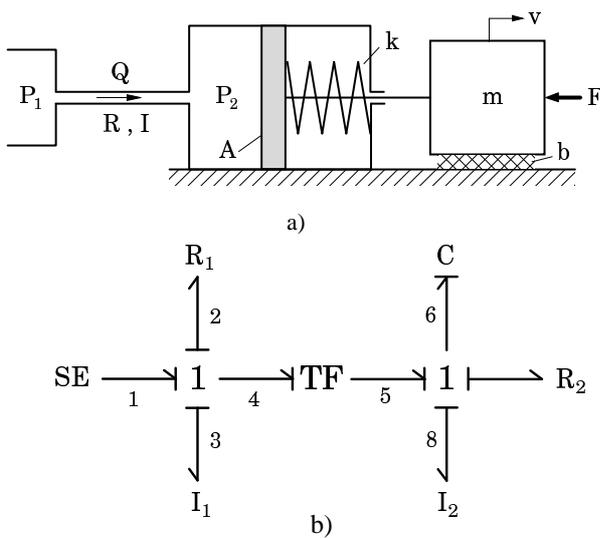


Fig. 1. Physical system (a) and its bond graph used in the examples (b).

Example 1

Kalibond is started by typing kalibond and Enter at the MATLAB prompt. Then, after activating the drawmode and the radio button bond, the structure of the bond graph can be drawn step by step beginning with the tail end of bond 1 as shown in figure 2.

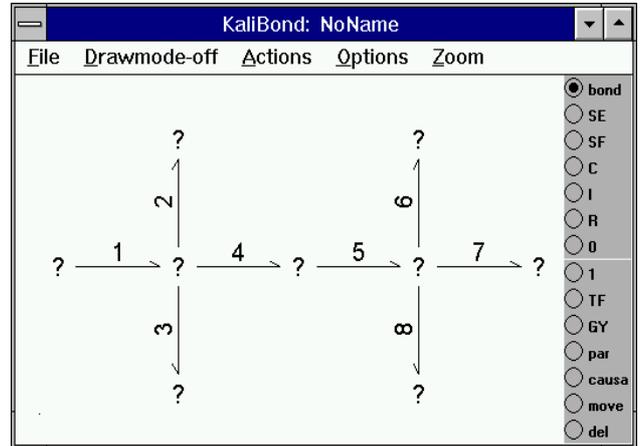


Fig. 2. Structure of the example bond graph.

The system elements are assigned to the dummy elements (question marks) by activating the radio buttons SE, I, C, R, TF and 1 as shown in figure 3. The automatic causality assignment can now be performed using the Actions mode and by activating the function Assign Causality. The augmented bond graph is depicted in figure 4.

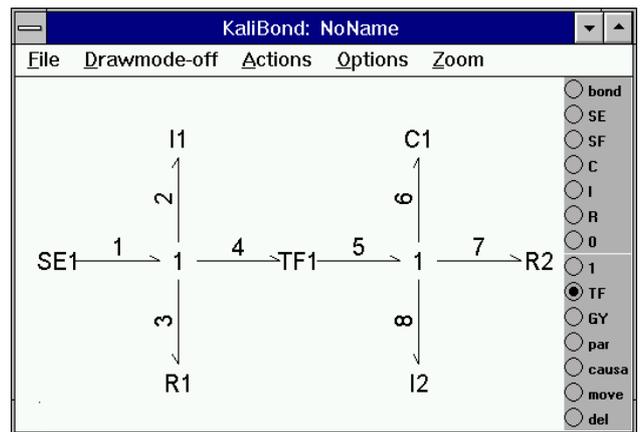


Fig. 3. Bond graph with attached system elements.

Numerical values to the elements are assigned, by activating the radio-button par and by "clicking" on the individual element. The numerical value is entered into an edit-window on the top of the KaliBond window and the Enter key is pressed. Now the bond graph as shown in figure 5 is complete.

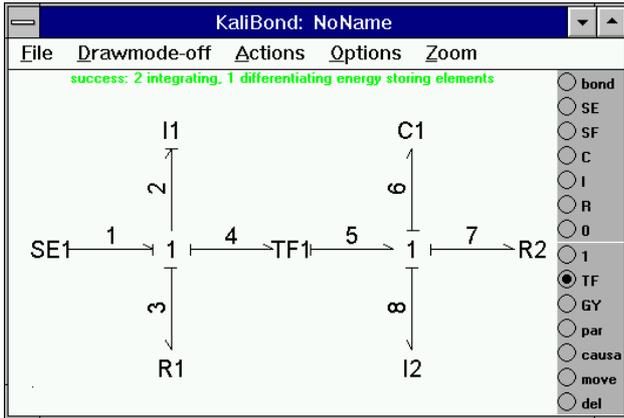


Fig. 4. Bond graph with assigned causalities.

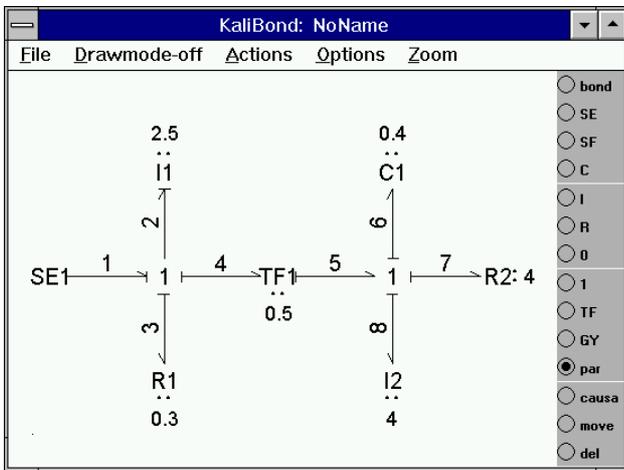


Fig. 5. Bond graph after parameterization.

Next, the function Output Vector is activated to choose the system output. If, e.g. the power variable f_8 is to be chosen, the string f_8 is entered into the edit window, the key Enter is pressed and the assignment is confirmed by "clicking" the menu-item OK. Figure 6 shows the information about the system state space representation in the MATLAB-workspace and figure 7 the resulting state space matrices in the MATLAB workspace.

In order to obtain a quick view the system dynamic behavior in form of the unit-step- or the unit-impulse-response of the selected output, the menu-item Actions - Simulate - Step-Response is chosen. Figure 8 shows the unit-step-response of f_8 . The possibility to display several output variables simultaneously is also provided by KaliBond.

Example 2

If, for some reason the derivative causality to bond 8 is not acceptable, the causality re-assignment can be performed as follows.

```

MATLAB Command Window
File Edit Options Windows Help
>>
input-vector u
-----
e1
state-vector x
-----
p2
q6
output-vector y
-----
f8
the state-space equations:
-----
x = A*x + B*u + E*xu
y = C*x + D*u + F*xu

```

Fig. 6. Information about the system state space representation in the MATLAB-workspace.

```

MATLAB Command Window
File Edit Options Windows Help
A =
    -0.3714    -0.8929
     0.2000         0
B =
     0.7143
         0
C =
     0.2000         0
D =
         0
E =
         0
         0
F =
         0

```

Fig. 7. Resulting state space matrices in the MATLAB workspace.

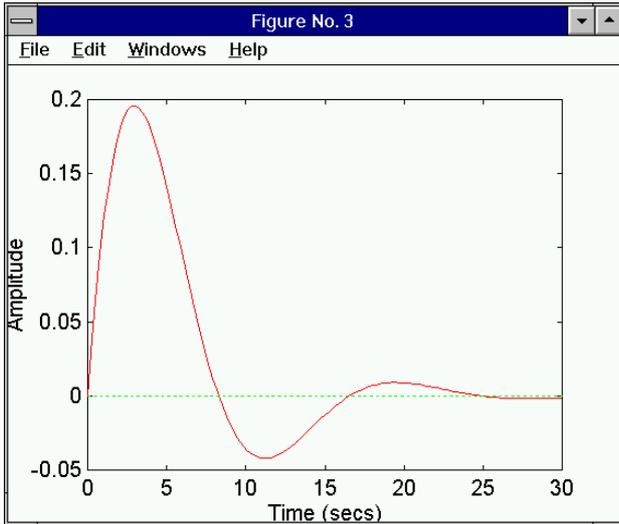


Fig. 8. Unit-step response of the output variable.

First, selecting the menu-item Actions - Delete Causal Strokes all causal assignments are deleted. Then, in drawmode on, bond 8 is assigned integral causality by activation the function (radio button) *causa*. Next, the bond number (8) and the element I2 are "clicked", thus assigning integral causality to bond 8. To complete the causality assignment, the menu-item Actions - Assign Causality is used. (see figure 9).

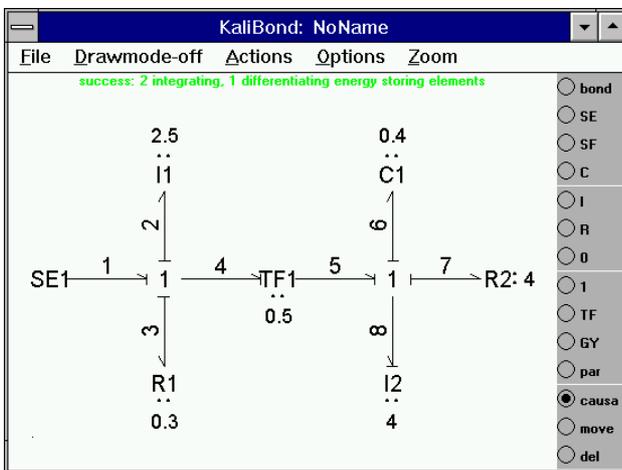


Fig. 9. Bond graph after manually assigning integral causality to the element I2.

Example 3

In this example, the intention is to add an effort-sink (negative effort source; load force) to the right 1-element. Selecting the button *move*, the R2-element is moved upwards by "clicking" it and holding the left mouse key pressed down. Now, the new element is added by activating the radio button *SE* and by "clicking" the position where the effort source is to be located. The

graph is completed by connecting the 1-element and the SE-element using the radio button *bond*. Here it is important to "click" the 1-element (bond tail) first, thus making sure that a "negative" source is created. The causality assignment completes the graph as shown in figure 10.

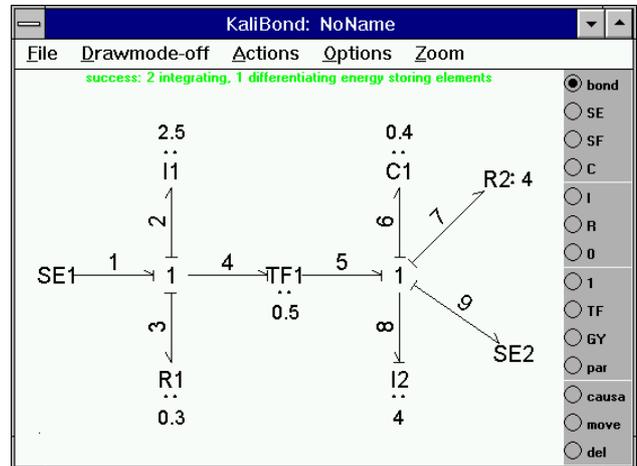


Fig. 10. Bond graph after adding an additional negative effort source (effort sink)

5. CONCLUSIONS

The software tool KaliBond allows the menu driven drawing of a bound-graph, its automatic augmentation with causality, the computation of the system state space representation and a quick view of its dynamic behavior in form of the unit-step- or unit-impulse-response. The state space model is obtained in a MATLAB-compatible format in the MATLAB-workspace, thus enabling subsequent manipulations with any MATLAB-toolbox. KaliBond has been successfully used in teaching a course on dynamic system modeling for Mechanical Engineering students at Vienna University of Technology.

REFERENCES

- Gawthrop, P. and L. Smith (1996). *Metamodelling: Bond graphs and dynamic systems*, Prentice Hall International Series in Systems and Control Engineering, London New York Toronto.
- Karnopp, D.E., D.L. Margolis and R.C. Rosenberg (1990). *System Dynamics: A Unified Approach*, John Wiley & Sons, Inc., New York.
- The MathWorks (1992). *MATLAB, MATLAB Reference Guide*, , Inc., Cochituate Place, 24 Prime Park Way, Natick, 01760 MA, USA.
- Thoma, J.U. (1990). *Simulation by Bondgraphs*, Springer-Verlag, Berlin Heidelberg New York.