

A Bond Graph-Based Method of Automated Generation of Automatic Transmission Mathematical Model

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ABSTRACT

The ever-present pressure on shortening the development cycle of transmission systems requires development of numerical methods and tools that would speed up those processes. This paper contributes to the field by proposing a method for automated generation of the full-order automatic transmission (AT) model from a bond graph model that directly reflects the AT structure. The proposed numerical method is implemented within the 20-sim and MATLAB software environments, where 20-sim is used to draw the bond graph and export it to a MATLAB script (or simulate it). A proposed method relies on a system identification method that extracts the characteristic full-order model state-space matrices from either a 20-sim-Matlab exported script or 20-sim-simulated bond graph model. The automated modeling method is demonstrated on an example of an advanced 10-speed AT. The paper also outlines a numerical method of transforming the full-order model into the corresponding reduced-order model for a user-specified clutch state, including implementation aspects for the MATLAB environment. The possibility of deriving the reduced-order model directly from a corresponding 20-sim bond graph model is discussed, as well.

CITATION: Ranogajec, V. and Deur, J., "A Bond Graph-Based Method of Automated Generation of Automatic Transmission Mathematical Model," *SAE Int. J. Engines* 10(3):2017, doi:10.4271/2017-01-1142.

INTRODUCTION

In recent years, new automatic transmission architectures have been introduced in order to meet regulatory and market requirements (such as CO₂ reduction, fuel economy improvement, and enhanced driving experience) [1,2]. The pressure on shortening the development cycles in automotive industry requires development of numerical methods and related software tools in support of those processes. For instance, in [3] an automated modeling procedure is developed, which enables search through all designs with different configurations, clutch locations, and operating modes with the aim of improving the hybrid electric powertrain efficiency.

From the perspective of system dynamics analyses and control system designs, the development of methods that allow for automated generation of computationally efficient mathematical models is of a particular interest [4,5]. In the field of automatic transmissions (ATs), automated modeling would ultimately include generation of a full-order, minimum-realization state-space mathematical model directly from an AT schematic. The work presented in this paper makes a contribution toward fully-automated AT modeling by proposing a method for automated numerical generation of the full-order mathematical model from a bond graph that directly reflects the structure of AT. The proposed method is based on the use of 20-sim [6] and MATLAB software packages. 20-sim supports bond graph modeling and includes certain automated modeling features (e.g. Scripting Toolbox that allows automatic execution of 20-sim commands using MATLAB scripts, including the model export into MATLAB).

In addition to automated generation of the full-order AT model, it is of interest to derive a method/tool for automated creation of a reduced-order model for an arbitrary clutch state. Namely, various control system simulation and optimizations studies, such as those presented in [7, 8, 9], are based on reduced-order AT dynamics models that are related to specific gears or shifts. In the available literature, generation of reduced-order model for a user-specified clutch state (i.e. gear or shift) is predominantly carried out in a "manual" way [10,11]. For example, the approach presented in [11] (and similarly in [10]) is based on "manual" modification of system matrices by applying boundary conditions for specific gear or shift. In this paper, an automated model-order reduction (MOR) method from [12] is incorporated into the tool for automated generation of the full-order AT model, thus creating a unique tool which generates a minimum realization AT model for an arbitrary clutch state directly from the bond graph model (BGM) implemented in 20-sim.

The remaining part of the paper is organized as follows. The next (second) section presents the full-order gearbox model in bond graph and state-space forms. Two methods for automated generation of the full-order AT model based on the 20-sim-implemented BGM are presented in the third section. The fourth section outlines two methods for generation of the reduced-order AT model. Verification of automated modeling methods is presented in the fifth section. Concluding remarks are given in sixth section.

FULL-ORDER GEARBOX MODEL

Design of different powertrain control systems (e.g. shift control) requires exhaustive simulation and optimization studies. For covering a full spectrum of operating conditions, a full-order gearbox model is often used. In this paper, modeling of a 10-speed AT is demonstrated, which is considered as a generic example of an advanced transmission system. Figure 1a shows the AT gearbox schematic, which includes four planetary gears and six clutches [13].

Bond Graph Gearbox Model

One of the common approaches for modeling the AT dynamics is based on the bond graph method [14, 15, 16]. The BGM of the gearbox from Figure 1a is shown in Figure 1b (see Appendix and [17] for definition of BGM elements). As illustrated in Figure 1, the bond graph directly reflects the schematic of AT gearbox (i.e. the structure of transmission mechanics). Moreover, the bond graph method is characterized by ease of determining and handling the redundant state variables, and simplicity of reducing the model order, which is particularly useful in AT modeling [16]. The BGM in Figure 1b is built around four triangular structures that describe the kinematics of four planetary gears $h_i, i = 1, \dots, 4$ [15]. The elements **R** and **I** describe clutch friction and gear inertia, respectively, and the junction points **0** and **1** represent torque and speed summation points, respectively (Appendix, [17]). The causality analysis (related to the strokes associated with each bond; Appendix, [17]) shows that five out of nine gearbox inertia elements have integral causality. In Figure 1b, the integral causality is assigned to the following inertia elements (denoted with red bonds): $I: I_{C2,r}, I: I_{R1}, I: I_{C1R4}, I: I_{C3},$ and $I: I_{C4,os}$.

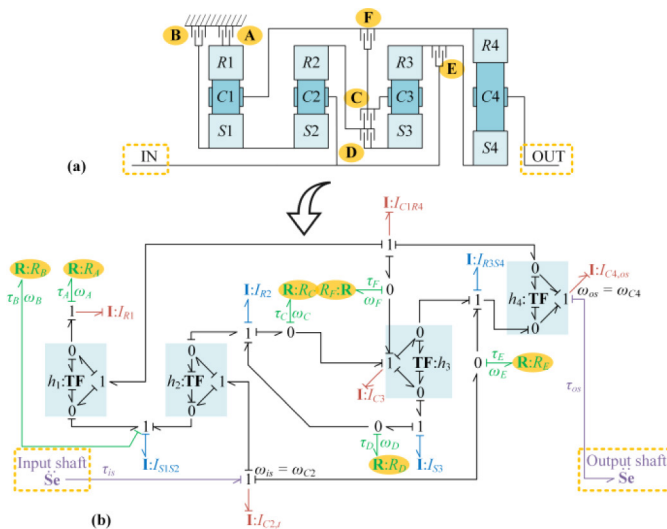


Figure 1. Schematic of 10-speed AT gearbox [13] (a) and corresponding bond graph model (b).

20-sim Implementation of Gearbox BGM

The original BGM from Figure 1b can readily be redrawn in 20-sim by using the built-in library of standard bond graph elements (see Figure 2). In order to allow for the clutch torque (capacity) modulation, **R** elements are replaced with **MR** (Modulated Resistor) elements in

Figure 2. The causality analysis can be performed automatically in 20-sim, i.e. it automatically determines that the considered gearbox model has five independent states. Causality of inertia elements **I** is assigned based on its causality priority settings [6]. The following priority options are offered: 1) Fixed effort/flow out, 2) Preferred effort/flow out, 3) Likes effort/flow out, and 4) Indifferent [6]. During the 20-sim model processing phase, the assignment of the causal forms goes in accordance with the rank in the list in 20-sim (first all elements with a fixed out assignment are set, then elements with a preferred out assignment, then with a likes assignment, and finally with an indifferent assignment). In order to assign the causalities in accordance with the BGM from Figure 1b, the priority settings of bond graph **I** elements are set as indicated in Figure 2.

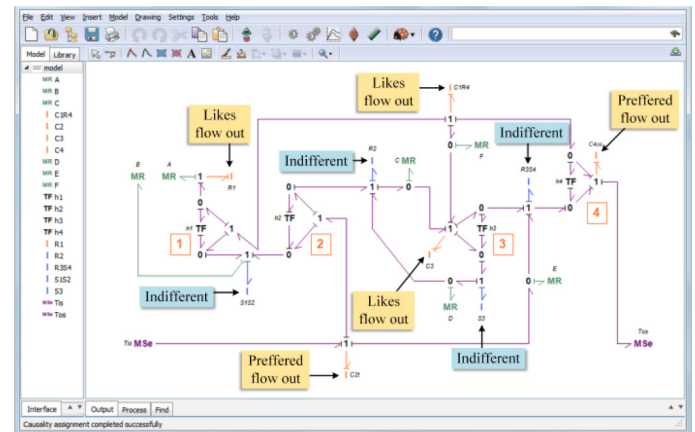


Figure 2. Bond graph model of 10-speed AT in 20-sim environment including causality priority settings of **I** elements.

State-Space Gearbox Model

By using the bond graph modeling methodology [17], the bond graph in Figure 1b can be transformed into the following state-space model [12]:

$$\begin{aligned} \mathbf{A} \begin{bmatrix} \dot{\omega}_{C2} & \dot{\omega}_{R1} & \dot{\omega}_{C1R4} & \dot{\omega}_{C3} & \dot{\omega}_{C4} \end{bmatrix}^T \\ \dot{\omega}_s \\ = \underbrace{\begin{bmatrix} \mathbf{B}_{cl} & \vdots & \mathbf{B}_{oi} \end{bmatrix}}_{\mathbf{B}} \underbrace{\begin{bmatrix} \tau_A & \tau_B & \tau_C & \tau_D & \tau_E & \tau_F & \vdots & \tau_{os} & \tau_{is} \end{bmatrix}^T}_{\boldsymbol{\tau}_{in}} \end{aligned} \quad (1)$$

where $\mathbf{A} \in \mathbb{R}^{n \times n}$ is the inertia matrix, while $\mathbf{B} \in \mathbb{R}^{n \times nin}$ is the input matrix (note that $n = 5$ and $nin = 8$ apply for the particular 10-speed gearbox model). Note also that the input matrix **B** is divided into two sub-matrices related to clutch torque and input/output torque input sub-vectors. After introducing the matrix $\mathbf{L} \in \mathbb{R}^{n \times nin}$ such that $\mathbf{L} = \mathbf{A}^{-1}\mathbf{B}$, Equation (1) is transformed to:

$$\dot{\omega}_s = \mathbf{L} \boldsymbol{\tau}_{in} \quad (2)$$

Integrating the state equation (2) gives the speed state vector $\omega_s \in \mathbb{R}^n$, which is then used to determine the clutch slip speed vector, and extract the input and output shaft speeds:

$$\begin{aligned} & \underbrace{\begin{bmatrix} \omega_A & \omega_B & \omega_C & \omega_D & \omega_E & \omega_F & \vdots & \omega_{os} & \omega_{is} \end{bmatrix}^T}_{\omega} \\ & = \begin{bmatrix} \omega_{cl} & \vdots & \omega_{oi} \end{bmatrix}^T = \underbrace{\begin{bmatrix} U_{cl} \\ \vdots \\ U_{oi} \end{bmatrix}}_U \omega_s \end{aligned} \quad (3)$$

The vector ω_s is also used to determine the energy dependent variables (i.e. the speed variables associated with the inertia elements with derivative causality):

$$\underbrace{\begin{bmatrix} \omega_{R3S4} & \omega_{S1S2} & \omega_{R2} & \omega_{S3} \end{bmatrix}^T}_{\tilde{\omega}} = T \omega_s \quad (4)$$

By using the power conservation law, it can be proven (see proof in [12]) that the following relation is generally valid:

$$U = \begin{bmatrix} U_{cl} \\ u_o^T \\ u_i^T \end{bmatrix} = \begin{bmatrix} -B_{cl} & -b_o & b_i \end{bmatrix}^T, \quad (5)$$

where $B = [B_{cl} \ b_o \ b_i]^T$ applies and u_o and u_i are sub-vectors of the matrix U_{oi} from Equation (3) [12]. This special feature of the model matrices will be used in the following section to extract the inertia and input matrix from the lumped matrix L .

AUTOMATED GENERATION OF FULL-ORDER MODEL MATRICES

In the previous section, the state-space model, i.e. the matrices of full-order AT model have been determined analytically, based on the bond graph modeling methodology [16], with the final analytical expressions given in [12]. In order to speed-up the modeling process, the full-order AT model matrices can be obtained in an automated way. In this section, two methods of automated AT modeling are proposed, which are based on 20-sim software tool and its interaction with MATLAB. Both methods start from the AT BGM that can readily be implemented in 20-sim (see Figure 2). The first method is based on identification of the system matrices from symbolic equations contained in the 20-sim-exported MATLAB script, while the second approach utilizes identification based on the 20-sim BGM simulation results. The overall automated modeling process is illustrated in Figure 3. The process is facilitated by the 20-sim Scripting Toolbox that allows to run tasks in 20-sim automatically using MATLAB scripts [6].

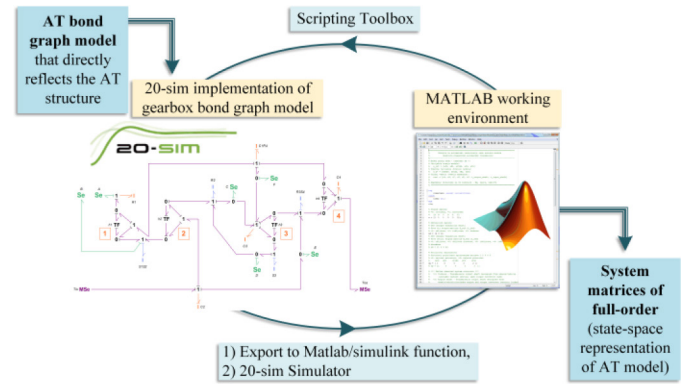


Figure 3. Illustration of automated generation of full-order model matrices.

Model Export from 20-sim to MATLAB/Simulink

20-sim provides the possibility of exporting the BGM into a MATLAB script containing the symbolic model state-space equations. For the purpose of determining the model matrices, the 20-sim-based BGM from Figure 2 should be somewhat redesigned. The redesign includes: (i) implementing the model in a sub-model form that allows for explicit definition of model inputs and outputs, and (ii) replacing the nonlinear clutch resistance (R/MR) elements with source-of-effort/torque (Se) elements to form the full torque input vector $\tau_{in} \in \mathbb{R}^{nin}$ in Equation (1). The gearbox submodel outputs are defined in 20-sim by the following four vectors (see the illustration in Figure 4 and Equations (1)-(4)):

- Vector of clutch slip speeds and input/output speeds, $\omega \in \mathbb{R}^{nin}$
- State variable vector, $\omega_s \in \mathbb{R}^n$
- Vector of time-derivatives of state variables, $\dot{\omega}_s \in \mathbb{R}^n$
- Vector of energy-dependent variables, $\tilde{\omega} \in \mathbb{R}^{ndep0}$

For the purpose of exporting the model into MATLAB, the above vectors are concatenated to form a single output vector denoted as $\hat{\omega} = [\omega \ \omega_s \ \dot{\omega}_s \ \tilde{\omega}] \in \mathbb{R}^{nin+2n+ndep0}$

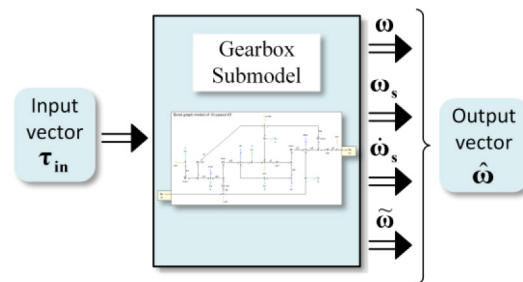


Figure 4. Illustration of 20-sim implementation of gearbox model for model export into MATLAB/Simulink.

Identification of System Matrices from Matlab Model Script

From the symbolic equations/code contained in the MATLAB-imported script, the full-order model matrices L , U , and T can be determined by a system identification method. Namely, multiple