Chances of the Application of Multi-Domain Simulation Tools in the Field of Train System Engineering

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Abstract

Complex mechatronic systems, such as modern trains, demand interdisciplinary software tools in order to test systems as a whole and predict operational behavior. Caused by the intention of cost savings and pushing the market launch time, computer-aided modelling and simulating of the behavior of single devices, such as thermal effects, stresses, deformations and also electrical state variables, have long since become state-of-the-art. This method leads to well-matured products. The component integration into the system as a whole, however, often causes trouble due to the lack of computer and software assistance. Furthermore, the diverse engineering fields do not have the expertise to collaborate. Therefore, joined system testing and improving is difficult and uncommon. Since the different mechanical and electrical components are being developed and tested independently, overall system behavior can hardly be forecast. As a consequence, during the system assembly phase, unpredicted incompatibilities and system malfunctions can appear. In order to integrate the train subsystems into an overall system and allow for a better synchronization and proper system testing, the application of multi-domain modelling and simulating is recommended. In this regard, the benefits brought by multi-domain applications will be discussed in this publication, using the example of a modern train. Thereafter, a case study of a pneumatic train brake application follows. Its results are exemplarily being shown to demonstrate future perspectives. Models and simulation results of the brake and air supply components already turn out allowing for comparisons with the actual system. System start-up times of the simulation match actually measured times adequately.

1. Introduction

High-speed railways are amongst the biggest and most complex mechatronic systems that the modern industry manufactures. Continuously, mechanical components are being replaced by electronic and mechatronic components, such as, electromagnetic valves in the pneumatic brake system (electro-pneumatic brake), computational train control systems or mechatronic measuring devices, to mention only a few.

As operational malfunctions that impact the kinetics of a train can cause collateral damage, satisfying the growing demands for safety cases about any operational function is a very serious issue for railway system engineers, especially about the brake system and air supply. If an emergency occurs, such as lack of electricity, for example, the air reservoirs have to provide enough compressed air to perform an emergency braking maneuver until the train stops after running a shortest possible distance. Additionally, hilly tracks require higher braking capacities than tracks in lowlands. In that case, a reinforced brake system is necessary, such as an electromagnetic rail brake completing the traditional pneumatic brake system [1].

Besides testing the individual components independently, overall system testing is also indispensable, because the system integration can cause system malfunctions, unpredicted behavior and performance loss [2]. In order to achieve this, fully configured trains are being built and set up. After adding measuring equipment, the railway is ready to run on a test track. By measuring significant variables, such as exemplarily temporal pressure drop, drive torque and brake force distributions, faults can be determined and the drive characteristics can be measured. As the reader can easily comprehend, this method is both, time and cost consuming. Nevertheless, currently it is the standard testing procedure

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for railways. Step by step, the sources of errors are being corrected until the system function is fully established, which is also linked to high effort and expenses, because it leads to required design modifications or replacement of already existing components [3].

2. Overview of the Field of Application Regarding Railway System Engineering

Figure 1 shows the hierarchies and complexity of the communication systems of a modern high-speed train. In this particular case, there are two communication systems (BUS). The Train BUS (TB) is the leading communication level, which transports information and commands through the entire train [4]. If the train driver gives a command, the TB will conduct this command to every single subordinated communication system in the several wagons. The vehicle BUS (VB) is the subordinated communication system, which every vehicle has in order to control the subsystems of the vehicle.

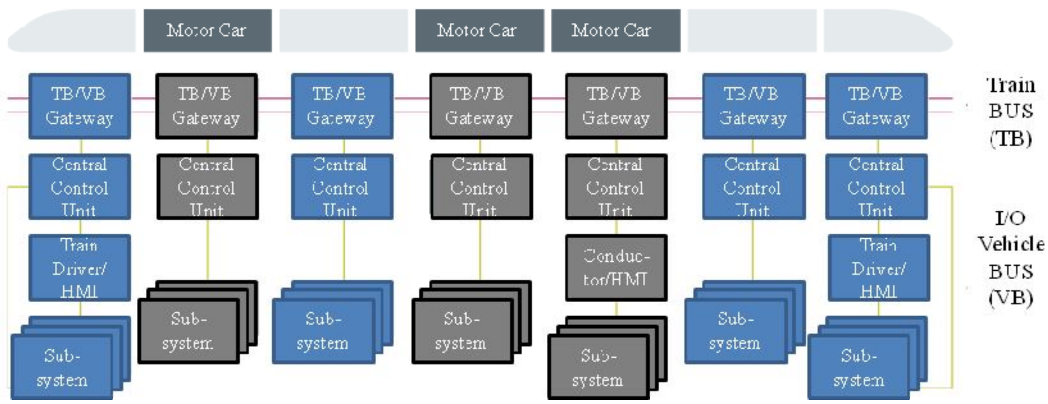

Figure 1. Relation between the components of an indirect braking system [5].

Regarding Figure 2, the communication systems, central control unit and the drive subsystems can be seen. By employing sufficient simulation software, the mechanical subsystems and the control can be implemented and simulated, so that disturbances during train operation can be analyzed on the computer [6-8]. Hence, testing costs and delays of the product release can be decreased.

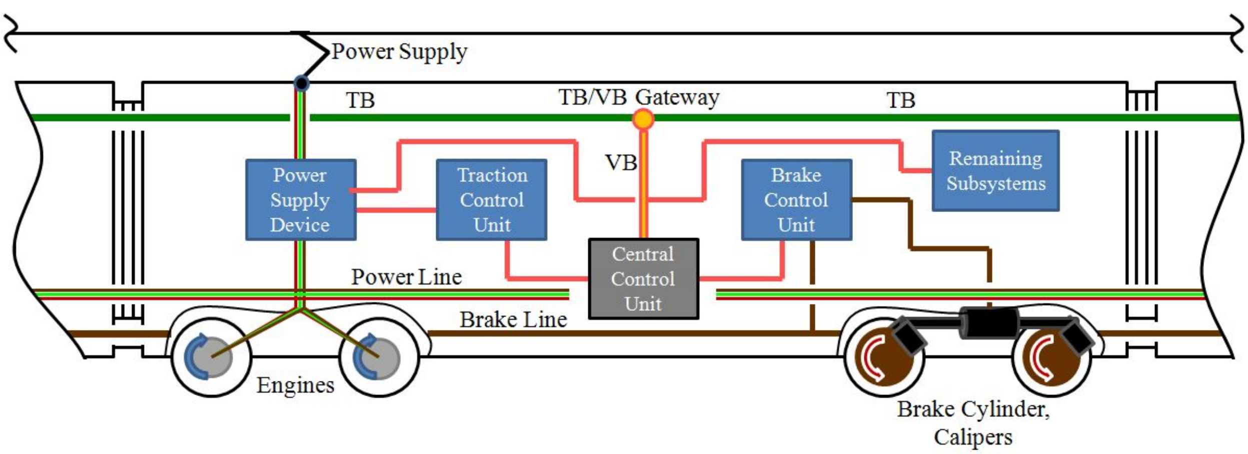

Figure 2. Control systems and subsystems of a railway [4].

Nowadays, there are several simulation tools providing profound libraries of diverse mechatronic components, such as valves, for example. They also feature classical mechanic, pneumatic and hydraulic components, such as cylinders, pipes, gears and so on [9]. The components of diverse engineering fields can be connected and controlled with control components, such as time depending signals and mathematical functions, for example. Modern object-oriented modeling language allows for freely programmable extension of pre-implemented libraries, so that complex components can be created and pre-defined, for example, a train bogie, containing motors, gears and rotated masses. After saving such an individual component, it can be used with pre-defined parameters and functions as often as is wanted [10]. This is an important achievement towards modeling automation.

Advantageous functions of simulation tools utilizing object-oriented modeling languages are usually different post processing methods, such as frequency analysis. Therefore, a system capable of oscillating can be stimulated over a range of frequencies in order to analyze eigenvalues and system orders [11, 12]. A well-known issue in the field of simulation, especially in designing computer models before the final design has been developed, is finding valid parameters, so that the system behavior is within the specs and stable. Hence, some software tools feature methods for automated design of experiments, which allows for varying parameters of a preset range, and successively run simulations with the different sets of parameters [13]. Well-known object-oriented, Modelica-based modeling tools are OpenModelica, SimulationX, Dymola, and Wolfram SystemModeler, for example. Another study also shows that modelica-based simulation tools can also be used in a wide range of the application, e.g., in production systems [14-16].

Figure 3 shows how object-oriented programming and Modelica are implemented in SimulationX. Once opened a parameterization window, Modelica-conform equations can be entered in the parameterization fields, optionally using object references, such as ‘springDamper1.k’, e.g., which addresses the stiffness of the first spring-damper ‘SpringDamper1’. ‘self.k’ references the stiffness of one self .

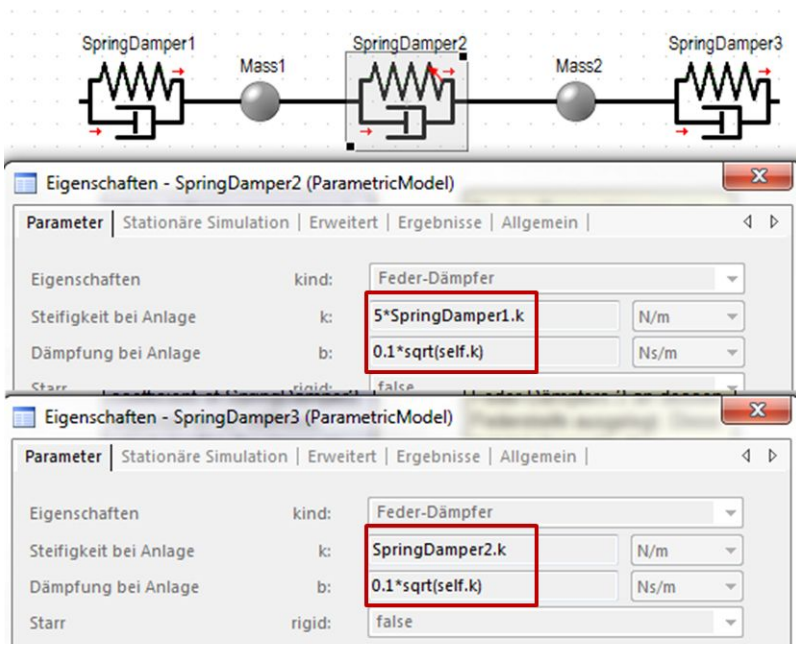

Figure 3. Referencing in SimulationX.

3. Insight into Railway System Engineering and Need for Multi-Domain Application

In this chapter, two brief applications in the field of railway system engineering will be discussed. The exemplary applications are based on results of the final thesis of the author.

3.1. *Implementing a Distributor Valve of a Railway Brake System*

Even though the evolution from old steam locomotives in the 19th century until modern high-speed railways has come along with fundamental changes, the basic function of the brake system has not changed. The brake calipers are still powered pneumatically, so that in case of lack of electricity the train is able to perform an emergency stop, just as in case of train separation. In order to guarantee autonomous operation, trains are equipped with a brake pipe (BP), which acts as a control line, the main reservoir pipe (MRP) and the supply air reservoirs (SAR). The latter provide the brake cylinders over the MRP with pneumatic energy. For the BP it is highly important that it contains a very small volume in order to reach short response times, whereas the MRP and supply air reservoirs are designed to have big volumes in order to store and being able to provide big amounts of energy. The function of the indirect brake works as follows. Basically, a pressure drop of the BP pressure p_{BP} causes a pressure increase of the final brake pressure p_C (pressure inside the brake cylinder), so that p_C is inversely proportional to p_{BP}. This function is being implemented by the distributor valve (DV), which works without any electricity. It is pneumatically driven only. Pressure drops inside the DV move pistons and bars, whose positions are being connected to a three-way valve. The inputs of the DV are a line to the BP and one to the SAR, while it returns the precontrol pressure p_{CV}. The final brake pressure p_C is a function of p_{CV} and the output pressure p_T of the axle's weighing unit. The latter considers the vehicle's load, in order that the wagons braking forces can be set individually, so that the change of velocity does not differ from one wagon to another. The influence of p_T is being implemented by the Einheitsdruckumsetzer (EDU). It detects p_{CV} and p_T and proportionally opens a valve between the SAR and the brake cylinder in a way that the final p_C develops [17, 18].

The indirect brake is a part featured by every existing train using public rail network. It can also be assigned to the brake subsystem in Figure 2. As the brake cylinder and the calipers are yet visible, the DV and the EDU are part of the brake control unit. Besides the indirect brake, many modern railways have a direct brake, not using the BP, but the actual brake signal. Figure 4 shows the relation between the components of the indirect brake.

Quintessentially, the brake pressure p_C is a function of the weight unit pressure p_T and the precontrol pressure p_{CV}, whereas p_{CV} is a function only of p_{BP}, which is expressed in the linear Equations 1, 2 and 3.

$$p_C = f(p_{CV}, p_T) \tag{1}$$

$$p_{CV} = f(p_{BP}) \tag{2}$$

$$p_T = f(\text{load}) \tag{3}$$

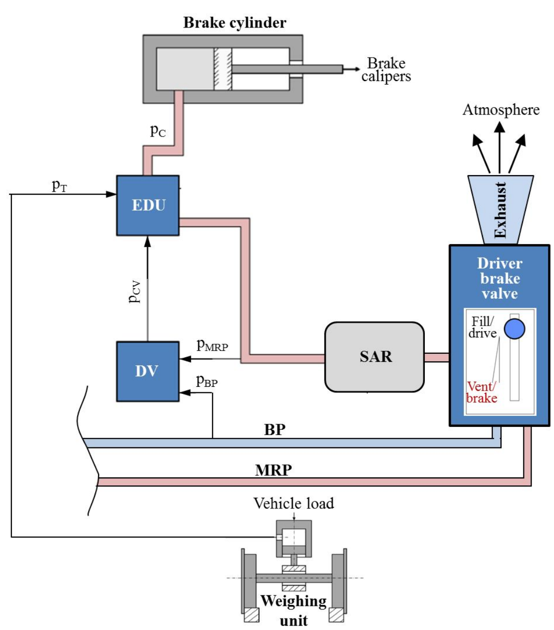

Figure 4. Relation between the components of an indirect braking system [18].

Combining the Equations 1, 2 and 3 results in the linear Equation 4.

$$p_C = f(p_{CV}(p_{BP}),\ p_T(\text{load})) \tag{4}$$

After having broken down the main physical components of the indirect brake system, such as the BP, MRP, SAR, DV, and the brake driver valve, as well as having described the remaining components with linear mathematical functions, such as the EDU and the weighing unit, the multi-domain implementation will be discussed, hereafter. The work has been done with a software featuring many libraries of pneumatic, hydraulic and mechanic components as well as control engineering components, such as pistons, valves, pipes, reservoirs, actuators, movable masses, signals, mathematical functions, logical operators etc. Once they are being parameterized, such as, e.g., pipe diameter, piston area, initial pressure, volume etc., a simulation can be run. The transient simulation runs over a preset period of time, e.g., 100 s. The simulation results are being graphically displayed in windows, in which any variable distribution can be drawn, such as pressures at certain positions. Signals can be temporally delayed, so that events at particular moments in time can be simulated, such as setting the train driver valve to a certain position after a certain period of time. Therefore, a model and its operation mode can be analyzed and validated thoroughly.

In the following, the simulation results of the DV and EDU will be discussed. Figure 5 shows a typical pressure distribution of the BP pressure p_{BP} in the left chart. In the right chart, there are 2 different p_C distributions. The p_C distributions represent Equation 4. While Equation 2 is implemented by reproducing the actual physics of a DV, the EDU mathematically implements Equation 3. The solid line represents the maximum load p_C distribution, while the dotted line stands for the p_C distribution according to no additional load at all. It can easily be seen that only the solid line exhausts 100 % of braking capacity, whereas the dotted line falls below. The plotted behavior corresponds with the aforementioned characteristics of the EDU. The scale of the charts has been transformed into percent.

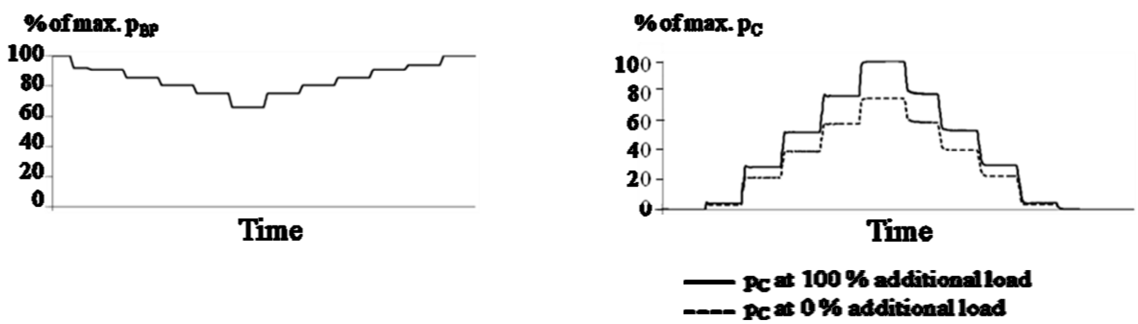

Figure 5. Measurements and simulations results of p_C [18].

3.2. Implementation of the Air Supply and a Start-Up Procedure

Even for air supply engineers, it is a very important matter to know about the start-up time and characteristics in order to design the components correctly. Exemplary tasks are to know, when the brake system is fully functional or the earliest possible time for a parking brake release. As soon as the air compressor powers up, the pressure level of the MRP will increase.

However, the start-up procedure is based on 2 steps in order to allow for an early system operation. The idea behind this system characteristic is to respond to the demand of a fully operational brake system, since the railway cannot drive until the brake system is powered. As soon as the remaining system caught up, the brake system and the remaining system will fill simultaneously from now on, until the maximum MRP pressure p_{MRP} is reached. Once accomplished, the compressor stops running. The described characteristics can be seen in Figure 6 and 7. Figure 6 shows a measurement, while Figure 7 displays the simulation results.

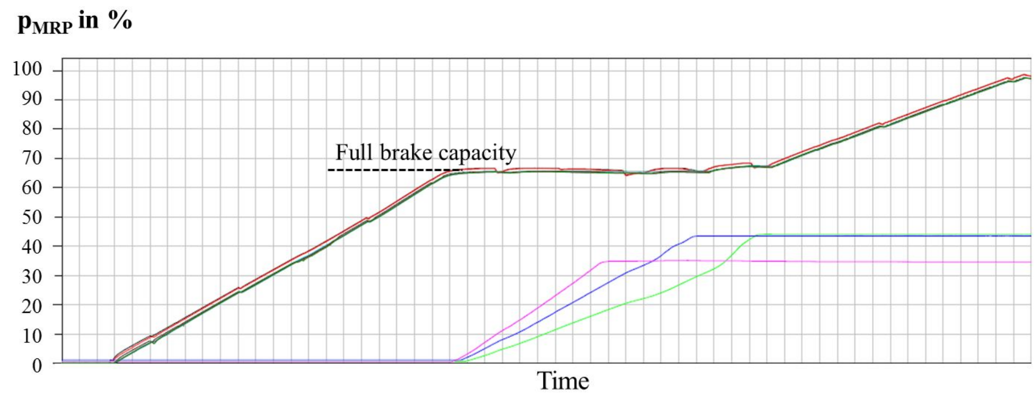

Figure 6. Measurement of a railway start-up characteristic.

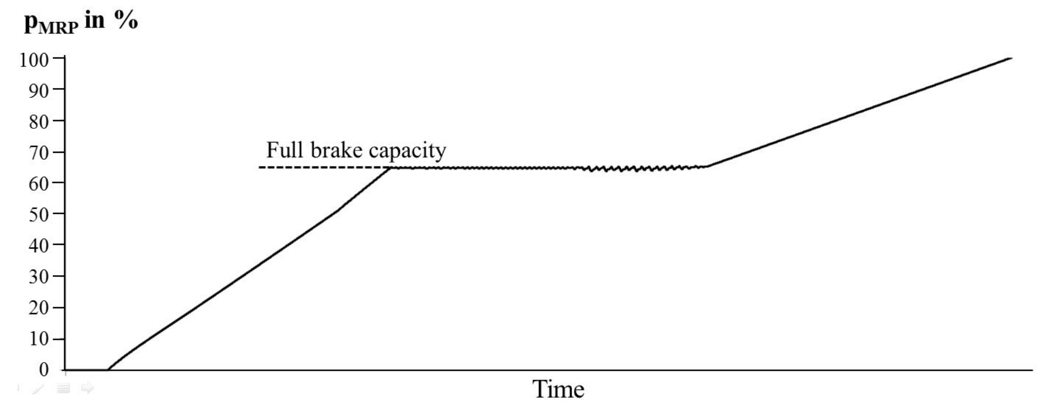

Figure 7. Simulation results of a railway start-up characteristic.

The lower curves in green, blue and purple are not of relevance. As the reader can comprehend, the BP begins filling, as soon, as the full brake capacity is being established, so that the train can release the brakes early. If the entire system started up simultaneously, the point of brake release would happen later, because the train would take longer to reach the same pressure level. As the charts show, the simulated characteristic meets the measured one adequately in aspects of quality. However, as the reader can see, the first ascending line in Figure 7 is steeper than the line in Figure 6, whereas the right lines match. This behavior is caused by too largely estimated brake volumes and underestimated volumes of the remaining system. Since during the preparation of the author’s final thesis more precise estimations were not applicable, the improvement of the parameters is a matter of the author’s future research.

4. SUMMARY

The importance of future overall system modeling and simulation in the field of railway system engineering has been explained in Chapter 1. High product development costs, testing efforts and long product release times can reduce the profitability of a new railway product significantly. By engaging multi-domain simulation tools in order to implement the train system and perform detailed simulation analysis, final designs can be achieved earlier, the testing comprehension and subsequent design modifications can be decreased, which leads to lower development costs and competitive advantages.

In Chapter 2, the complexity of modern railway systems has been discussed. Main communication and kinetic systems have been introduced, as well as their interaction has been graphed. The goal of a multi-domain approach is the implementation and simulation analysis of such a model. Object-oriented modeling languages allow for modeling automation by providing freely programmable functions and combining components to compounds, which can be saved as a new component and applied as often as it is demanded by the user. Frequency analysis helps learning about the eigenvalues and orders of a system capable of oscillating. Freely programmable design of experiments automates the identification process of component and system parameters.

Two actual applications are being discussed in Chapter 3. In the first application, the distributor valve of an indirect brake is being implemented and analyzed. The second example provides insight into the air supply and the start-up procedure of a modern railway system. In either application, the simulation results match actual distributions adequately over the time and represent actual characteristics of the railway systems. Both are part of the overall system mentioned in Chapter 2. In the future, they can be completed by modeling other environmental systems in order to enable versatile and accurate system analysis.

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