Modelling elastomer buffers with DyMoRail

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Abstract

In this paper a model for elastomer buffers for longitudinal railway vehicle dynamics is presented. This model is part of the more extended DyMoRail library which allows to simulate longitudinal dynamics of entire railway trains. With this library an efficient simulation of complete train compositions in various combinations is possible. The elastomer buffer can be used in combination with other buffer models and couplers in different test scenarios. We present details of our rubber spring model based on the one-dimensional, non-linear rubber spring model proposed by M. Berg [1][2][3]. To illustrate the behavior of the friction force modelled in the latter, it is compared to a diode model for Coulomb friction similar to the one in the Modelica Standard Library. Simulations for 40 J-buffer known as ”Miner40” used for freight waggons during shunting at speeds up to 12 km/h are shown. Also shown are simulations of an entire S-Bahn combination with sixteen cars and fifteen elastomer buffers.

Keywords: mechanics, railway

1 Introduction

The tough competition in the railway industry is forcing operators to continuously set higher quality and comfort standards. Buffers on railway vehicles, as fabricated by Schwab Verkehrstechnik, are no more simple devices but have to be considered Hi-Tech components. They have to be be absolutely reliable and present optimal properties to absorb run-up energy from trailing wagons safely. They have to absorb minor impacts, take up slack between locomotive and wagons and bear the load of preceding wagons when pushing. Years ago it was good enough for couplers and buffers to fulfill UIC (International Union of Railways) standards. But nowadays manufacturers only survive in this competitive market if they are able to offer optimized solutions regarding force, energy absorption, and driving comfort. The manufacturer has to be able to react quickly and flexibly to the challenges of rail operators and rolling stock manufacturers and offer final products and customized solutions with high customer value landlord. Since hardware tests are extremely costly, modeling and simulation step into the optimization process. DyMoRail allows to optimize buffers and couplers in different configurations for safety, energy absorption and costs. Train composition can be chosen by the user.

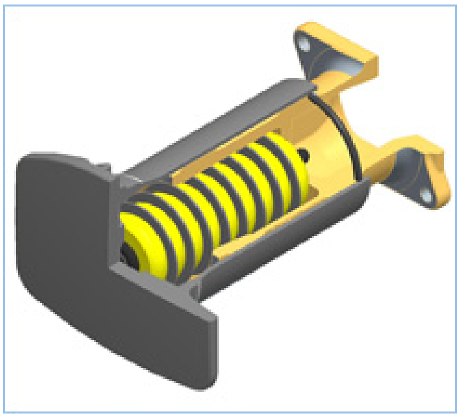

Figure 1: Drawing of a buffer (Seitenpuffer Kategorie A by Schwab Verkehrstechnik).

Schwab Verkehrstechnik AG and ZHAW carried out a project funded by CTI (Swiss Federal Commission for Technology and Innovation) to develop a tool which allows to simulate longitudinal dynamics of entire railway trains. During the following years a Modelica library has been developed, which is called DyMoRail. The DyMoRail library allows an efficient simulation of complete train compositions in various configurations. The library has been presented at Modelica 2012 [4] and a description of the coupler models can be found in references [5][6]. In this paper we focus on our elastomer buffer library and we will present details of our rubber spring model.

The elastomer buffers consists of a series of ring rubber pads put in series separated by metallic shims, as shown in Figure 1. When compressed energy is stored within the material of the rubber pads as strain energy. The energy is dissipated within the material during both the compression and extension of the material due to the internal friction rising from the long cross linked polymers within the material. Elastomer buffers present a non linear force–stroke–diagram.

2 Library

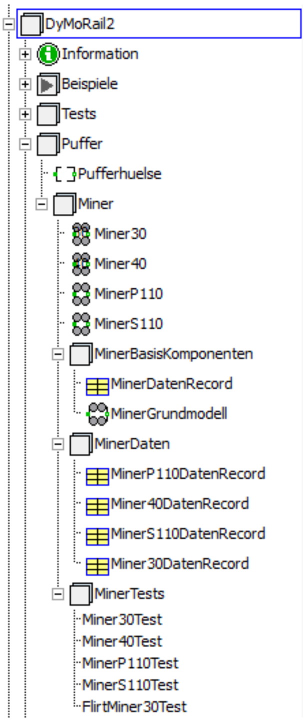

Figure 2: Structure of the buffer sublibrary ”Puffer”.

The buffer library, shown in Figure 2 has been completely redesigned. All buffer models are based on the partial model ”Pufferhuelse” (buffer bush) where the different modes and overall buffer force are modeled. A detailed description of the connectors and the partial model used to build the buffer model is shown in Figure 3. Force and stroke are calculated and, in addition, the energy absorbed by the buffer. The modes are divided into two categories: four operation modes and three motion modes. For the operation modes, we distinguish free, pretension, deformation and arrested. In free mode, the buffer plates do not touch and the force is zero. In the pretension mode the force increases slowly. In the deformation mode the buffer spring is loaded. In the arrested mode the force increases steeply. The motion modes include forward, backward and halt. They describe the current motion of the bush. We will come back to these modes, when discussing the friction model. In the basic buffer model, the Coulomb friction force in the buffer bush is also modeled. A maximum of two buffers can be placed both in series and parallel. European standard configuration consists of two buffers in parallel. A crash between two cars is modelled as two buffers in series on each side, one buffer per car.

```
connector FlanschLinks "positive Richtung nach rechts "

  SI.Position s "absolute Position des Flansches";
  flow SI.Force F "Kraft auf den Flansch";
  a;
end FlanschLinks;
```

```
partial model Verformbar "mechanisches Eintor"

  SI.Distance s_rel "Relativdistanz zwischen linkem und rechtem Ende
  SI.Force F "Kraft, Stärke des durchfliessenden Impulsstromes";

equation
  s_rel = flanschL.s - flanschR.s;
  flanschL.F = F;
  flanschR.F = -F;
  a;
end Verformbar;
```

```
partial model Pufferhuelse
  "Basishuelse fuer verschiedene Puffertypen"
  extends DyMoRail2.Mechanik.Verformbar;

  Real s_puff( quantity="Length", unit="m", start=0, displayUnit="mm")
    "Hub eines einzelnen Puffers";
  Real F_puff( quantity="Force", unit="N", displayUnit="kN") "Kraft pro Puffer";
  SI.Energy W "Energieaufnahme pro Puffer";
  SI.Length s_frei "Freiraum zwischen den Puffern";
  SI.Force F_Huels "Kraft pro Puffer ohne Feder oder Hydraulik";
  parameter Integer n(
    min=1,
    max=2) = 2 "Zahl der Puffer nebeneinander (parallel)";
  parameter Integer m(
    min=1,
    max=2) = 2 "Zahl der Puffer hintereinander (seriell)";
protected
  parameter SI.Force Fvor=10000 "Reibkraft beim Einfahren";
  parameter SI.Force Frueck=500 "Reibkraft beim Auseinanderfahren";
  parameter Real D2(
    final unit="N/m",
    final min=0) = 1e9 "Federkonstante bei Block";
  parameter Real kv(
    final unit="N.s/m",
    final min=0) = 20 "Konstante zu DummyDaempfer";
  parameter SI.Force Fm=(Fvor - Frueck)/2 "mittlere Reibkraft";
  parameter SI.Force DFR=(Fvor + Frueck)/2
    "Abweichung der Reibkräfte von der mittleren Reibkraft";
  parameter Real k=1e-3 "Hilfsgrösse zur Berechnung der statischen Hysterese";
  constant Integer Frei=-1;
  constant Integer Spann=0;
  constant Integer Puff=1;
  constant Integer Block=2;
  constant Integer Vor=1;
  constant Integer Still=0;
  constant Integer Rueck=-1;
  SI.Length L_un "Pufferhub wird in den Folgemodellen parametrisiert";
  SI.Velocity v_rel "Relaivgeschwindigkeit zwischen FL und FR";
  SI.Force F0 "Vorspannkraft wird in den Folgemodellen definiert";
  Integer mode_s "Zustand des Puffers";
  Integer mode_v "Bewegungszustand des Puffers";
  SI.Length DeltaL "Anfangsverformung";
  Real dmax "maximale relative Aenderung der Federkonstante";
  Real d "relative Aenderung der Federkonstante";
  Real sv "interner Parameter zur Beschreibung des d-s-Verhaltens";
equation
  dmax = DFR/(Fm + F0);
  DeltaL = (Fm + F0)/D2;
  v_rel = der(s_rel);
  s_frei = if mode_s == Frei then -s_rel else 0;
  s_puff = (s_rel + s_frei)/m;
  mode_s = if s_rel < 0 then Frei else if s_rel < m*DeltaL then Spann else
    if s_rel < m*(L_un + DeltaL) then Puff else Block;
  mode_v = if sv > dmax then Vor else if sv < -dmax then Rueck else Still;
  d = if mode_v == Rueck then -dmax else if mode_v == Vor then dmax else sv;
  v_rel = if mode_v == Rueck then sv + (1 - k)*dmax else if mode_v == Vor then
          sv - (1 - k)*dmax else k*sv;
  F_Huels = if mode_s == Frei then -F0 else if mode_s == Spann then
    -F0 + D2*(1 + d)*s_puff else if mode_s == Puff then Fm + DFR*d/dmax else D2*(
    1 + d)*(s_puff - L_un) - F0;
  der(W) = v_rel*F_puff/m;
  a;
end Pufferhuelse;
```

Figure 3: Models for connectors and partial models.

Based on this partial model, the actual buffer model is built, including the elastomer spring. Data sheets provided by the manufacturer are included with the help of records in ”Miner Daten”.

For their acceptance test, railway companies define several crash scenarios with different crash partners at different speeds. Those test scenarios are implemented by means of a test library ”Miner Tests”. It allows for comparability, consistency and easy reproduction of the total set of test cases.

3 Model

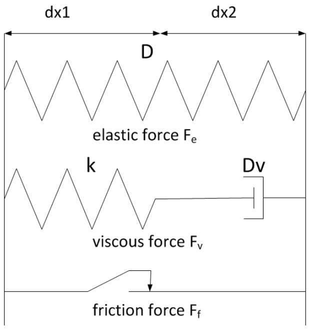

Figure 4: Model for a rubber spring proposed by M. Berg.

For model implementation of the DyMoRail library, the Modelica based simulation software Dymola is used. The elastomer model is taken from the non-linear rubber spring model by M. Berg [1][2][3]. The model proposed in these papers is one-dimensional and based on the superposition of three forces (elastic, friction and viscous force) and contains five parameters. For better understanding, a schematic drawing is shown in Figure 4.

In the model by M. Berg, the elastic force is linearly modelled with a stiffness constant `D`:

$$F_e = D \cdot x \qquad (1)$$

The viscous force is modelled by a linear spring (spring constant `Dv`) in series with a linear viscous damper (damping constant `k`):

$$F_v = Dv \cdot x - kv \qquad (2)$$

The friction force F_{Coul} depends both on the displacement x and on a reference state (x_s, F_{Rs}) in the friction force versus displacement characteristic. Depending on the position relative to this reference state, the friction force is expressed with two parameters maximum force F_{Rmax} and constant x_2. A small value of x_2 gives a steep increase in the friction force and thereby high frictional stiffness. The friction force F_{Coul} in the model is, depending on how x is related to the reference displacement x_s, defined by the equations below.

The reference state is set to $x_s = 0$ and $F_{Rs} = 0$.

$$F_{Coul} = F_{Rmax} \frac{s_{rel}}{s_{rel} + x_2}$$

For backward movement $xs = x1$ and $FRs = FR1$:

$$F_{Coul} = F_{R1} + (F_{Rmax} + F_{R1}) \times \frac{s_{rel} - x_1}{x_2 \left(1 + \frac{F_{R1}}{F_{Rmax}}\right) - (s_{rel} - x_1)}$$

For backward movement $xs = x1$ and $FRs = FR1 = FRmax$:

$$F_{Coul} = F_{Rmax} \left(1 - 2 \frac{s_{rel} - x_1}{2x_2 - (s_{rel} - x_1)}\right)$$

For forward movement $xs = x3$ and $FRs = FR3$:

$$F_{Coul} = F_{R3} + (F_{Rmax} - F_{R3}) \times \frac{s_{rel} - x_3}{x_2 \left(1 - \frac{F_{R3}}{F_{Rmax}}\right) + (s_{rel} - x_3)}$$

For forward movement $xs = x3$ and $FRs = FR3 = -FRmax$:

$$F_{Coul} = F_{Rmax} \left(s \frac{s_{rel} - x_3}{2x_2 + (s_{rel} - x_3)} - 1\right)$$

When the buffer is at rest $xs = x5$ and $FRs = FR5$:

$$F_{Coul} = F_{R5} + F_{Rmax} \frac{s_{rel} - x_5}{x_2 + (s_{rel} - x_5)}$$

When the buffer is at rest mode $xs = x5$ and $FRs = FR5 = \pm FRmax$:

$$F_{Coul} = F_{Rmax} \left(\pm 1 + \frac{s_{rel} - x_5}{x_2 + (s_{rel} - x_5)}\right)$$

The implementation of these equations in Modelica is as follows

```
dx = dx1 + dx2
dv2 = der(dx2)
k * dv2 = Dv * dx1
Vorzeichen = if dv > 0
    then1
    else if dv < 0
    then - 1
    else0
FCoul = FCouls+
(dx - dxs) * (FCoulmax - Vorzeichen * FCouls)
/(x2 * (1 - Vorzeichen*
FCouls/FCoulmax)
+Vorzeichen * (dx - dxs))
when change(Vorzeichen)then
dxs = pre(dx)
FCouls = pre(FCoul)
end when
F = D * dx + Dv * dx1 + FCoul
der(W) = P
```

where `dx1` is the displacement of spring `Dv` and `dx2` is the displacement of the damper k.

To illustrate the behavior of the M. Berg friction model, it (Figure 5) is compared to a diode model for Coulomb friction, similar to the one of the Modelica Standard Library (Figure 6), as described for example in reference [7]. As can be seen from these graphs, the hysteresis loop of the Modelica Standard Library model has a rectangular form, whereas the M. Berg friction model shows sharp corners at the maximum and minimum displacements with a smooth transition between the upper and lower branch of the hysteresis.

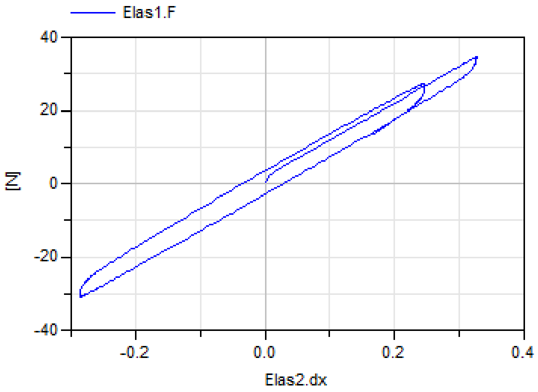

Figure 5: Friction force versus displacement. Simulation of the friction model for a rubber spring proposed by M.Berg. $F_{max} = 2$ and $x_2 = 0.002$.

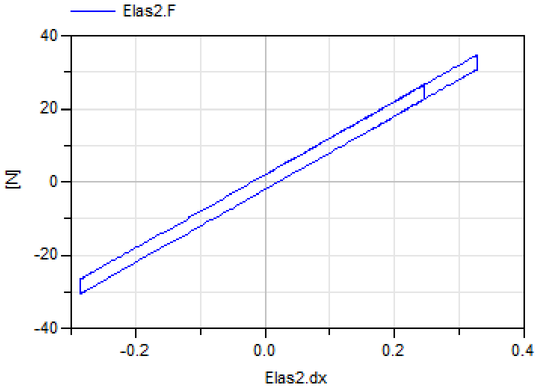

Figure 6: Friction force versus displacement. Simulation of the friction model for the basic model for Coulomb friction in the Modelica Standard Library. $F_{max} = 2$ and $x_2 = 0.002$.

In the final model for the Miner buffer in the DyMoRail library, the total force:

$$F = F_e + F_v + F_{Coul} \tag{3}$$

is taken to the exponent of an exponential function. This corresponds more to reality, shown by a thorough parameter study.

4 Simulation

For their acceptance test, railway companies define several crash scenarios with different crash partners at different speeds.

Figure 7 shows simulations for 40 J-buffer known as ”Miner40” at different initial speeds. This type of buffers is exclusively used for freight wagons. The acceptance tests demand reversible shunting at speeds up to 12 km/h. During collisions at low speeds, the energy has to be absorbed by the buffers. Absolutely no damage should occur to the rolling stock. The acceleration must remain below 4.0 g.

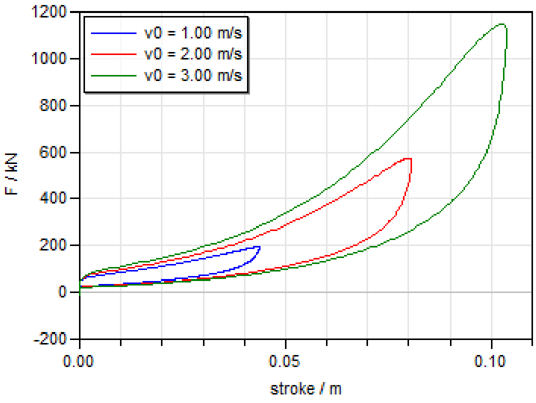

Figure 7: Simulation of the buffer model with different initial speeds. Force vs stroke diagram.

The elastomer model works also in combination with other coupler or buffer models in complete train configuration. Figure 8 shows a simulation of three S-Bahn combinations colliding with a single combination at rest during shunting. Each S-Bahn contains four cars and three Miner models, so in total the model contains sixteen cars and fifteen buffer models. In this graph, one can distinguish the different cars colliding one after the other.

5 Conclusion

In this paper a model for elastomer buffers for railway vehicle dynamics is presented. This model is part of the more extended DyMoRail library which allows to simulate longitudinal dynamics of entire

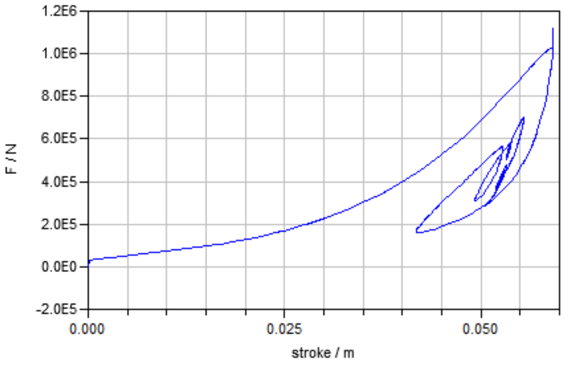

Figure 8: Simulation of three S-Bahn combinations colliding with a single combination at rest during shunting.

railway trains. With this library an efficient simulation of complete train compositions in various combinations is possible. The elastomer buffer can be used in combination with other buffer and couplers models. The acceptance test scenarios can be simulated with the help of this model.

6 Acknowledgements

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