**UNIVERSAL MECHANISM 9** 



# **MagLev Simulation**

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# 29. UM Module for simulation of maglev trains

# 29.1. General information

Program package Universal Mechanism includes a specialized module **UM MagLev** for analysis of 3D dynamics of both single magnetic levitation vehicle and trains. The module includes additional tools integrated into the program kernel.

UM MagLev is close to the UM Monorail train module and requires it. In particular, the user may add tires to the maglev vehicle, which can be useful for modeling EDS systems.

The module is available in the UM configuration if the sign + is set in the corresponding line of the **About** window, the **Help** | **About...** menu command, Figure 29.1.

About	
	Universal Mechanism Simulation program
	Version 1.0.0.0 32bit All rights reserved (c), 1993-2016 Computational Mechanics Ltd.
	Configuration
	UM Loco (+)  UM Loco/Track Quality Estimation (+) UM Loco/External Contact Model (+)
	UM Loco/Non-elliptical Contact Model (+) UM Loco/Multi-point Contact Model (+)
	UM Loco/CONTACT add-on interface (+) UM Loco/Wheel Profile Wear Evolution (+) UM Monorail Train (+)
	UM MagLev(+)
	UM Rail/Wheel Wear (+) 🔻
	www.universalmechanism.com
	e-mail: um@universalmechanism.com
	Close



**UM MagLev** contains the following main components:

- tools for generation and visualization of guideway structure (bridge) geometry;
- tools for generation and visualization of guideway roughness (irregularities);
- mathematical models of magnetic levitation and guidance forces;
- set of typical dynamic experiments.

**UM Maglev** allows the user to solve the following problems:

- analysis of control system stability;
- estimation of vehicle vibrations due to irregularities;
- estimation of vehicle dynamic performances on curving;

• parametric optimization of vehicle elements according to various criteria.



## **29.2. Base system of coordinates**

Figure 29.2. Base system of coordinates (SC0)

Inertial system of coordinates (SC0) in UM MagLev meets the following requirements (Figure 29.2).

- Axis Z is vertical, axis X coincides with the vehicle longitudinal axis at its ideal position at the moment of motion start; direction of X axis corresponds to the motion direction of the vehicle.
- Origin of SC0 lies at the centerline of the ideal upper surface of track beam.

# **29.3. Development of vehicle model**

The user develops the vehicle model in UM Input.exe program. The model consists of bodies, joints and force element. We recommend to start the model development with studying the model delivered with UM <u>{UM Data}\Samples\MagLev\MagLev vehicle</u>.

# 29.3.1. Maglev vehicle identification

Variables Curves Attributes
General Options Sensors/LSC
Transform into subsystem
Hansionninto subsystem
Path D:\UM70_WORK\Tests\Monorail\Test
Object identifier
JMObject
Comments
Monoral
Generation of equations
© Symbolic
- Syntooic
Numeric-iterative
R MagLev force
📲 Gearing
🗞 Chain gear
[] Combined friction
● Cam
g Spring Pack
C Bushing
Tyre
MagLey force
% Mechanical converter of rotation
⊕ Fluid coupling
Hydraulic torque converter
Z Hydrostatic drive
🛃 Planetary gearing

Figure 29.3. Text attribute 'Monorail'. Special forces 'MagLev force'

UM identifies the model as a maglev vehicle or a maglev train if the following two requirements are met in the model description:

- The standard text comment 'Monorail' must be set in the **Comments** box on the **General** tab of the data inspector, Figure 29.3, left;
- Special forces of the **MagLev force** type are presented in the model, Figure 29.3.

Name: Magnet SL 1 - 북 북북 - 등	Name: Magnet GL 1 - 나
Comments/Text attribute C	Comments/Text attribute C
Body1: Body2:	Body1: Body2:
Magnet S L V Base0 V	Magnet G L V Base0
Type: Magley force	Type: AddLev force
Attachment points	Attachment points
Magnet S I	Magnet G L
-magnet_s_t <sup>ic</sup>	-magnet_g_lC
Type of force	Type of force
<ul> <li>Levitation magnet</li> </ul>	C Levitation magnet
🔘 Guidance magnet	Guidance magnet
Force axis	Force axis
Axis Z : (0,0,1)	Axis Y : (0,1,0)
0 <u>n</u> 0 <u>n</u> 1 <u>n</u>	0 <u>n</u> -1 <u>n</u> 0 <u>n</u>
Accelerometer variable	Accelerometer variable
Sensors.Z RL.a_sensor	-
Force identifiers	Force identifiers
Force:	Force:
8	8
<u>S</u>	fy_magnet_gl1
fz_magnet_sl1	1
Torque:	Torque:
<u> S</u>	8
8	2
<u> S</u>	[8

## 29.3.2. Modeling levitation and guidance magnets

Figure 29.4. Force elements for levitation and guidance magnets

Both levitation and guidance magnets are modeled by special force elements of the **MagLev force** type, Figure 29.4.

## Bodies

The first body in the force element model must be levitation or guidance magnet. The second body must be Base0.

#### **Attachment points**

The magnet force is applied to magnet at point, which coordinates are set in the local coordinates system of the magnet. The coordinates can be parameterized by identifiers.

#### Force axis

The force axis is a unit vector along the magnet force. As a rule, it is (0, 0, 1) the levitation magnets, and (0, -1, 0) or (0, 1, 0) for the left or right guidance magnets.



Figure 29.5. Visualization of attachment point and magnet axis

Geometric data are visualized in the animation window by a red vector, which origin and direction coincide with the attachment points and the force axis, Figure 29.5.

#### Type of force

Each of the force element can describe either levitation or guidance electromagnetic force. U-shaped levitation magnets can be used for a passive guidance system, Section 29.6.3 *U-shaped magnet*.

#### Accelerometer variable



Figure 29.6. Selection of acceleration variable

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Usually the magnet control includes an acceleration term, Section 29.6.2 *Single pole magnet model*. The acceleration value can be obtained from the model of accelerometer, Section 29.3.3 *Model of accelerometer*. The variable corresponding to the accelerometer data is selected from the drop down list, Figure 29.6.

## **Force identifiers**

If force computation is implemented with Matlab/Simulink interface, *unique* identifiers must be assigned to nonzero force and torque components. The components are specified in the track coordinate system. It is not correct to assign one identifier to several force elements.

## 29.3.3. Model of accelerometer



Figure 29.7. Accelerometer

Use of mechanical model of accelerometers is recommended if acceleration is included in the magnet control. An alternative computation of acceleration implements the acceleration prediction and does not allow correct linearization of equations of motion in UM.

Here we consider a standard UM model of a simplified mechanical accelerometer, which can be used in models of maglev vehicles. The model in located in the directory

{UM Data}\Samples\MagLev\Accelerometer

and describes a mass-spring mechanical system with damping, Figure 29.7.

Name: Casing		
Name: Casing	-1-2	
Comments/Text at	ttribute C	
Oriented points	Vectors	2D Contact
Decementer of the second secon	Vectors	SD Contact
Parameters	Position	Points
Internal joint		
🖲 6 d.o.f	🔘 0 d.o	o.f
Coordinates (PP):	Quaternior	•
Go to element		r 🕄
Image:	Vis	ible
Casing		•
Compute autom	atically	
Inertia parameter	s	
Mass:		C

Figure 29.8. Fictitious body

The model includes a fictitious massless body **Casing** with internal 6 d.o.f. joint, Figure 29.8. This joint will be automatically removed after coupling the casing with the corresponding magnet. Other model elements are

- Body Mass
- Translational joint **jMass** connecting the mass body with the fictitious one; the joint allows motion of mass along the Z axis of the casing

			×.
Name:	Spring		'
Comm	nents/Text attrib	ute C	
Body 1	:	Body2:	
Mass	•	Casing -	
GO:	spring	•	
Auto	detection		
Attack	nment points		h
Mass	C	C h concer/2 C	
		n_sensor/2 🖻	
Casing			
			IJ
Length	n 0.015		
Lin	lear	•	J
F=F0	-c*(x-x0) - d*	v + Q*sin(w*t+a)	
Force/	moment (F0):	p0 C	
Stiffne	ss coef. (c):	k_sensor	
Length	(x0):	h_sensor/2	
Dampir	ng coef. (d):	c_sensor	

Figure 29.9. Spring as bipolar force element

• The bipolar force element **Spring** models linear spring and damping, Figure 29.9. A correct use of this element for evaluation of acceleration requires setting the stationary value of the spring force, which is parameterized by the identifier p0. This value is equal to the projection of the weight force of the masspoint on the accelerometer axis with the opposite sign. Thus, for vertical upward sensor orientation p0 is equal to the weight of the mass point, and for the horizontal orientation of the accelerometer p0=0.

29-11

Gen	eral	Options	Sensors/LSC
Vari	ables	Curves	Attributes
ð B	- ₽		
Туре	Name	Expression	n
var	XS	coordinate	e( "jMass", 1 , 0 )
var	a senso	-xs*s_factor	

Figure 29.10. Variables

• The list of variables computes the accelerometer data. The corresponding variable is *a\_sensor*.

The approximate value of measured acceleration a is computed according to the formula

$$a = \frac{k}{m} dx \,,$$

where dx is the spring deflection from the equilibrium position, which is presented by the variable *xs* (Figure 29.10); *k* is the spring constant, and *m* id the mass of the sensor masspoint. The ratio k/m is equal to the value of identifier *s\_factor*, Figure 29.11.

Name	Expression	Value	Comment
ms	0.01		Mass
ps	ms*9.81	0.0981	Weight
beta	0.3		Damping ratio
fs	500		Natural frequency (Hz)
k_sensor	sqr(2*pi*fs)*ms	9.8696044E+4	Spring constant
c_sensor	2*beta*sqrt(k_sensor*ms)	18.849556	Damping constant
dx_static	ps/k_sensor	9.9396081E-7	Static deflection
s_factor	k_sensor/ms	9.8696044E+6	Acceleration factor
r_sensor	0.005		Casing radius
h_sensor	0.03		Casing length
p0	0		Static force

Figure 29.11. List of identifiers in accelerometer model

Parameterization of the accelerometer model by identifiers is shown in Figure 29.11.

## 29.3.4. Sliding contacts

Sliding contact forces are used for modeling contact interaction of vehicle with the track. The corresponding force element is the **Points-Plane** contact, Figure 29.12.

#### 29-12

Name: Upper contact	<u>_1</u> <u>+</u> <u>+</u> <u>+</u> <u>+</u>	-1-5
Comments/Text attribute	С	
Body1:	Body2:	
Frame 💌	Base0	-
Type: 🛃 Points-Plane		•
Parameters Geometry		
Sliding parameters		
Friction coef. (f):	f_contact	C
Friction coef. (f0):	f_contact*1.2	С
Velocity (vs):		С
Stribeck coef. (delta):	1	C
Friction coef. (nu):		C
Parameters of normal	contact	
Stiffness coef. (c):	k_contact	С
Damping coef. (d):	c_contact	C
Unilateral contact		
Unlimited plane		
Close contact		

Figure 29.12. Example of sliding contact

The sliding contact at each of the contact points produces a normal and a friction force between one of the vehicle bodies (i.e. a bogie frame, a magnet holder) and the **Base0** body. Contact points are assigned to the first body, and the plane belongs to the track. The plane normal is defined in the track system of coordinates moving together with the vehicle. The origin of this moving system of coordinates follows the projection of the contact body center of mass on the track centerline.

The sliding contact can be used for modeling

- equilibrium position of vehicle with disabled levitation magnets;
- bumpstop elements in lateral and vertical directions.

Contact forces should be described as *unilateral* ones, Figure 29.12. Necessary gaps between the contact points and the contact plane must be foreseen, see Section 29.4.1.7. *Sliding contact elements*.

## 29.3.5. Accelerometer positioning



Figure 29.13. Accelerometer fixed to a guidance magnet

A necessary number of accelerometers are included to the maglev bogic model as included subsystems. The accelerometer casing is fixed to a body, which acceleration should be measured, Figure 29.13.

₩	R	
Name: jSensor Y FL 🕂 🗎 🗸 🗸	Name: jSensor Y FR 🕂 🖬 🐨	Geometry Coordinates
Body1: Body2: GMagnet L ▼ Sensors.Y FL.Sensor ▼	Body 1:     Body 2:       GMagnet R     ▼       Sensors.Y FR.Sensor     ▼	Translational degrees of freedom:
Type: 🔪 6 d.o.f. 👻	Type: 🔪 6 d.o.f. 👻	x 0.0000000000 X
Geometry Coordinates	Geometry Coordinates	Y 0.0000000000 1
Body 1 Body 2	Body 1 Body 2	Z 0.0000000000 🔀
C Visual assignment	Visual assignment	Rotitional
x: gmagnet_base/2	x: gmagnet_base/2	deg ees of freedom: Orientation angles
y: 0.03 C	y: -0.03 C	3,1,2 <b>•</b>
z:C	Z:C	1 0.0000000000 1
Rotation	Rotation X -90 C	2 0.000000000 1
		3 0.0000000000 24

Figure 29.14. Sensor fixing to guidance magnet by a joint

A joint with zero d.o.f. is used to set the sensor in desired position and orientation, Figure 29.14. The first body in the joint is a magnet, and the fictitious body **Casing** in the sensor model is assigned as the second joint body.

The joint shift for the first body specifies the accelerometer position. In the case of a guidance magnet, the accelerometer axis must set in the horizontal direction, which is done by a rotation on 90° about the X axis for the left magnets and on -90° for the right ones, Figure 29.14.

## 29.3.6. Vehicle suspension and standard force elements

Suspension elements are models with standard force elements such as *generalized* linear force elements, bipolar force elements, bushings and so on. More information can be found in the file <u>Chapter 26</u>.

# 29.4. Maglev test models

Here we consider models of maglev vehicles, which allow the user to verify the correctness of simulation with UM MagLev and to get experience in development and analysis of maglev vehicles.

## 29.4.1. Maglev bogie model



Figure 29.15. Model of maglev bogie

We consider two bogie models

{UM Data}\Samples\MagLev\Bogie\_6DOF,

{UM Data}\Samples\MagLev\Bogie.

The model with 6 DOF is the most simple maglev model for testing main features of UM Mag-Lev, and for comparison of simulation result with analytical ones. In this model the magnet holders are rigidly connected with a frame. In the second model the magnets have additional degrees of freedom, which correspond to the primary suspension of the maglev vehicle. 29.4.1.1. Frame



The frame body has 6 degrees of freedom, which are introduced by the joint jFrame. The inertial parameters are set by the identifiers

*m\_frame* - mass

*iframe\_x, iframe\_z, iframe\_z* - central moments of inertia relative to the X, Y, Z axis  $z_cg_frame$  - vertical coordinate of the center of gravity.

			👝
Namo	iFra		⊠ √⊒ ∓
Name.	Jira		
Body	1:	Body2:	
Base0	)	▼ Frame	-
Type:	۹ 🔍	5 d.o.f.	•
Geom	netry	Coordinates	
Tran	slatio	nal	
degr	ees o	of freedom:	
1	x	0.00000000000	*∕₊
1	Y	0.00000000000	1
1	Ζ	0.00000000000	1
Rota	tiona	l	
degr	ees o	of freedom:	
Orier	ntatio	n angles	
3,1,	2		•
1	1	0.00000000000	1
1	2	0.00000000000	1
1	3	0.00000000000	1

Figure 29.16. Six degrees of freedom for frame

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#### 29.4.1.2. Levitation magnets



In the case of the **Bogie\_6DOF** model, two levitation magnet holders **LMagnet L** (levitation magnet left), **LMagnet R** (levitation magnet right) are rigidly connected to the frame by the joints with zero degrees of freedom **jLMagnet L**, **jLMagnet R**, Figure 29.17, left. For the model **Bodie** with primary suspension, the levitation magnets have tree DOF, Figure 29.17, right.

Identifiers parameterize both geometric and inertia data:

*m\_magnet\_l* - mass

*ix\_magnet\_l, iy\_magnet\_l, iz\_magnet\_l* - central moments of inertia relative to the X, Y, Z axis

*z\_cg\_magnet\_l* - vertical coordinate of the center of gravity

*lmagnet\_y, lmagnet\_z* - lateral and vertical position parameters

Name: jLl	Magnet L	<u> 바라 -</u> 주	Name: jL	Magnet L	t <u>tt</u> ₹
Body1:	Body2:		Body1:	Body2:	
Frame	✓ LMagnet L	•	Frame	<ul> <li>LMagnet</li> </ul>	L 🔻
Туре: 🔎	6 d.o.f.	-	Туре: 🔎	6 d.o.f.	•
Geometry	y Coordinates		Geometr	y Coordinates	
Translati	ional		Translat	ional	
degrees	of freedom:		degrees	of freedom:	
🔲 X	0.00000000000	1	🔽 X	0.00000000000	1
🔲 Y	0.00000000000	1	🔲 Y	0.00000000000	*∕₊
🔲 Z	0.00000000000	1	🔽 Z	0.00000000000	*∕₊
Rotation	al		Rotatic	nal	
degrees	of freedom:		degree	of freedom:	
Orientat	on angles		Orienta	ion angles	
3,1,2	-	•	3,1,2		•
1	0.00000000000	1	1	0.00000000000	1
2	0.00000000000	*	2	0.00000000000	1
3	0.00000000000	*∕₊	<b>V</b> 3	0.00000000000	*∕.

Figure 29.17. Rigid and 3 DOF coupling of levitation magnet

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#### 29.4.1.3. Guidance magnets



In the case of a bogie\_6DOF model, two guidance magnet holders **GMagnet L** (guidance magnet left), **GMagnet R** (guidance magnet right) are rigidly connected to the frame by the joints with zero degrees of freedom **jGMagnet L**, **jGMagnet R**, Figure 29.18, left. For the model **Bodie** with primary suspension, the levitation magnets have tree DOF, Figure 29.18, right.

Identifiers parameterize both geometric and inertia data:

*m\_magnet\_g* - mass

*ix\_magnet\_g, iy\_magnet\_g, iz\_magnet\_g* - central moments of inertia relative to the X, Y, Z axis

*z\_cg\_magnet\_g* - vertical coordinate of the center of gravity

gmagnet\_y, gmagnet\_z - lateral and vertical position parameters

	<b>X</b>	
Name: jQ	GMagnet L <u>그북 북북 그루</u> ▼	Name: jGMagnet L+ ♀ ♀ · ▼
Body1:	Body2:	Body1: Body2:
Frame	✓ GMagnet L	Frame  GMagnet L
Type:	● 6 d.o.f.	Type: 🔎 6 d.o.f.
Geometr	y Coordinates	Geometry Coordinates
Translat degrees	tional s of freedom:	Translational degrees of freedom:
X	0.0000000000 1	X 0.0000000000
🔲 Ү	0.0000000000 1	V 0.0000000000 1
🔲 Z	0.0000000000 1	z 0.0000000000 🔪
Rotatic	nal	Rotational
degree	of freedom:	degrees of freedom:
Orienta	tion angles	Orientation angles
3,1,2	▼	3,1,2
1	0.0000000000 1	✓ 1 0.0000000000 ▲
2	0.0000000000 1	2 0.0000000000 1
3	0.0000000000 1	3 0.0000000000 1

Figure 29.18. Rigid and 3 DOF coupling of guidance magnet

## 29.4.1.4. Sensors





The model contains a subsystem **Sensors** with 8 accelerometers for measuring magnet accelerations. Each of the accelerometers is added as an included subsystem, Figure 29.19.



Figure 29.20. Joints for sensor positioning

Joints with zero degrees of freedom are used for positioning the accelerometers, Figure 29.20, Section 29.3.5 *Accelerometer positioning*.

## 29.4.1.5. Magnet forces

Two magnets are connected to each of the magnet holders.



Figure 29.21. Magnet forces

Four levitation magnets are LMagnet LF (levitation magnet left front), LMagnet LR (levitation magnet left rear), LMagnet RF, LMagnet RR. Identifiers parameterizing the forces are

*lmagnet\_base* - the lateral distance between the magnets

*fz\_lmagnet\_lf, fz\_lmagnet\_lr, fz\_lmagnet\_rf, fz\_lmagnet\_rr* – identifiers for external computation of levitation forces in Matlab/Simulink.

Four guidance magnets are **GMagnet LF** (guidance magnet left front), **GMagnet LR** (guidance magnet left rear), **GMagnet RF**, **GMagnet RR**. Identifiers parameterizing the forces are *gmagnet\_base* - the lateral distance between the magnets

*fz\_gmagnet\_lf, fz\_gmagnet\_lr, fz\_gmagnet\_rf, fz\_gmagnet\_rr* – identifiers for external computation of guidance forces in Matlab/Simulink.

Accelerometer data are assigned to each of the magnet force.

## 29.4.1.6. Primary suspension: Bushings



Figure 29.22. Magnet forces

The magnet holders are coupled with the frame by linear viscous-elastic bushings, which correspond to the *primary suspension* of the maglev vehicle. The bushings have no effect in the case of the model with 6 DOF, when the holders are rigidly connected with the frame by the joints. These elements are used in the model with primary suspension **Bogie**.

Spring and damper constants for the primary suspension are computed according to the frequency and damping ratio constants, which are set by the +identifiers *f\_prim* and *beta\_prim*, Figure 29.23.

Весь список	Control Bushings		
Name	Expression	Value	Comment
f_prim	7		Primary suspension: frequency (Hz)
beta_prim	0.4		Primary suspension: damping ratio
x_bush_l	1		Bushing longitudinal position (levitation)
z_bush_s	-0.8		Bushing vertical position (levitation)
k_bush_s	<pre>sqr(2*pi*f_prim)*m_magnet_l/2</pre>	5.8033274E+5	Bushing stiffness (levitation)
ka_bush_s	1.000000E+5		Bushing angular stiffness (levitation)
c_bush_s	2*beta_prim*sqrt(k_bush_s*m_magnet_l)	1.4928087E+4	Bushing damping (levitation)
ca_bush_s	1000		Bushing angular damping (levitation)
x_bush_g	1		Bushing longitudinal position (guidance)
z_bush_g	-0.18		Bushing vertical position (guidance)
y_bush_g	1.6		Bushing lateral position (guidance)
k_bush_g	<pre>sqr(2*pi*f_prim)*m_magnet_g/2</pre>	5.8033274E+5	Bushing stiffness (guidance)
ka_bush_g	1.000000E+5		Bushing angular stiffness (guidance)
c_bush_g	2*beta_prim*sqrt(k_bush_g*m_magnet_g)	1.4928087E+4	Bushing damping (guidance)
ca_bush_g	1000		Bushing angular damping (guidance)

Figure 29.23. Parameterization of primary suspension

### 29.4.1.7. Sliding contact elements

The bogic model includes a sliding contact force element **Upper contact**, which allows the equilibrium positioning of the bogic in case of disable levitation magnets as well as the vehicle landing on the track in emergency cases, Figure 29.24-Figure 29.26.

The element contains four contact points. The gap is parameterized by the identifier *s0\_contact*, Figure 29.26.



Figure 29.24. Sliding contact

Name: Upper contact					
Comments/Text attribute C					
Body1: Body2:					
Frame  Base0	-				
Type: 🔛 Points-Plane	•				
Parameters Geometry					
Points (Frame)	۵				
x_contact y_contact s0_contact					
x_contact -y_contact s0_conta	s0_contact				
-x_contact y_contact s0_conta	ct				
-x_contact -y_contact s0_conta	s0_contact				

Figure 29.25. Contact points



Figure 29.26. Gap between contact points and contact plane

#### 29.4.1.8. Identifiers for magnet control

The model includes a list of identifiers, which are necessary for parameterization of magnet control parameters. The parameterization is used in linear analysis of maglev vehicles as well in multivariant computations. It allows the user to analyze the levitation properties in dependence on the control parameters.

Whole list Co	ntrol Bushinas Inertia	Geometry C	ontact Magnet force identifiers
Name	Expression	Value	Comment
UL_0	0		Stationary voltage (levitation)
UL_s	0		Proportional control (levitation)
Ul_v	0		Differential control (levitation)
Ul_a	0		Acceleration control (levitation)
Ul_is	0		Integral control (levitation)
Ug_0	0		Stationary voltage (guidance)
Ug_s	0		Proportional control (guidance)
Ug_v	0		Differential control (guidance)
Ug_a	0		Acceleration control (guidance)
Ug_is	0		Integral control (guidance)
Fz0	m_control*9.81/1000	10.791	Nominal control force (kN)
Fy0	0		Stationary force (guidance)
s0_l	10		Levitation: nominal gap (mm)
s0_g	10		Guidance: nominal gap (mm)

Figure 29.27. Parameterization of control parameters

## 29.4.2. Bogie model with U-shaped magnets



Figure 29.28. Model for tests of U-shaped magnets

The model illustrates a passive guidance maglev system, see Section 1.6.3 U-shaped magnet. It is located in the directory

{UM Data}\Samples\MagLev\MagLev vehicle

The model is based on the previous bogie model with some changes:

- guidance magnets are excluded;
- a car body reduced to one bogie is added;
- the Suspension bushing describes a simple linear secondary suspension;
- the identifier *lambda\_ratio* is added for parameterization of the lateral force ratio, Section

# 29.5. Track macro profile and roughness

Guideway geometry is composed of two components: macro profile, and roughness.

## 29.5.1. Track macro profile

Track macro profile contains 3D information about the geometry of the centerline on the top of track beam. More information about the monorail track geometry can be found in the file <u>Chapter 26</u>.

## 29.5.2. Track roughness (irregularities)

Development of track roughness (irregularities) files \*.irr is described in details in <u>Chapter 12</u> file, Sect. *Micro profile (irregularities)*.

Start 0	Finis	n 1500	Start	0	Finish	500
Expression Slump Spectru Selection of spec Shanghai	Points um Tra ctrum Poi	From file ick ISO	Expres Slump Selectio () Sha	sion Po Spectrum on of spectr nghai	oints F Track um Points	rom file ISO
Lmin 1.00	Lmax	100.00	C A/w	^m	Expres	ssion
A(m) 1.5E-07	m	2.00	Levi	tation	🔘 Guidar	ice
Number of harm	onics		Number	of harmon	ics	
3000		1	3000			*∕₊
Co	mpute			Com	oute	

Here we consider some features related to maglev systems.

Figure 29.29. Variants of PSD for maglev track roughness

Roughness files for maglev track are generated in the tool available in the UM Simulation by the **Tools** | **Irregularity editor...**| **Monorail track** main menu command. The irregularities are generated by standard power spectral density (PSD) function, Figure 29.29.

The following PSD function is considered in [1], [2], [3]

$$S(\Omega) = \frac{A_s}{\Omega^2}, \ \Omega = \frac{2\pi}{\lambda}$$

where  $\Omega$  is the wave number,  $\lambda$  is the wave length in meters,  $A_s$  is the roughness parameter or amplitude, Figure 29.29, left . For a very smooth guideway, the roughness parameter may be assumed to be  $A_s = 1.5e^{-7}$  m [1], Figure 29.30, top.



Figure 29.30. Generated roughness curves

The following PSD function

$$S(\Omega) = \frac{A(\Omega^2 + B\Omega^3 + C)}{\Omega^4 + D\Omega^3 + E\Omega^2 + F\Omega + G}$$

is considered in paper [4] for the Shanghai Maglev track basing on analysis of measurements. The parameters A-G proposed in this paper are implemented as 'Shanghai' spectrum both for the levitation and guidance track level, Figure 29.29, right. An example of the generated roughness on the levitation level is sown in Figure 29.30, bottom.

Four irregularities files can be assigned as track roughness data (Figure 29.31)

- Levitation level (left, right)
- Guidance level (left, right)





Information about other parameters of the track roughness can be found in the file  $\underline{\text{Chap-ter 26}}$ .

# 29.6. Magnet models

In this section we consider models of levitation and guidance magnets for simulation of EMS maglev vehicles.

## 29.6.1. Spring-damper model

A spring-damper model of a magnet is the simplest one. It does not take into account the controller effects, but sometimes this model is useful, [5], [6]. In particular, such model is recommended to be used for evaluation of natural frequencies of UM maglev models.

The linear model produces the magnet force

 $F = F_0 + k_p (S - S_0) + c_p \dot{S} ,$ 

where  $F_0$  is the nominal magnet force,  $S_0$  is the nominal gap, S is the current gap value, and  $k_p, c_p$  are the spring and damper constants.

## 29.6.2. Single pole magnet model



Figure 29.32. Magnet

A single pole magnet model is the most frequently used in maglev simulation; see e.g. [7], [8], [9], [10], [11], [12].

The electromagnet force is computed according to the formula

$$F = \kappa \left(\frac{I}{S}\right)^2,\tag{29.1}$$

where I is the current, S is the magnet gap, and  $\kappa$  is the magnet constant

$$\kappa = \frac{\mu_0 A N^2}{4}.$$

Here A is the area of the magnet pole, N is the number of magnet coil turns, and  $\mu_0$  is the permeability of vacuum.

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The single pole magnet model includes the voltage equation

$$\frac{d(LI)}{dt} = -RI + U,$$

where R is the resistance, U is the voltage, and L is the inductance depending on the gap S and the magnet constant  $\kappa$ 

$$L = \frac{2\kappa}{S}.$$

Then,

$$L\dot{I} = -RI + \frac{LI}{S}\dot{S} + U \; .$$

Consider first a stationary state of the magnet model. Let  $F_0, S_0$  be the nominal magnet force and gap. Then the stationary values of other variables are

$$I_0 = S_0 \sqrt{F_0 / \kappa},$$
$$U_0 = RI_0,$$
$$L_0 = \frac{2\kappa}{S_0}$$

The magnet control model considered in this section is

$$U = U^{0} + U_{s}\Delta S + U_{v}\dot{S} + U_{is}\int_{0}^{t}\Delta Sdt - U_{a}\ddot{Z}$$
$$\Delta S = S - S_{0}$$

The vertical magnet coordinate Z is opposite in direction to the gap S, Figure 29.32. If the integral part of the control model is not presented, i.e.  $U_{is} = 0$ , then the initial voltage value is equal to the nominal one  $U^0 = U_0 = RI_0$ .

Taking into account the control model, the final voltage equation is

$$L\dot{I} = -RI + U^{0} + U_{s}\Delta S + (U_{v} + LI/S)\dot{S} + U_{is}\int_{0}^{t} \Delta Sdt - U_{a}\ddot{Z}.$$

Thus, the list of parameters describing the magnet model is

$$F_0, S_0, \kappa, R, U^0, U_s, U_v, U_{is}, U_a$$
.

This model is applied both to the levitation and guidance magnets with different lists of magnet and control parameters.

## 29.6.3. U-shaped magnet

U-shaped magnets produce lateral forces, which can be used for passive guidance in cases of low and medium speed maglev systems. In addition to the axial attractive force, such magnets produce a side force. We consider two different models of U-shaped magnets, Models A and B.

<u>Model A</u>. The approximate force Model A of the U-core magnet was derived in [13] and used by many authors in maglev systems research [14], [15], [16].

According to [13], the axial (levitation)  $F_z$  and lateral  $F_y$  forces are

$$F_{z} = F\left(1 + \frac{2S}{\pi W_{m}} - \frac{2y}{\pi W_{m}}\arctan\frac{y}{S}\right),$$
  
$$F_{y} = F\frac{2S}{\pi W_{m}}\arctan\frac{y}{S},$$

where F is the force value according to Eq. (29.1), y is the lateral shift of the magnet, and  $W_m$  is the pole width.

Let us introduce the lateral force ratio

$$\lambda_{\rm A} = \frac{2S_0}{\pi W_m}$$

Then the final expressions for the U-shaped magnet Model A are as follows:

$$F_{z} = F\left(1 + \lambda_{A} \frac{S}{S_{0}} - \lambda_{A} \frac{y}{S_{0}} \arctan \frac{y}{S}\right) = F\left(1 + \lambda_{A} \frac{S}{S_{0}}\right) - F_{y} \frac{y}{S},$$

$$F_{y} = F\lambda_{A} \frac{S}{S_{0}} \arctan \frac{y}{S} = F\psi_{A}(y, S, S_{0}).$$
(29.2)

If  $\lambda_A = 0$ , the model (29.2) exactly corresponds to the magnet model (29.1).

<u>Model B</u>. The next model was proposed in [17]. Using the above designations, the levitation  $F_z$  and lateral  $F_y$  forces are computed according to the formulas

$$F_{z} = \frac{1}{4}N^{2}\mu_{0} \left[ \frac{(W_{m} - y)}{S^{2}} + \frac{4y}{4S^{2} + \pi Sy} \right] U^{2} = \frac{1}{4}N^{2}\mu_{0} lW_{m} \left(\frac{I}{S}\right)^{2} - F_{y}\frac{y}{S},$$
  
$$F_{y} = \frac{1}{4}N^{2}\mu_{0} \left[ \frac{1}{S} - \frac{4}{4S + \pi y} \right] U^{2} = \frac{1}{4}N^{2}\mu_{0} lW_{m} \left(\frac{I}{S}\right)^{2} \frac{\pi S_{0}}{4W_{m}} \frac{1}{(1 + \pi y/(4S))}\frac{y}{S_{0}},$$

where l is the length of magnet.

Taking into account that  $A = lW_m$  and introducing the lateral force ratio

$$\lambda_{\rm B} = \frac{\pi S_0}{4W_m} = \frac{\pi^2}{8} \lambda_{\rm A} = 1.234 \lambda_{\rm A},$$

we obtain

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Figure 29.33. Comparison of Models A,B

To compare Models A, B, consider plots of functions  $\psi_A$ ,  $\psi_B$  versus lateral shift y in Figure 29.33. The functions are computed for  $S = S_0 = 8$ mm,  $\lambda_A = 0.3$  and  $\lambda_B = \lambda_A$  (Variant 1) or  $\lambda_B = 1.234\lambda_A$  (Variant 2). For small lateral shift Variant 2 gives a good correlation of Models A and B.

The user should select one of the Models A or B and set a value of the lateral force ratio  $\lambda$  in UM simulation program before simulation start, Figure 29.34, Section 29.8.2 Maglev control parameters.

It is allowed modeling staggered configuration of U-shaped levitation magnets, 29.8.3 *Staggered configuration of U-core levitation magnets*.

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bject simulation ins	pector					
Solver	Id	lentifiers	I	nitial condit	ions	Object variables
XVA Information Tools 🚍 Mo			🚍 Monorail train			
≥ 8   <u>k</u>						
Options and paramete	rs Tools	Identification	Resistance	Speed	Flexible t	rack MagLev
Levitation Options						
Levitation magnet m	odel					
Spring/damper		Magnet	:		🔘 Ide	entifiers
Acceleration model						
Sensor			$\bigcirc$	rediction		
Linear caring (damag	r madel Sir	ole nole magne	+			
Specified parameter	's	igie pole magne	•			
Name	-			Ider	ntifier	Value
Nominal gap S0 (mm	1)					10
Force for nominal g	ap F0 (kN)			Fz0		10.791
Mass of magnet (kg	)			m_c	ontrol	1100
Magnet force paran	neter Kappa	(F=Kappa*I^2	/S^2)			0.01
Resistance (Ohm)						1
Lateral force ratio (	lambda)			lamb	oda_ratio	0.3
Voltage UU (V)				01_0	)	9.111
Control gap factor Us (V/m) Ul_s 2000						2000
Control gap velocity factor Uv (Vs/m) Ul_v 820						820
Integral control factor Uis (V/ms) Ul_is 0						0
Control acceleration	n factor Ua (	Vs^2/m)		Ul_a	1	4
Maximal voltage (V)						1000

Object simulation ins	pector							
Solver	Identifiers	In	itial conditions	Object variables				
XVA	Information		Tools	🚍 Monorail train				
🖻 🖪 🗎								
Options and paramete	rs Tools Identification	Resistance	Speed Flexible	track MagLev				
Levitation Options								
U-shaped magnet mo	odel							
Model A								

Figure 29.34. Specifying U-shaped magnet model

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## 29.6.4. External magnet models

S
S
S
S
S
S

Figure 29.35. Parameterization of force for guidance magnet

The user may develop own models of magnets. User's models are based on programming identifiers, which parameterize force and torque acting on the magnet, Section 29.3.2 *Modeling levitation and guidance magnets*.

The identifiers correspond to the force and torque components in the track system of coordinates (TSC), Figure 29.35. The origin of TSC coincides with the projection of the magnet point on the ideal central axis of the track; the X axis coincides with the track tangent, the Y axis lies in the track plane on the left to the motion direction, and the Z axis is directed upwards.

**Remark.** According to this description of force components, guidance forces for the left and right guidance magnets must differ in sign4 the force is positive for the right magnet and negative for the left one. The user should remember that if he rotates about a vertical axis on 180 degrees a subsystem with magnets, the guiding forces change their signs.

The force models are constructed with use of UM variables corresponding gaps, their time derivatives and integrals, Section 29.8.6.2 *Gap*, as well as the variables corresponding to the model identifiers and so on.

The following tools and modules van be used for programming identifiers:

## **Identifier control**

The tool allows develop very simple models such as a spring-damper one. This method is use for test of the identifiers programming only; it cannot be applied in complex cases, see Section 29.10.4 *Spring/damper magnet model as identifier control*.

#### **Block editor**

See <u>Chapter 24</u> for development of model with the Block editor tool.

#### Interface to Matlab/Simulink

See the gs\_um\_control.pdf file to get information about the development of force models in Matlab/Simulink

#### **Programming in control file**

Theoretically the forces of any complexity can be computed in the Control file, see <u>Chapter 5</u>.

## 29.6.5. Theoretical results on stability

Consider a one degree model of a magnetic suspension to get basic results on stability of electromagnetic suspension. The model is shown in Figure 29.32. The 1 d.o.f. model of the controlled magnet is described by two equations

$$m\ddot{Z} = -F_0 + \kappa \left(\frac{I}{S}\right)^2$$
  
$$L\dot{I} = -RI + U_0 + U_s \Delta S + (U_v + LI/S)\dot{S} - U_a \ddot{Z}$$

Here m is the magnet mass. The integral control is not considered.

Let us introduce dimensionless variables

$$i = \frac{I - I_0}{I_0}, s = \frac{S - S_0}{S_0} = -\frac{Z - Z_0}{S_0}$$
$$mS_0 \ddot{s} = F_0 - \kappa \left(\frac{I_0}{S_0}\right)^2 \left(\frac{1 + i}{1 + s}\right)^2 = -F_0 \left(\frac{1 + i}{1 + s}\right)^2 + F_0,$$
$$\frac{L_0 I_0}{1 + s} \dot{i} = -RI_0 (1 + i) + U_0 + U_s S_0 s + (U_v S_0 + LI_0 / (1 + s)) \dot{s} + U_a S_0 \ddot{s}$$

Suggesting that the variables *s*, *i* are small, the linearization of equation gives

$$\frac{mS_0}{2F_0}\ddot{s} = s - i,$$
  
$$\frac{L_0}{R}\dot{i} = -i + \frac{U_sS_0}{U_0}s + \left(\frac{U_vS_0}{U_0} + \frac{L_0}{R}\right)\dot{s} + \frac{U_aS_0}{U_0}\ddot{s}.$$

Now we introduce two time constants

$$T = \sqrt{\frac{mS_0}{2F_0}}, T_i = \frac{L_0}{R}$$

and dimensionless control parameters

$$k_s = \frac{U_s S_0}{U_0}, \ k_v = \frac{U_v S_0}{U_0 T}, \ k_a = \frac{U_a S_0}{U_0 T^2}.$$

Finally, the linearized electromagnet equations for stability analysis looks like

$$T^{2}\ddot{s} = s - i,$$
  

$$T_{i}\dot{i} = -i + k_{s}s + (k_{v}T + T_{i})\dot{s} + k_{a}T^{2}\ddot{s}.$$

Searching the solution of this equations as

$$s = c_s e^{\lambda t}, i = c_i e^{\lambda t}$$

leads to the matrix equation

$$\begin{pmatrix} T^2 \lambda^2 - 1 & 1 \\ -k_a T^2 \lambda^2 - (k_v T + T_i) \lambda - k_s & T_i \lambda + 1 \end{pmatrix} \begin{pmatrix} c_s \\ c_i \end{pmatrix} = 0$$

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The determinant of the matrix must be zero, so the characteristic equation is

$$det \begin{pmatrix} T^{2}\lambda^{2} - 1 & 1 \\ -k_{a}T^{2}\lambda^{2} - (k_{v}T + T_{i})\lambda - k_{s} & T_{i}\lambda + 1 \end{pmatrix} = 0,$$
  

$$T^{2}T_{i}\lambda^{3} + T^{2}(1 + k_{a})\lambda^{2} + k_{v}T\lambda + k_{s} - 1 = 0,$$
  

$$a_{0} = T^{2}T_{i}, a_{1} = T^{2}(1 + k_{a}), a_{2} = k_{v}T, a_{3} = k_{s} - 1.$$
  
The Hurwitz matrix

 $\begin{pmatrix} a_1 & a_3 & 0 \\ a_0 & a_2 & 0 \\ 0 & a_1 & a_3 \end{pmatrix}$ 

gives the stability conditions

$$a_1a_2 - a_0a_3 > 0, a_3 > 0$$

or

$$k_s > 1, \ k_v > \frac{T_i(k_s - 1)}{T(1 + k_a)} = k_v^*, \ k_a > -1.$$

The stability conditions for the initial control parameters are

$$U_s > U_s^* = \frac{U_0}{S_0}, U_v > U_v^* = \frac{U_0 T k_v^*}{S_0}, U_a > -U_a^*, U_a^* = \frac{U_0 T^2}{S_0}.$$

According to this result, the stable levitation requires both proportional and differential control. Increase of the proportional control factor  $U_s$  requires increased value of the differential control parameter  $U_y$ . In contrary, the use of acceleration control  $U_a > 0$  allows decreasing the differential control factor  $U_y$ .

## 29.7. Track models

In UM, three types of monorail track models can be applied: an **undeformed** or **rigid track**, a **flexible beam** one and use of **FEM subsystems** for dynamic simulation of track parts. Detailed information about the track models can be found in the file <u>Chapter 26</u>.

#### 29.7.1. Use of FEM subsystem for simulation of track parts

Creation of a FEM subsystem for dynamic simulation of a monorail track is described in <u>Chapter 26</u>, item "Simulation of track as FEM subsystem". Among other things, that chapter shows how macro profile of track can be specified using nodes of the FEM subsystem.

In this chapter, let us consider some features of simulation of interactions of maglev train with the subsystems.

As opposed to the wheel monorail vehicle, maglev bogie does not contact with the track; it slides over the track surface with some gap. In a UM model, its value can exceed 0.2 m (particularly, if some parts of the magnet construction are ignored in the model), Figure 29.36.



Figure 29.36. Gap between magnet of maglev train bogie and surface of FEM subsystem

Therefore, the tab sheets **Monorail track** | **General** differ for wheel and maglev monorail track subsystem. For maglev, the tab contain checkbox **Control gap** and field **Gap** to set gap value (see Figure 29.37). These controls are absent for wheel track but check box **Simulation of entry on edge** is added (see Figure 29.38).

FEM subsystems 🕴 Tools 🛛 📮 Monorail	train					
Subsystem: FEMTrack						
General Simulation Image Solution						
Options Damping Monorail track						
General Image						
Subsystem is monorail track						
Options						
Control gap						
Gap: 0.3 n						
Constant mass matrix						
Separate simulation						

Figure 29.37. Tab sheet Monorail track | General for maglev monorail track subsystem

FEM :	subsystems	Tools	Í 📮	Monorail train	ĺ	
Subsyst	em: FEM	Track				
General	Simulation	Image Solution				
Options	Damping	Monorail track				
Genera	Image					
🔽 Sub	system is m	onorail track				
Option	ns					
Co	Constant mass matrix					
Separate simulation						
🗹 Sin	nulation of e	ntry on edge				



## 29.7.2. FEM track variables

All types of variables used for analysis of FEM subsystem can be applied for FEM track. In addition, the variables calculating track displacements under magnets are supported (see item 29.8.6.6).

## 29.7.3. Example

The example of simulation of flexible track parts of maglev monorail is available in site <u>www.universalmechanism.com</u> by link <u>um\_samples\_fem\_maglev\_monorail.zip</u>.

The FEM subsystem simulates the curvilinear part of the monorail track with constant radius 100 meters (see Figure 29.39 and Figure 29.40). General view and some parameters of the FEM subsystem are presented in Figure 29.41.

In Figure 29.42, the displacements under the front magnets and in the middle of the spans of the flexible track part are shown.



Figure 29.39. General view of the model from the example



Figure 29.40. Horizontal macro profile of the track in the example



Figure 29.41. FEM subsystem simulating curvilinear part of the track in the example



Position of the first magnet on the track, m

Figure 29.42. Displacements of the FEM part of the track

## 29.8. Simulation of maglev dynamics

In case of maglev systems, many of simulation parameters are similar to that for the monorail trains, see <u>Chapter 26</u>. The following sections there are useful for simulation of maglev trains:

Identification of longitudinal velocity control Creating longitudinal velocity functions Creating beam section profile Modes of longitudinal motion of monorail Kinematic characteristics relative to track system of coordinates

## 29.8.1. Preparing for simulation

Object simulation inspect	or							
Solver Identifiers	Initial co	nditions	Obje	ect variables	XVA			
Information	Т	ools		Monorail ti	rain			
🖻 🖻 🛓								
Resistance Speed Flexible track MagLev								
Options and Parame	ters	Tools		Identific	ation			
Use irregularities	_			-				
Type of track								
Output		Flexib	le					
Macro-geometry								
C:\Users\Public\Do	cuments\UM	I Software L	.ab\Uni	versal Mechanis	sm\8' 😹			
Track roughness								
Levitation (left)	C:\Use	ers\Public\D	ocume	nts\UM Softwa	re Lal 😅			
Levitation (right)	C:\Use	ers\Public\Do	ocume	nts\UM Softwa	re Lał 😅			
Guidance (left)	C:\Use	rs\Public\Do	ocume	nts\UM Softwar	e Lat 😹			
Guidance (right)	C:\Use	rs\Public\Do	ocumer	nts\UM Softwar	e Lat 🚔			
Factor	1.000							
Coherent right irregula	rities							
Wired beam image								
Parameters								
Numeric parameters								
Name		Value						
Guideway base (m)		7						
Bridge pillar base (m)	30							
Shift along Z of pillar GO	Shift along Z of pillar GO (m) -2							
Beam-image step (m)		2						
Kinetic energy for stop (J) 0.01								
Integration	М	essage		Close	9			

Figure 29.43. Object simulation inspector

The most part of the maglev specific data is entered and modified with the help of the **Monorail train** tab in the **Object simulation inspector**, Figure 29.43. Use the **Analysis | Simulation...** menu command of the **UM Simulation** program to open the inspector.

Here we consider maglev specific parameters.

The maglev simulation parameters are saved in vehicle configuration files \*.mrt. Use the buttons on the tab to read/write data.

General information about **UM Simulation** program and its tools are concentrated in <u>Chapter 4</u>.

The user should follow some definite steps to make a new created monorail model ready for simulation.

- 1. Create a maglev train model in **UM Input** program.
- 2. Run the **UM Simulation** program.
- 3. Assign a preliminary created file of macro-geometry by the 善, Figure 29.43. Use the 善 button to view/modify the macro-geometry.
- 4. Set levitation and guidance magnet models and parameters.
- 5. If necessary, set lateral shift of U-shaped levitation magnets to model staggered configuration of magnets, Section 29.8.3 *Staggered configuration of U-core levitation magnets*.
- 6. Set beam section profile.
- If necessary, check the option Use Irregularities and assign irregularity files, Figure 29.43. The Factor increases (<1) or decreases (>1) assigned irregularities.
- 8. Set the guideway structure geometrical parameters, Figure 29.43:
  - **Guideway base (m)** distance between two parallel guiding beams, has a visual effect only.
  - **Bridge pillar base (m)** distance between bridge pillars in longitudinal direction, has a visual effect only.
  - Shift along Z of pillar go (m) allows matching the pillar vertical position.
  - **Beam image step (m)** is the discretization step of the longitudinal beam image. Decrease of this parameter makes smother the beam curve in animation window, has a visual effect only.
- 9. Set the **Kinetic energy for stop** parameter (Figure 29.43), which is used in equilibrium simulation (speed mode v=0).

## 29.8.2. Maglev control parameters

Options and	Parameters	Tools	Identification	Resistance	Speed	Flexible tra	ck MagLev	
Levitation	Guidance ma	gnets						
Model of levitation magnet								
Spring	Spring damper 💿 M			agnet 🔘 Identifiers				
Acceleration model								
Sensor     Prediction								
Spring and	l damper mod	lel Sing	gle pole magnet	t				
Identifiers								
Name			Identifie	ier Value				
Nominal g	ap S0 (mm)		s0_l		10			
Force for	Force for nominal gap F0 (kN)		Fz0		9.3195			
Mass of m	Mass of magnet (kg)		m_mag	jnet_l	300			
Spring co	nstant Kp (N/			1E8				
Damper c	onstant Cp (I	Ns/m)			10000			

Figure 29.44. Levitation and guidance magnet parameters

The **MagLev** tab in simulation inspector is used for specification of the magnet control parameters, Figure 29.44. Identical sets of parameters are available for levitation and guidance magnets.

#### Model of levitation magnet

The type of magnet model is selected according to Section 29.6, Magnet models.

#### Acceleration model

0

If magnet acceleration is used for levitation or/and guidance control (see Section 29.6.2), here the type of acceleration evaluation is selected.

- **Sensor**: acceleration is estimated according to the mechanical sensor data; see Section 29.3.3 *Model of accelerometer*.
- **Prediction**: acceleration is predicted by Lagrangean polynomial of degree 3.

Options and Parameters	Tools	Identification	Resistance	Speed	Guideway structure	MagLev
Levitation Guiding						
Guidance magnet model						
Spring/damper		Magnet		(	Identifiers	
Acceleration model						
Sensor			Predic	tion		
Compensate accelerat	tion in c	curves				
Sensor: compensate gravity acceleration						
Linear spring/damper mo	odel Si	ingle pole magr	net			
Identifiers						

Figure 29.45. Compensation of lateral acceleration

There are some features in computation of the lateral acceleration for guidance control. First, the curving acceleration can be compensated, i.e. the term  $v^2/R$  is added to the lateral accelera-

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tion or subtracted from it depending on the curve direction right/left. Second, the gravity acceleration due to the rotation of the sensor about the longitudinal axis is compensated from the sensor, i.e. the term  $\alpha g$  is subtracted from the accelerometer data, where g is the gravity acceleration, and  $\alpha$  is the angle of sensor rotation about the longitudinal axis. The corresponding options are (Figure 29.45):

#### • Compensate acceleration in curves

## • Sensor: compensate gravity acceleration

An example of compensation for the lateral sensor is shown in Figure 29.46. The left plot compares acceleration without compensation of the acceleration in a curve and two plots with compensation. Compensated accelerations are small and compared in the right figure. The right figure shows that the sensor data for acceleration with compensated gravity is near to zero in the circular curve.



Figure 29.46. Lateral sensor acceleration with and without compensation

## Spring and damper model

A table in Figure 29.44 is used for setting parameters of the spring–damper magnet model from Section 29.6.1 *Spring-damper model*.

**Remark.** It is important that identifiers can be assigned to magnet model parameters. For example, three identifiers from the model list are assigned for the spring and damper magnet control in Figure 29.44, the identifier *s0\_l* and so on. To assign an identifier, double click by the left mouse button on the corresponding cell of the table and select the desired identifier, Figure 29.47. These assignments are useful in linear analysis of magnet controls and in multivariant computations.

Solver       Identifiers       Initial conditions       Ot         Solver       Identifiers       Initial conditions       Ot         Options and Parameters       Tools       Identifiers         Options and Parameters       Tools       Identifiers         Model of guidance magnets       Model of guidance magnet       Ma         Acceleration       Model       Ma         Acceleration       model       Sensor         Spring and damper       Single pole         Identifiers       Identifiers	iject variables XVA Information Tools Monorail train	
Name	Identifier Value	
Force for nominal gap F0 (kN) Mass of magnet (kg) Spring constant Kp (N/m) Damper constant Cp (Ns/m)	<ul> <li>□ Ul_a=2 (Acceleration control (levitation))</li> <li>□ Ul_is=0 (Integral control (levitation))</li> <li>□ Ug_0=10.9 (Stationary voltage (guidance))</li> <li>□ Ug_s=2000 (Proportional control (guidance))</li> <li>□ Ug_v=150 (Differential control (guidance))</li> <li>□ Ug_a=0 (Acceleration control (guidance))</li> <li>□ Ug_is=0 (Integral control (guidance))</li> <li>□ Ug_is=0 (Integral control (guidance))</li> <li>□ □ Fz0=9.3195 (Nominal control force (kN))</li> </ul>	
Integration	<ul> <li>Fy0=5 (Stationary force (guidance))</li> <li>S0  =10 (Levitation: nominal gap (mm))</li> <li>S0_g=10 (Guidance: nominal gap (mm))</li> <li>Sensors</li> <li>monorail bridge</li> </ul>	

Figure 29.47. Assignment of identifier to the guidance nominal gap

#### Single pole magnet

The single pole model of magnet is described in Section 29.6.2 *Single pole magnet model*. Both for the levitation and guidance magnet models, the tab contains two groups of parameters: *specified parameters*, which values should be set by the user, and *estimated parameters* automatically computed be the program, Figure 29.48.

Sense of specified parameters is clear from the comments in the table in Figure 29.48. The estimated parameters are computed according to the following formulas from Sections 29.6.2, 29.6.5:

$$\begin{split} I_0 &= S_0 \sqrt{F_0/\kappa}, \, U_0 = RI_0, \, L_0 = \frac{2\kappa}{S_0}, \, T = \sqrt{\frac{mS_0}{2F_0}}, \, T_i = \frac{L_0}{R}, \\ U_s^* &= \frac{U_0}{S_0}, \, U_v^* = \frac{U_0 T k_v^*}{S_0}, \, U_a^* = \frac{U_0 T^2}{S_0}, \\ k_s &= \frac{U_s S_0}{U_0}, \, k_v = \frac{U_v S_0}{U_0 T}, \, k_a = \frac{U_a S_0}{U_0 T^2}, \\ k_v^* &= \frac{T_i (k_s - 1)}{T(1 + k_a)}. \end{split}$$

These values help the user to set the correct values of control parameters.

Specified parameters			
Name		Identifier	Value
Nominal gap S0 (mm)			10
Force for nominal gap F0 (kN)		Fz0	10.791
Mass of magnet (kg)		m_control	1100
Magnet force parameter Kappa (F=Kappa	a*I^2/S^2)		0.01
Resistance (Ohm)			1
Lateral force ratio (lambda)			0
Voltage U0 (V)		UL_0	10.388
Control gap factor Us (V/m)		UL_s	2000
Control gap velocity factor Uv (Vs/m)		UL_V	205
Integral control factor Uis (V/ms)		Ul_is	0
Control acceleration factor Ua (Vs^2/m)		Ul_a	4
Estimated values			
Name	Value		
Nominal voltage U0 (V)	10.388		
Nominal current IO (A)	10.388		
L0 (H)	0.5		
Nominal time constant T (s)	0.0225762		
Circuit time constant Ti (s)	0.5		
Us*	1038.8		
Uv*	56.1785		
Ua*	0.529458		
Unitless control gap factor Ks	1.9253		
Unitless control gap velocity factor Kv	8.74123		
Kv*	2.39546		

Figure 29.4	8. Parameters	of single	pole	magnet	and	control
0		0	1	0		

Remark. The parameter Lateral force ratio (lambda) has a positive value for U-shaped magnets. It allows simulating a passive guidance by levitation magnets, Section 29.6.3U-shaped magnet

## 29.8.3. Staggered configuration of U-core levitation magnets

XVA		Information	1	rools	-	Monorail train
₽ 🖪 🖡						
options and parar	neters To	ols Identificatio	n Resistance	Speed F	lexible track	MagLev
Latertal shift of lev	litation ma	gnets (mm)				
Parameters						
Identifiers						
Name	Identif	ier Valu	e			
LMagnet LF		2				
LMagnet LR		0				
LMagnet RF		-2				

Figure 29.49. Lateral shift of levitation magnets

To model staggered U-shaped levitation magnets [16], set the lateral shift of magnets on the **Monorail train** | **Identification** tab. Select the **Lateral shift of levitation magnets** item in the drop down menu, Figure 29.49. Shift values are set in millimeters. The positive value corresponds to the shift in the positive Y direction, Figure 29.2. *Base system of coordinates (SCO)*.

Golver Id	entifiers Initial con	ditions Object variables	XVA Information Tools Monorail train
Coordinat	tes Constraints on	n initial conditions	
— <b>P</b>		x-0 y-0 ☆	
		×-0 v-0 <u>+</u>	
bogie_6d	of.		
ψ̈́	✓ Coordinate	Velocity	Comment
1.13	0	0	Sensors.Y RL.jMass 1c
1.14	0	0	Sensors.Y RR.jMass 1c
1.15	0	9.65375574582	Add. vars (ODE order 1):1 I :LMagnet LF
1.16	0	0	Add. vars (ODE order 1):2 Integral(ds) :LMagnet LF
1.17	0	9.65375574582	Add. vars (ODE order 1):3 I :LMagnet LR
1.18	0	0	Add. vars (ODE order 1):4 Integral(ds) :LMagnet LR
1.19	0	9.65375574582	Add. vars (ODE order 1):5 I :LMagnet RF
1.20	0	0	Add. vars (ODE order 1):6 Integral(ds) :LMagnet RF
1.21	0	9.65375574582	Add. vars (ODE order 1):7 I :LMagnet RR
1.22	0	0	Add. vars (ODE order 1):8 Integral(ds) :LMagnet RR
1.23	0	14.1421356237	Add. vars (ODE order 1):9 I :GMagnet LF
1.24	0	0	Add. vars (ODE order 1):10 Integral(ds) :GMagnet LF
1.25	0	14.1421356237	Add. vars (ODE order 1):11 I :GMagnet LR
1.26	0	0	Add. vars (ODE order 1):12 Integral(ds) :GMagnet LR
1.27	0	14.1421356237	Add. vars (ODE order 1):13 I :GMagnet RF
1.28	0	0	Add. vars (ODE order 1):14 Integral(ds) :GMagnet RF
1.29	0	14.1421356237	Add. vars (ODE order 1):15 I :GMagnet RR
1.30	0	0	Add. vars (ODE order 1):16 Integral(ds) :GMagnet RR

## 29.8.4. Additional coordinates for magnet models

Figure 29.50. Additional magnet variables

Two additional coordinates are used for each of the magnet, if the *Single pole magnet model* is selected (Figure 29.50):

Current in magnet circuit I, Section 29.6.2

Integral of the gap deviation on the nominal value  $I_s = \int_0^t \Delta S dt$ 

Both of the coordinates satisfy first order ODEs

$$\frac{d(LI)}{dt} = -RI + U,$$
$$\frac{dI_s}{dt} = \Delta S.$$

UM solves second order ODEs, that is why the first order are converted to the second order as

$$\frac{dq}{dt} = I, \quad \frac{d(LI)}{dt} = -RI + U,$$
$$\frac{dQ_s}{dt} = I_s, \quad \frac{dI_s}{dt} = \Delta S.$$

Thus, the  $q, Q_s$  variables are computed, and I,  $I_s$  are their time derivatives. Please note that the initial values for the circuit current in Figure 29.50 are set to the time derivative of coordinates in the **Velocity** column.

If not the simple pole magnet model is used for computation of magnet forces, the additional variables are ignored.

## 29.8.5. Speed control

Solver	Identifiers	Initial o	condition	ns Object var	iables	XVA	Inform	nation	Tools	Monorail train	
🖻 E	£.					_					
Option	s and Paran	neters	Tools	Identification	Resis	tance	Speed	Flexib	e track	MagLev	
Speed	l mode										
🔘 Ne	utral				9	) Profile	e				
🔘 v=	const				$\bigcirc$	) v=0					
Speed	l profile										
⊡⊊i	D:\UM70_\	NORK	Tests\Ma	agLev\Bogie07	′_Z\0-	30.lvp					ê

Figure 29.51. Vehicle speed options

Options and Pa	rameters	Tools	Identification	Resistance	Speed	Flexible track	MagLev	
Control longitudinal velocity								
Parameters								
Numeric parameters								
Name	Value							
Gain	50000							

Figure 29.52. Speed control gain

If constant speed or a profiles speed modes are selected (Figure 29.51), the speed control force if applied to the magnets in the longitudinal direction. The control force is computed as

$$F = -\frac{K(v - v_d)}{N_m},$$

where K is the control gain (Figure 29.52), v is the current velocity of the vehicle,  $v_d$  is the desired velocity, and  $N_m$  is the number of magnets.

An example of speed profile as well as simulation speed is shown in Figure 29.53.

#### 29-47





## 29.8.6. Maglev train specific variables

📑 Wizard of	variables								×		
Variables	for group of bod	lies	Joint forces	Bipolar	forces		Angular variables	Linear	variables		
Expression	Track coordin	ate system	User variables	Reactions	Coordina	ates	Solver parameters	All forces	Identifiers		
Contact	forces	Contact	forces for bodies		Variables		Bushing	MagLev forces			
🖃 🔳 bogie_	5dof	Selected	Selected								
	inet LF inet LR	LMagnet L	LMagnet LF								
- UMag	inet RF inet RR gnet LF gnet LR gnet RF gnet RR	Imaginet Li         Imaginet Li									
Object: LMag	net LF	Multiple	e selection - comme	ents are not	available				5		
Fx (LMagnet L Fy (LMagnet L Fz (LMagnet L Fm (LMagnet L Fv (LMagnet L	F) F) F) F) F)										



Magnet variables are available on the **MagLev forces** tab of the **Wizard of variables**, Figure 29.54. Use the **Tools** | **Wizard of variables...** menu command to open this window.

Use other tabs of the wizard to create kinematic and dynamic variables different from the magnet variables.

See <u>Chapter 4</u> to get information about creating variables and their usage.

## 29.8.6.1. Force, Moment

The variable corresponds to magnet forces (Figure 29.54) and moments:

- Fx(Mx) projection on longitudinal direction of the track system of coordinates;
- Fy(My) projection on lateral direction of the track system of coordinates;
- Fz(Mz) projection on vertical direction of the track system of coordinates (upwards positive);
- |F|(|M|) module of force/moment;
- F(M) vector of force/moment.

Force and moment variables are measured in kN, kN m.

If a spring-damper or a single magnet models are used for computation of magnet forces, the moment value is zero, and Fz or Fy force components are available only for the levitation or guidance magnets respectively, Sections 29.6.1, 29.6.2.

External magnet models are applied by the user, non-zero components depend on the model, and the forces components are available through the corresponding identifiers as well.

## 29.8.6.2. Gap

Contact forces for bodies	Variables	Bushing	MagLev forces
bogie_6dof     LMagnet LF     LMagnet LR     LMagnet RF     LMagnet RR     GMagnet LF     GMagnet LR     GMagnet RR     GMagnet RF     GMagnet RF	Selected LMagnet LF Variables Force Moment Gap Gap Gap Gap Gap Gap	t relocity ntegral <b>prity</b>	
Object: LMagnet LF	Multiple select	ion - comments	are not available 🛱
S (LMagnet LF) VS (LMagnet LF) I(S) (LMagnet LF)			

Figure 29.55. Magnet gap

The gap variables

$$S, \dot{S}, \int_{0}^{t} \Delta S dt$$

are available for all magnet models, see Section 29.6.2 *Single pole magnet model*. The gap is measured in mm and takes into account the track irregularities.

#### 29.8.6.3. Lateral shift

bogie     V LMagnet LF     LMagnet LR     LMagnet RF     GMagnet LF     GMagnet LF     GMagnet R     GMagnet R     GMagnet RF     GMagnet RF	Selected LMagnet LF Length unit mm m m Variables Force Moment Gap Velocity of later Irregularity Circuit Beam kinematic Magnet position alo	Force unit kN ral shift s ong track	© N	
Object: LMagnet LF	Multiple selection - co	mments are not availal	ble	F
y (LMagnet LF) Vy (LMagnet LF)	41 L			

Figure 29.56. Lateral shift of magnets

The variables compute the lateral shift y of magnets and its time derivative  $y^{\cdot}$ . The magnet shift is used for computation of lateral force in the case of U-shaped electromagnets, Section 29.6.3 *U-shaped magnet*.

#### 29.8.6.4. Irregularity

Contact forces for bodies	Variables	Bushing	MagLev force	es
bogie_6dof     LMagnet LF     LMagnet LR     LMagnet RF     GMagnet LF     GMagnet LF     GMagnet LR     GMagnet RF     GMagnet RF     GMagnet RR	Selected LMagnet LF  Variables Force Gap Gap VIrregula VIrregula VIrregula VIrregula VIrregula VIrregula	t ularity ularity derivative		
Object: LMagnet LF	Multiple select	ion - comments	are not available	7
Irr (LMagnet LF) dIrr (LMagnet LF)				

Figure 29.57. Irregularity variable

The variables correspond to the track roughness for levitation and guidance magnets as well as their derivatives with respect to the distance. The irregularity is measured in mm, its derivative is unitless.

## 29.8.6.5. Circuit

Contact forces	Contact forces for bodies	Variables	MagLev forces
Bogie_6dof      UMagnet LF      UMagnet R      Magnet R      GMagnet LF      GMagnet LF      GMagnet R      GMagnet RF      GMagnet RF      GMagnet RR	Selected LMagnet LF  Variables  Force  Gap  Circuit  Voltage Voltage component S (V) Voltage component IS (V) Voltage component IS (V) Voltage component A (V) E Beam displacement C Acceleration		
Object: LMagnet LF	Multiple selection - comments are	not available	5
I (LMagnet LF) U (LMagnet LF) U (S) (LMagnet LF) U (VS) (LMagnet LF) U (I(S)) (LMagnet U (A) (LMagnet LF)			

Figure 29.58. Magnet circuit variables

The variable corresponds to the circuit variables according to the *Single pole magnet model*:

- I Current (A),
- U voltage (V),
- $U_{s}\Delta S$  voltage component S (V),
- $U_v \dot{S}$  voltage component S (V),
- $U_{is} \int_{0}^{t} \Delta S dt$  voltage component IS (V),
- $-U_a\ddot{Z}$  voltage component A (V).

#### 29.8.6.6. Beam displacements

Contact forces	Contact force	s for bodies	Variables	Bushing	MagLev forces
bogie_6dd     V LMagne     LMagne     LMagne     LMagne     GMagne     GMagne     GMagne     GMagne     GMagne     GMagne	of tLF tLR tRF tRR tLF tLR tRF tRR	Selected LMagnet LF	bles orce oment ap regularity ircuit eam displace Dy Dz cceleration agnet position	ement along track	
Object: LMagne	t LF	Multiple	selection - o	comments	are not av 🐬
d:y (LMagnet LF) d:z (LMagnet LF)	)				

Figure 29.59. Flexible beam deflections

These variables are used if the flexible beam track model is used. The variables correspond to the lateral and vertical beam deflections in the magnet force position.

The deflections are measured in mm.

#### 29.8.6.7. Acceleration

Contact forces for bodies	Variables	Bushing	MagLev forces	
bogie_6dof     LMagnet LF     LMagnet LR     LMagnet RF     LMagnet RR     GMagnet LF     GMagnet RR     GMagnet RR     GMagnet RF     GMagnet RF	Selected LMagnet LF  Variables Force Moment Gap Gap Gruit Gap Gap Gruit Gap	ity placement tion or) iction) trol) sition along track		• III
Object: LMagnet LF	Multiple selectio	n - comments ar	e not available	7
a:sensor (LMagne a:prediction (LMa a:control (LMagne				

The variables correspond to vertical accelerations of levitation magnets and lateral acceleration of guidance magnet relative to then track system of coordinates. Accelerations are measured in  $m/s^2$ . The '*Control*' corresponds to compensated acceleration, if the compensation option is checked, Section 29.8.1 *Preparing for simulation*.

## 29.8.6.8. Magnet position along the track

The variable corresponds to the position of the magnet along the track and computed according to the formula

 $L = l_0 + l(t)$ 

where  $l_0$  is the initial position of the magnet point is SC0 (the base coordinate system, Section 29.2), and l(t) is the distance along the track from the motion start.

# 29.8.7. Kinematic characteristics relative to track system of coordinates

Kinematical variables of bodies should be often projected on the track system of coordinates (TSC). The X-axis of the TSC is the tangent to the guiding beam centerline including the beam vertical slope; the Y-axis is perpendicular to the X-axis taking into account the superelevation.

Note that axes of the TSC and SC0 in a straight track are parallel, and projections of vectors on these SC are the same.

📑 Wizard of variables					×
🔺 🖨 monorail vehicle	Expression	Identifier	Special F	All forces	Joint force
Base0	Coordinates	Angular var.	Reaction F	Linear var.	Linear F U <u>s</u> er
CarBody	Track SC	Monorail tra	in Solver	FEA colo	ouring scheme
▷ 🗳 Bogie1	Body				
Dogiez	<u>CarBody</u>		0	0	0
	Туре			0.	
	Coordinat	e 🧕	Acceleration	C Ang.	.veloc.
		$\odot$	Angles	C Ang.	.accel.
	Component			0	
	© X	0	Y	© Z	
	Vncompe	insated accele	ration		

Figure 29.60. Kinematic characteristics of bodies in the track SC

Use the **Track SC** tab of the Wizard of variables to get any kinematic variable in projection of the TSC. To create a variable, perform the following steps:

- select a body in the list in the left part of the wizard;
- select the type of variable: a linear variable (Cartesian coordinates, velocity or acceleration) or an angular variable (angles, angular velocity and angular acceleration);
- set a point in SC of the body, which coordinate, velocity or acceleration should be computed, if a linear variable is selected;
- set an axis of the TSC for projection.

For the lateral component of acceleration, either the uncompensated acceleration or the usual acceleration is selected (Figure 29.60).

# **29.9. Maglev static and linear analysis**

Analysis of linearized equations of maglev vehicles as a very important tool, which allows the user to analyze the stability of levitation and guidance systems, and well as to evaluate proper values of control parameters. Detailed information about this tool can be found in the user's manual file <u>Chapter 4</u>. Here we consider some features of this analysis related to maglev systems.

# 29.9.1. Computation of equilibrium position

🖔 Static and linear analysis	
Equilibrium Frequencies/Eigenvalues Root locus L	inear vibrations Identifiers Initial conditions Options
General options Parameters Forces	
Equilibrium computation type	
Solving equations	Integration of equations of motion
Automatically compute equilibrium	
Set zero velocities	
✓ Interrupt iterations when singular Jacobian	

Figure 29.61. SLA options for maglev vehicle

Computation of equilibrium position is possible by the integration method, Figure 29.61. The reason for this limitation is the following: solving nonlinear equilibrium equations by the Newton-Raphson method does not converge for single pole and external magnet models.

It is recommended to compute the equilibrium position by simulation at v=0 speed mode, and uncheck the **Automatically compute equilibrium option**, Figure 29.61.

# 29.9.2. Frequencies and eigenvalues

✓ Ei Us Si	g <u>envalues</u> se zero vek sip damping	ocities g matrix				
Freq	uency/Dan	nping ratio				
Sort	by: freque	ncy				
	f (Hz)	Beta(%)/r				
1	1.68475	9.519				
2	3.31706	2.826				
3	3.34442	4.821				
4	3.84923	5.405				
5	4.45281	8.554				
6	476.769	29.894				
7	476.821	29.921				
8	476.86	29.942				
9	476.97	30.000				
10	476.97	30.000				
11	476.97	30.000				
12	476.97	30.000				
13	476.971	30.000				
14	0	-1.97026				
15	0	-1 97551				

Magnet forces are non-conservative ones, and computation of natural frequencies is correct for the spring-damper magnet models only. Moreover, in the case of external modeling magnet forces, neither frequencies nor eigenvalues are correct because equations for magnets are not available.

Evaluation of eigenvalues is recommended for the single pole magnet models. If acceleration control is used, the *sensor* type of acceleration computation is necessary; use of *predicted* acceleration leads to wrong results equivalent to  $U_a = 0$ , see Figure 29.44.

## 29.9.3. Root locus

Type of problem Frequencies Dependence on parameter dentifier MLa 1 1 6648/9 52% 1 1 6648/9 52% 3 3 3441/4.82% 3 3 3391/4 - 13% 3 4 44/4.82% 3 3 3391/4 - 13% 3 3 3391/4 - 13% 3 3 3391/4 - 13% 3 4 44/4.82% 3 3 3391/4 - 13% 3 3 3391/4 - 13% 3 3 3391/4 - 13% 3 4 44/4.82% 3 3 3391/4 - 13% 3 3 3391/4 - 13% 3 3 3391/4 - 13% 3 4 44/4.82% 3 3 3491/4 - 13% 3 4 4/6 37/30.00% 4 76 597/30.00% 4 76 597/30.00% 5 70 70% 5 7	Equilibrium Frequ	uencies/Eigenvalues	Root locus	Linear vibrations	Identifiers	Initial co	onditio	ns Options	
Prequences	Type of problem						Sort	by: frequency	
Dependence on parameter dentifier dentifier ULa inits 0 0 0 0 0 0 0 0 0 0 0 0 0	Frequencies		Ro	ots			Jon	by: nequency	
O       0.22         Inits       0         Inits	Dependence on I	narameter					Freq	uency/Damping rat	io 🔻
dentifier       ULa       1       1       1.0648/9.52%       1.0648/9.52%         inits       0       1       1.0648/9.52%       1.0648/9.52%         inits       0       1       1.0648/9.52%       3.344/4.82%         3.3495/7.10%       3.3841/6.13%       3.3441/4.82%         3.3495/7.10%       3.3841/6.13%       3.3441/4.82%         Source       4.1       2.4         Auto       4.57/3.00%       476.97/3.00%         Auto       7476.97/3.00%       476.97/3.00%         Stepwise       In       1         Matto       7476.97/3.00%       476.97/3.00%         Yes Portoci ULa       7476.97/3.00%       476.97/3.00%         Variables       2       Root loci       2         Peta=30%       Beta=20%       9       476.97/3.00%         Beta=20%       9       9       1.0548/9         Beta=30%       Beta=30%       9       9         Beta=30%       9       9       9       1.0548/9         Instable       1       1.0548/9       9       9         Instable       1.0548/9       9       9       9         Instable       9       9       9		purumeter						0	0.2
Jints       0       2       3.3494/4.82%       3.3841/-6.13%         Source       8       3       3.3995/7.10%       3.3441/-6.13%         Source       41       3/4       3.441/-6.55%       3.3951/-5.20%         Save coordinates and identifiers       Animation of root locus       476.97/30.00%       476.97/30.00%         Auto	Identifier	ULa				-	1	1.6848/9.52%	1.6848/9.52%
8       3       3.3397,10%       3.381/-6.13%         Source       3.331/-6.13%       3.3931/-5.20%         Count       41       3.941/-6.35%       4.567/-3.38%         Save coordinates and identifiers       476.97/30.00%       476.96/29.99%         Auto       7476.97/30.00%       476.96/29.99%         Auto       9       476.97/30.00%       476.97/30.00%         Stepwise       In       1       Points.       1         Variables       7       Points.       7       7         Cool cid ULa       Image: Coo	Limits					0 💼	2	3.3444/4.82%	3.3444/4.82%
Count       4       3.9351/5.20%         Save coordnates and identifiers       4.3344/6.33%       4.567/3.98%         Animaton of root locus       6       476.97/30.00%       476.95/29.99%         Auto       7.476.97/30.00%       476.97/30.00%       476.97/30.00%         Stepwise       In       1       Points.       9       476.97/30.00%       476.97/30.00%         Stepwise       In       1       Points.       1       476.97/30.00%       476.97/30.00%         Root loci UI_a       In       1       Points.       In       1       Points.       In							3	3.3895/-7.10%	3.3841/-6.13%
Count       41       5       4.547/5.348       4.567/3.38%         Save coordnates and identifiers       Animaton of root bcus       745.87/30.00%       476.95/29.99%         Auto       745.87/30.00%       476.95/30.00%       476.95/30.00%       476.95/30.00%         Stepwise       In       1       Points.       9       476.97/30.00%       476.97/30.00%         Stepwise       In       1       Points.       9       476.97/30.00%       476.97/30.00%         Variables       In       1       Points.       9       476.97/30.00%       476.97/30.00%         Root loci UI_a       In       In       Points.       9       476.97/30.00%       476.97/30.00%         Beta=20%       Beta=20%       In       In       In       In       In       In         Beta=20%       Beta=30%       In       In </td <td></td> <td></td> <td></td> <td></td> <td></td> <td>8</td> <td>4</td> <td>3.9414/-6.35%</td> <td>3.9351/-5.20%</td>						8	4	3.9414/-6.35%	3.9351/-5.20%
Save coordinates and identifiers       6       476.97/3.00%       476.97/3.00%       476.97/3.00%         Auto       7       476.97/3.00%       476.97/3.00%       476.97/3.00%       476.97/3.00%         Auto       9       476.97/3.00%       476.97/3.00%       476.97/3.00%       476.97/3.00%         Stepwise       In       1       1       Points.       1       476.97/3.00%       476.97/3.00%         Stepwise       In       1       1       Points.       1       476.97/3.00%       476.97/3.00%         Stepwise       In       1       1       Points.       1       476.97/3.00%       476.97/3.00%         Variables       Variable       Variables	Count	41					5	4.5746/-5.34%	4.567/-3.98%
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	-16	-12		8	-4	0		4	8

Figure 29.62. Root loci

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Root loci give the most useful tool for choice rational values of control parameters in the case of the single pole magnet model. Parameterization of control parameters by identifiers allows computing eigenvalues loci and drawing conclusions on stability and damping level both the levitation and guidance systems, Section *Identifiers for magnet control*. For example, analysis of stability and damping ratio in dependence on the control parameter  $U_a$  parameterized by the identifier  $Ul_a$  is presented in Figure 29.62.

## 29.10. Test cases

Here we consider some simulation tests with maglev models.

## 29.10.1. Equilibrium with disabled magnets

Consider the bogie model <u>{UM Data}\Samples\MagLev\Bogie\_6DOF</u>. 1. Load the model.

1 <u>12</u> U	IM - Simula	tion - d:\un	m70_wor	'k∖test	s\ma	glev\bog	ie_6dof	-	-	
File	Analysis	Scanning	Tools	Wind	ows	Help				
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	Load conf	iguration		•		Desktop	)		Ctrl	+R
	Save confi	guration		×		Disable	d magne	ts		
	Exit		AI	t+X	_	last				

Figure 29.63. Configuration 'Disabled magnets'

Solver	Ide	ntifiers	Initial	condition	าร	
Object variables	XVA	Tools	Monorail train			
Test Forces			_			
📝 Notify about t	turned off	forces				
Force				D 🗎	J	
LMBushing RR				1	4	
GMBushing LF				~	V	
GMBushing LR				~	۷	
GMBushing RF				~	4	
GMBushing RR				~	V	
LMagnet LF						
LMagnet LR						
LMagnet RF						
LMagnet RR						
GMagnet LF						
GMagnet LR						
GMagnet RF						Ξ
GMagnet RR						

Figure 29.64. Disabled force elements

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2. Read the *Disabled magnets* configuration, Figure 29.63. In this configuration we made disabled all the magnets, Figure 29.64. Thus, this test corresponds to the bogie positioning on the upper contacts, Section *Sliding contact elements*.

Solver	Identifiers	Initial (	conditior	ns Object v	ariables	XVA	Inforr	nation	Tools	Monorail train
🖻 E	1 <u>1</u>							-		
Option	s and Paran	neters	Tools	Identificatio	n Resis	stance	Speed	Flexib	le track	MagLev
Speed	mode									
🔘 Ne	utral				0	Profile				
<b>⊘</b> v=	const				0	/=0				
✓ Aut ✓ Loc	omatic tern k horizonta	nination I shift	n of equi	ibrium test						

Figure 29.65. Zero speed mode

cFrc-N[1](Upper contact):z - Separate contact normal force 1 for element Upper contact, friction. Resolved in Base0
 cFrc-N[2](Upper contact):z - Separate contact normal force 2 for element Upper contact, friction. Resolved in Base0
 cFrc-N[3](Upper contact):z - Separate contact normal force 3 for element Upper contact, friction. Resolved in Base0
 cFrc-N[3](Upper contact):z - Separate contact normal force 4 for element Upper contact, friction. Resolved in Base0
 cFrc-N[4](Upper contact):z - Separate contact normal force 4 for element Upper contact, friction. Resolved in Base0



Figure 29.66. Contact forces vs. time



Figure 29.67. Contact forces

3. Run simulation. The speed mode is v=0, Figure 29.65 and simulation stops after the kinetic energy becomes small enough. Initial coordinates are zeroes, and the equilibrium position is achieved after a series of collisions, Figure 29.66. Four read vectors in Figure 29.67 correspond to the normal contact forces.

## 29.10.2. Bogie uplifting

1. Load the model <u>{UM Data}\Samples\MagLev\Bogie\_6DOF</u>.

2. Read the *Uplifting* configuration. In this configuration, all magnets are enabled and the single pole magnet model is used. Initial position of the bogic corresponds to it equilibrium position on contacts according to the test *Equilibrium with disabled magnets*. The value of voltage U0=9.654 V is equal to the nominal value for the nominal gap 10mm. The integral control parameter  $U_{is}$  (Section *Single pole magnet model*) is zero.



Figure 29.68. Uplifting test variables

3. Run simulation. Some plots for the uplifting process are shown in Figure 29.68.

4. Now consider effects on use of the integral control  $U_{is}$  parameter. Reload the *Uplifting* configuration and set zero levitation magnet voltage U0, Figure 29.69.

5. Run simulation for different value of integral control parameter  $U_{is}$ , Figure 29.70. It is clear, that there is a static deviation of the gap from the nominal value for zero integral control.

Spring and damper model Single pole magnet		
Specified parameters		
Name	Identifier	Value
Nominal gap S0 (mm)		10
Force for nominal gap F0 (kN)	Fz0	9.3195
Mass of magnet (kg)	m_control	950
Magnet force parameter Kappa (F=Kappa*I^2/S^2)		0.01
Resistance (Ohm)		1
Voltage U0 (V)	UL_0	0
Control gap factor Us (V/m)	UL_s	2000
Control gap velocity factor Uv (Vs/m)	UL_V	200
Integral control factor Uis (V/ms)	Ul_is	0
Control acceleration factor Ua (Vs^2/m)	Ul_a	2

Figure 29.69. Levitation magnet control parameters



Figure 29.70. Voltage and gap for different integral control

## 29.10.3. Stability: comparison of simulation with theory

In this section we compare theoretical results on levitation stability with simulation results.

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- 1. Load the model <u>{UM Data}\Samples\MagLev\Bogie\_6DOF</u>.
- 2. Read the *Stability* configuration. The model is in equilibrium position at v=0 speed mode.

Solv	ver	Identifiers	Initial conditions	Object variables	XVA					
Coordinate	s Con	straints on initial conditio	ons							
🗁 💾	$\begin{array}{c c} & \textcircled{\blacksquare} & \textcircled{\textcircled{\blacksquare}} & \textcircled{\textcircled{\blacksquare}} & \textcircled{\textcircled{\blacksquare}} & \swarrow & \checkmark & \checkmark & \checkmark & & & & & \\ \hline & & & & & & & & & & & & \\ \hline & & & &$									
Dogle_6001				1	<u> </u>					
	ψ∢	Coordinate	Velocity	Comment	<u>^</u>					
1.1		0	0	jFrame 1c						
1.2		0	0	jFrame 2c						
1.3		-0.0005	0	jFrame 3c						
1.4		0	0	jFrame 4a						
		-	-							

Figure 29.71. Initial deviation of frame from equilibrium

3. Set a deviation of the frame from the equilibrium position 2mm, Figure 29.71.

Linear spring/damper model Single pole m	agnet			
Specified parameters				
Name		Identifier	Value	-
Nominal gap S0 (mm)			10	
Force for nominal gap F0 (kN)		Fz0	9.3195	
Mass of magnet (kg)		m_control	950	
Magnet force parameter Kappa (F=Kappa	*I^2/S^2)		0.01	
Resistance (Ohm)			1	
Lateral force ratio (lambda)			0	
Voltage U0 (V)		UL_0	9.654	
Control gap factor Us (V/m)		Ul_s	2000	
Control gap velocity factor Uv (Vs/m)		Ul_v	235	
Integral control factor Uis (V/ms)		Ul_is	0	-
Estimated values				
Name	Value			-
Nominal voltage U0 (V)	9.65376			_
Nominal current I0 (A)	9.65376			
L0 (H)	2			
Nominal time constant T (s)	0.0225762			
Circuit time constant Ti (s)	2			
Us*	965.376			
Uv*	226.656			
Ua*	0.492036			
Unitless control gap factor Ks	2.07173			-
	40 7005			•

Figure 29.72. Boundary value of control parameter Uv\*



Figure 29.73. Stable and instable levitation

4. Set the control parameter Uv=235 a bit more than the boundary stable value Uv\*, Figure 29.72. Run simulation. Now change Uv to 220, which is instable, Figure 29.73.

📩 Static and line	ar analysis									x
0 🕨		V : *								
Equilibrium Frequ	encies/Eigenvalues	Root locus	Linear vibrations	Identifiers	Initia	conditi	ons Options			
Type of problem		@ Roo	ts			Sort	y: frequency			•
Dependence on n	arameter	0.000				Frequ	ency/Damping ratio			•
zdentifiere							150	153	156	
Identifier	UI_V					1	2.0106/-7.94%	2.0257/-7.52%	2.0408	
Limits				150		2	2.0348/-7.16%	2.0497/-6.77%	2.0646	5
				300		3	2.0644/-7.25%	2.0798/-6.85%	2.0952	1
Count	51					4	2.131/1.95%	2.131/1.95%	2.131/	
Cave coordinat	an and identifiers				~	5	3.3622/1.21%	3.3622/1.21%	3.3622	2
Animation of root	locus				=	6	476.87/29.94%	476.87/29.94%	476.87	1
Auto		0				7	476.87/29.95%	476.87/29.95%	476.87	1
		_				8	476.87/29.95%	476.87/29.95%	476.87	1
Stepwise	In 1 🕺	Points.				9	476.97/30.00%	476.97/30.00%	476.97	,
						10	170 00150 254	476 07/20 000/	470.07	,

Figure 29.74. Verification of stability by root locus

Let us analyze the stability of levitation with linear analysis.

5. Set the frame vertical coordinate to zero and open the SLA (static and linear analysis) window.

6. Open the **Root locus** tab, select the  $Ul_v$  identifier and set the interval for analysis like in Figure 29.74. Run root locus computation by the  $\bigcirc$  button, and draw roots by the  $\bowtie$  button. Click on the **Stepwise** button to animate the locus. Verify that the stability bound corresponds to the theoretical results, Figure 29.75.

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- Remark 1. In this test we have set moments of inertia of the frame, which give close values of eigenvalues or rotation about X and Y axis to the eigenvalue for the vertical degree of freedom. In this case the stability bounds for these degrees of freedom are almost the same. If you change the frame inertia parameters, stability results will differ from the theoretical one because the stability for rotational degrees of freedom will differ from the levitation.
- Remark 2. Theoretical stability results in Section 29.6.5 can be applied with the model of bogie with rigid coupling of magnets with frame. The results cannot be directly valid for bogie models with a primary suspension, and numerical stability analysis with SLA tool is required.

## 29.10.4. Spring/damper magnet model as identifier control

Here we consider a simple model of levitation as an example of user's models of magnet force.

1. Load the model <u>{UM Data}\Samples\MagLev\Bogie\_6DOF</u>.

Options and parameters Tools Ident	tification	Resistance	Speed	Flexible track	MagLev					
Levitation Guiding										
Levitation magnet model										
Spring/damper Mag	Spring/damper Magnet Identifiers									
Acceleration model										
Sensor		Prediction	ו							
Linear spring/damper model Single p	ole magr	net								
Identifiers										
Name	Identifie	er	Value							
Nominal gap S0 (mm)	s0_l		10							
Force for nominal gap F0 (kN) Fz0 9.3195										
Mass of magnet (kg) m_magnet_l 300										
Spring constant Kp (N/m) k_magnet_l 2000000										
Damper constant Cp (Ns/m) c_magnet_l 10000										

Figure 29.76. Levitation model by identifiers

2. Read the *Identifier control* configuration. The model is at v=0 speed mode.

The levitation magnet model is **Identifiers**, the guidance magnets are spring/damper. Levitation spring-damper forces are computed by variables created in the wizard of variables, Figure 29.77. The variables are assigned for the force identifiers with the Identifier control tool, Figure 29.78. Please note that the **Compute after kinematics** option is used in the identifier control.

3. Run simulation. Initial position of the frame is shifted slightly from the equilibrium position, so that a transient process can be seen in the plot. Change the levitation magnet model to the **Spring/Damper** one and compare simulation results, which must completely coincide.

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The Wizard of variables											
Variables for group	Joint forces		Bipolar forces		Angular variables			Linear variables			
Coordinates Solver p		oarameters		All forces	All forces		Identifiers		Contact forces		
Contact forces for bodies		Vari		ables	Bushin		g Magi		agLe	gLev forces	
Expression	Track	coord	inate sy	stem	l	User variables			Reactions		
+/=-×		_x1:= _x2:=	_x1:= S-S0 (LMag			× k_r		ignet_ ignet_	J	* ==	
	-	_x3:=	3:= Fz0			×		1000			
sart sign atan In avn		_x4:=		_x1	+		_x2				
		_x5:=	_x5:=x4		•	+ _x		,x3	3		
	wog (pow										
Fz Levitation LF	S	pring-d	amper levita	ation	force,	front lef	t, N		5		
VS (LMagnet LF) S-S0 (LMagnet LF) VS (LMagnet LR) S-S0 (LMagnet LR) VS (LMagnet RF) S-S0 (LMagnet RF) VS (LMagnet RR) S-S0 (LMagnet RR) Fz0 k_magnet_l c_magnet_l											



		Identifier contro	ol	<b>×</b>
		<ul> <li>Enabled</li> <li>Compute after kir</li> <li>Refresh depender</li> <li>Identifier</li> <li>fz_Imagnet_If</li> </ul>	nematics nt elements	E
		Assign value to iden	ntifiers with the sam	ne name
		No	All	<ul> <li>In subsystems</li> </ul>
		Comments		
Solver Identifiers	Initial conditions	Ordinate		
List of identifiers Identifier control		Assigned variable		Type of description
		Fz Levitation LF		<ul> <li>Variable</li> </ul>
Identifier	Comment	Abscissa		Tura
V fz_lmagnet_lr		Variable		I ype I me
V fz_Imagnet_rr		Time		🔘 Variable
V fz_Imagnet_rf		Accept	Cancel	

Figure 29.78. Identifier control for levitation force identifiers

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