UNIVERSAL MECHANISM 10

User`s manual

Simulation of MBS with Pneumatic Systems

2024

Contents

1. Simulation of multibody systems with pneumatic elements

1.1. General information

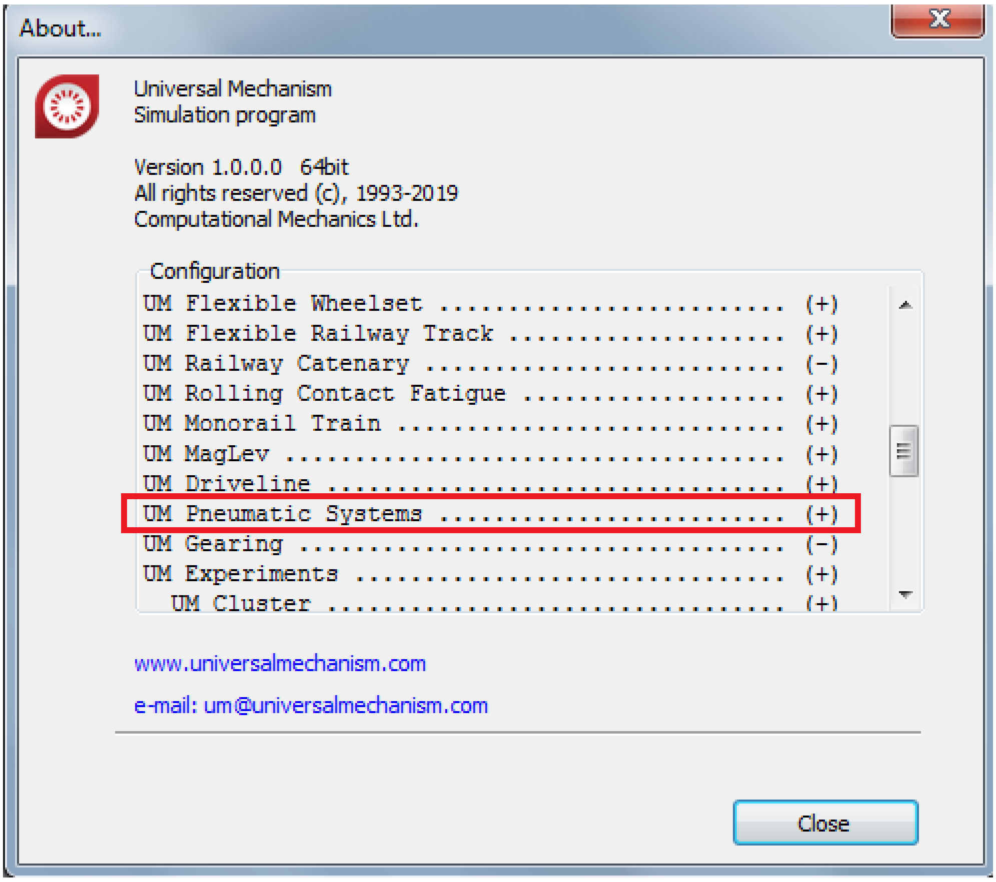


Figure 1.1. **'About'** window. List of available modules

Program package Universal Mechanism includes a specialized module **UM Pneumatic Systems** (UM PS), which contains tools for simulation of models with pneumatic elements, Figure 1.1. The following elements are available in the module:

- Air springs;
- Rigid chambers;
- Pneumatic lines;
- Orifices;
- Height control valves, HCV (leveling valves);
- Compressors.

In this manual we use the following designations:

p - pressure (Pa);

V - volume (m^3);

T - temperature (K);

R= 287.058 - specific gas constant (J/(kg·K));

n - polytropic index;

m - mass (kg);

d, *D* - diameter;

A - area (m^2);

L - length (m).

Standard Reference Atmospheric conditions (ANR):

$$p_0 = 101.325 \text{ kPa},$$ (1.1)

$$T_0 = 293.15 \text{ K} = 20°\text{C},$$

$$RH_0 = 65\% \text{ (relative humidity)}$$

Air is considered as an ideal gas satisfying the law

$$pV = mRT.$$ (1.2)

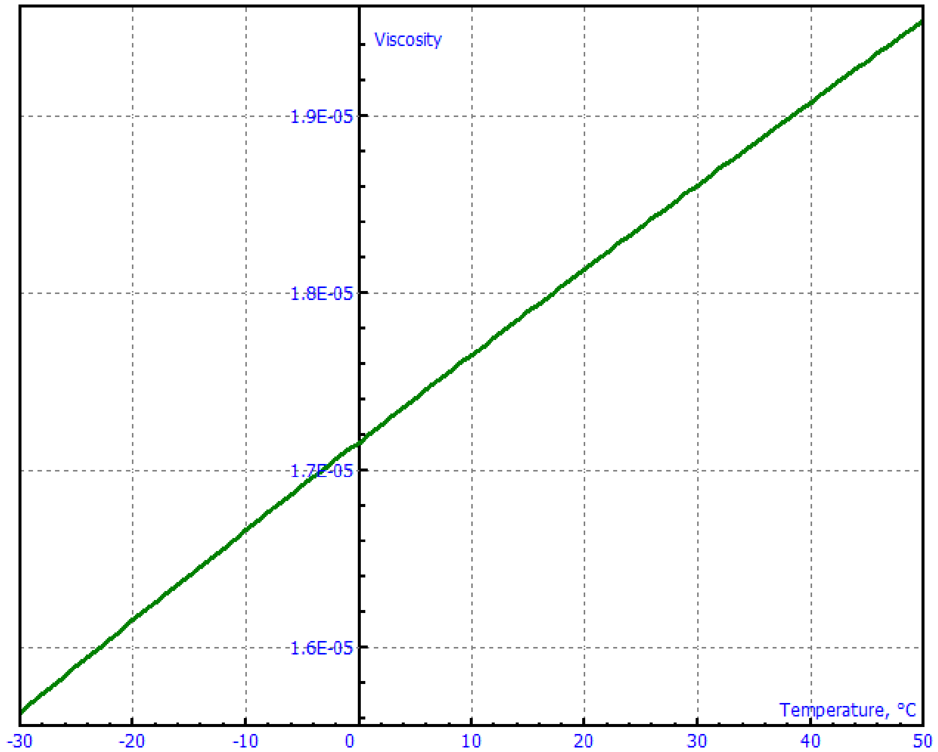


Figure 1.2. Dynamic viscosity of air versus temperature

Sutherland's law is used for evaluation of dynamic viscosity of air on temperature, Figure 1.2, [1]:

$$\mu = \mu_0 \frac{T_{ref}+S}{T+S}\left(\frac{T}{T_{ref}}\right)^{3/2},$$ (1.3)

Where μ_0=1.716kg/(ms), T_{ref}=273,15 K, S=110.4 K.

1.2. Pneumatic elements

Here we consider pneumatic elements, which are included in the module UM Pneumatic Systems.

1.2.1. Chambers

The chamber state is described by the polytropic thermodynamic process

$$p\left(\frac{V}{m}\right)^n = c = \text{const.} \tag{1.4}$$

Here *p* is the pressure, which is assumed to be the same inside the chamber, *V* is the chamber volume, and *n* is the polytropic index. The air mass in a chamber is computed as

$$m = m_0 + \sum_i \int_0^t \dot{m}_i \, dt,$$

where $\dot{m}_i$ is the mass flow rate of the connected line or orifice *i*, Sect. 1.2.5 *Pneumatic lines*, 1.2.6. *Orifices*.

Taking into account the ideal gas law (1.2), the temperature is computed as

$$T = \frac{pV}{mR}.$$

1.2.2. Rigid chambers

This element corresponds to a chamber with a constant volume *V*=const and a variable air mass. The chamber pressure is computed directly from the equation of polytropic process (1.4)

$$p = cm^n V^{-n}.$$

1.2.3. Air springs

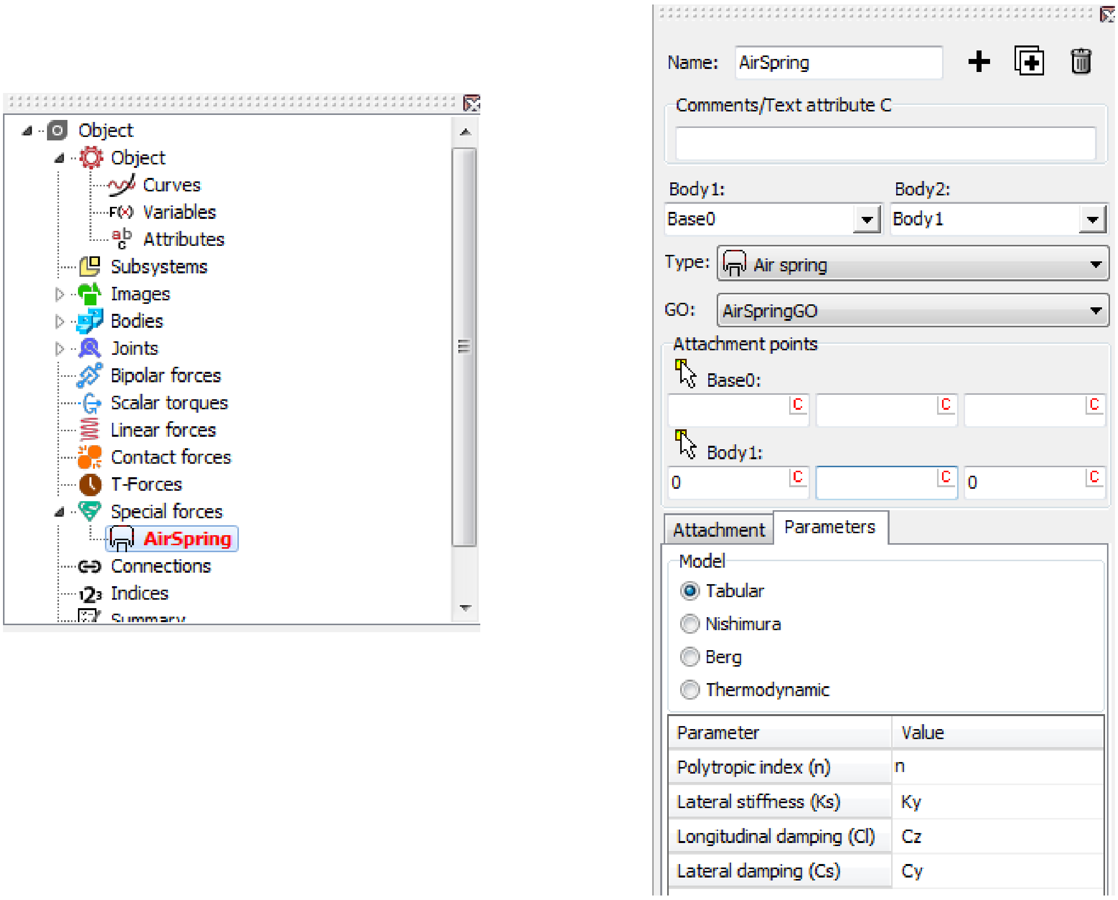


Figure 1.3. Air spring as a special force element

UM Pneumatic Systems (PS) includes advanced models of air springs (AS) as special force elements, Figure 1.3. The following air spring models are available in UM:

- **Tabular model**: the description of force element includes tabular experimental data on force and volume; this model is considered as the most exact one
- Nishimura model
- Berg model
- Thermodynamic model

It is important that only the **tabular model** of AS can be included in PS, i.e. it can be connected by pneumatic lines or orifices with other elements of PS. Other models of AS are independent, i.e. the state of any AS does not depend on other AS and elements of PS.

1.2.3.1. Tabular model of air spring

Manufacturers often supply information about AS properties in the form of a static data charts, which include load/height and volume/height diagrams. Examples of such charts for 1T15-M0 [2] and Numatics ASNS10-2-1 [3] are shown in Figure 1.4. Such data allow development of rather exact mathematical models of AS as it is described below.

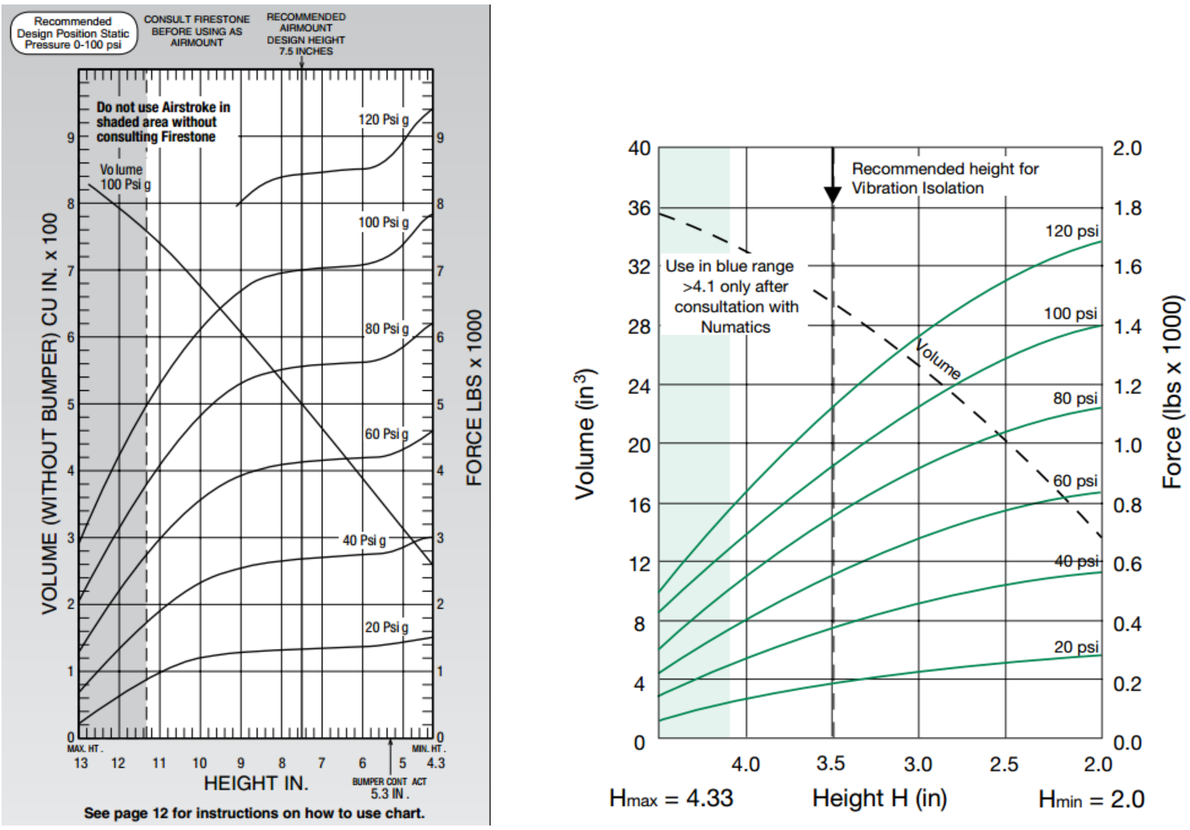


Figure 1.4. Force and volume versus deflection for air spring 1T15-M0 (left) and Numatics ASNS10-2-1

1.2.3.1.1. Parameters of tabular air spring in Input program

Tabular AS description in Input program requires specifying the following list of parameters (Figure 1.3):

- polytropic index; the default and recommended value for AS is n=1.38, see [4], [5];

- lateral stiffness and damping constants as well as the longitudinal damping constant.

These data can be parameterized by identifiers.

Tabular description of AS should be done in Simulation program, Sect. 1.2.3.1.3.4. *Creating UM files *.ast with tabular air spring models.*

1.2.3.1.2. Tabular data format

H \ P	20	40	60	80	100
9.5	2537.2	4782.7	7035	9410.5	11966
10	2385.2	4553.9	6792.5	9140.6	11579
10.5	2246.8	4467.6	6677.4	8966.7	11346
11	2233.1	4379.9	6511.6	8733.8	11061
11.5	2194.7	4251.1	6336.3	8498.1	10775
12	2119.4	4134.7	6165	8274.8	10496
12.5	2048.2	4019.6	6025.3	8106.3	10276
13	1983.8	3936	5929.4	8004.9	10128
13.5	1938.6	3886.7	5880	7951.5	10059
14	1898.8	3862	5859.5	7922.7	10027
14.5	1886.5	3851.1	5832.1	7900.8	10006
15	1874.2	3845.6	5819.8	7876.1	9984.6
15.5	1870.1	3827.8	5804.7	7869.3	9957.2
16	1863.2	3812.7	5788.3	7850.1	9947.6

a)

H \ P	20	40	60	80	100
9.5	775.42	837.07	898.72	960.37	1022
10	809.67	879.54	949.41	1019.3	1089.2
10.5	905.57	967.22	1028.9	1090.5	1152.2
11	954.89	1022	1089.2	1156.3	1223.4
11.5	1007	1078.2	1149.4	1220.7	1291.9
12	1050.8	1126.1	1201.5	1276.8	1352.2
12.5	1098.7	1176.8	1254.9	1333	1411.1
13	1149.4	1228.9	1308.3	1387.8	1467.3
13.5	1219.3	1294.7	1370	1445.4	1520.7
14	1249.4	1331.6	1413.8	1496	1578.2
14.5	1304.2	1386.4	1468.6	1550.8	1633
15	1328.9	1419.3	1509.7	1600.2	1690.6
15.5	1390.6	1478.2	1565.9	1653.6	1741.3
16	1448.1	1534.4	1620.7	1707	1793.3

b)

H \ P	100
9.5	1022
10	1089.2
10.5	1152.2
11	1223.4
11.5	1291.9
12	1352.2
12.5	1411.1
13	1467.3
13.5	1520.7
14	1578.2
14.5	1633
15	1690.6
15.5	1741.3
16	1793.3

c)

Force Volume

Figure 1.5. Tabular data for air spring in Imperial units (fragment): force (a) and volume (b,c)

Tables. This type of AS description requires two tables: force/height and volume/height for different values of pressure like in Figure 1.5. Data should be ordered in the growth of the height (H) and pressure (P). Table columns correspond to the pressure. Volume can be given for one pressure (Figure 1.5 c), whereas the force data should correspond to the entire region of AS operation.

Other requirements:

- The force table must include data for at least two pressure and two height values.
- The force value must increase with the growth of the pressure.
- The volume table must include data for at least one pressure and two height values.
- The volume value must increase with the growth of both the pressure and the height.

Units. Data can be prepared both in SI and Imperial units, Table 1.

Table 1. Table data units

System of units	Height	Force	Pressure	Volume
SI	m	N	Pa	m^3
Imperial	in	lbf	psi g, psi a	in^3

Pressure type. Both absolute and gauge pressure data can be used.

1.2.3.1.3. Preparing and input tabular data

1.2.3.1.3.1. Chart digitizing

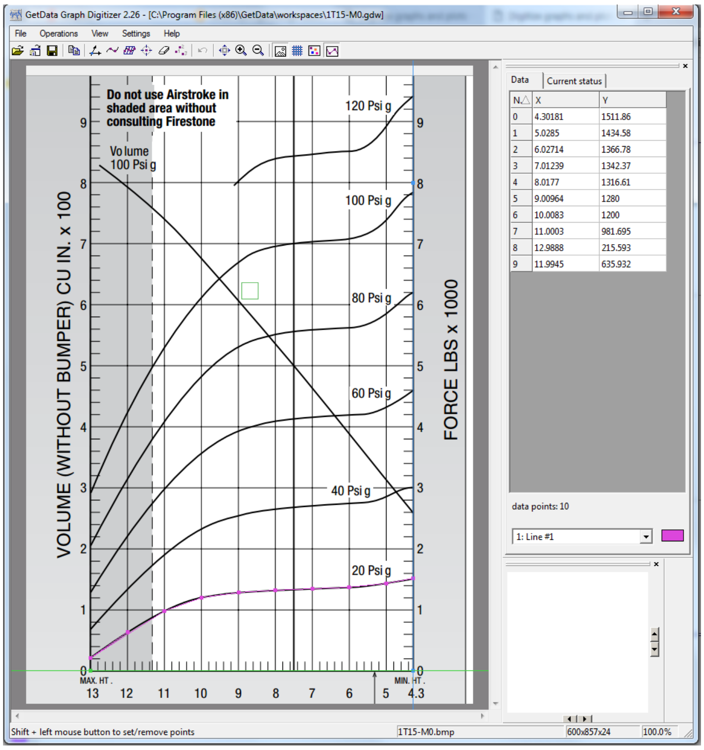
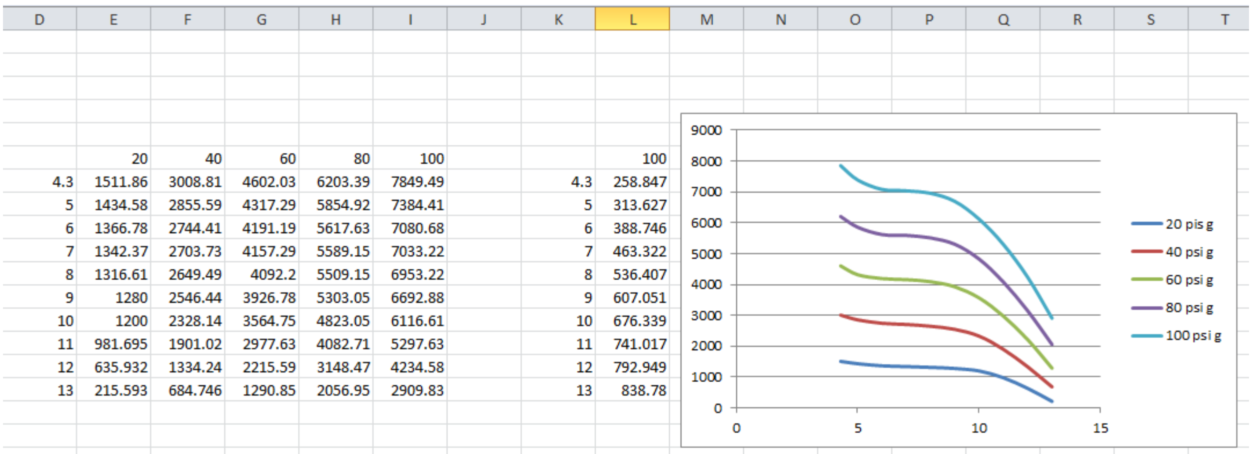


Figure 1.6. Digitizing plots for air spring 1T15-M0

If AS data are available as a chart like in Figure 1.4, software for plot digitizing should be used. We use the GetData Graph Digitizer software, Figure 1.6, [6].

1.2.3.1.3.2. Data preparing in Microsoft Excel

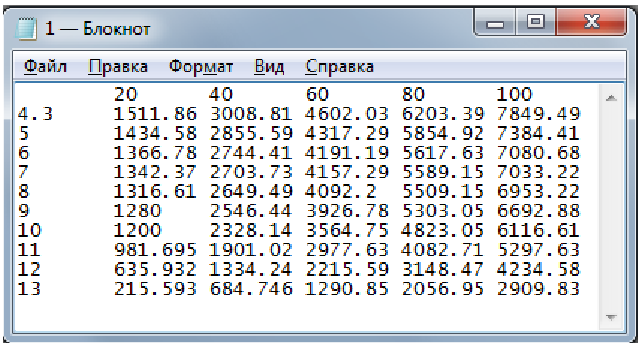
We recommend using the Microsoft Excel for preparing data according to the format and unit requirements. Data units can be easily changed with this tool to the desired ones; for example liters should be changed to m^3 and bars to Pa.



D	E	F	G	H	I	J	K	L
	20	40	60	80	100			100
4.3	1511.86	3008.81	4602.03	6203.39	7849.49		4.3	258.847
5	1434.58	2855.59	4317.29	5854.92	7384.41		5	313.627
6	1366.78	2744.41	4191.19	5617.63	7080.68		6	388.746
7	1342.37	2703.73	4157.29	5589.15	7033.22		7	463.322
8	1316.61	2649.49	4092.2	5509.15	6953.22		8	536.407
9	1280	2546.44	3926.78	5303.05	6692.88		9	607.051
10	1200	2328.14	3564.75	4823.05	6116.61		10	676.339
11	981.695	1901.02	2977.63	4082.71	5297.63		11	741.017
12	635.932	1334.24	2215.59	3148.47	4234.58		12	792.949
13	215.593	684.746	1290.85	2056.95	2909.83		13	838.78

Figure 1.7. Force and volume data for 1T15-M0 in Microsoft Excel

1.2.3.1.3.3. Data preparing in text file



	20	40	60	80	100
4.3	1511.86	3008.81	4602.03	6203.39	7849.49
5	1434.58	2855.59	4317.29	5854.92	7384.41
6	1366.78	2744.41	4191.19	5617.63	7080.68
7	1342.37	2703.73	4157.29	5589.15	7033.22
8	1316.61	2649.49	4092.2	5509.15	6953.22
9	1280	2546.44	3926.78	5303.05	6692.88
10	1200	2328.14	3564.75	4823.05	6116.61
11	981.695	1901.02	2977.63	4082.71	5297.63
12	635.932	1334.24	2215.59	3148.47	4234.58
13	215.593	684.746	1290.85	2056.95	2909.83

Figure 1.8. Force data for 1T15-M0 in a text file

Force and volume data can be prepared in a text file, Figure 1.8. Numbers in the text should be separated by blanks or Tab symbols.

1.2.3.1.3.4. Creating UM files *.ast with tabular air spring models

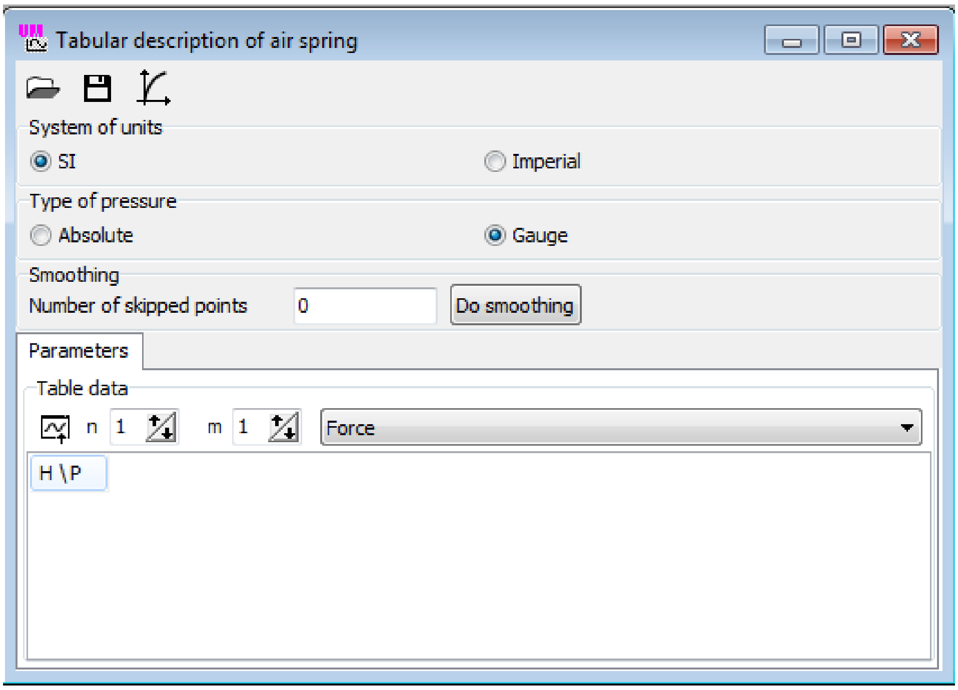


Figure 1.9. Window for creating a file with tabular air spring model

Tabular data with an AS model should be saved as a *.ast file. The default location of these files is the directory **{UM data}\AirSpring**, for example,

c:\Users\Public\Documents\UM Software Lab\Universal Mechanism\2023\AirSpring\

To create a file

- Run UM Simulation program;
- Click on the **Tools | Pneumatic elements | Tables for air springs…** command of the main menu to open the window *Tabular description of air spring*, Figure 1.9;
- If necessary, change

  - System of units

- Pressure type

- Select the type of data **Force** or **Volume**,
- Copy tabular data from the Excel or the text file:

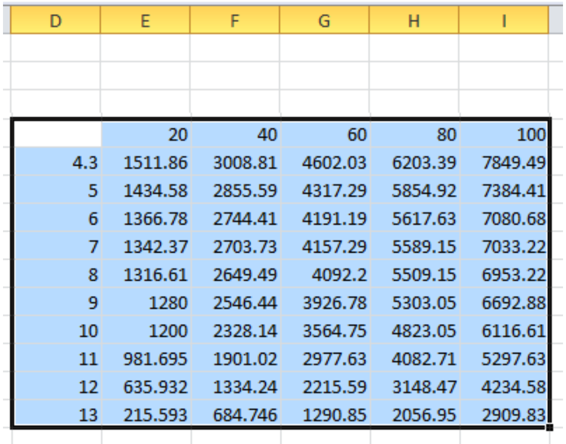
- Select the data including the first row with pressure values, Figure 1.10;

- Copy data in the clipboard by Ctrl+C;

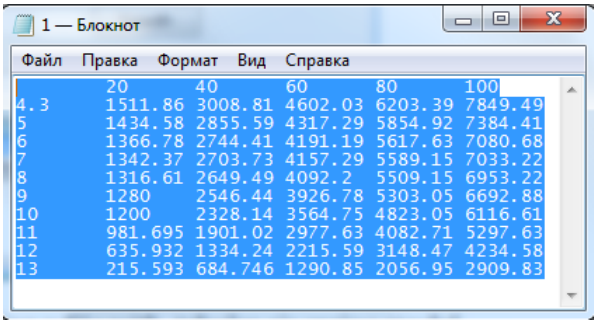
- Click by the mouse on the empty area with tabular data in the window *Tabular description of air spring* Figure 1.9 to make the area active;

- Paste the data from the clipboard by Ctrl+V.

- After entering, verifying and possible modification data for the force and volume, save data to an *.ast file by the button.

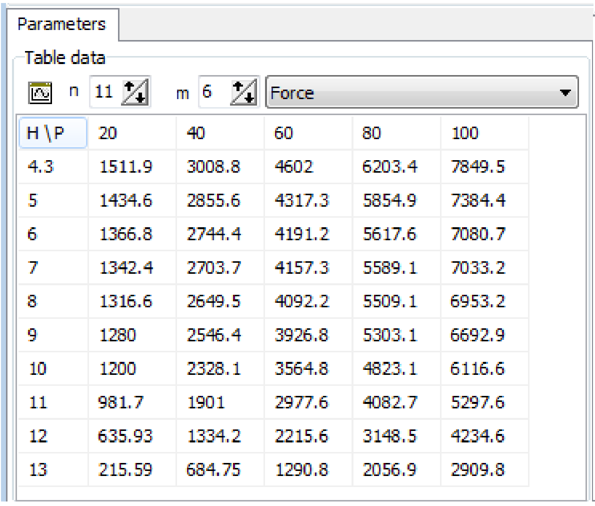


D	E	F	G	H	I
	20	40	60	80	100
4.3	1511.86	3008.81	4602.03	6203.39	7849.49
5	1434.58	2855.59	4317.29	5854.92	7384.41
6	1366.78	2744.41	4191.19	5617.63	7080.68
7	1342.37	2703.73	4157.29	5589.15	7033.22
8	1316.61	2649.49	4092.2	5509.15	6953.22
9	1280	2546.44	3926.78	5303.05	6692.88
10	1200	2328.14	3564.75	4823.05	6116.61
11	981.695	1901.02	2977.63	4082.71	5297.63
12	635.932	1334.24	2215.59	3148.47	4234.58
13	215.593	684.746	1290.85	2056.95	2909.83

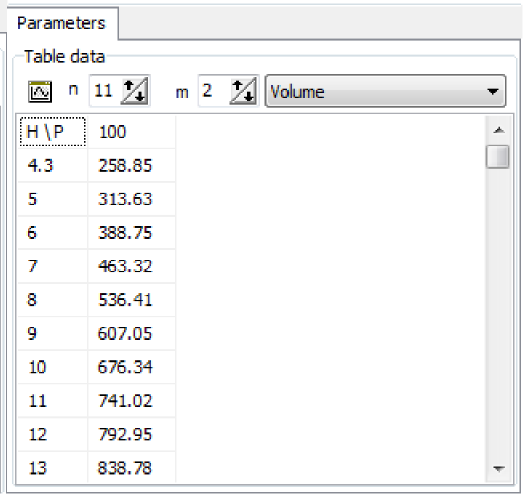


	20	40	60	80	100
4.3	1511.86	3008.81	4602.03	6203.39	7849.49
5	1434.58	2855.59	4317.29	5854.92	7384.41
6	1366.78	2744.41	4191.19	5617.63	7080.68
7	1342.37	2703.73	4157.29	5589.15	7033.22
8	1316.61	2649.49	4092.2	5509.15	6953.22
9	1280	2546.44	3926.78	5303.05	6692.88
10	1200	2328.14	3564.75	4823.05	6116.61
11	981.695	1901.02	2977.63	4082.71	5297.63
12	635.932	1334.24	2215.59	3148.47	4234.58
13	215.593	684.746	1290.85	2056.95	2909.83

Figure 1.10. Selecting data in Microsoft Excel and in text editor



H \ P	20	40	60	80	100
4.3	1511.9	3008.8	4602	6203.4	7849.5
5	1434.6	2855.6	4317.3	5854.9	7384.4
6	1366.8	2744.4	4191.2	5617.6	7080.7
7	1342.4	2703.7	4157.3	5589.1	7033.2
8	1316.6	2649.5	4092.2	5509.1	6953.2
9	1280	2546.4	3926.8	5303.1	6692.9
10	1200	2328.1	3564.8	4823.1	6116.6
11	981.7	1901	2977.6	4082.7	5297.6
12	635.93	1334.2	2215.6	3148.5	4234.6
13	215.59	684.75	1290.8	2056.9	2909.8



H \ P	100
4.3	258.85
5	313.63
6	388.75
7	463.32
8	536.41
9	607.05
10	676.34
11	741.02
12	792.95
13	838.78

Figure 1.11. Ready air spring data for 1T15-M0 in Imperial system

Smoothing tabular data

Click on the **Smooth** button in Figure 1.9 one or several times for smoothing with a B-spline the experimental tabular data in columns, Figure 1.12. Skipping points allows a more cardinal smoothing of the experimental data.

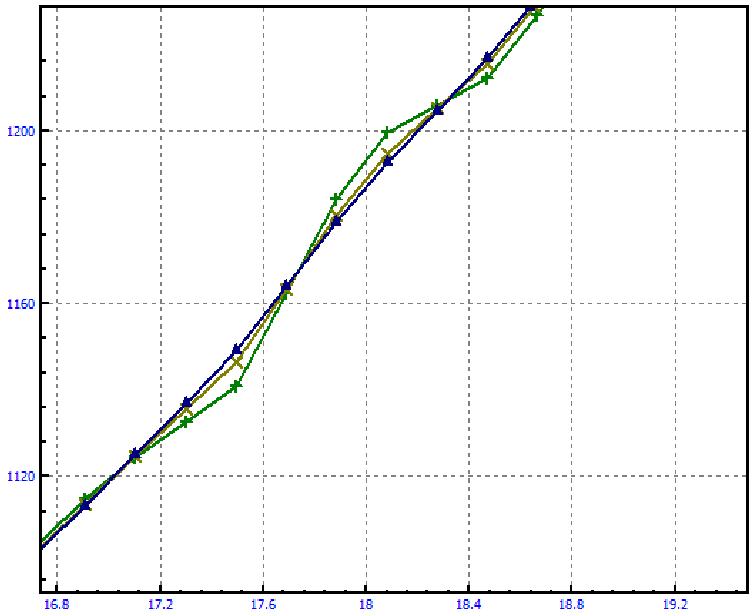


Figure 1.12. Single and double smoothing the tabular data

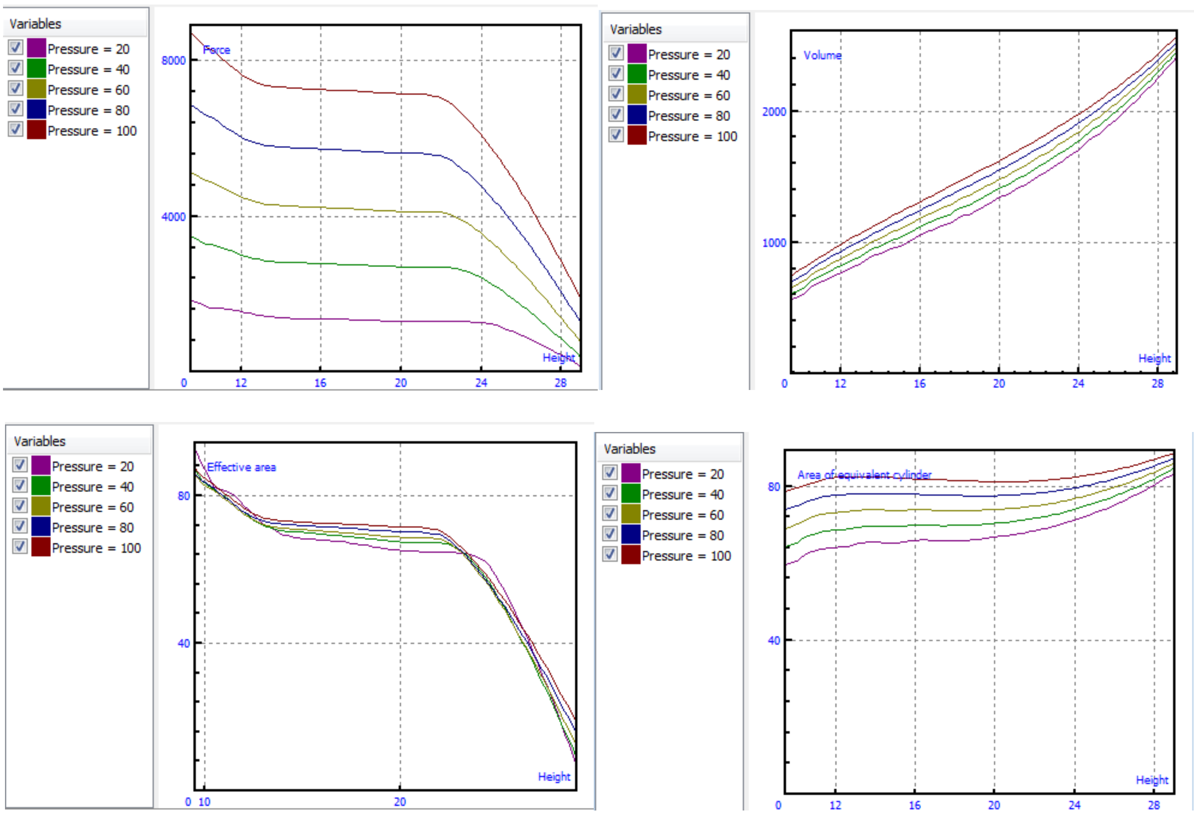


Figure 1.13. Plots for file 'Test data.ast'

Data plots

Use the  button in Figure 1.9 to get plots (see Figure 1.13)

- force F,
- volume V,
- effective area $A = F/p$,
- area of equivalent cylinder $A_c = V/h$.

1.2.3.1.3.5. Creating tabular data by effective area

Air spring description is often available as a dependence of the effective area on the height. Click on the button in Figure 1.9 to open the window for generation of tabular data by the charts of the effective area and volume verses height, Figure 1.14.

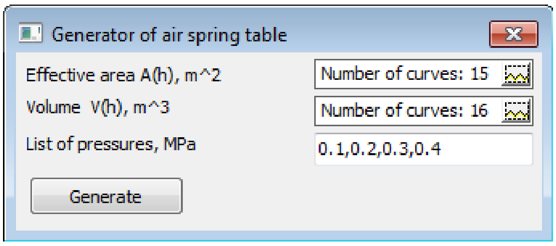


Figure 1.14. Window for input of effective area and volume

Both the effective area and the volume data are entered by the button. List of tabular values of the pressure in the increasing order should be specified as well. Figure 1.16 shows the curves corresponding to the AS description in paper [7].

After input of necessary data

- curve: effective area vs. height,
- curve: AS volume vs. height,
- list of tabular pressure values,

click on the **Generate** button to create the tables for the force and volume, Figure 1.17.

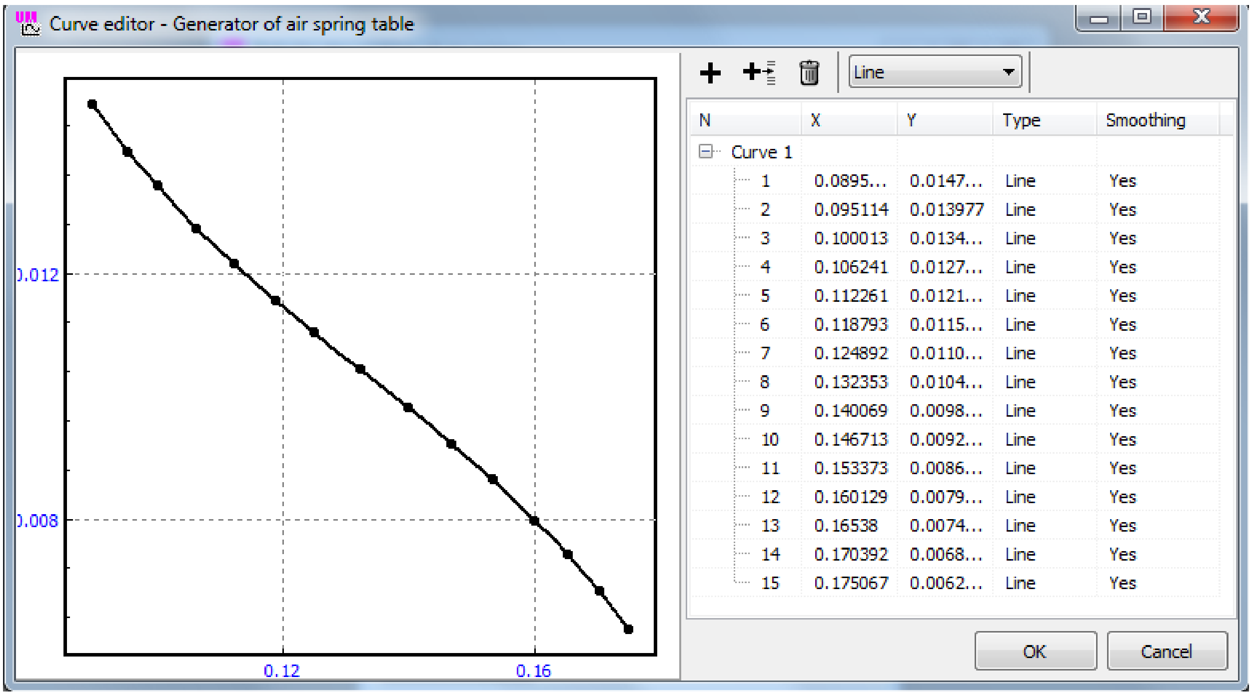


Figure 1.15. Effective area versus height

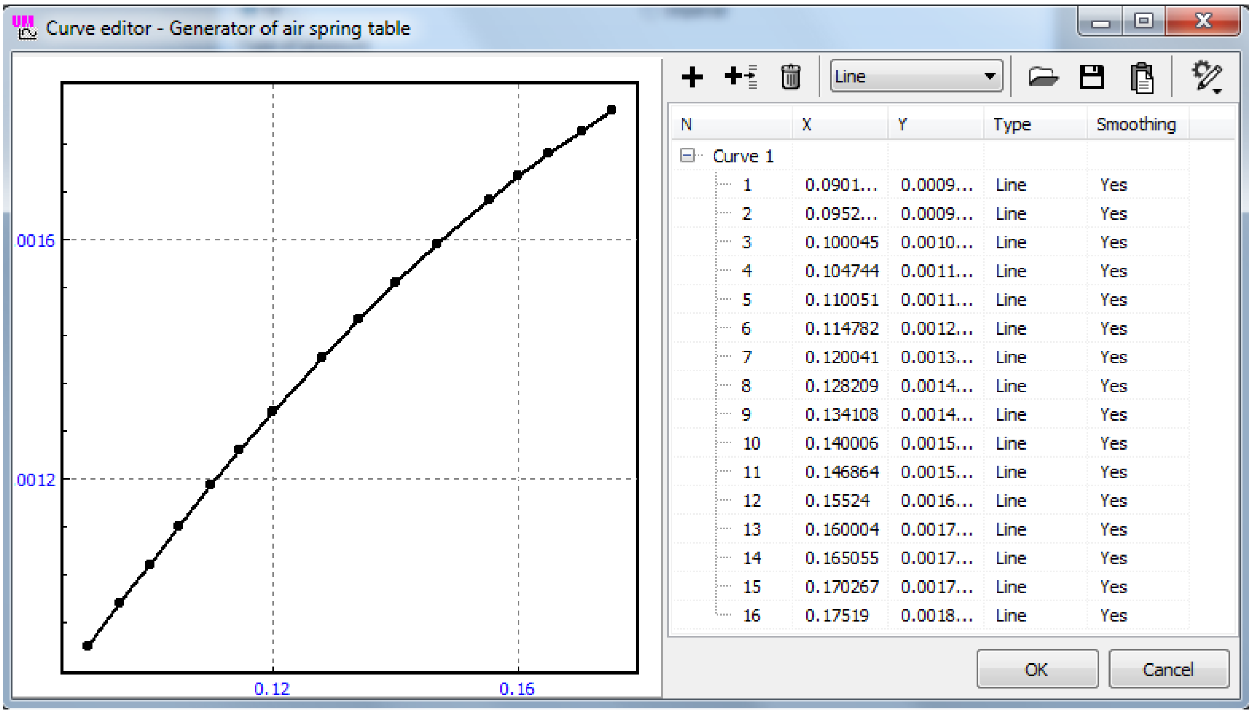


Figure 1.16. Volume versus height

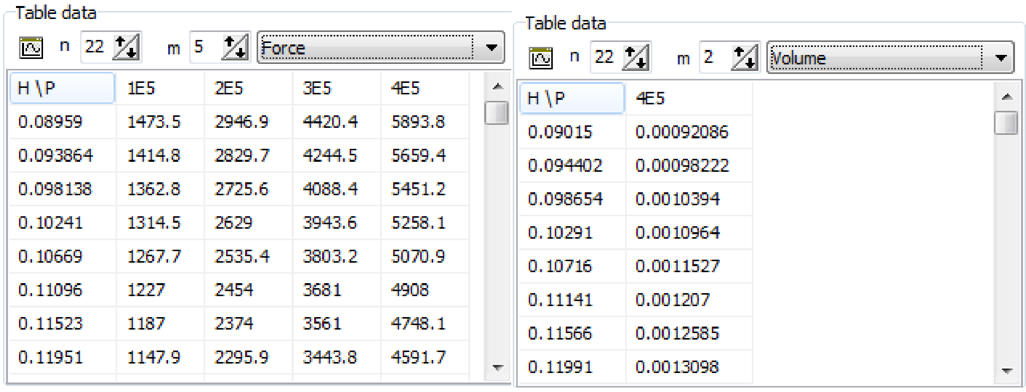


Figure 1.17. Generated tabular data

1.2.3.1.4. Mathematical model of air spring by tabular description

This model of AS uses experimental **static tabular data** on dependence of force F and the air bag volume V on the spring height h and air pressure p, which correspond to the isobaric change of the AS height, Figure 1.13.

$$F_s = F_s(p,h), \ \ V_s = V_s(p,h). \tag{1.5}$$

UM uses both polynomial, in particular linear, and spline interpolation or extrapolation of the tabular data to get continuous functions (1.5) over the whole operation region of height and pressure.

A **dynamic load model** is the dependence of the force, pressure on height and volume in the case of the polytropic compression or depression of the AS bellow during change of its height. The model is computed for definite static load F_0 and height h_0, which can correspond to the equilibrium position of the UM object. Air mass inside the AS bellow is considered as constant, i.e. this is the model of an isolated AS.

$$F_d = F_d(h, F_0, h_0), V_d = V_d(h, F_0, h_0), p_d = p_d(h, F_0, h_0). \quad (1.6)$$

Let us consider an algorithm for computation of dynamic characteristics of AS (1.6).

- Compute static pressure p_0 from the nonlinear equation, which is the first of Eq. (1.5): $F_0 = F_s(p, h_0)$.
- Compute static volume from the second of Eq. (1.5): $V_0 = V_s(p_0, h_0)$.
- Compute static air mass from the law of the ideal gas for the given value of the temperature of environment T_e: $m_0 = p_0 V_0/(RT_e)$.
- Compute polytropic constant from Eq. (1.4): $c = p_0 \left(\frac{V_0}{m_0}\right)^n$.
- For each value of the height h compute V_d, p_d from the system of two nonlinear equations for the polytropic process (1.4) and the second of Eq. (1.5). Compute the force F_d from the first of Eq. (1.5).

This algorithms is applied to computation of AS force in the case of connection of the AS bellow with other chambers by pneumatic lines and orifices. The only difference consists in the variation of air mass inside the AS bellow, which is computed as

$$m = m_0 + \sum_i \int_0^t \dot{m}_i \, dt,$$

where $\dot{m}_i$ is the mass flow rate of the connected line or orifice i, Sect. 1.2.5 *Pneumatic lines*, 1.2.6. *Orifices*.

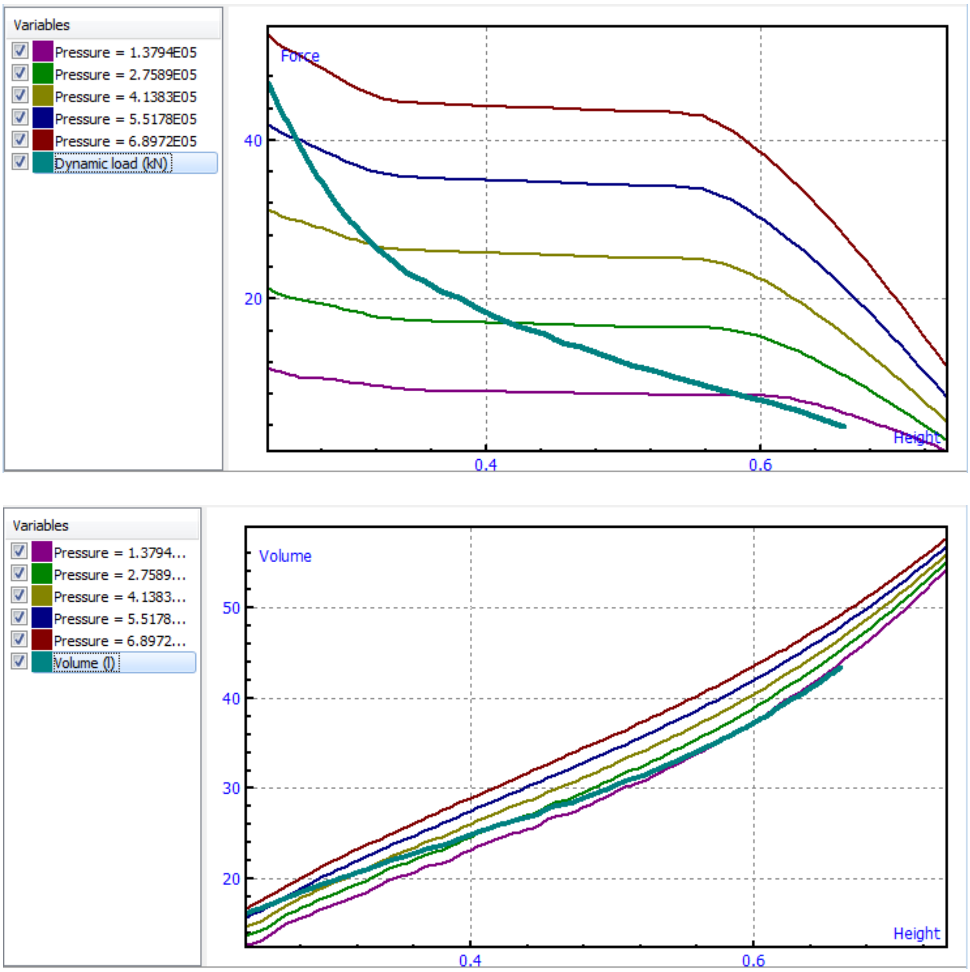


Figure 1.18. Force and volume for static and dynamic load, file 'Test data.ast'

Force and volume versus height for static and dynamic load are compared in Figure 1.18. Plots for dynamics load are drawn by thick lines. Results are computed for n = 1.38, $F_0 = 12$kN, h_0 = 0.5m.

Air spring specifications contain often a dependence of the volume on the height for one pressure only, Figure 1.7. Therefore, it is possible to use the simplified version of Eq. (1.5), when the dependence of the volume on the pressure is ignored:

$$F_s = F_s(p, h), \quad V_s = V_s(h). \tag{1.7}$$

The above algorithm is easily applied to this simplified case.

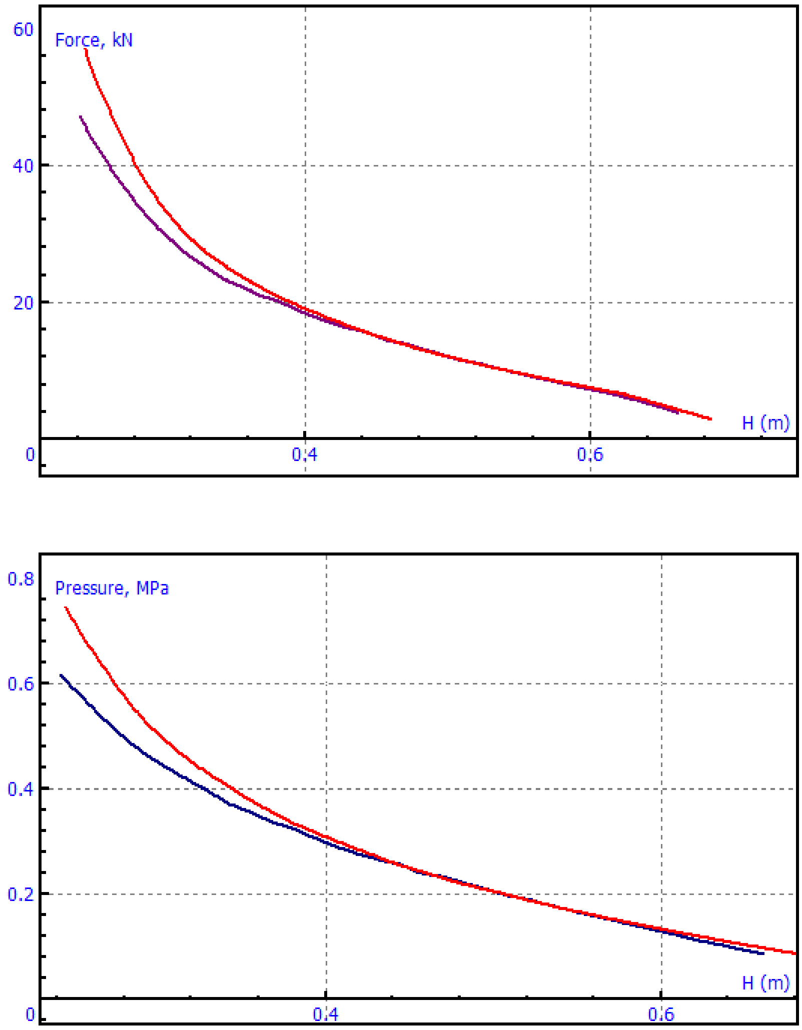


Figure 1.19. Comparison of force and pressure vs. height for dynamic load: full and simplified (red) models

Solutions for dynamic load in the case of the full AS tabular model (file 'Test data.ast') with a simplified model, where the force/height static load model is the same, but volume/height curve is used for one (the maximal) pressure only (file 'Test data 2.ast'). This example shows that the simplified model has results close to the full one in the region of heights near the static value h_0. The maximal deviation about 20% is observed for the low AS heights.

1.2.3.1.5. Verification of mathematical model

Compare mathematical model described in the previous section with the standard engineering calculation of dynamic load according to [5], [4]. Consider AS 1T15-M0 as an example. The dynamic load is computed in UM according to the algorithms described in the previous section for static load F_0 =18kN and static height h_0 = 0.2032m. Eq. (1.4) with polytropic index n=1.38 and a spline interpolation of tabular data form Figure 1.11 converted to SI (Figure 1.21) for Eq. (1.7) are used for dynamic load computation.

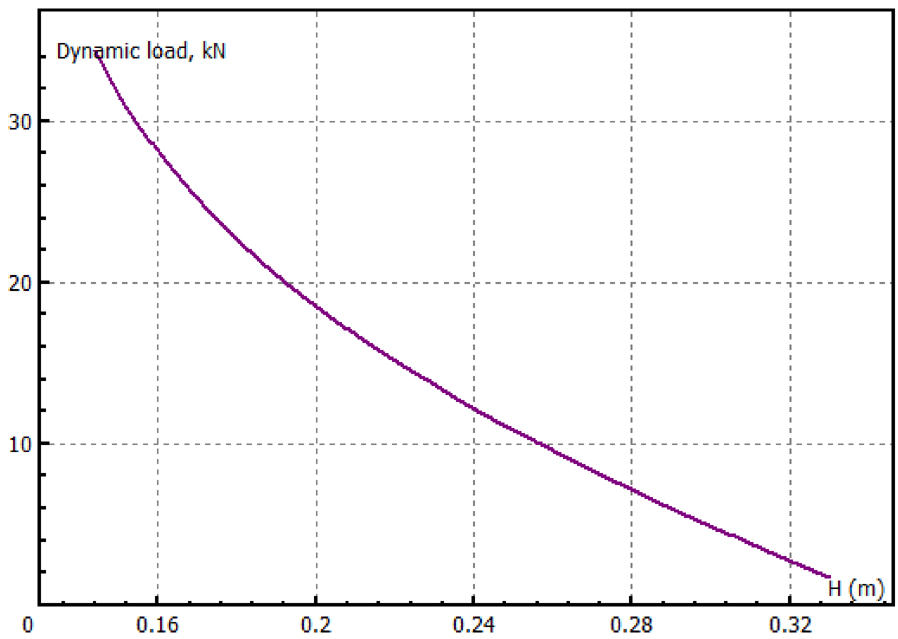


Figure 1.20. Dynamic load vs. height for AS 1T15-M0

H \ P	1.3794E5	2.7589E5	4.1383E5	5.5178E5	6.8972E5
0.10922	6727.5	13389	20478	27604	34929
0.127	6383.6	12707	19211	26053	32859
0.1524	6081.9	12212	18650	24997	31508
0.1778	5973.3	12031	18499	24871	31297
0.2032	5858.7	11790	18210	24515	30941
0.2286	5695.8	11331	17473	23598	29782
0.254	5339.8	10360	15862	21462	27218
0.2794	4368.4	8459.2	13250	18167	23573
0.3048	2829.8	5937.1	9859	14010	18843
0.3302	959.35	3047	5744	9153	12948

H \ P	6.8972E5
0.10922	0.0042417
0.127	0.0051394
0.1524	0.0063704
0.1778	0.0075925
0.2032	0.0087901
0.2286	0.0099478
0.254	0.011083
0.2794	0.012143
0.3048	0.012994
0.3302	0.013745

Force (N) Volume (m^3)

Figure 1.21. Data for 1T15-M0 in SI

Let us compute the dynamic load for two AS heights h_1 =0.1524m and h_2 =0.254m following the detailed instructions in design guide [5].

- Volume at static position from Figure 1.21: V_0 =0.0087901m^3;
- Force at h_0 = 0.2032m from the third column in Figure 1.21: F_{r0} =18210N;

- Pressure at $h_0 = 0.2032$m from the third column in Figure 1.21 p_r =413830Pa;
- Effective area at static position $A_0 = F_{r0}/p_r$= 0.0440036m^2;
- Gauge pressure at static position $p_{0g} = F_0/A_0$=409058Pa;
- Absolute pressure at static position $p_{0a} = p_{0g} + 101325$ =510383Pa;
- Volume at position 1 from Figure 1.21: V_1 =0.0063704m^3;
- Force at position 1 from the third column in Figure 1.21: F_{r1} =18650N;
- Effective area at position 1: $A_1 = F_{r1}/p_r$= 0.0450668m^2;
- Absolute pressure at position 1 from Eq. (1.4): $p_{1a} = p_{0a}(V_0/V_1)^{1.38}$=795898Pa;
- Gauge pressure at position 1: $p_{1g} = p_{1a} - 101325$ =694573Pa;
- Dynamic load at position 1: $F_1 = p_{1g}A_1$ =31302N;
- Volume at position 2 from Figure 1.21: V_1 =0.011083m^3;
- Force at position 2 from the third column in Figure 1.21: F_{r2} =15862N;
- Effective area at position 2: $A_2 = F_{r2}/p_r$= 0.0383297m^2;
- Absolute pressure at position 2 from Eq. (1.4): $p_{1a} = p_{0a}(V_0/V_2)^{1.38}$=370664Pa;
- Gauge pressure at position 2: $p_{2g} = p_{2a} - 101325$ =269339Pa;
- Dynamic load at position 2: $F_2 = p_{2g}A_2$ =10324N;

Now we get load values from UM graphic window by mouse picking:

$$F_{1UM} = 31756\text{N},\ F_{2UM} = 10125\text{N},$$

which gives the deviation 1.4% and 1.9% from the above values F_1, F_2.

1.2.4. Simple nodes

A simple node is a connection of any number of pneumatic lines. The simple node has two state variables: pressure and temperature. Let *i* be the index of a simple node and $\dot{m}_{ij}$ are the mass flow rate of line *l* connected to the node. The mass flow rate is positive $\dot{m}_{il} > 0$, if the flow comes into the node, i.e. the node pressure p_i is lower than the pressure of another chamber or node adjusted to the line. The mathematical model of the node corresponds to the Kirchhoff's law

$$\sum_l \dot{m}_{il} = 0. \tag{1.8}$$

1.2.5. Pneumatic lines

A line connects two nodes *i*,*j*, each of them is a chamber or a simple node. The line length is *L*, the diameter is *d* or *D*.

A *stationary* line model includes a dependence of the mass flow rate on the pressure drop

$$\Delta p = p_1 - p_2 \tag{1.9}$$

where $p_1 = \max(p_1, p_2)$, $p_2 = \min(p_1, p_2)$.

A *time domain* line model is described by a system of partial differential equations for the pressure and the mass flow rate

$$p = p(x,t), \dot{m} = \dot{m}(x,t),$$

where *x* is the longitudinal coordinate along the line.

Below we consider both stationary and dynamic models for the line, which are implemented in UM.

1.2.5.1. Stationary pipeline models

1.2.5.1.1. Mass flow rate model "Atlas"

The model is based on the ISO 6358 nozzle model for the flow rate [8]

$$\dot{m} = \begin{cases} p_1 C \rho_0 \sqrt{\frac{T_0}{T_1}} \sqrt{1 - \left(\frac{\frac{p_2}{p_1} - b}{1 - b} \right)^2}, & \frac{p_2}{p_1} > b \\ p_1 C \rho_0 \sqrt{\frac{T_0}{T_1}}, & \frac{p_2}{p_1} \le b \end{cases} \quad (1.10)$$

where C is the sonic conductance, b is the critical pressure ratio, T_1 the temperature in the node 1 (K), and ρ_0, T_0 are the reference density (kg/m^3) and temperature (K) (1.1).

The "Atlas" model [9] includes empirical formulas for the C, b parameters

$$C = \frac{0.029\mathrm{D}^2}{\sqrt{\frac{L}{D^{1.25}} + 510}}, b = \frac{474C}{D^2}. \quad (1.11)$$

It is known a disadvantage of the ISO 6358 model from the computation point of view: the derivative of the mass flow rate tends to infinity when the pressure drop goes to zero,

$$\frac{d\dot{m}}{d\Delta p} \xrightarrow[\Delta p \to 0]{} \infty. \quad (1.12)$$

This fact results in problems for numerical methods. Following to suggestion in [8], we replace the model (1.10) with the linear one in the region of the laminar flow. Let us derive the critical value of the ratio $r_b = p_2/p_1$ corresponding to Re*=2000.

$$\dot{m}^* = A\rho_1 w^* = \frac{A\mu \mathrm{Re}^*}{D} = p_1 C \rho_0 \sqrt{\frac{T_0}{T_1}} \sqrt{1 - \left(\frac{r_b^* - b}{1 - b} \right)^2} \approx p_1 C \rho_0 \sqrt{1 - \left(\frac{r_b^* - b}{1 - b} \right)^2},$$

$$r_b^* = b + (1 - b) \sqrt{1 - \left(\frac{A\mu \mathrm{Re}^*}{DC\rho_1} \right)^2} \approx 1 - 0.5(1 - b) \left(\frac{A\mu \mathrm{Re}^*}{Dp_1 C \rho_0} \right)^2.$$

Here A is the line section area. Consider an example: for a line with L=10m, D=5mm, $p_1 = p_0$ we obtain $r_b^* \approx 0.991$. The laminar flow model is

$$\dot{m} = \dot{m}^* \frac{1 - r_b}{1 - r_b^*}, \qquad r_b = \frac{p_2}{p_1} > r_b^*. \quad (1.13)$$

1.2.5.1.2. Mass flow rate model "Fluid mechanics"

This model is based on the fluid energy equation, [10]

$$\ln \frac{w_1}{w_2} + \frac{p_2^2 - p_1^2}{2p_1 \rho_1 w_1^2} + \frac{\lambda(w_1)L}{2D} = 0 \quad (1.14)$$

where w is the flow velocity, and $\lambda(w_1)$ is the friction factor, depending on the Reynolds number

$$\mathrm{Re} = \frac{\rho_1 D w_1}{\mu}.$$

For the laminar flow [8]

$$\lambda = \frac{64}{\mathrm{Re}}, \mathrm{Re} < 2000. \quad (1.15)$$

In the case of a turbulent flow, the Blasius equation is used

$$\lambda = \frac{0.3164}{\mathrm{Re}^{0.25}}, \mathrm{Re} > 4000 \tag{1.16}$$

or the Nikuradse–Prandtl–Karman (NPK) implicit equation

$$\frac{1}{\sqrt{\lambda}} = 2\log\left(\mathrm{Re}\sqrt{\lambda}\right) - 0.8. \tag{1.17}$$

We use the linear interpolation of the friction factor between the boundary values computed according to Eq. (1.15) and (1.16) or (1.17) for $\mathrm{Re} \in [2000, 4000]$.

In addition, we assume that

$$\frac{w_1}{w_2} \approx \frac{p_1}{p_2}$$

and Eq. (1.14) can be rewritten as

$$w_1 = \sqrt{\frac{p_1^2 - p_2^2}{2p_1\rho_1\left(\frac{f(w_1)L}{2D} + \ln\frac{p_1}{p_2}\right)}} \tag{1.18}$$

Eq. (1.18) is the nonlinear function of the flow velocity w_1. It can be solved by direct iterations.

The mass flow rate is then computed as

$$\dot{m} = \mathrm{A}\rho_1 w_1 = \frac{\pi D^2}{4}\rho_1 w_1 \tag{1.19}$$

1.2.5.1.3. Darcy-Weisbach equation

The Darcy-Weisbach equation [11] is a relation between the head loss h in a pipe and the average flow velocity *w*

$$h = \frac{(p_1 - p_2)}{\rho_1 g} = \frac{fL}{D}\frac{w_1^2}{2g}$$

or

$$w_1 = \sqrt{\frac{2D(p_1 - p_2)}{f(w_1)\rho_1 L}}. \tag{1.20}$$

The Darcy friction factor f is obtained from the Rose or Moody diagrams [11], [12], Figure 1.22. It requires an additional parameter: the relative pipe roughness

$$\frac{\varepsilon}{D}. \tag{1.21}$$

The nonlinear equation (1.20) is solved by direct iterations to find the flow velocity w_1. Finally, Eq. (1.19) gives the mass flow rate.

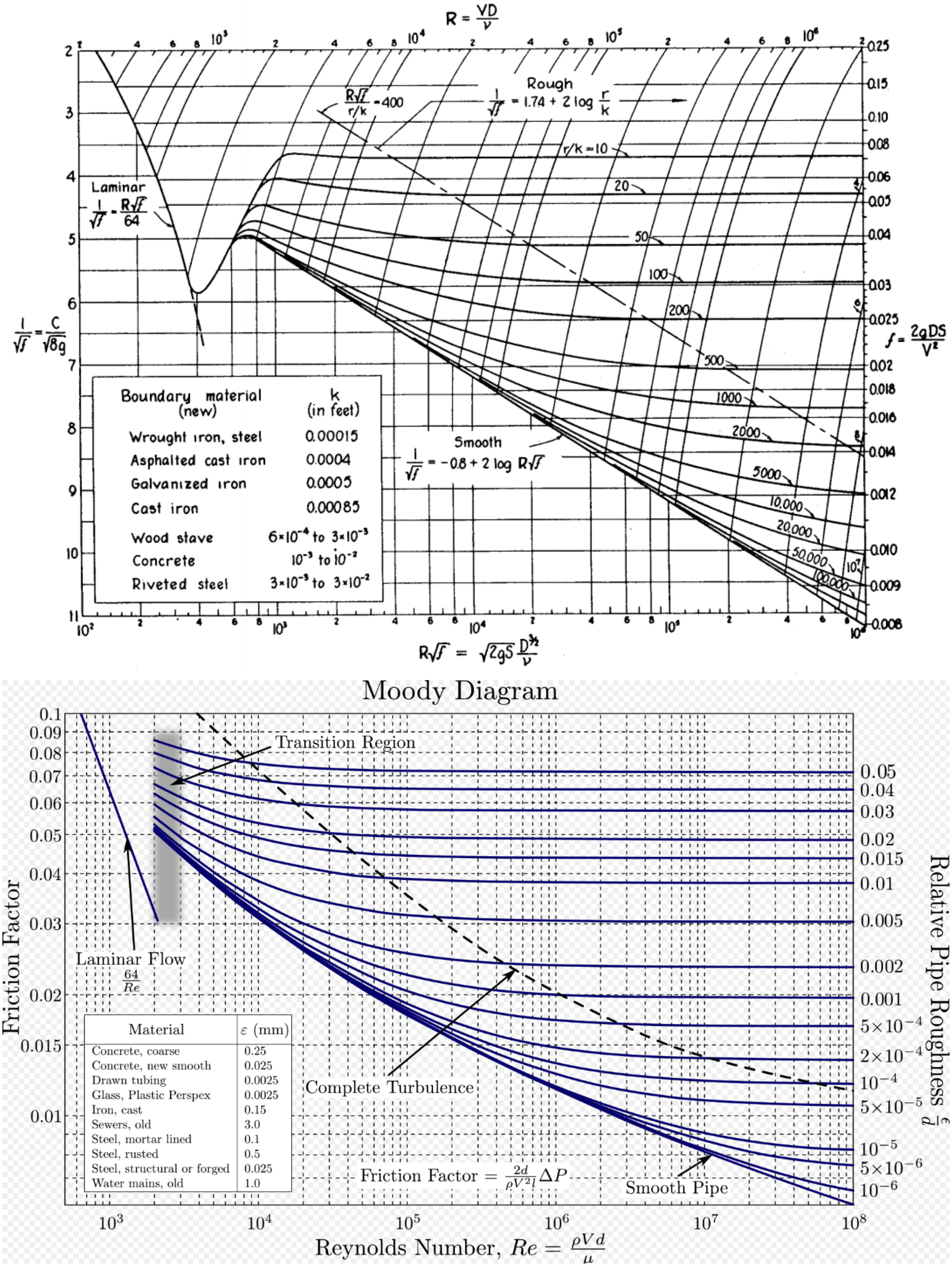


Figure 1.22. Rose and Moody diagram for friction factor

1.2.5.1.4. Comparison of models

"Atlas" and "Fluid mechanics" mass flow rate equations give similar result for different length of lines, Figure 1.23. The Darcy-Weisbach equation can be used as well for long lines if the pipe roughness is $\varepsilon/D\sim0.01$ for $p_2\sim0$ and $\varepsilon/D\sim0$ for $p_2\sim5$ bar. The laminar flow region with a linear grows of the flow rate is shown in Figure 1.24 for a small pressure drop.

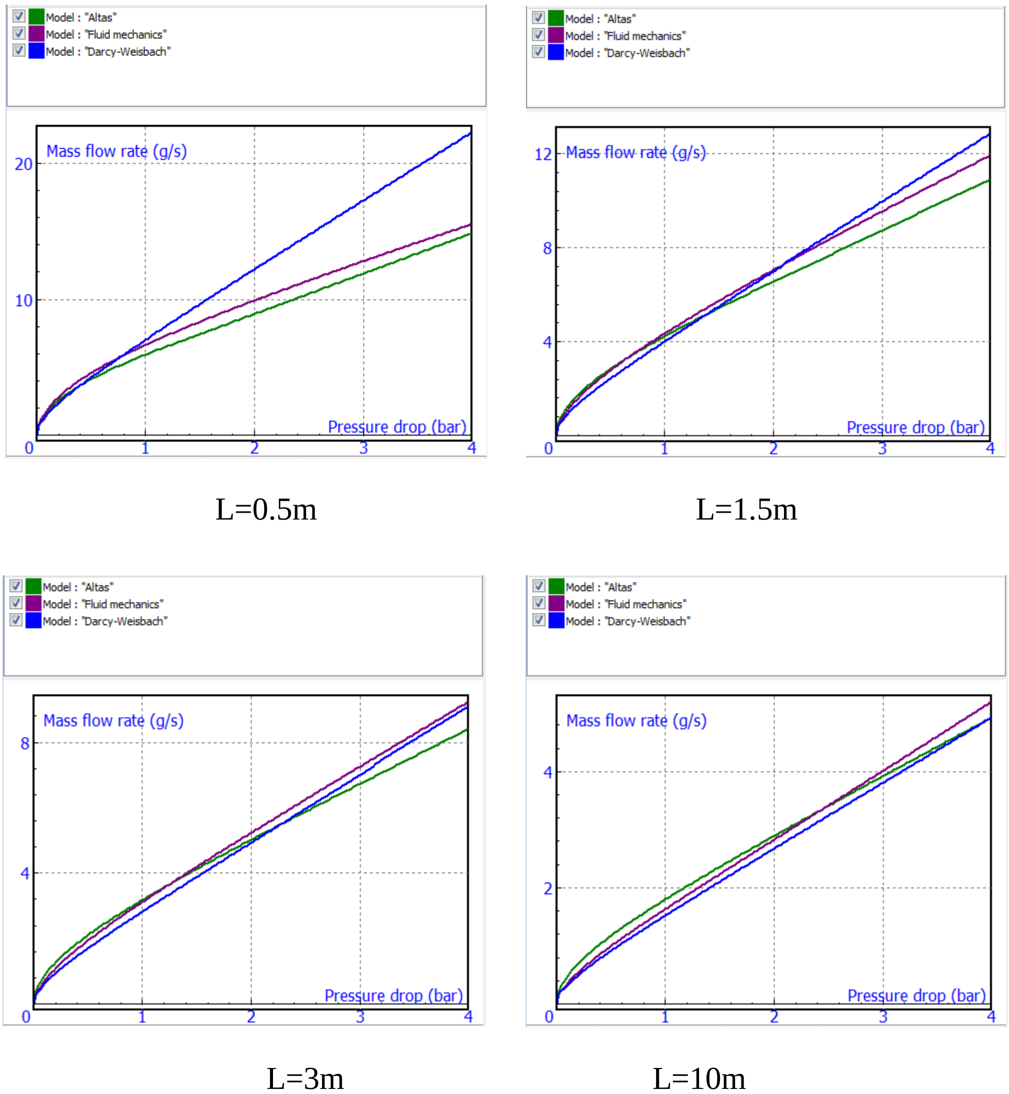


Figure 1.23. Comparison of mass flow rate models for different line length, D=5mm.

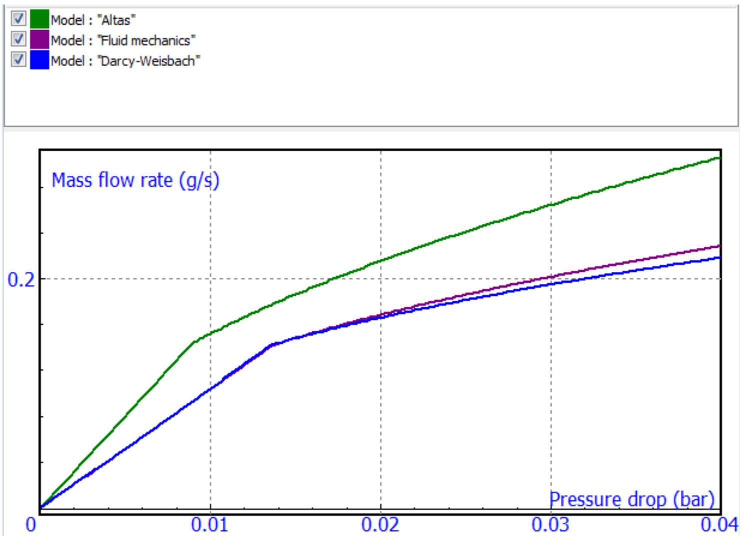


Figure 1.24. Comparison of mass flow rate models for small pressure drop, L=10m, D=5mm.

1.2.5.2. Dynamic pipeline model

It is known that the stationary model of a pipeline flow can be used for the low frequency processes only [8]. In contrary, the time domain model, which we consider here, can be applied both for low and for high frequencies. The model cannot be used for description of supersonic processes and shock waves.

1.2.5.2.1. Mathematical model

The dynamic pipeline model implemented in UM is a slightly generalized version of the model described in [8]. Firstly, the model includes the continuity equation

$$\frac{\partial\rho}{\partial t}+\frac{\partial\rho w}{\partial x}=\frac{\partial\rho}{\partial t}+w\frac{\partial\rho}{\partial x}+\rho\frac{\partial w}{\partial x}=\frac{d\rho}{dt}+\rho\frac{\partial w}{\partial x}=0, \tag{1.22}$$

where w is the flow velocity, and ρ is the density.

It is assumed that the polytropic process take place for the air inside the pipeline,

$$p\rho^{-n}=c=\text{const}. \tag{1.23}$$

Differentiation of Eq. (1.23) with respect to t gives

$$\rho^{-n}\frac{dp}{dt}-np\rho^{-n-1}\frac{d\rho}{dt}=0$$

or

$$\frac{d\rho}{dt}=\frac{\rho}{np}\frac{dp}{dt} \tag{1.24}$$

Substituting Eq. (1.24) in Eq. (1.22) and assuming

$$\frac{\partial\dot m}{\partial x}=\frac{\partial A\rho w}{\partial x}\approx A\rho\frac{\partial w}{\partial x}$$

we obtain the first equation

$$\frac{dp}{dt}+\frac{np}{A\rho}\frac{\partial\dot m}{\partial x}=0 \tag{1.25}$$

In [8] an isothermal process for the long lines is assumed, which can be obtained from Eq. (1.25) for polytropic index n=1 and taking into account the ideal gas law $p=\rho RT$.

The second equation is derived in [8] and corresponds to the equation of motion of a short section

$$\frac{d\dot m}{dt}+\mathrm{A}\frac{\partial p}{\partial x}=-A\frac{\lambda\rho}{2D}w^2. \tag{1.26}$$

Here λ is the friction factor, see Sect. 1.2.5.1.2 *Mass flow rate model "Fluid mechanics"*, and D, A are the diameter and section area of the pipe.

Following [8], consider an algorithm for numerical solving Eq. (1.25), (1.26). The line is divided into N segments of the equal length $\Delta L=L/N$. The continues variables $p=p(x,t),\dot m=\dot m(x,t)$ are replaced by the discrete variables at the segment ends

$$p_i=p(x_i,t),\quad \dot m_i=\dot m(x_i,t),$$
$$x_i=\Delta Li,\qquad i=0,\dots,N.$$

The partial derivatives with respect to the coordinate x are replaces by the left or right finite differences (the right differences are written below)

$$\left.\frac{\partial p}{\partial x}\right|_{x=x_i}=\frac{p_{i+1}-p_i}{\Delta L},\qquad \left.\frac{\partial\dot m}{\partial x}\right|_{x=x_i}=\frac{\dot m_{i+1}-\dot m_i}{\Delta L}$$

and the following system of ordinary differential equations are solved by UM

$$\frac{dp_i}{dt} = -w_i \frac{p_{i+1} - p_i}{\Delta L} - \frac{np_i}{A\rho_i \Delta L}(\dot{m}_{i+1} - \dot{m}_i) \tag{1.27}$$

$$\frac{d\dot{m}_i}{dt} = -w_i \frac{\dot{m}_{i+1} - \dot{m}_i}{\Delta L} - A\frac{p_{i+1} - p_i}{\Delta L} - A\frac{\lambda_i \rho_i}{2D} {w_i}^2$$

Equations (1.27) are written with the right finite differences. If necessary, they are replaced by the left ones, e.g. for $i = N$. The number of equations depends on boundary conditions. For example, if the pipeline connects two chambers, the pressure at begin and end of the pipeline are equal to the chamber pressures, and the pressure equations for $i = 0$ and $i = N$ are omitted. The total number of equations in this case is $2N$.

1.2.5.2.2. Verification of time domain model

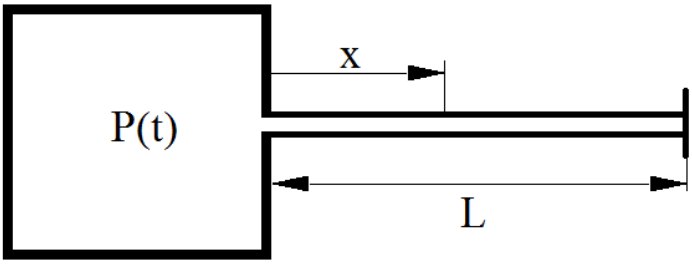


Figure 1.25. Sketch of experimental equipment for verification of time domain model of pipeline

Following to the book [8], consider simulation of the flow dynamics in a long pipe according to the experimental equipment in Figure 1.25. The inlet pressure of the pipe is a given function of time $p(0) = P(t)$, while the opposite end is locked. Consider comparison of simulation and experimental results for $p(L)$ when either step or harmonic functions are considered as $P(t)$. For the test we use the UM tool described in Sect. 1.3.2.3.3 *Player for time domain pipeline model*.

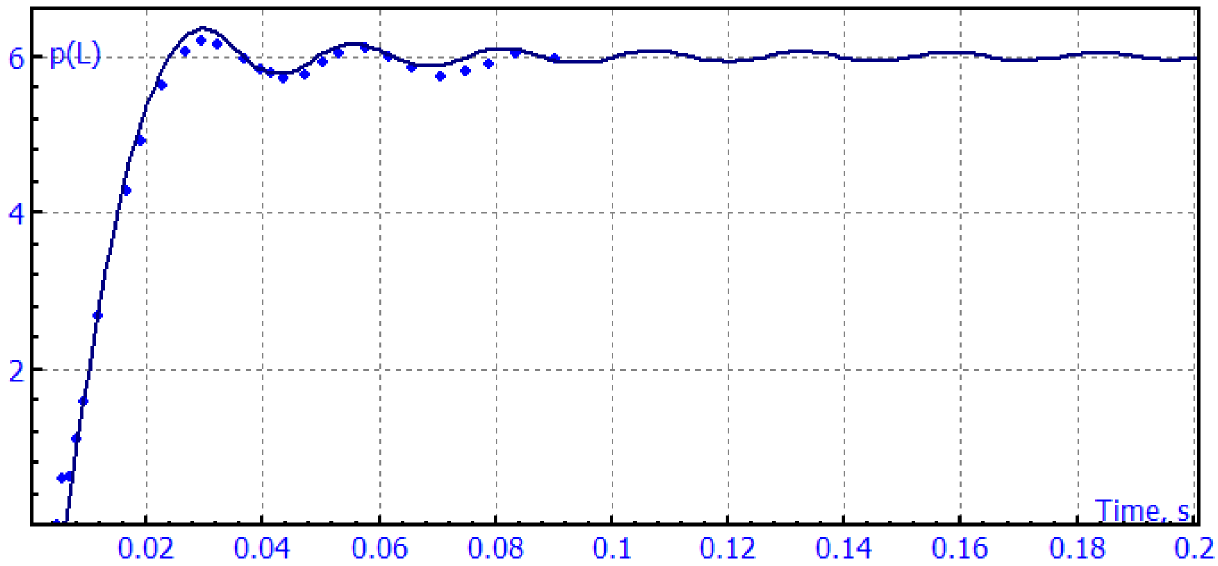


Figure 1.26. Step response. Comparison with experiment

Firstly, consider the step response, where the step function is approximated by the following expression:

$$P(t) = P_0\left(1 - e^{-t/T_s}\right)$$

with $P_0 = 6$ bar and $T_s = 0.005$ s. Comparison of simulation with experimental results from [8] is shown in Figure 1.26. The value of the polytropic index in this test is $n = 1.08$.

The next two tests are related to the response to harmonic excitations. In simulation we use the gliding frequency excitation

$$P(t) = P_0 + \Delta P \sin(2\pi(f_0 + \epsilon t/2)t).$$

In particular, the test allows us to compare the natural frequencies of the air in the pipeline with experimental and theoretical values. The theoretical natural frequencies of air in a pipeline in Figure 1.25 are

$$f_i = \frac{ic}{4L}, i = 1,3,5 \ldots$$

Here c is the sound velocity

$$c = \sqrt{\gamma \frac{p}{\rho}}$$

with γ=1.4.

Following the book [8] we consider two tests:

1. L = 1m, D = 2.5mm, $P_0 = 7$bar, $\Delta P = 0.1$bar, N = 15
2. L = 25m, D = 5.5mm, $P_0 = 7$bar, $\Delta P = 0.1$bar, N = 35

The first natural theoretical frequencies f_1 are 85.8Hz for Case 1 and 3.43Hz for Case 2.

Comparison of simulation and experimental results for the gain factor $(P(L) - P_0)/\Delta P$ is given in figures below. Experimental data from [8] are plotted by the marker.

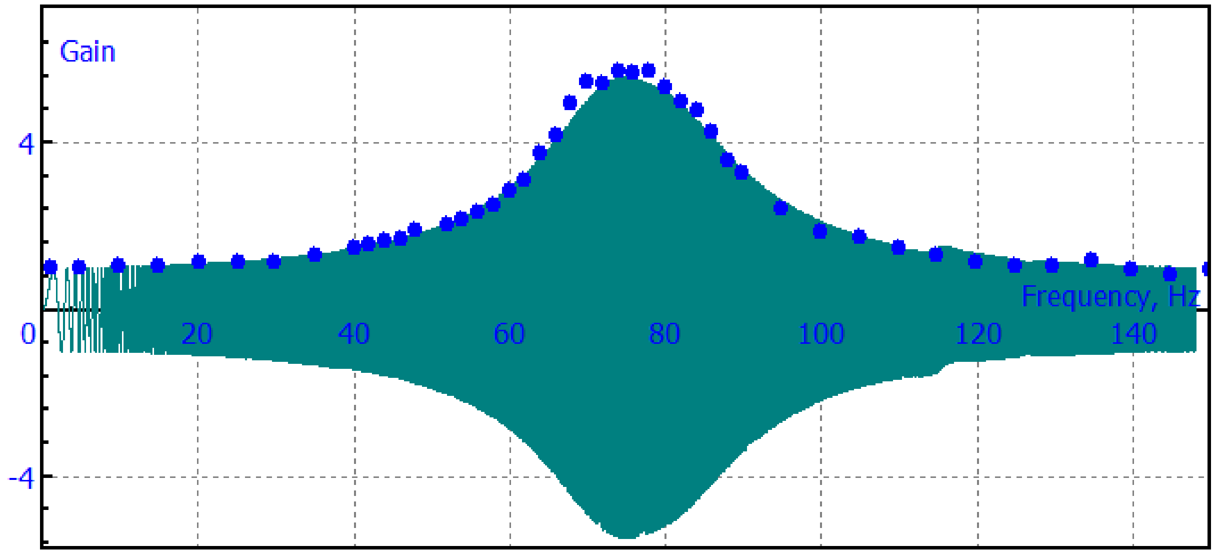


Figure 1.27. Frequency response for Case 1, the value of polytropic index n = 1.2

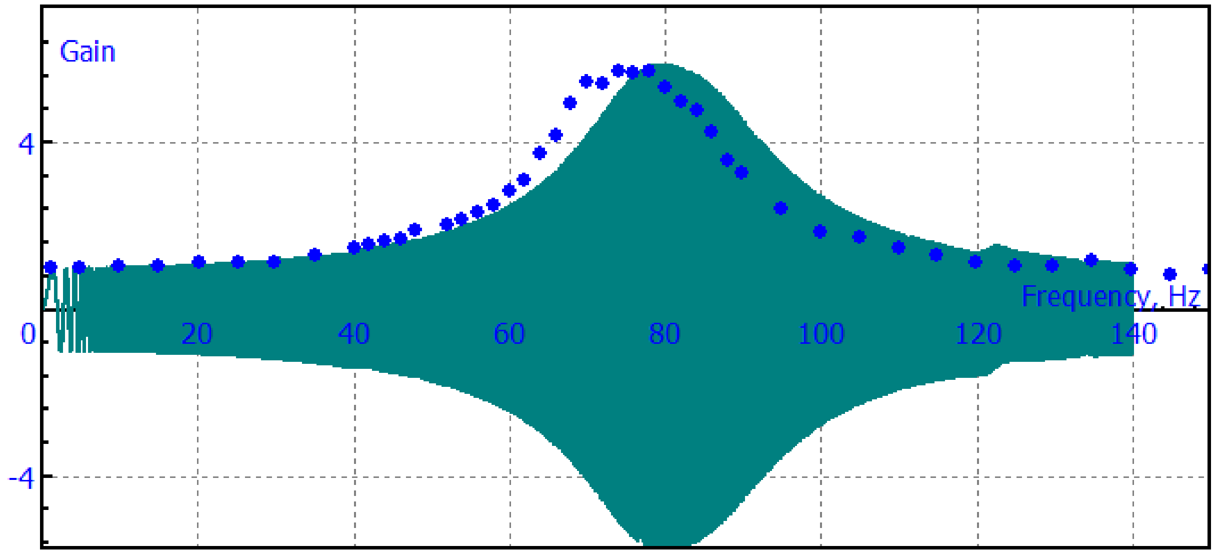


Figure 1.28. Frequency response for Case 1, the value of polytropic index $n = 1.4$

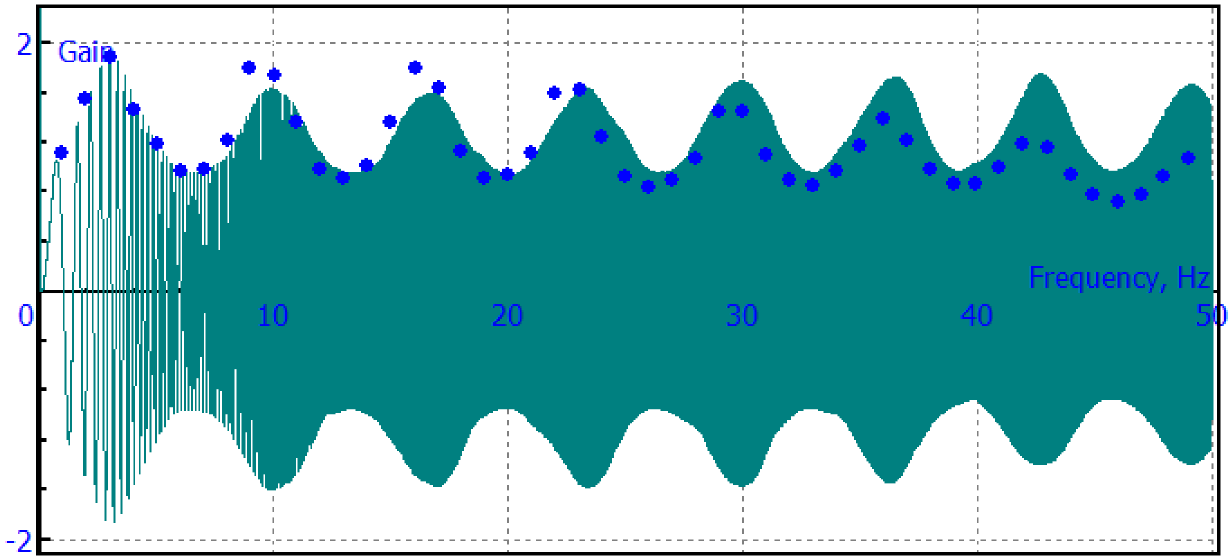


Figure 1.29. Frequency response for Case 2, the value of polytropic index $n = 1.4$

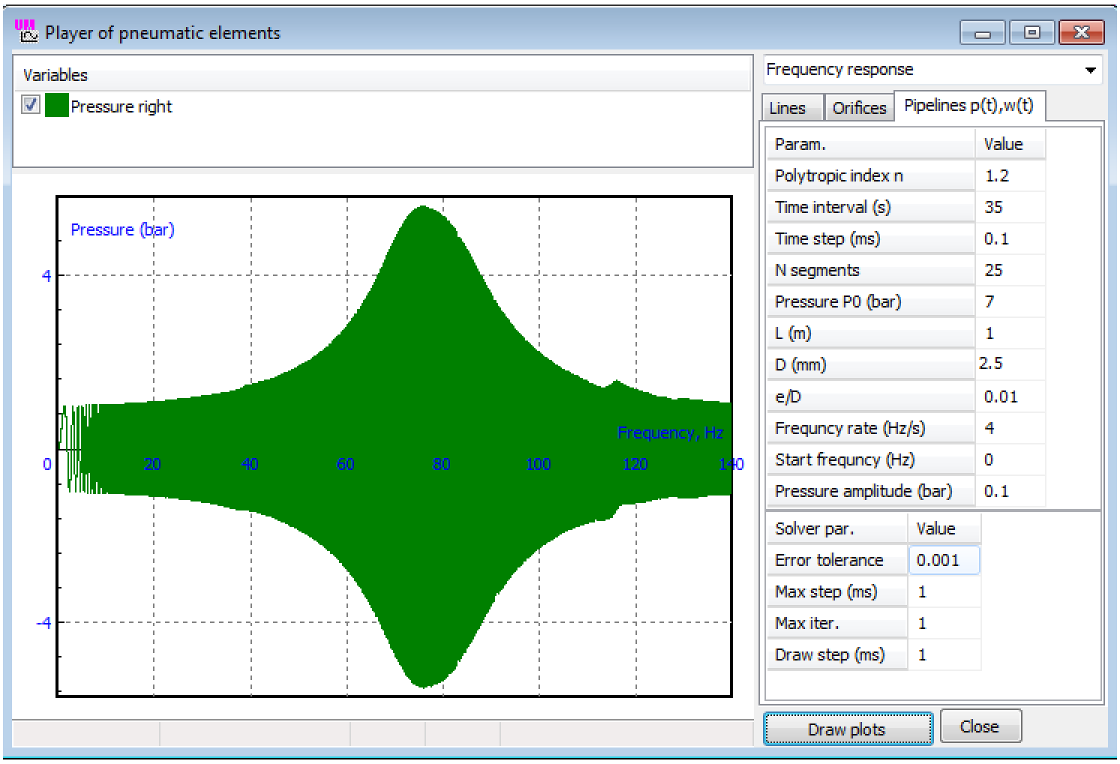


Figure 1.30. Simulation options for Case 1

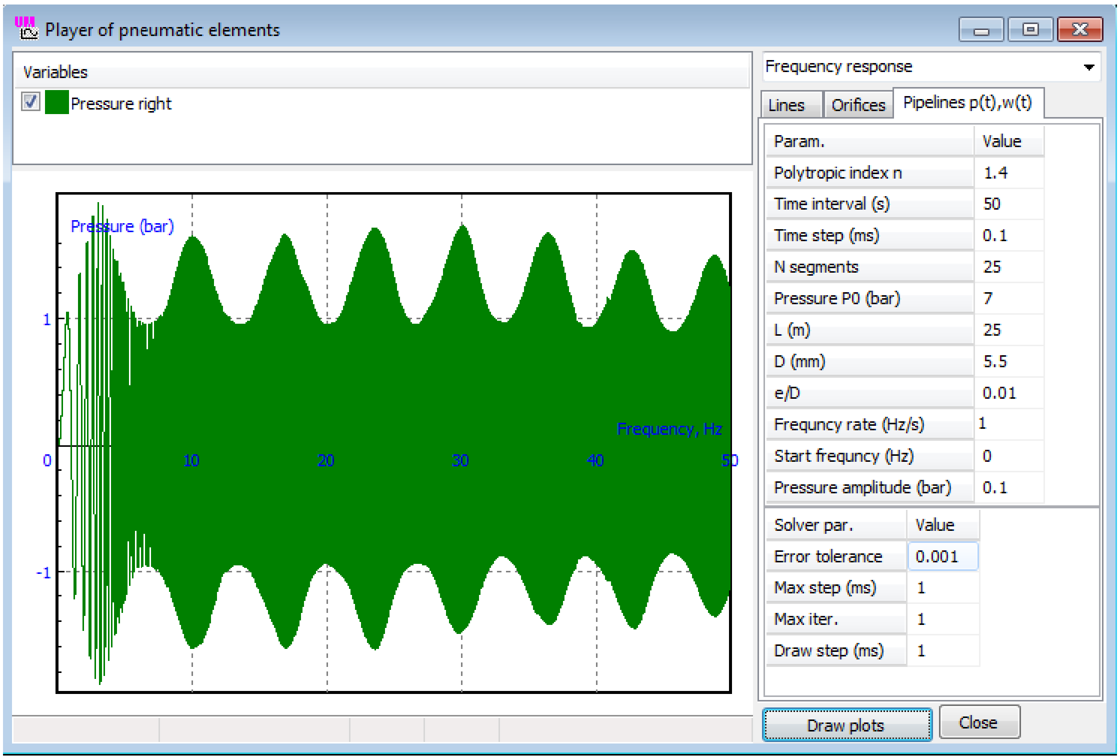


Figure 1.31. Simulation options for Case 2

1.2.6. Orifices

Similar to a line, an orifice (nozzle, valve) is a connection between two nodes of pneumatic system. The mathematical model of the orifice includes a dependence of the mass flow rate on the pressure drop.

1.2.6.1. Nozzle

Let $p_1 > p_2$ be the pressures in the connected nodes. Then the mass flow rate for a nozzle is computed as [8]

$$\dot{m} = AC_d p_1 \sqrt{\frac{2}{RT_1}}\psi(r_p), \tag{1.28}$$

$$\psi(r_p) = \begin{cases} \sqrt{\frac{\gamma}{\gamma-1}\left(r_p^{2/\gamma} - r_p^{(\gamma+1)/\gamma}\right)}, r_p > b \\ \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}}\sqrt{\frac{\gamma}{\gamma+1}} = 0.484, r_p \le b \end{cases}$$

$$b = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} = 0.528$$

$$r_p = \frac{p_2}{p_1}.$$

Here $\gamma = 1.4$, A is the nozzle area, C_d is the discharge coefficient. The parameters are given in SI (Pa, m^2, m^3).

The discharge coefficient $C_d \le 1$ depends on the nozzle geometry. In particular, for the well rounded nozzle $C_d = 1$. Values of this parameter for different sharp nuzzles can be found in [8].

Laminar flow.

Similar to the ISO 6358 model, the derivative of the mass flow rate tends to infinity when the pressure drop goes to zero (1.12). Consider Eq. (1.28) for small pressure drop

$$r_p = 1 - \epsilon, \epsilon \ll 1$$

and derive the pressure ratio for the boundary Reynolds number Re^*=2000.

$$\psi(r_p) = \sqrt{\frac{\gamma}{\gamma-1}\left((1-\epsilon)^{2/\gamma} - (1-\epsilon)^{(\gamma+1)/\gamma}\right)} \approx \sqrt{\frac{\gamma}{\gamma-1}(-\epsilon\, 2/\gamma + \epsilon\,(\gamma+1)/\gamma)} = \sqrt{\epsilon},$$

$$\mathrm{Re}^* = \frac{\dot{m}^* D}{A\mu} = \frac{AC_d p_1 D}{A\mu}\sqrt{\frac{2}{RT_1}}\sqrt{\epsilon^*},$$

$$r_p^* = 1 - \epsilon^* = 1 - \frac{RT_1}{2}\left(\frac{A\mu \mathrm{Re}^*}{AC_d p_1 D}\right)^2.$$

The final expression for the laminar region is

$$\dot{m} = \dot{m}^* \frac{1 - r_b}{1 - r_b^*},\;\; r_b = \frac{p_2}{p_1} > r_b^*, \tag{1.29}$$

$$\dot{m}^* = AC_d p_1 \sqrt{\frac{2\epsilon^*}{RT_1}}.$$

Example for a circular orifice D = 5mm: ϵ^* ≈0.00022, $r_b^* \approx 0.99978$.

1.2.6.2. ISO 6358

The ISO 6358 model for the flow rate [8] is already used above in Sect. 1.2.5.1.1 *Mass flow rate model "Atlas"*, Eq. (1.10). Here we point out that for the "Orifice" element we use this model in two forms:

- **Standard**. The user should set the numerical value of the sonic conductance *C*, and the critical pressure ratio *b*.
- The ratio C/d^2 model for an restriction offered in [13], [14]:
  $\frac{C}{d^2}$ = 8 $dm^3/(min\cdot bar\cdot mm^2)$ = 1.33×10^{-9} $m^3/(s\cdot Pa\cdot mm^2)$

1.2.6.3. Comparison of orifice models

The nozzle model for definite values of the discharge coefficient C_d and the pressure ratio b give results very close to those from Sect. 1.2.6.2 ISO 6358. To obtain the correspondence of the parameters C_d and C, consider condition of the equal choked flow at $p_2/p_1 = b$ for Eqs. (1.10) and (1.28)

$$p_1 C \rho_0 \sqrt{\frac{T_0}{T_1}} = AC_d p_1 \sqrt{\frac{2}{RT_1}} \psi(b) = \frac{1}{4}\pi d^2 10^{-6} C_d p_1 \sqrt{\frac{2}{RT_1}} 4.84,$$

$$\frac{C}{d^2} = 0.121 \cdot 10^{-6} \frac{\pi}{\rho_0} \sqrt{\frac{2}{RT_0}} = 1.539 \cdot 10^{-9} C_d$$

The orifice diameter in this formula is measured in millimeters.

Thus, the nozzle model gives similar results with the ISO 6358 ratio C/d^2 model from the previous section for the following value of the discharge coefficient, Figure 1.32:

$$C_d = 0.866.$$

Models are compared for small pressure drop in Figure 1.33 to illustrate the region of the laminar flow.

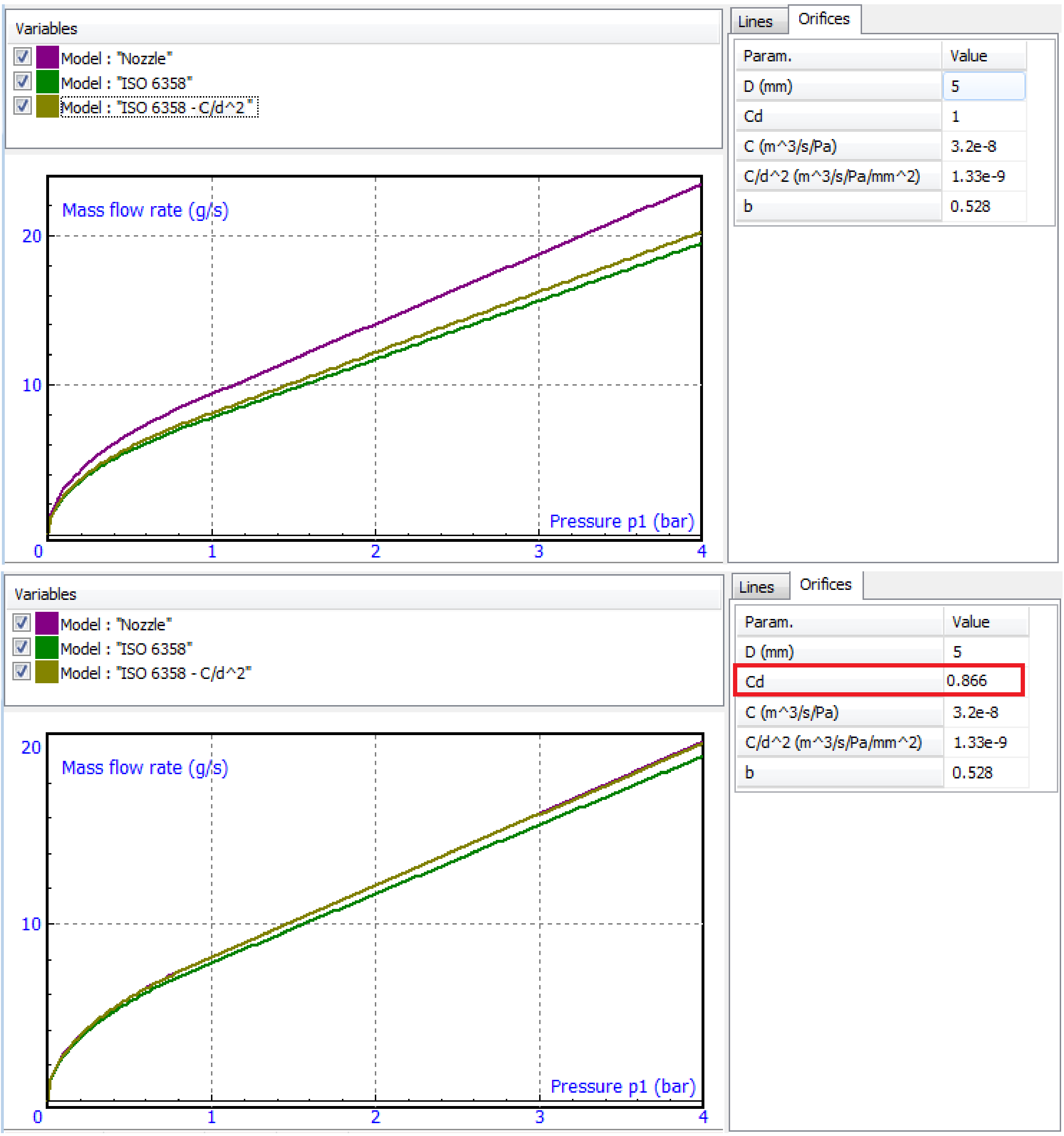


Figure 1.32. Comparison of mass flow rate for different orifice models

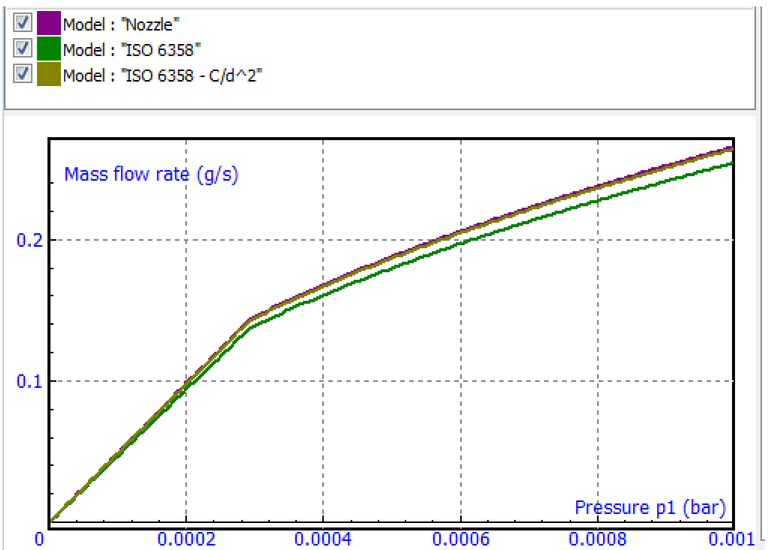


Figure 1.33. Comparison orifice models for small pressure drop

1.2.7. Valves

1.2.7.1. Height control valves (HCV)

Figure 1.34.Examples of HCV

A height control valve or leveling valve is used in automotive and railway industry for supporting a desired value of the suspension height when the load changed.

HCV is a 3/3 valve, i.e. it has three ways and three positions. The ports are

1 – connecton to supply air line;

2 – delivery air line to suspension;

3 – exhaust port.

Positions are

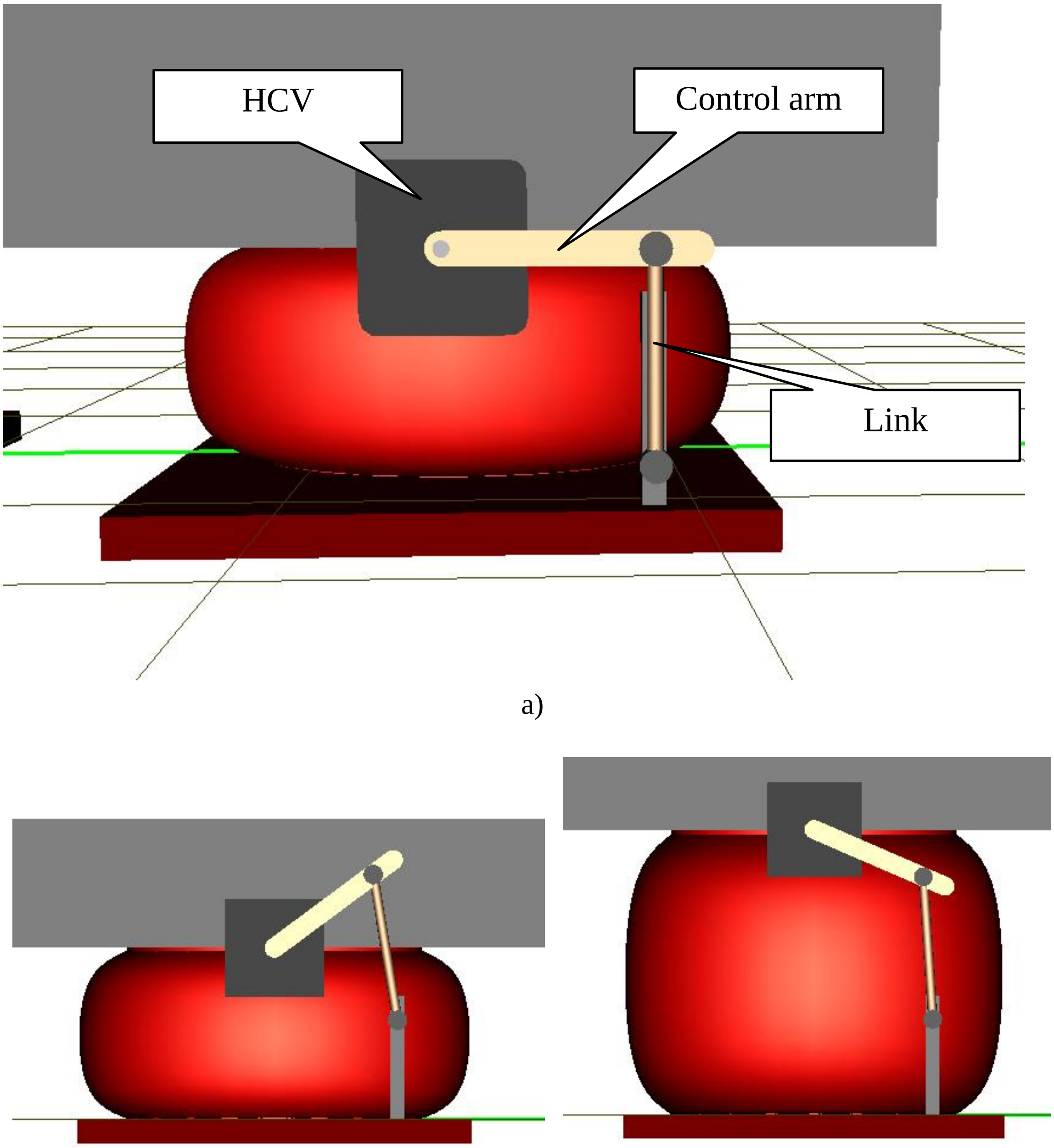
1 – all lines are closed;

2 – connects lines 1-2, the pressure in the suspension is increased;

3 – connects lines 2-3, the pressure in the suspension is decreased.

In Positions 2 and 3 the flow though the valve is changed continuously by the control arm, Figure 1.35. Ports 1, 3 are closed in the neutral arm position (the dead band). Rotation of the arm in one direction opens the supply port; rotation in another direction opens the exhaust port.

The HCV is usually mounted on the truck or rail vehicle frame. The control arm is connected to the truck axle or to a bogie frame by a link, Figure 1.35. The link length should be chosen so that the neutral control arm position corresponds to the desired height of the suspension. In the case of a lower suspension position, the control arm must open the supply line to increase the pressure in air springs.



a)

b) c)

Figure 1.35. UM model with HCV in the neutral a), supply b) and exhaust c) positions

1.2.7.1.1. HCV flow curve

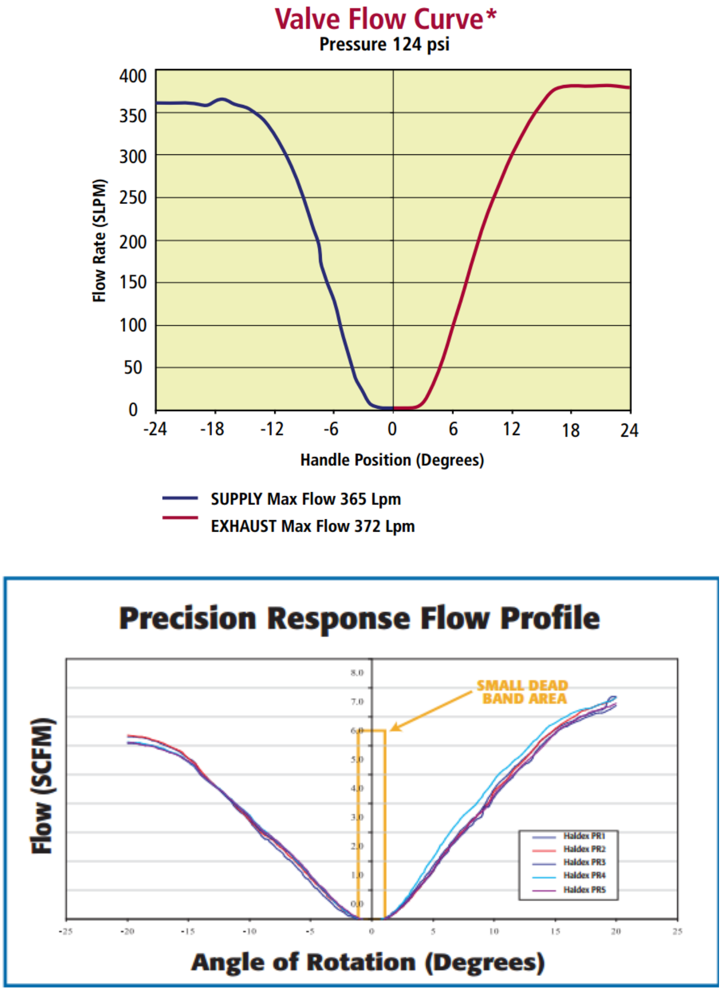


Figure 1.36. Examples of flow rate curves

The main HCV characteristic is the dependence of the volume flow rate on the control arm angle δ for the given value of pressure drop p^*. Figure 1.36 shows examples of the volume flow rate curves for valves produced by Hendrickson and Haldex companies. Files with information about these valves are available at the links

https://www.hendrickson-intl.com/getattachment/2c9528e0-ca6d-47ec-aad6-94343380cca0/L1024.pdf.

http://www.heightcontrolvalve.com/docs/Haldex/Precision-Response-HCV-Product-Information.pdf

The supply and exhaust ports are closed at the neutral arm position (the dead band). Rotation in one direction (the negative angle in Figure 1.36) opens the line connecting the suspension to the reservoir with compressed air to increase the pressure in air springs and to raise the suspension. Rotation in the opposite direction (the positive angle in Figure 1.36) opens the exhaust port to decrease the pressure and the suspension height.

1.2.7.1.2. Mathematical model of HCV

The valve mathematical model is based on the mass flow rate formula for a nozzle Eq. (1.28)

$$\dot{m} = C(\delta) p_1 \sqrt{\frac{2}{RT_1}} \psi(r_p),$$

The discharge coefficient $C(\delta)$ is expressed in terms of the dependence $\dot{m}(\delta)$ of the mass flow rate on the angle, which is derived from the curve similar to Figure 1.36,

$$C(\delta) = \frac{\dot{m}(\delta)}{p^* \psi^*} \sqrt{\frac{RT^*}{2}},$$

$$\psi^* = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \sqrt{\frac{\gamma}{\gamma+1}} = 0.484.$$

Here p^*, T^* are the absolute pressure and temperature (K) for which the HCV flow curve is obtained.

1.2.7.1.3. Generation of UM files *.hcv with models of height control valves

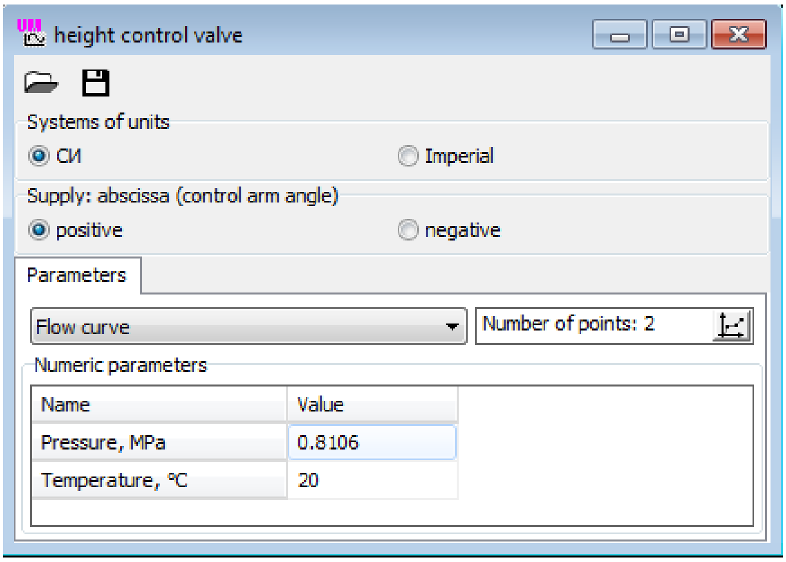


Figure 1.37. Window for generation of HCV model

HCV models should be stored as *.hcv files. These files are located in the directory **{UM Data}\AirSpring**

For example
c:\Users\Public\Documents\UM Software Lab\Universal Mechanism\2023\AirSpring\

System of units. The volume flow rate should be set in SLPM (standard liter per minute). Pressure is measured in MPa (SI) or psi (the Imperial system)

To create a file

- Run UM Simulation;

- Use the **Tools | Pneumatic elements | Height control valves…** menu command to open the HCV window, Figure 1.37;
- In necessary, change the system of units;
- Prepare the flow curve similar to the air spring curves as it is described in Section 1.2.3.1.3 *Preparing and input tabular data*. Figure 1.38 illustrates the curve digitization with the GetData Graph Digitizer software.
- Open the curve editor by the button and enter data, Figure 1.39.
- Select the branch of the flow curve corresponding to the supply line: the positive abscissa (the left branch) or the negative one. In Figure 1.36, the negative (left) branch corresponds to the supply.
- Set the value of the gauge pressure for which the curve was measured (124 psi in the figure).

Use the button to save data to a file.

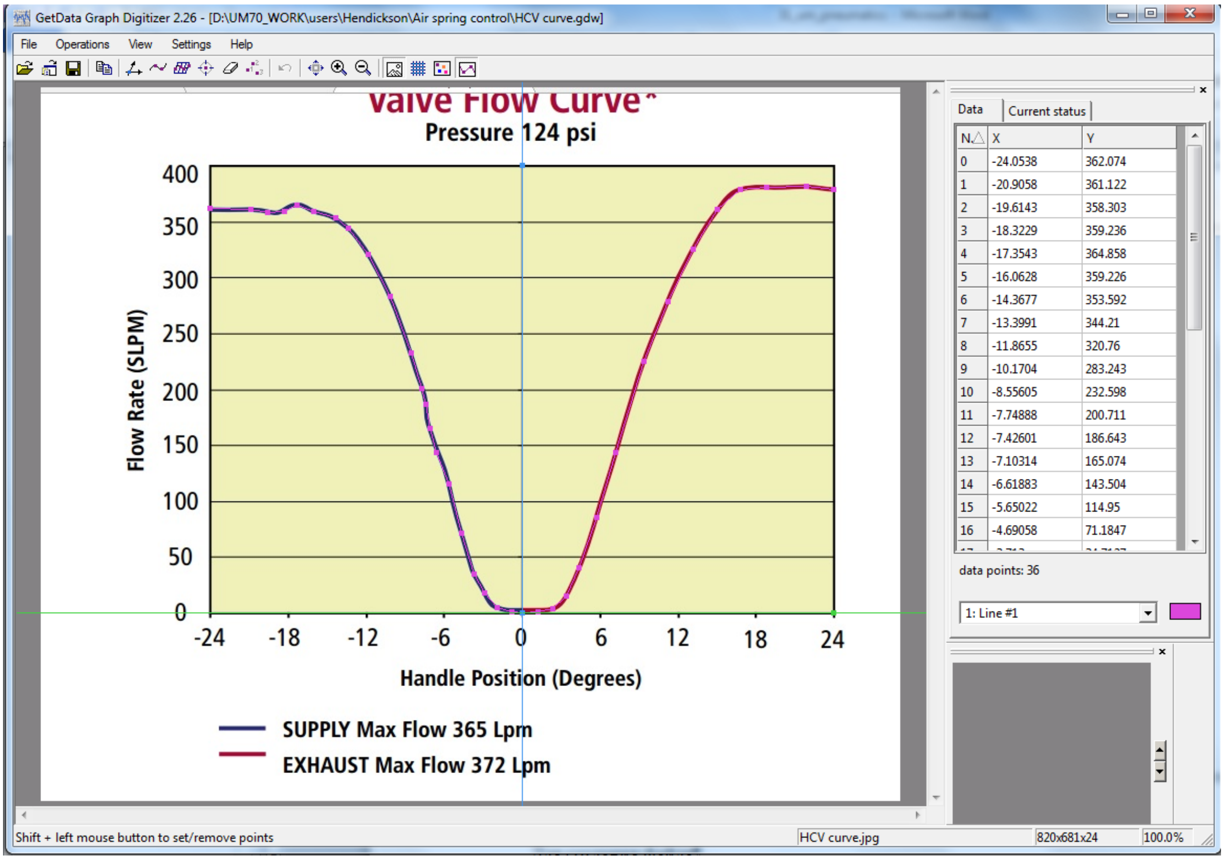


Figure 1.38. Digitization of HCV flow curve in GetData Graph Digitizer

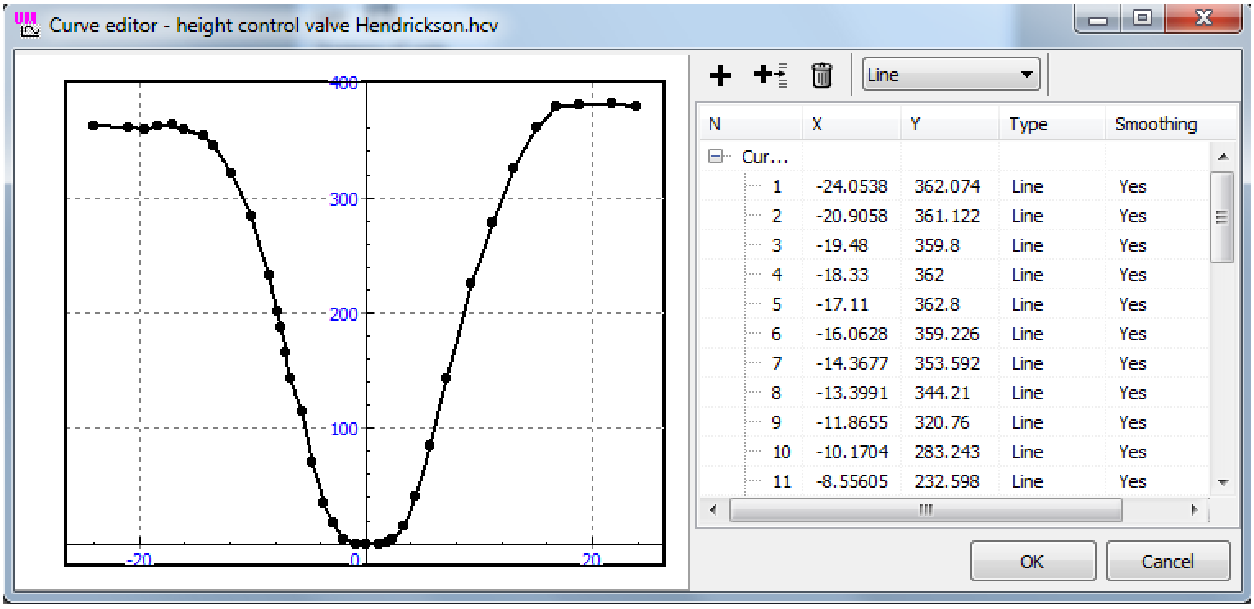


Figure 1.39. HCV flow curve in editor

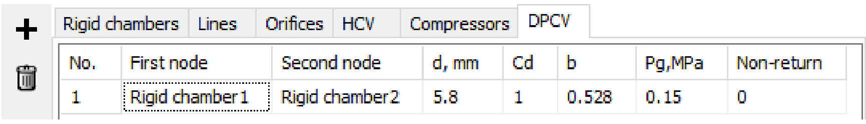
1.2.7.2. Differential pressure control valve (DPCV)

A model of the DPCV has been added in UM10. The valve connects two chambers and limits the pressure difference p_g between the chambers. The valve opens if the pressure difference is greater than this value. A modified nozzle model (1.28) is used to calculate the flow.

$$\dot{m} = \begin{cases} AC_d(p_1 - p_g)\sqrt{\dfrac{2}{RT_1}}\psi(r_p), & p_1 > p_2 + p_g, \quad r_p = \dfrac{p_2}{p_1 - p_g} \\ 0, & p_1 < p_2 + p_g \end{cases}$$

The valve parameters are shown in Figure 1.40. It is recommended to select the parameters of the diameter d and the discharge coefficient C_d based on the use of experimental data. The example in Figure 1.41 shows a comparison of simulation results with experiment for the process of air outflow into the atmosphere from a 95-liter chamber through a valve with the index p_g=0.15 MPa. Based on the available experimental data from the Dr. Zhuang Qi's thesis, the diameter value d=5.8 mm was selected, ensuring good agreement between the modeling results (solid line) and the experiment (marker). The corresponding model is located in the directory

{Data UM}\SAMPLES\ Pneumatics\DPCV



No.	First node	Second node	d, mm	Cd	b	Pg,MPa	Non-return
1	Rigid chamber1	Rigid chamber2	5.8	1	0.528	0.15	0

Figure 1.40. DPCV parameters

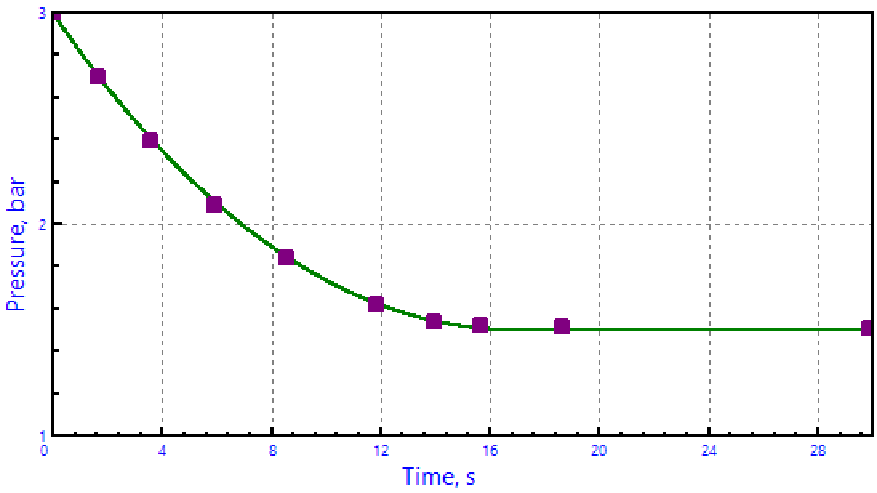
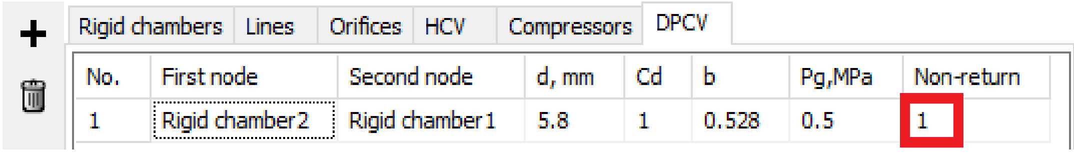


Figure 1.41. Comparison of DPCV simulation with experiment

1.2.7.3. Non-return valve



No.	First node	Second node	d, mm	Cd	b	Pg,MPa	Non-return
1	Rigid chamber2	Rigid chamber1	5.8	1	0.528	0.5	1

Figure 1.42. Parameters of non-return valve

The non-return valve is implemented as a special case of the DPCV valve. The valve opens only for flow from the first reservoir to the second one when the condition is met

$$p_1 > p_2 + p_g, \qquad p_g \geq 0.$$

The sign of a non-return valve is a unit in the last cell of the table, Figure 1.42. To operate the valve in two directions, set 0 in this cell, Figure 1.40.

1.2.8. Compressors

A compressor in UM is used for supporting the desired pressure in reservoirs. The compressor is on if the pressure in a reservoir is less than the value P_{min}, and off if it reaches the value P_{max}.

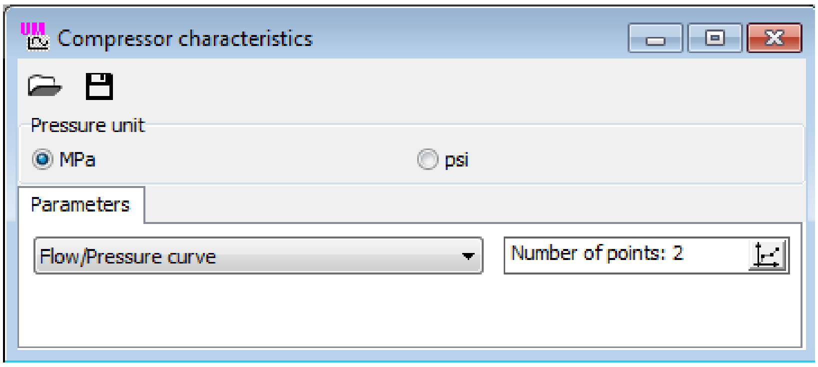


Figure 1.43. Window for development of compressor model

The model of a compressor includes a flow curve for the dependence of the volume flow rate from the reservoir pressure. The model file *.cmpr is stored in the directory **{UM Data}\AirSpring**, for example

c:\Users\Public\Documents\UM Software Lab\Universal Mechanism\9\AirSpring\

Units of measurements. The flow rate should be set in SLPM (standard liter per minute). The gauge pressure is measured in MPa (SI) or psi (Imperial system)

To create a compressor model file

- run UM Simulation program;
- use the **Tools | Pneumatic elements | Compressors…** menu command to open the compressor window, Figure 1.43;
- if necessary, change the system of units;
- click the button to open the curve editor and to enter the volume flow data, Figure 1.44.

Use the button to save the data to a file *.cmpr.

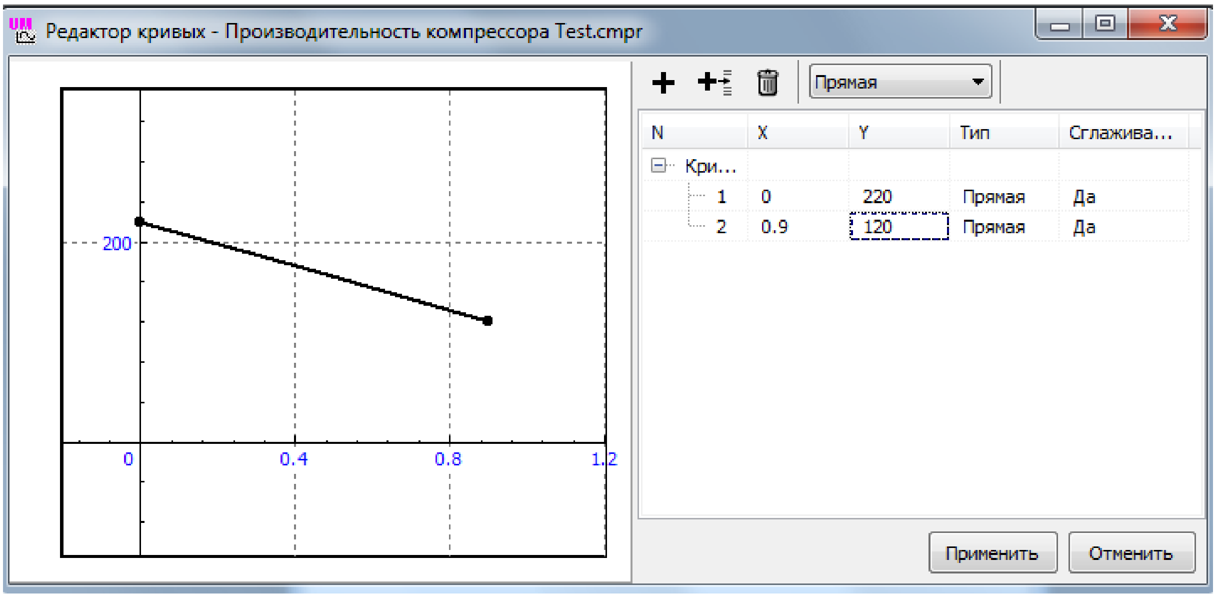


Figure 1.44. Curve editor: flow rate vs. the reservoir pressure

1.3. Pneumatic systems

A pneumatic system (PS) in UM is considered as a graph, which nodes are connected by edges. Each node of a graph corresponds to one of the pneumatic elements

- Rigid chamber, Sect. 1.2.2;
- Air spring, Sect. 1.2.3;
- Simple node, Sect. 1.2.4.

The graph edges are

- Pneumatic lines, Sect. 1.2.5;
- Orifices, Sect. 1.2.6;
- Height control valves, Sect. 1.2.7.1.

1.3.1. Parameters of tabular air springs

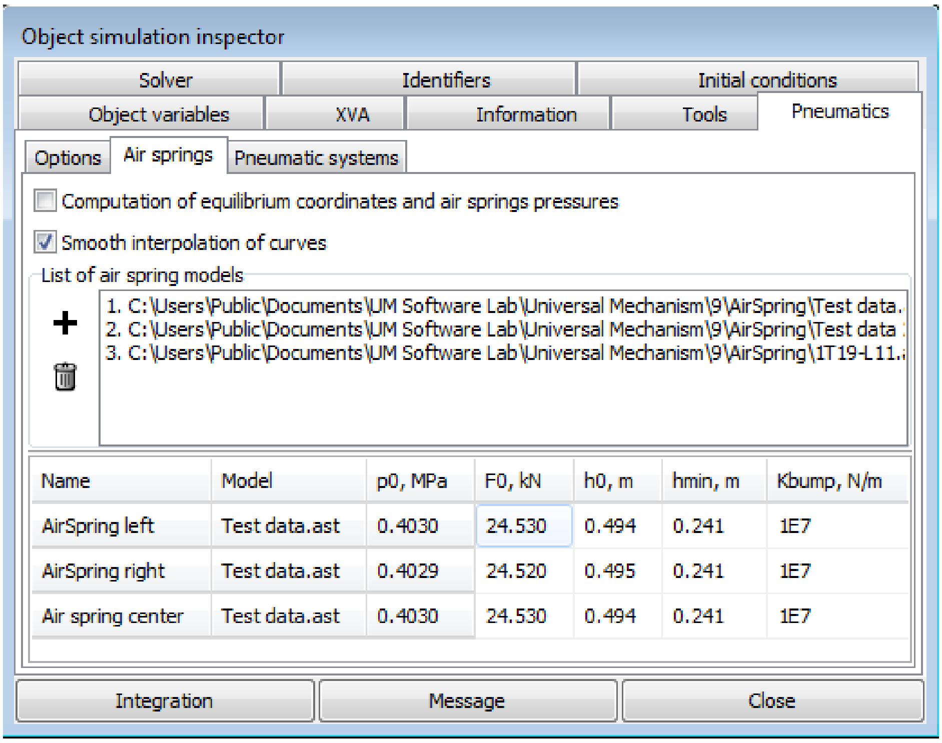


Figure 1.45. Tabular air springs parameters

Tabular air spring (AS) parameters are entered on the **Pneumatics | Air springs** tab, Figure 1.45.

List of tabular AS force element is shown in the tab bottom. All AS should be added to the model as special force elements in UM Input program, Sect. 1.2.3.1.1 *Parameters of tabular air spring in Input program*.

Files *.ast contain tabular AS models, Sect. 1.2.3.1.3.4 *Creating UM files *.ast with tabular air spring models*. By default, the files are located in the directory **{UM data}\AirSpring.**

List of tabular AS models must include at least one element. Use the **+** and  buttons to add and remove models from the list.

Double click on the file name in the list of AS models to open the window with the corresponding model, Figure 1.9.

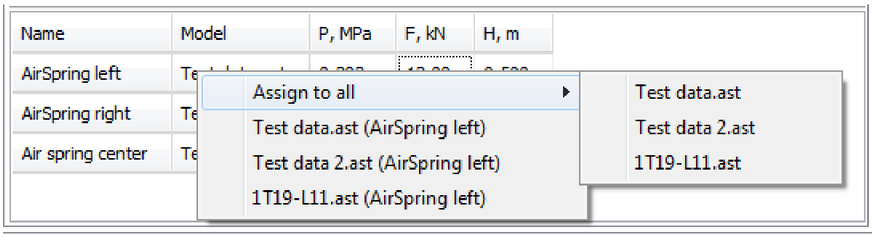
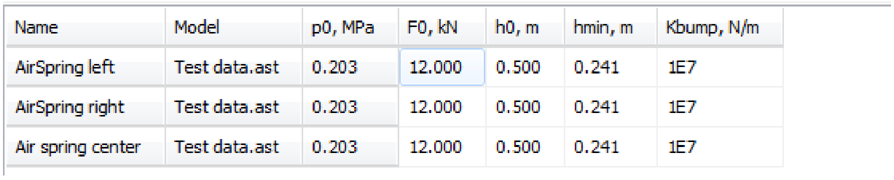


Figure 1.46. Assignment of AS model

To assign a model to AS force element, move the mouse cursor to the necessary force in the list, click the right mouse button and select the tabular model in the popup menu, Figure 1.46.



Name	Model	p0, MPa	F0, kN	h0, m	hmin, m	Kbump, N/m
AirSpring left	Test data.ast	0.203	12.000	0.500	0.241	1E7
AirSpring right	Test data.ast	0.203	12.000	0.500	0.241	1E7
Air spring center	Test data.ast	0.203	12.000	0.500	0.241	1E7

Figure 1.47. Air spring force elements with assigned tabular model and static values of force and height

Set the static force and height F_0, h_0 to each of the force elements, Figure 1.47. The corresponding pressure p_0 is computed automatically.

The minimal height (**hmin**) and the **bump stop stiffness constant** (**Kbump**) for each of the AS are important if the tabular model does not include the bump stop description. Nonlinear bump stop models can be described by additional force elements in UM Input program in parallel to the AS force elements; in such cases, zero values should be set for the **Kbump** parameter.

Double click on the force element with assigned tabular model and static parameters to get plots for force, volume and pressure versus height according to the **dynamic load model,** Figure 1.48**, Sect. 1.2.3.1.4** *Mathematical model of air spring by tabular description***.**

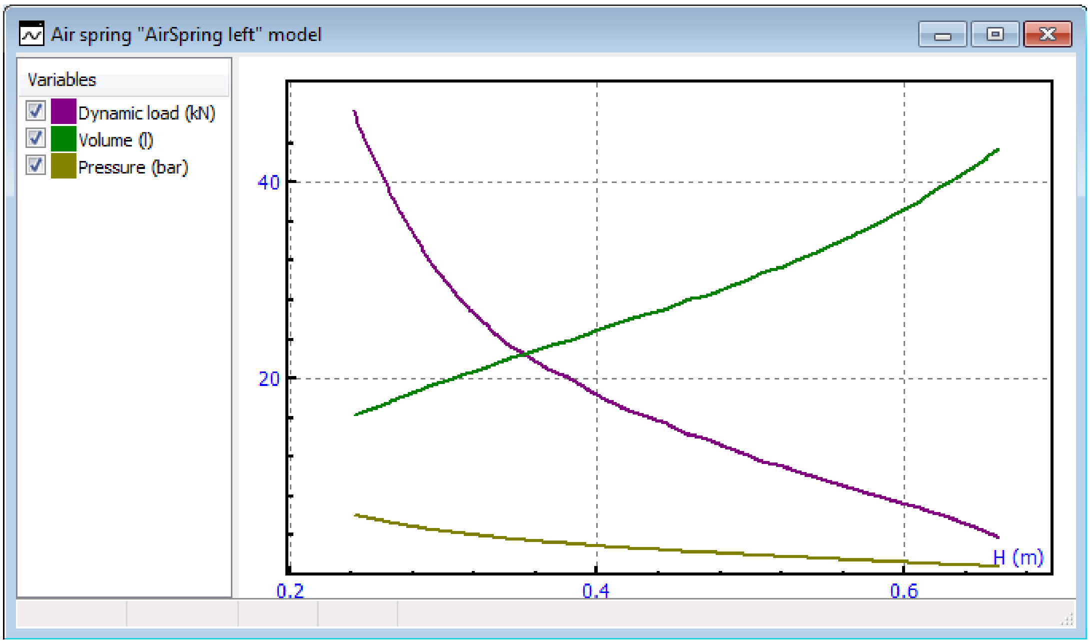


Figure 1.48. Dynamic load model of air spring

The **Computation of equilibrium coordinates and air springs pressures** option is used for automatic computation of body coordinates and pressure in air springs in equilibrium position for the given value of suspension height if HCV is included in the model of a PS, Sect.1.4.4.4.3 *Test: computation of initial positions and pressures*. The simulation should be run for zero speed of a car or a rail vehicle.

Check the **Smooth interpolation of curves** option

- to interpolate the static tabular data for force and volume versus height by B-splines;
- to interpolate the static force a volume data versus pressure by polynomials of second order.

If an *AS is isolated* and not connected to other elements of a PS, its air mass is constant. In this case, the AS simulation properties are completely described by the dynamic load model, Figure 1.48. If the AS is connected by pneumatic lines and orifices with other nodes of a PS, its behavior is defined according to the solution a system of nonlinear equations of PS at each step of the simulation process.

1.3.2. Description of pneumatic systems

A PS is described by a graph, which vertices or nodes are simple nodes, air springs and chambers. PS graph edges are pneumatic lines and orifices connecting the nodes.

1.3.2.1. List of pneumatic systems

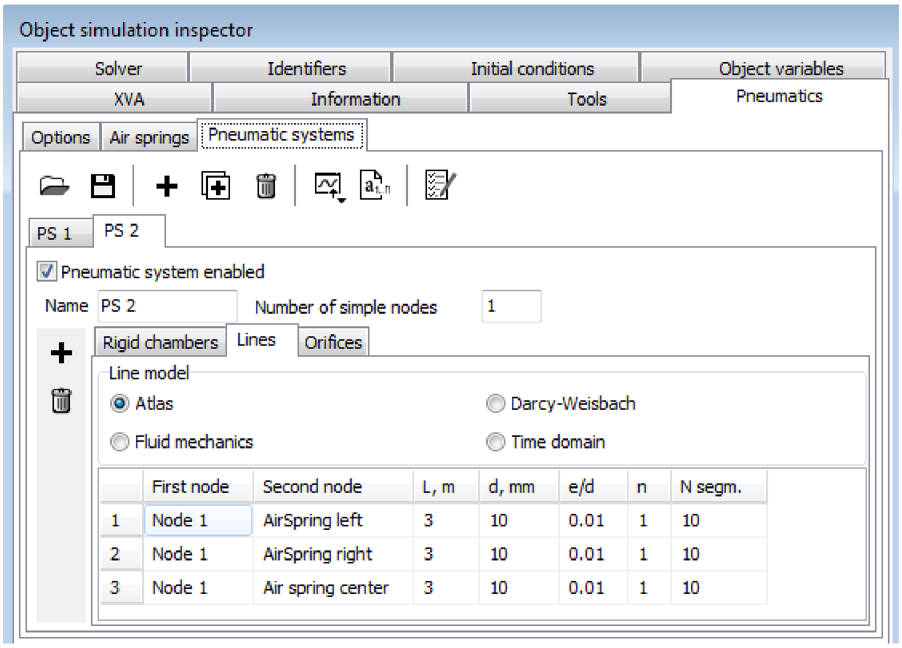


Figure 1.49. List of pneumatic systems

UM Model can include several PS, which are not interacting pneumatically. Buttons for managing the PS list as well as for call of some useful tools are located in the top of the **Pneumatic systems** tab, Figure 1.49.

 - read *.psc file with description of PS list.

 - save description of PS list in a *.psc file.

The description of the PS list is saved automatically in the general configuration file *.icf, in particular, in the last.isf file. The user can save the same description in an extra file *.psc, which could be useful in some cases.

- add a new PS to the list.

- add a copy of the current PS to the list.

- delete the current PS.

- open a player of line and orifice models, see Sect. 0.

- open a list of pneumatic variables; see Sect 1.3.2.4 *List of variables for pneumatic elements*.

- verify description of PS, Sect. 1.5.1 *Errors in pneumatic system model*.

Pneumatic systems can be either active (enabled) or not active (disabled). To disable a PS, uncheck the **Pneumatic system enabled** option, Figure 1.50.

Remark	If the user described several PS, he must remember that the enabled pneumatic systems must be *completely pneumatically independent on each other*. As a consequence, a tabular AS can be connected with one enabled PS only.

1.3.2.2. Description of pneumatic system

1.3.2.2.1. General parameters of pneumatic system

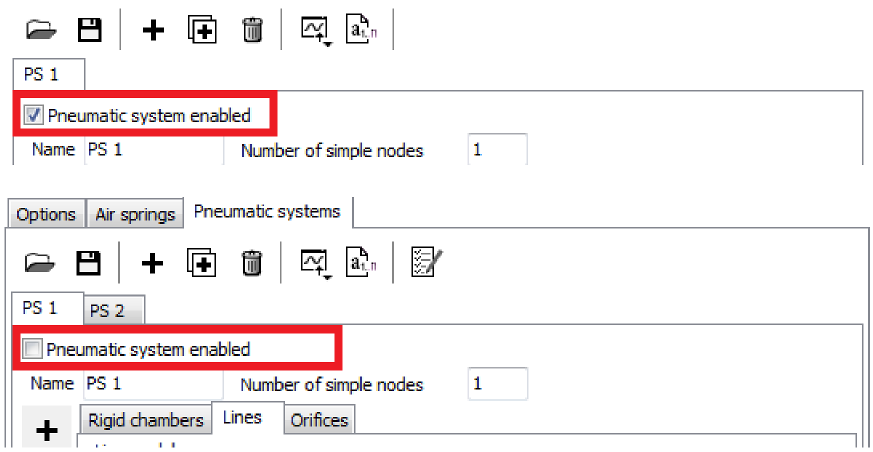


Figure 1.50. Enabled and disabled PS

Any PS in the list can be either **enabled or disabled**. The current PS is enabled, if the corresponding option is checked, Figure 1.50. Enabling and disabling allow the user a simple comparison of different variants of PS.

Remark	If a tabular AS is included in disabled PS only or not connected to any PS, the AS is considered as an isolated one and its simulation properties are computed according to the dynamic load model, Figure 1.48.

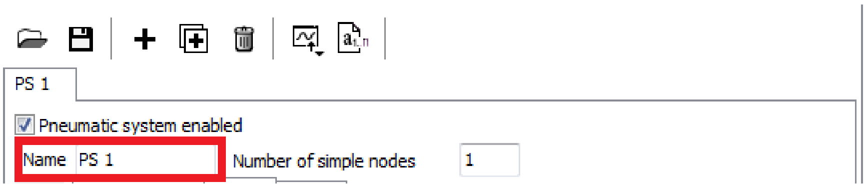


Figure 1.51. Name of PS

The **name of PS** identifies the PS in the case of several PS in the list, Figure 1.51.

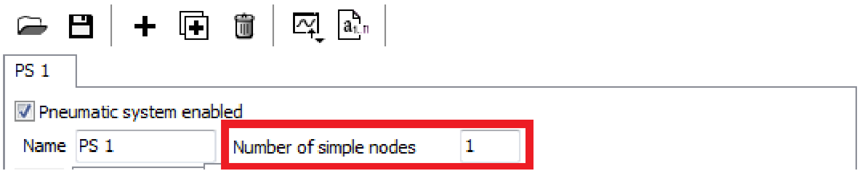


Figure 1.52. Number of simple nodes

Set the **number of simple nodes** if such elements are presented in the current PS, Figure 1.52, Sect. 1.2.4 *Simple nodes*.

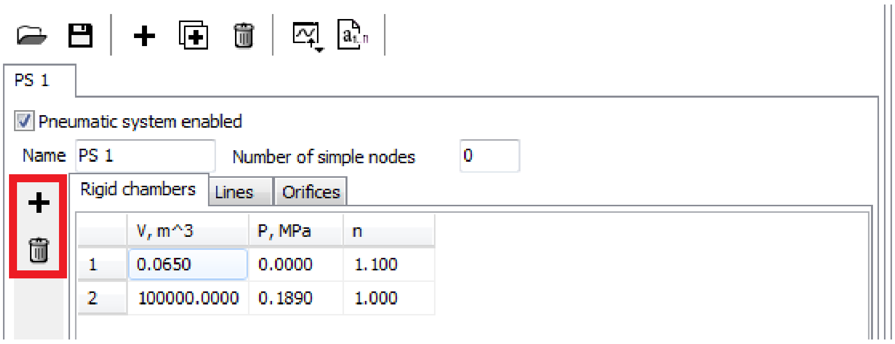


Figure 1.53. Buttons for adding and deleting pneumatic elements

Lists of pneumatic elements except AS force elements are created dynamically as parts of PS. The standard buttons are used for adding and deleting elements of lists of chambers, lines and orifices, Figure 1.53.

1.3.2.2.2. List of rigid chambers

Description of rigid chambers includes the following numerical parameters, Figure 1.53:

- Volume V, m^3
- Initial pressure P, MPa
- Polytropic index, n.

Remark To describe a connection to a source with a constant pressure, e.g. to environment, a rigid chamber with a large volume is used, see the second line in Figure 1.53.

1.3.2.2.3. List of pneumatic lines

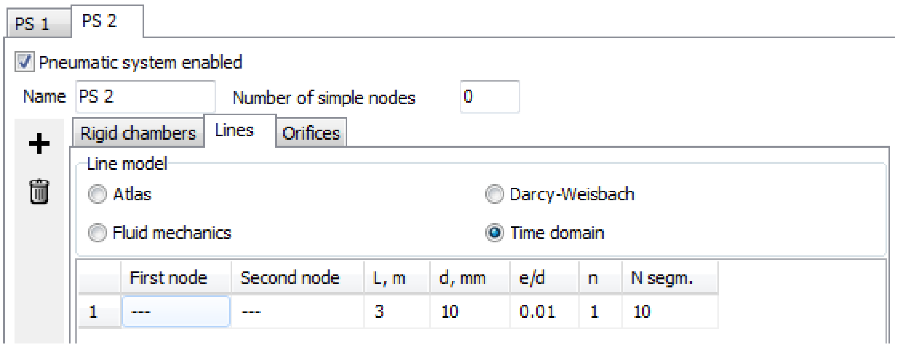


Figure 1.54. New pneumatic line

The user should select the **model of pneumatic lines**, Figure 1.54, see Sect. 1.2.5 *Pneumatic lines*.

The following **numeric parameters** should be set in the parameter table:

- Length of line L, m
- Line diameter d, mm
- The relative pipe roughness e/d (is used for the Darcy-Weisbach and Time domain models, Sect. 1.2.5.1.3 *Darcy-Weisbach equation*, 1.2.5.2 *Dynamic pipeline model*)
- The polytropic index **n** and the number of segments **N** are used for the Time domain model only, Sect. *1.2.5.2 Dynamic pipeline model*.

To assign **nodes connected by a line**, double click by the mouse on the cell

and select a node from the list, Figure 1.55. The node can be changed in the same manner.

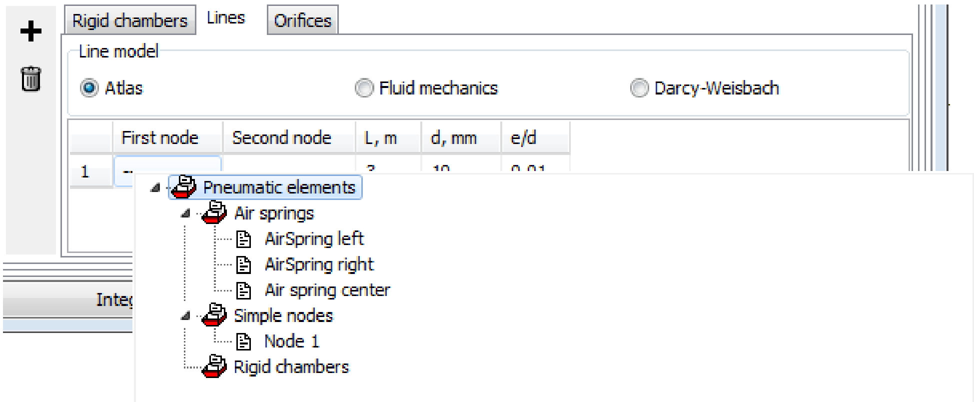
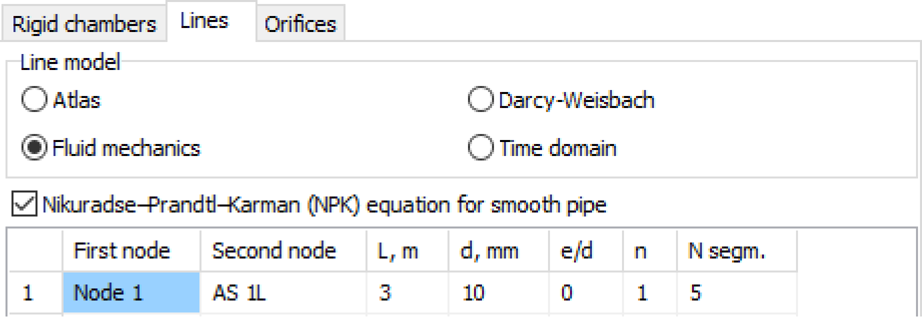


Figure 1.55. Assignment of nodes to a line



Check the **Nikuradse–Prandtl–Karman (NPK) equation for smooth pipe** option to use the corresponding model for the friction factor (1.17) otherwise the Blasius equation (1.16) is used. This factor is used for the **Fluid mechanics** model only.

1.3.2.2.4. List of orifices

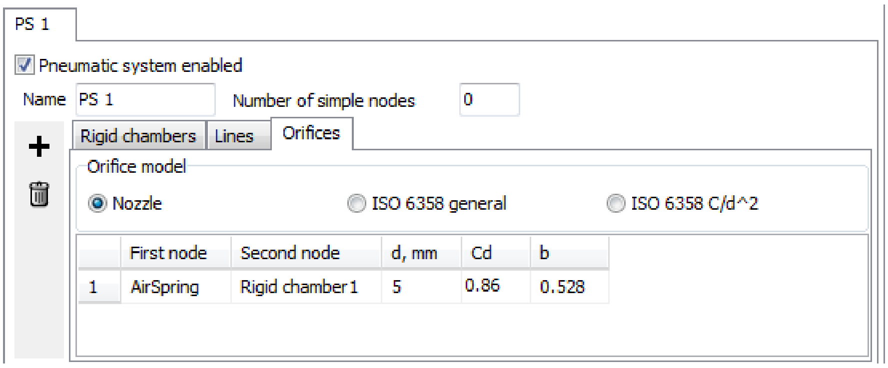


Figure 1.56. List of orifices

The user should select the **Orifice model**, Figure 1.56, see Sect. 1.2.6.

The following **numeric parameters** should be set in the parameter table:

- The orifice diameter d, mm
- Depending on the orifice model
  - the discharge coefficient Cd (nozzle),
  - the sonic conductance C (ISO 6358 general),
  - the ratio C/d^2 (ISO 6358 C/d^2)
- The critical pressure ratio *b*.

Nodes connected by the orifice are assigned by the double click of the mouse on the cells

, Figure 1.55.

1.3.2.2.1. List of height control valves

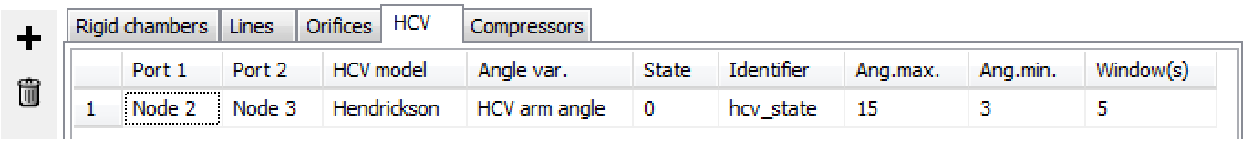


Figure 1.57. HCV list

The **HCV** page appears only if the UM program finds at least one file with the valve model in the directory **{UM Data}\AirSpring**, Sect. 1.2.7.1.3 *Generation of UM files *.hcv with models of height control valves*. Click on the + button to add a HCV to the PS model, Figure 1.58.

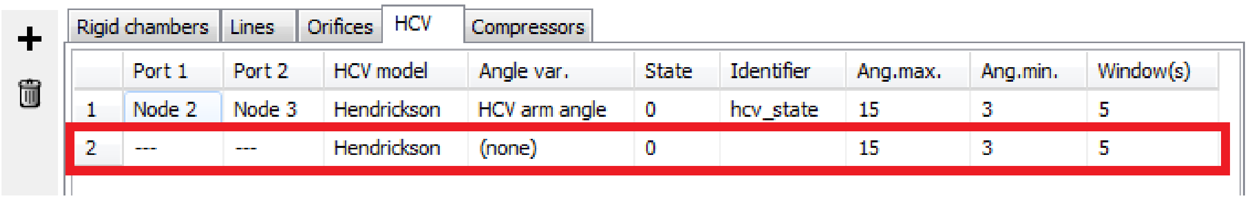


Figure 1.58. Adding a valve

The following data should be entered for a height control valve.

Port 1. A node corresponding to the supply line or directly a reservoir with compressed air.

Port 2. A node connecting the valve with the suspension.

The nodes are assigned by the mouse click on the cell ---, Figure 1.58.

HCV model. If a *.hcv file is assigned, its name is shown in the table cell. To change or modify the file, double click on the cell. The window with the HCV model appears, Sect. 1.2.7.1.3 *Generation of UM files *.hcv with models of height control valves*. Open another file or modify the data. Confirm or reject the modification after closing the window.

Angle var. (angle variable). A variable corresponding to the control arm angle (Figure 1.36) should be assigned to the valve. The variable is created in the Wizard of variables and dragged by the mouse to the cell of the table. Sect. 1.4.4.4.3 *Test: computation of initial positions and pressures*.

State is an integer number, which specifies the operation of the valve. The parameter value is set before the simulation start. Three HCV states are available.

0 – the valve is out of operation, ports are closed.

1 – the valve is in operation; the flow is controlled by the valve arm.

2 – an additional mode of automatic valve state control.

Identifier. The user can assign an identifier for parameterization of the valve state. The identifier is selected from the list by the double click on the table cell. The identifier can be used for switching the valve state 0/1 with the **Indentifier control** tool, Sect. 1.4.4.4.2 *Tests with control*.

Ang.max α_{max} (the maximal angle). In the automatic state (the valve state parameter equals 2), the valve is in operation if the absolute value of the arm angle is greater than α_{max} during the time interval T_w specified in the cell **Window**.

Ang.min α_{min} (the minimal angle). In the automatic state (the valve state parameter equals 2), the valve is off if the module of the arm angle is less than α_{min}.

Window (s). The parameter T_w is used in the automatic mode of the valve.

Automatic mode of the valve.

In this model of the valve control, the user set value 2 to the valve state. The valve is out of operation at the simulation start. The program verifies the arm angle α at each step of the simulation process. If $|\alpha|>\alpha_{max}$ continuously during the time interval T_w, the valve is switched on. The valve is off if $|\alpha|<\alpha_{min}$.

1.3.2.2.2. List of compressors

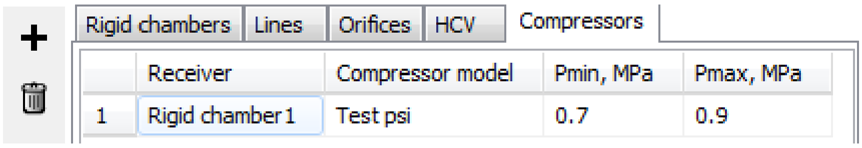


Figure 1.59. Compressors

The **Compressors** page appears only if the UM program finds at least one file with the compressor model in the directory **{UM Data}\AirSpring**, Sect. 1.2.8 *Compressors*. Click on the + button to add a compressor to the PS model, Figure 1.60.

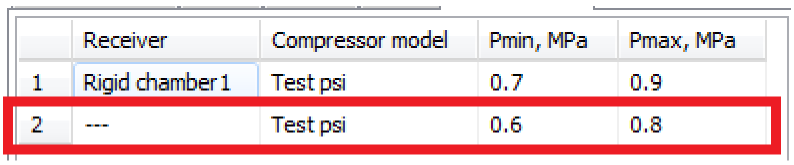


Figure 1.60. Adding compressor

The following parameters should be set.

Receiver. A rigid chamber. The receiver is assigned by the double mouse click on the cell ---, Figure 1.55.

Compressor model. If a *.cmpr file is assigned, its name is shown in the table cell. To change or modify the file, double click on the cell. The window with the compressor model appears, Sect. 1.2.8 *Compressors*. Open another file or modify the data. Confirm or reject the modification after closing the window.

Pmin is the gauge pressure in the receiver for which the compressor is turned on.

Pmax is the gauge pressure in the receiver for which the compressor is turned off.

1.3.2.3. Player for line and orifice models

Click on the button  (Figure 1.49) to open the window for graphical comparison of different mass flow rate stationary models for pipelines and orifices as well as for testing the time domain model of pipelines, Figure 1.62. The user can change the parameters in the right table and redraw the plots by the **Draw plots** button.

1.3.2.3.1. Stationary models of lines

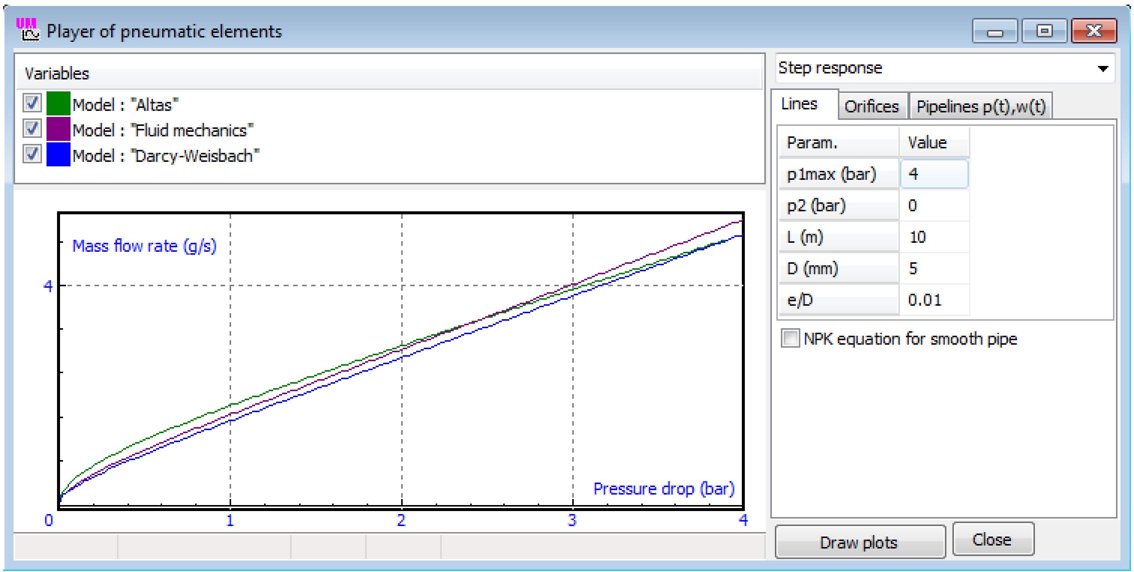


Figure 1.61. Comparison of stationary pipeline models

The gauge pressures are set in the table and drawn in bar. The mass flow rate verses the pressure drop $\Delta p = p_1 - p_2$ is computed for the given value pressure p_2 and different values of $p_1 > p_2$.

The relative pipe roughness **e/D** is used for the Darcy-Weisbach model, Sect. 1.2.5.1.3.

The **NPK equation for smooth pipe** option is applied to the "Fluid mechanics" model, Sect. 1.2.5.1.2.

1.3.2.3.2. Models of orifices

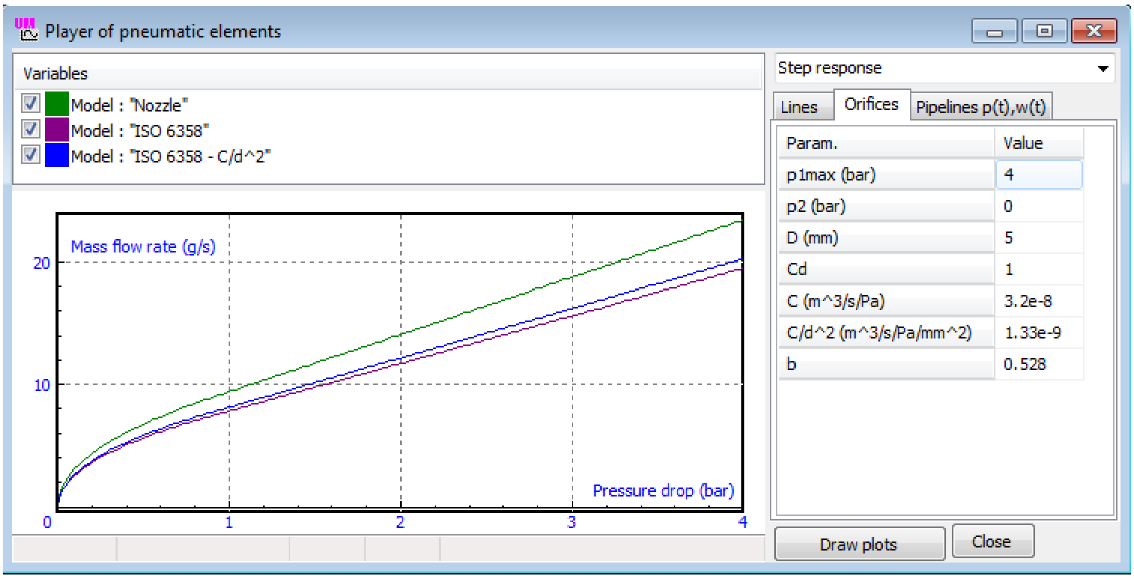


Figure 1.62. Comparison of orifice models

The gauge pressures are set in the table and drawn in bar. The mass flow rate verses the pressure drop $\Delta p = p_1 - p_2$ is computed for the given value pressure p_2 and different values of $p_1 > p_2$.

Cd is the discharge coefficient in the "Nozzle" orifice model, Sect. 1.2.6.1.

C is the **standard** sonic conductance in the "ISO 6358" orifice model, Sect. 1.2.6.1.

C/d^2 is the ratio C/d^2 model for an restriction offered in [13], [14].

1.3.2.3.3. Player for time domain pipeline model

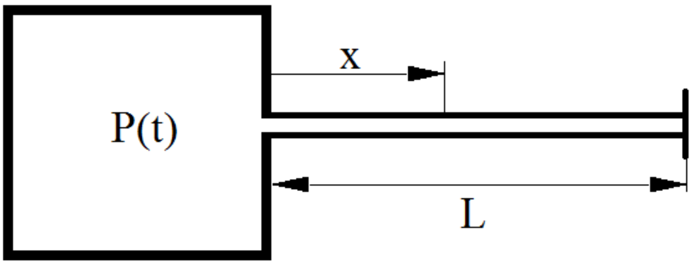


Figure 1.63. Model used in the player of dynamic pipeline

We implement the model of the pipeline excitation shown in Figure 1.63. The inlet pressure is a function of time $p(0) = P(t)$, and the pressure in the opposite locked end $p(L)$ is computed according to the time domain model described in Sect. 1.2.5.2.1.

The user can select the type of excitation from the drop down menu.

1. **Step response** $P(t) = P_0\left(1 - e^{-t/T_s}\right)$, Figure 1.64. T_s is the time constant specifying the smooth approximation of the step function. Smaller values of this constant increase the rate of the inlet pressure growth; see the **Pressure left** variable in Figure 1.64. The **Pressure right** variable is the pressure at the locked end of the line.

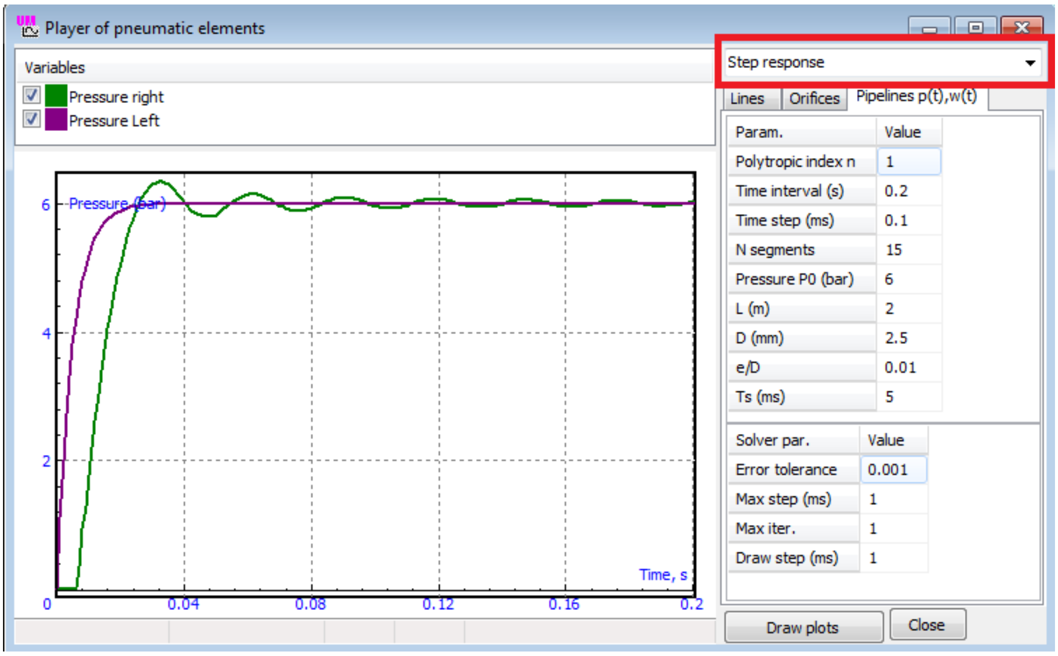


Figure 1.64. Step response

2. Frequency response $P(t) = P_0 + \Delta P \sin(2\pi(f_0 + \epsilon t/2)t)$. This model corresponds to the gliding frequency excitation, where the frequency decreases with the rate ϵ, $f = f_0 + \epsilon t$ Hz. The parameter ΔP corresponds to the **Pressure amplitude** row in the table, Figure 1.65.

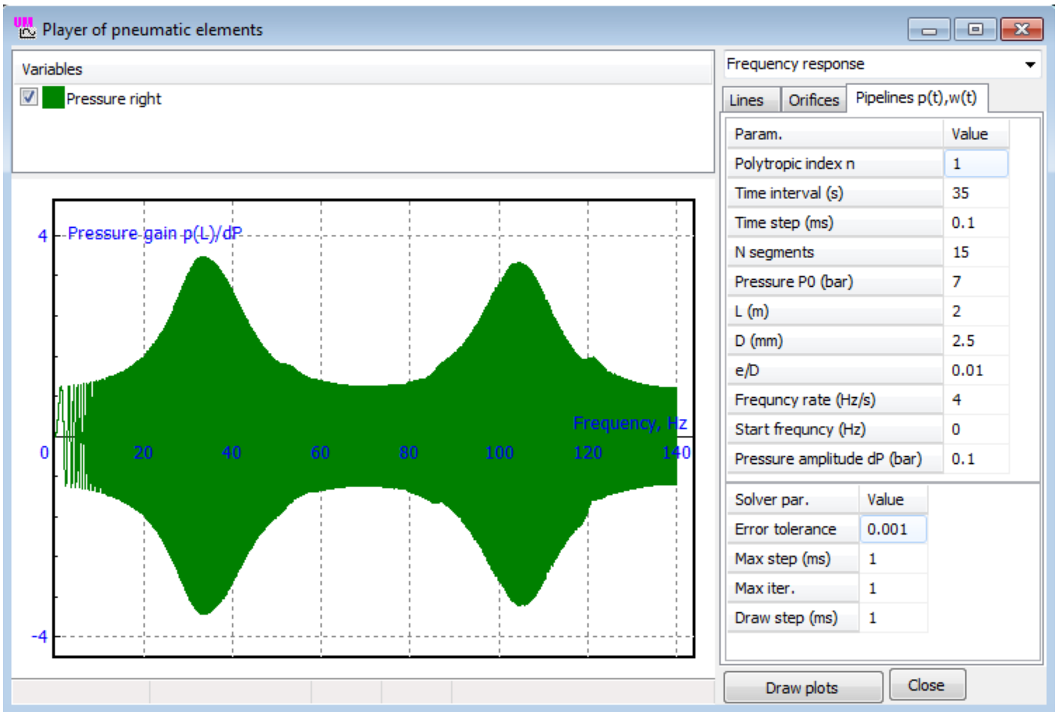


Figure 1.65. Frequency response

The user can get a single frequency response like in Figure 1.66 by setting zero value of the frequency rate, and the desired frequency value as the start frequency f_0.

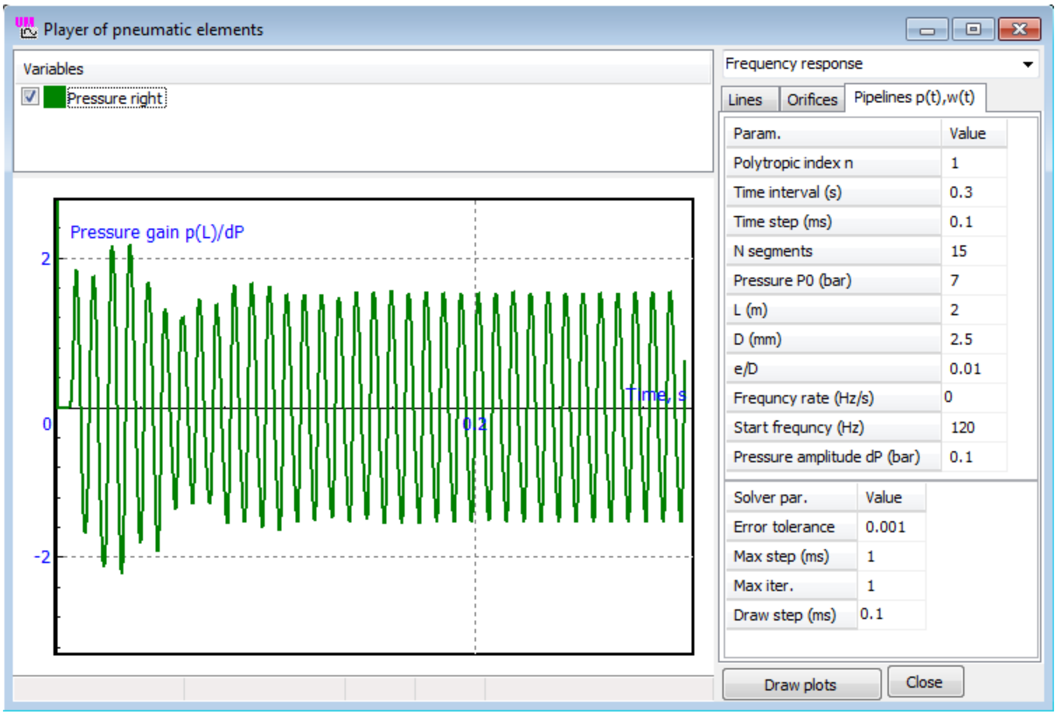


Figure 1.66. Single frequency response

1.3.2.4. List of variables for pneumatic elements

Click on the button (Figure 1.49) to generate the full list of pneumatic variables, Figure 1.67. The user can

- select a system of units: SI or Imperial, Table 2;
- add new pages with variables generated with the Master of Variables;
- save the list to a file;
- drag variables from the list to graphical windows.

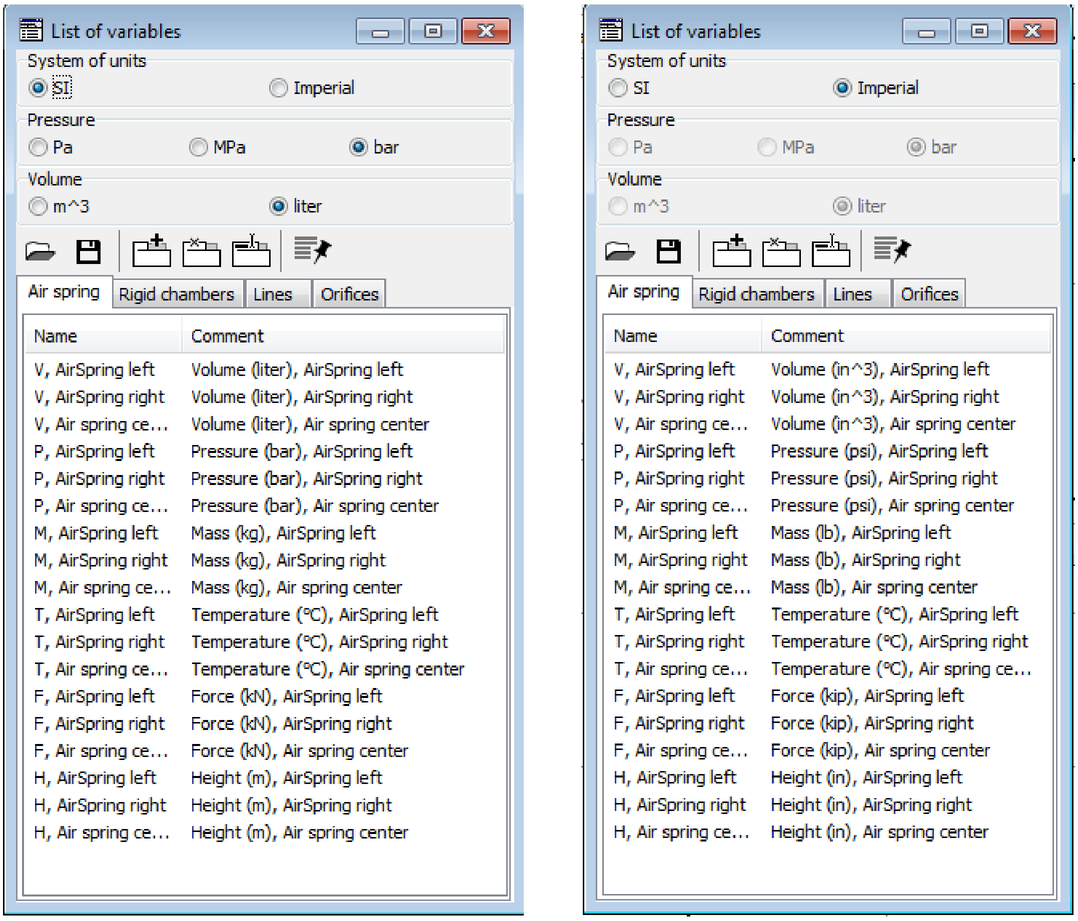


Figure 1.67. List of pneumatic variables in SI and Imperial systems of units

Table 2. Data units

System of units	Height	Force	Pressure	Volume
SI	m	N, kN	Pa, MPa, bar	m^3, liter
Imperial	in	kip	psi	in^3

1.3.3. General options in simulation of pneumatic systems

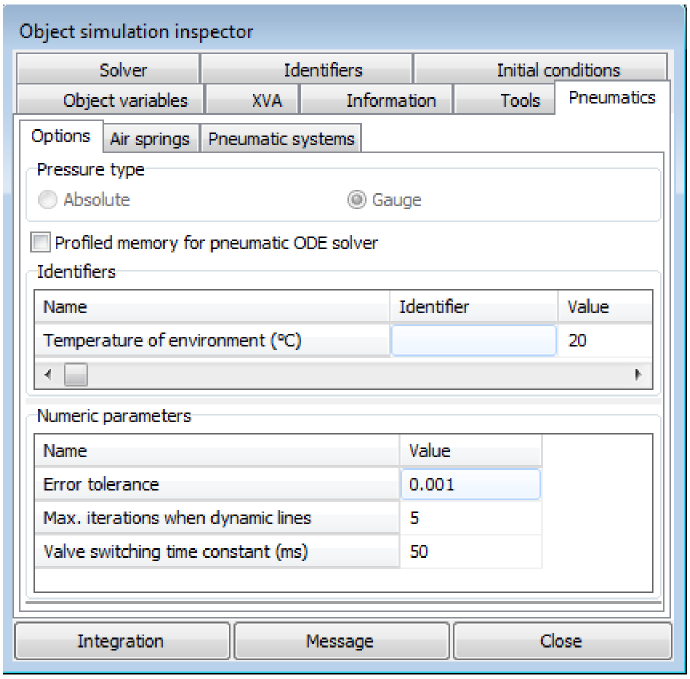


Figure 1.68. General options

Some general parameters and options in simulation of PS are available in then **Options** page, Figure 1.68.

Pressure type

The *gauge* pressure is used in PS description data. Usually the pressure values are given in MPa.

Profiled memory for pneumatic ODE solver

This option allows decreasing the memory required by the ODE solver in the case of dynamic models of pneumatic lines. This is a temporary option, which could be hidden in the future.

Temperature of environment

This parameter is used in computation of PS.

Error tolerance

This is the accuracy parameter in solving dynamic model of pneumatic lines. It is not recommended to decrease this parameter due to the possible divergence of numerical methods.

Max. iterations when dynamic lines

The parameter is applied when the dynamic (time domain) models of lines is used. Increasing the iterations number may help in stabilizing the numerical solver in the case of its divergence.

Valve switching time constant

This is a time interval corresponding to smoothing the flow rate while switching a valve. The smoothing is performed by the *step* function, Figure 1.69. Increasing the interval may help in stabilizing the numerical solver in the case of its divergence.

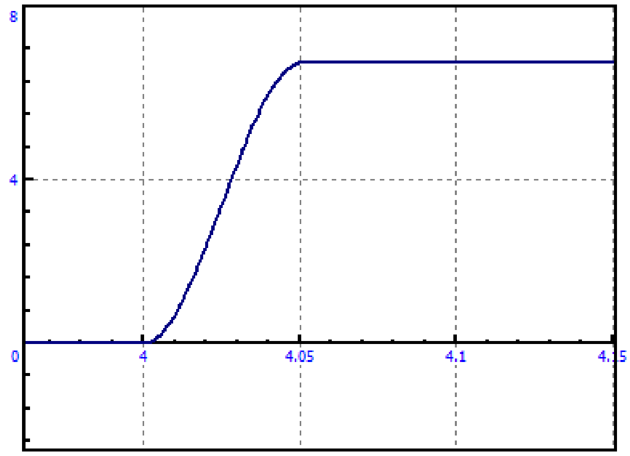


Figure 1.69. Smoothing the flow rate with the step function on time interval 50 ms

1.3.4. Computation of initial pressures for models with HCV

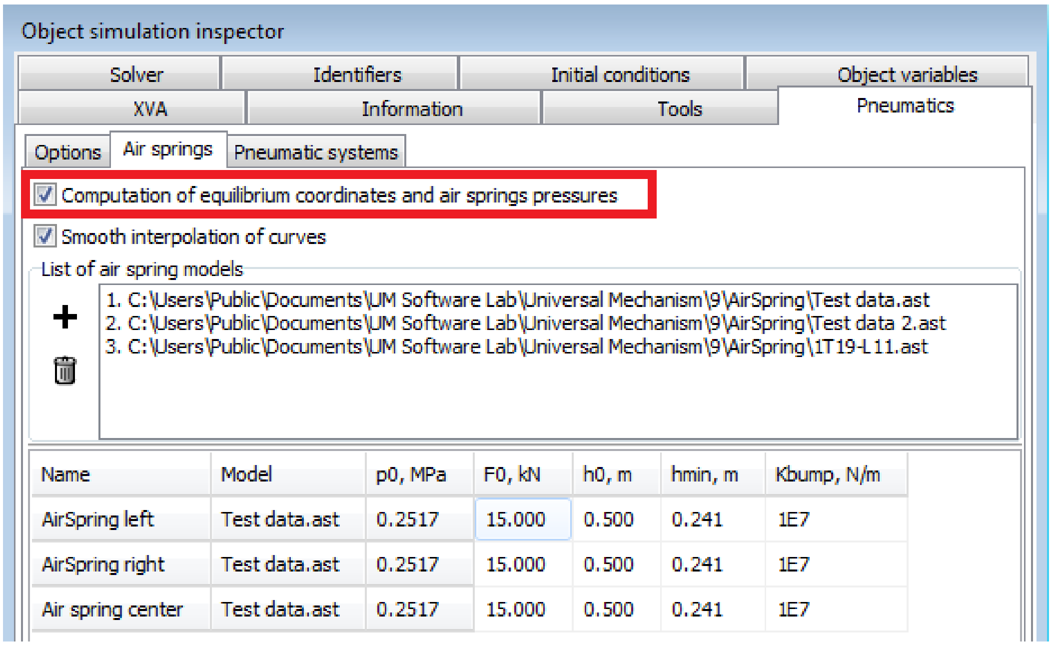


Figure 1.70. Option for computation of initial pressures

A special mode for computation of initial pressures in air springs is available for automotive and railway models. This mode is combined with the tests for equilibrium position of the model. The option for setting this mode is available on the page for air spring parameters, Figure 1.70.

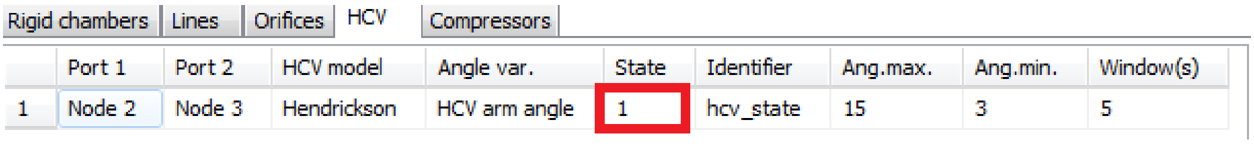


Figure 1.71. The valve state

The mode allows the user to set automatically the air spring pressure for the desired height and for the give load under control of a HCV. The HCV state must be set to 1, Figure 1.71.

Use of dynamic model is not recommended for pneumatic lines in this computation if a HCV with big flow rate is used. The messages

PS Sim: Negative pressure. Interruption

or

Integration step too small. Interruption

indicate the divergence of the solver for dynamic (time domain) models of lines. It is recommended to select a stationary model (Sect. 1.3.2.2.3 *List of pneumatic lines*) or to increase the **Valve switching time constant** (Sect. 1.3.3 *General options in simulation of pneumatic systems*).

Accepted results must be stored in the configuration file for pressure (*.icf) and initial coordinate file for body positions (*.xv). It is recommended to save the total configuration by the **File | Save configuration | All options** menu command.

Below we consider some details for automotive and rail vehicles.

1.3.4.1. Computation of initial pressures for automotive models

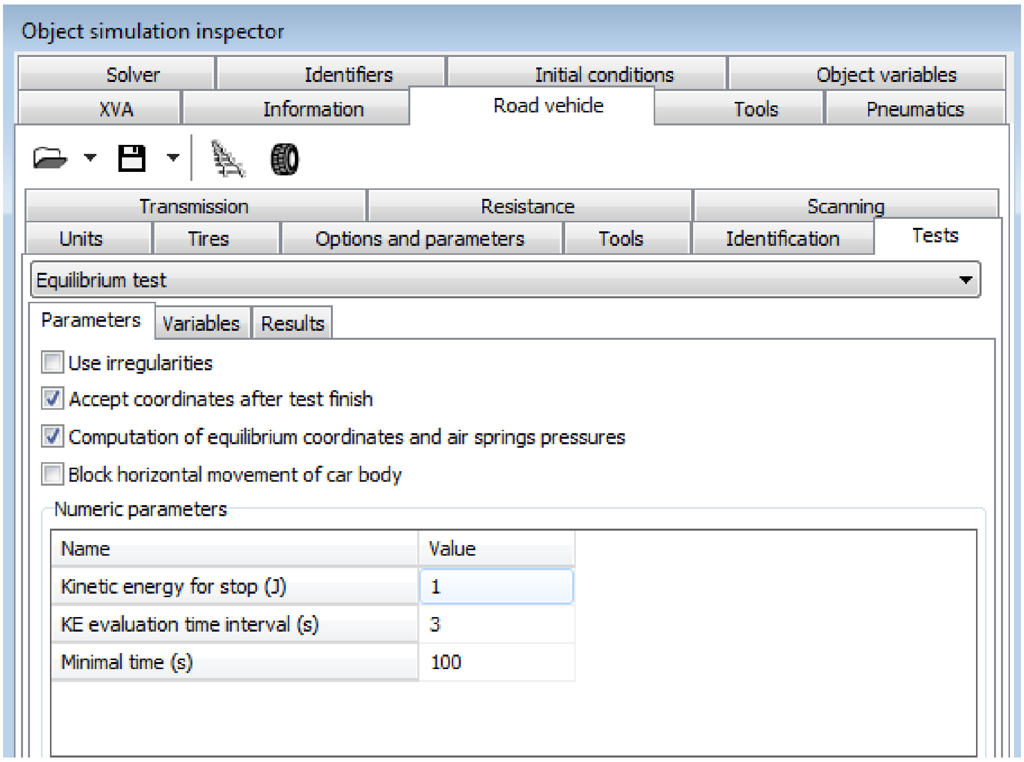


Figure 1.72. Equilibrium test parameters and options

The equilibrium test must be set for the automotive model. The following options and parameter values are required or recommended.

- The option **Computation of equilibrium coordinates and air spring pressures** must checked. This option is synchronized with the same one in Figure 1.70.
- The option **Accept coordinates after test finish** is recommended.
- The **Minimal time** parameter value must be increased to a value of expected time necessary to reach the desired suspension height. The value depends on the HCV flow rate curve.
- The **Kinetic energy for stop parameter** is recommended to be increased in comparison with the default value.
- The simulation time in then **Solver** page should be greater than the **Minimal time** parameter, say 200s.

The simulation process can be stopped both by the user and automatically.

1.3.4.2. Computation of initial pressures for railway models

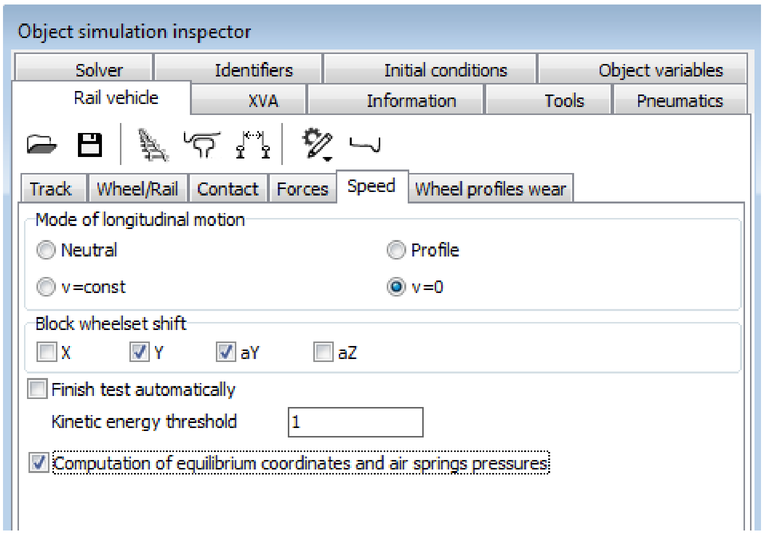


Figure 1.73. Equilibrium test parameters and options for rail vehicle

The zero speed mode must be set for the railway vehicle, Figure 1.73.

- The option **Computation of equilibrium coordinates and air spring pressures** must checked. This option is synchronized with the same one in Figure 1.70.
- The option **Finish test automatically** is ignored.
- The simulation time in **Solver** page must be big enough, say 200s.

The simulation process can be stopped by the user after the suspension height reaches the desired value.

1.4. Tests and examples

In this section we consider tests of PS models created taking into account publications of other authors. We selected a number of papers, which contain full information on PS as well as experimental results. Basing on these data we developed UM models of PS and compared our simulation results with experimental results from the papers.

1.4.1. Charge and discharge of tank

1.4.1.1. Case 1: Discharge

The model

{UM Data}\SAMPLES\ Pneumatics\Discharge

corresponds to paper [15]. Experimental data for a tank discharge are presented in this paper. The sonic conductance and the critical pressure ratio are given for two valves (V1, V2). Comparison of UM simulations (solid lines) and experimental data is shown in Figure 1.74. Plots correspond to the pressure fall verses time. Parameters of PS are stored in the files

Valve1.psc

Valve2.psc

located in the model directory.

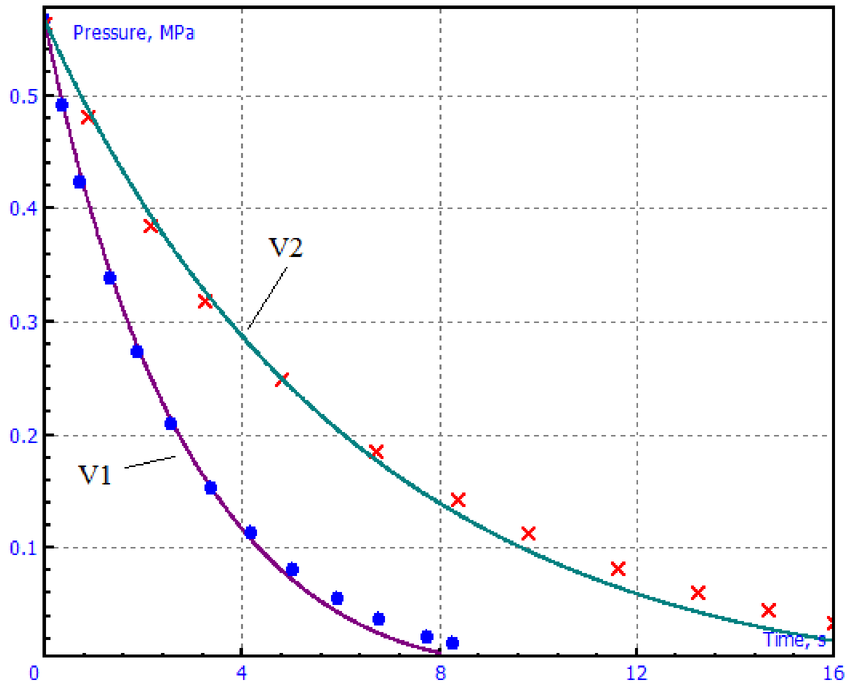


Figure 1.74. Comparison of simulation results and measurements for tank discharge

The model of PS contains two rigid chambers, Figure 1.75: the first one corresponds to the 10.6 l tank, and the second one with a large volume corresponds to the environment (constant pressure). An orifice connecting the chambers corresponds to a valve. The ISO 6358 standard is used for the valve model; the orifice diameter value is ignored in this test.

Thus, this example illustrates

- a good correlation of simulation and experiment;
- a source of a constant pressure as a rigid chamber with large volume.

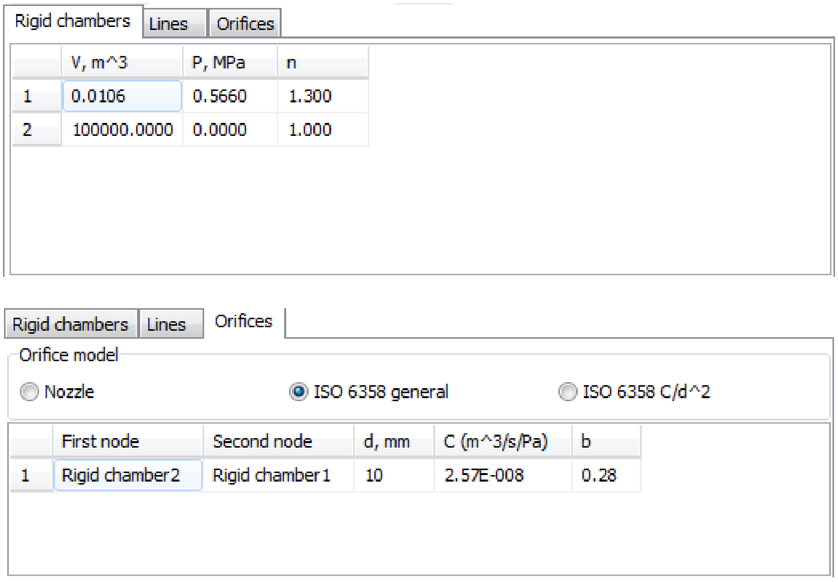


Figure 1.75. Rigid chambers and connecting orifice

How do repeat the test?

1. Open the model {UM Data}\SAMPLES\ Pneumatics\Discharge in UM Simulation.
2. Load the experimental results into the graphical window from two text files

P Valve 1 (experiment).txt,

P Valve 2 (experiment).txt

with the popup menu command, Figure 1.76.

3. Run simulation.

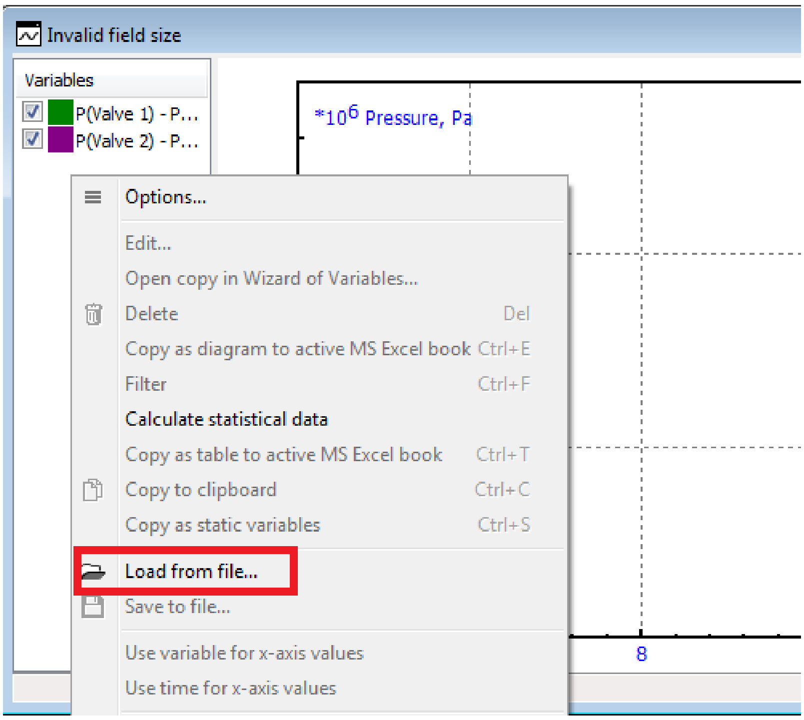


Figure 1.76. Appending plots from files

1.4.1.2. Case 2: Charge and discharge

The next test was taken from paper [16]. There the authors consider both the charge and discharge of a tank for several pressures. UM Model is

{UM Data}\SAMPLES\ Pneumatics\Charge and discharge.

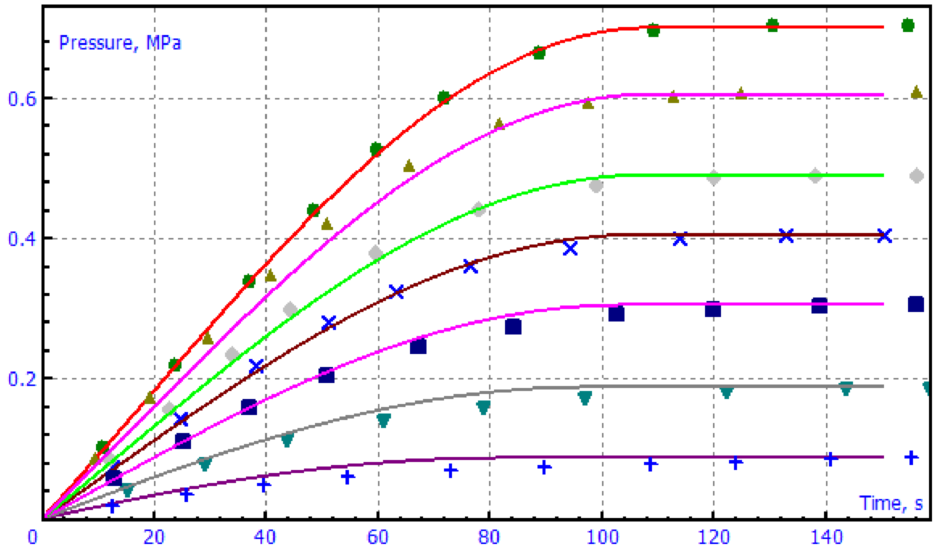


Figure 1.77. Comparison of simulation of tank charge process with measured data (markers) for different pressure values

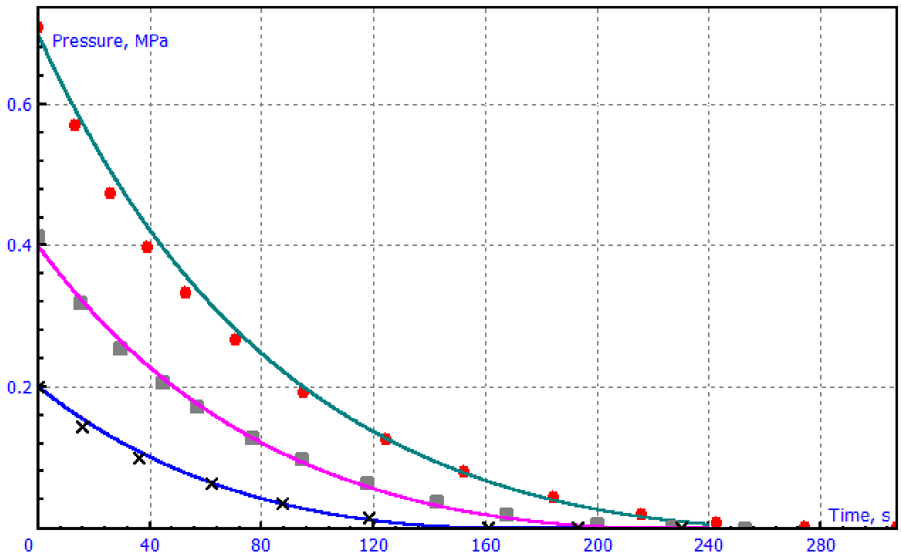


Figure 1.78. Comparison of simulation of tank discharge process with measured data (markers) for different pressure values

UM simulation results are compared with measurements in Figure 1.77 and Figure 1.78.

How do repeat the test?

1. Open the model {UM Data}\SAMPLES\ Pneumatics\Charge and discharge in UM Simulation.

2. Following Figure 1.76, load the experimental results into the graphical windows from text files:

- in the window with **P (Discharge)** variable:

Discharge 2bar.txt

Discharge 4bar.txt

Discharge 7bar.txt

- in the window with **P (Charge)** variable:

Charge 1bar.txt

Charge 1.9bar.txt

Charge 3bar.txt

Charge 4bar.txt

Charge 5bar.txt

Charge 6bar.txt

Charge 7bar.txt

3. Set the desired discharge value of pressure to the small chamber (pneumatic system **Discharge**) and the charge value for the large chamber (pneumatic system **Charge**), Figure 1.79.

4. Run simulation.

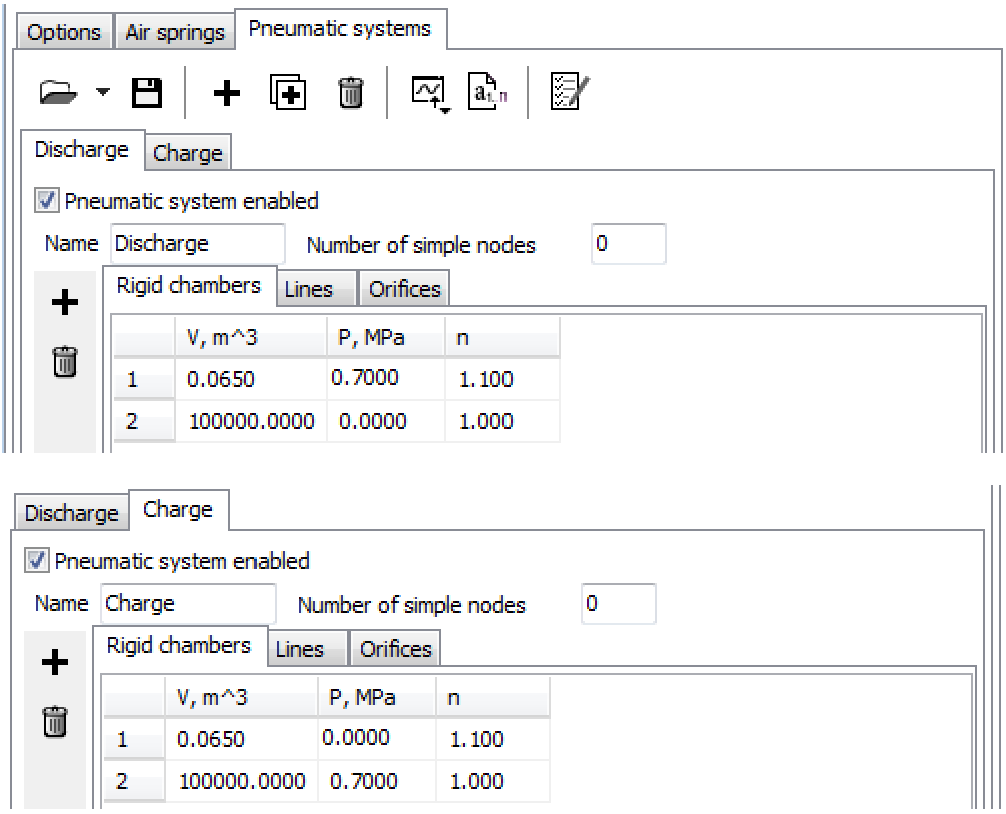


Figure 1.79. Pneumatic systems for charge and discharge simulation

1.4.2. Dynamic stiffness and damping

1.4.2.1. Case 1: Air spring connected by pipeline with auxiliary chamber

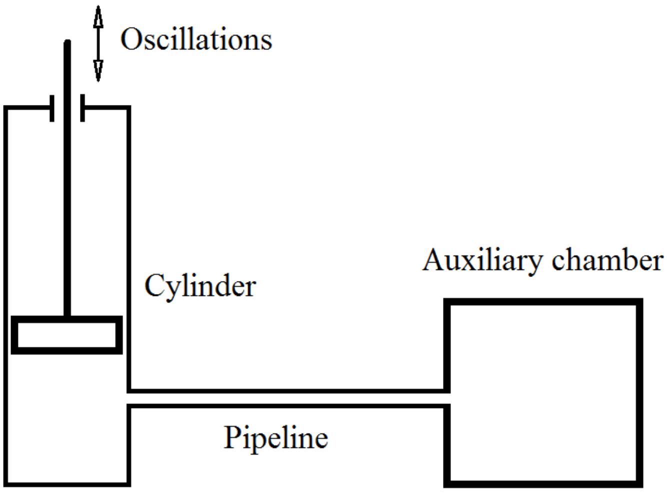


Figure 1.80. Scheme of experiment for study of pipeline influence on dynamic stiffness and damping of air spring with auxiliary chamber

The study corresponds to an experiments described in paper [17]. A pneumatic cylinder with 100mm diameter is considered as an air spring. The cylinder is connected with an auxiliary chamber by a pipeline. Harmonic oscillations are applied to the cylinder rod, and the force applied to the rod is measured to estimate the influence of the pipeline on the dynamic stiffness and damping of the air spring, Figure 1.80.

UM Model is

{UM Data}\SAMPLES\ Pneumatics\Dynamic pipeline.

Test parameters:

Cylinder volume at equilibrium: 1.1 liter;

Volume of auxiliary chamber: 2.2 liter;

Pipeline length and diameter: L=1.5m, D=7.5mm;

Static value of absolute pressure: 552 kPa.

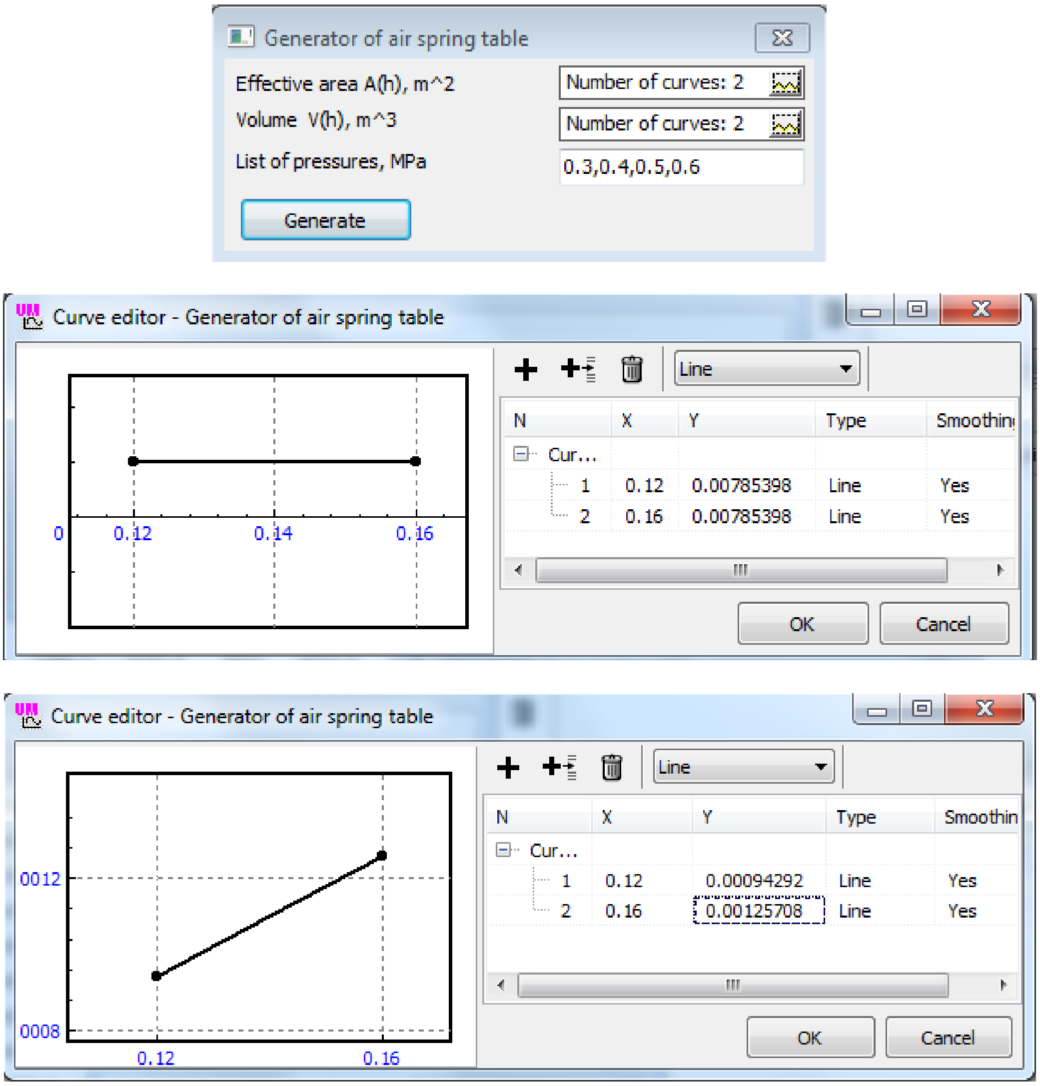


Figure 1.81. Generation of tabular model of cylinder as air spring

The model of the pneumatic cylinder as an air spring is created with the Generator of air spring table, Sect. 1.2.3.1.3.5. *Creating tabular data by effective area*. The effective area is constant

$$A_e = \pi D^2/4 = 0.00785398 \text{ m}^2$$

and the volume is the linear function of the height

$$V_{as} = A_e h$$

Description of the corresponding AS model is presented in Figure 1.81. The tabular model is generated and saved in the file "Pneumatic cylinder D100.ast".

Consider useful values of the AS stiffness constant for very low and very high frequencies of excitation. We use the expression for the air spring stiffness

$$K = \left|\frac{dF}{dh}\right| = \left|\frac{dp}{dh}\right| A_e$$

Assuming the polytropic process, the derivative dp/dh is computed from the relation

$$\frac{dpV^n}{dh} = \frac{dp}{dh}V^n + npV^{n-1}\frac{dV}{dh} = \frac{dp}{dh}V^n + npV^{n-1}A_e = 0,$$

$$\left|\frac{dp}{dh}\right| = \frac{npA_e}{V}$$

which results in

$$K = \frac{npA_e{}^2}{V}.$$

Using this result, we can compute the stiffness for low frequency, where the aggregate volume of the AS and the auxiliary chamber is substituted in the formula

$$K_L = 14.2 \text{ N/mm}.$$

as well as the stiffness constant for the high frequencies, where only the AS volume should be taken into account

$$K_H = 42.7 \text{ N/mm}$$

The computations were done for the polytropic index n=1.38.

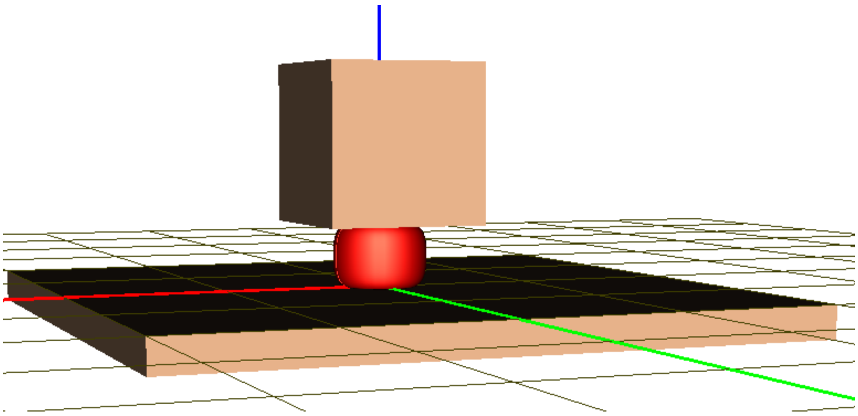


Figure 1.82. Mechanical part of model "Dynamic pipeline"

Let us consider now simulation of the model with UM. The mechanical part of the model "Dynamic pipeline" contains two bodies, connected by the AS force element:

- Base - the lower body, which can oscillate with a constant or variable frequency;
- Body - the upper body, which is fixed.

So, the oscillation of the Base leads to the corresponding change of the AS height.

The jBase joint implements the oscillations of the base with the gliding frequency

$$f = f_0 + \epsilon t \text{ Hz},$$

see Figure 1.83. The following identifiers parameterize the expression:

- f0 - start frequency;
- eps - frequency rate;
- ampl - amplitude of oscillations.

If eps=0, the harmonic oscillations with the frequency f_0 take place.

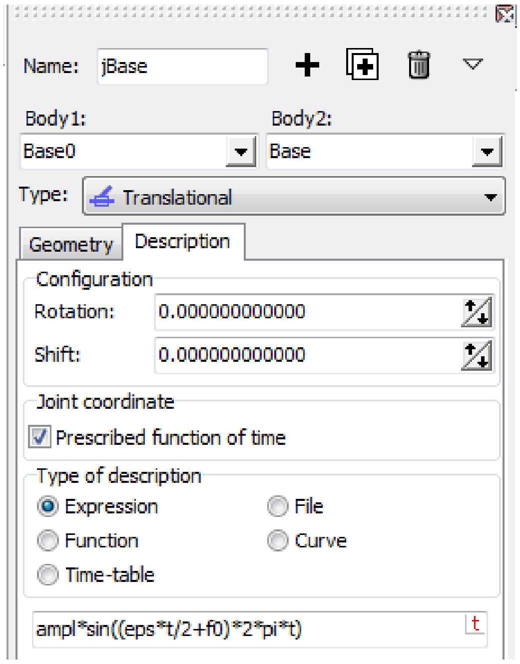


Figure 1.83. Oscillation with gliding frequency

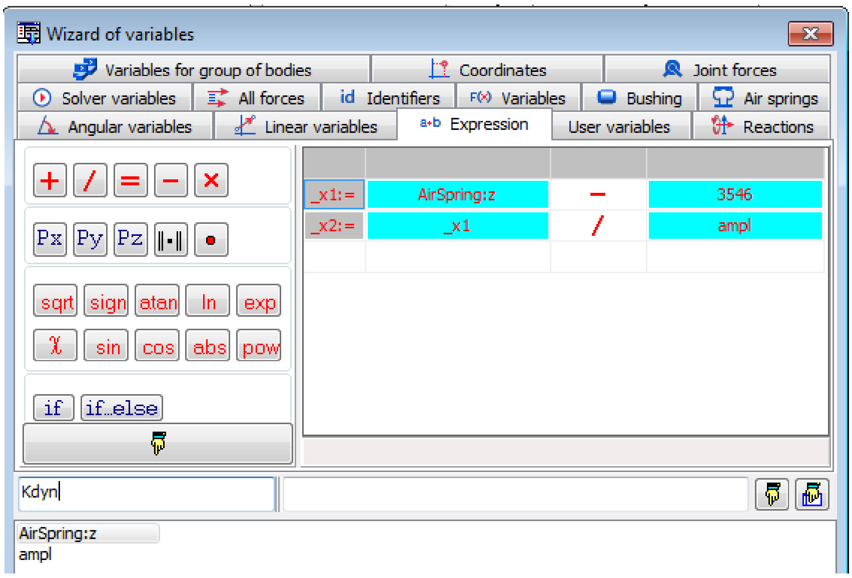


Figure 1.84. Variable for evaluation of dynamic stiffness of AS

With this model we compare simulated and measured dynamic stiffness of the air spring. With this purpose, the variable *Kdyn* is created, which is the centralized air spring force divided by the amplitude of oscillations, Figure 1.84. The enveloping curve on the plot of this variable versus the frequency corresponds to the dynamic stiffness of the AS.

Parameters of the line model are shown in Figure 1.85. It is worth to draw attention to the type of the **Time domain** line model, and to the e/d = 0.01 value for the relative pipe roughness. It is interesting that neither polytropic index nor the number of segments affect considerably on simulation results shown below.

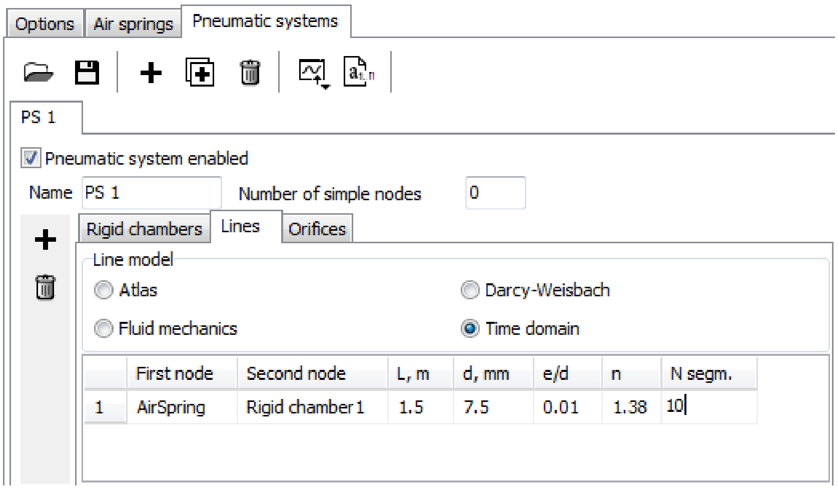


Figure 1.85. Parameters of line model

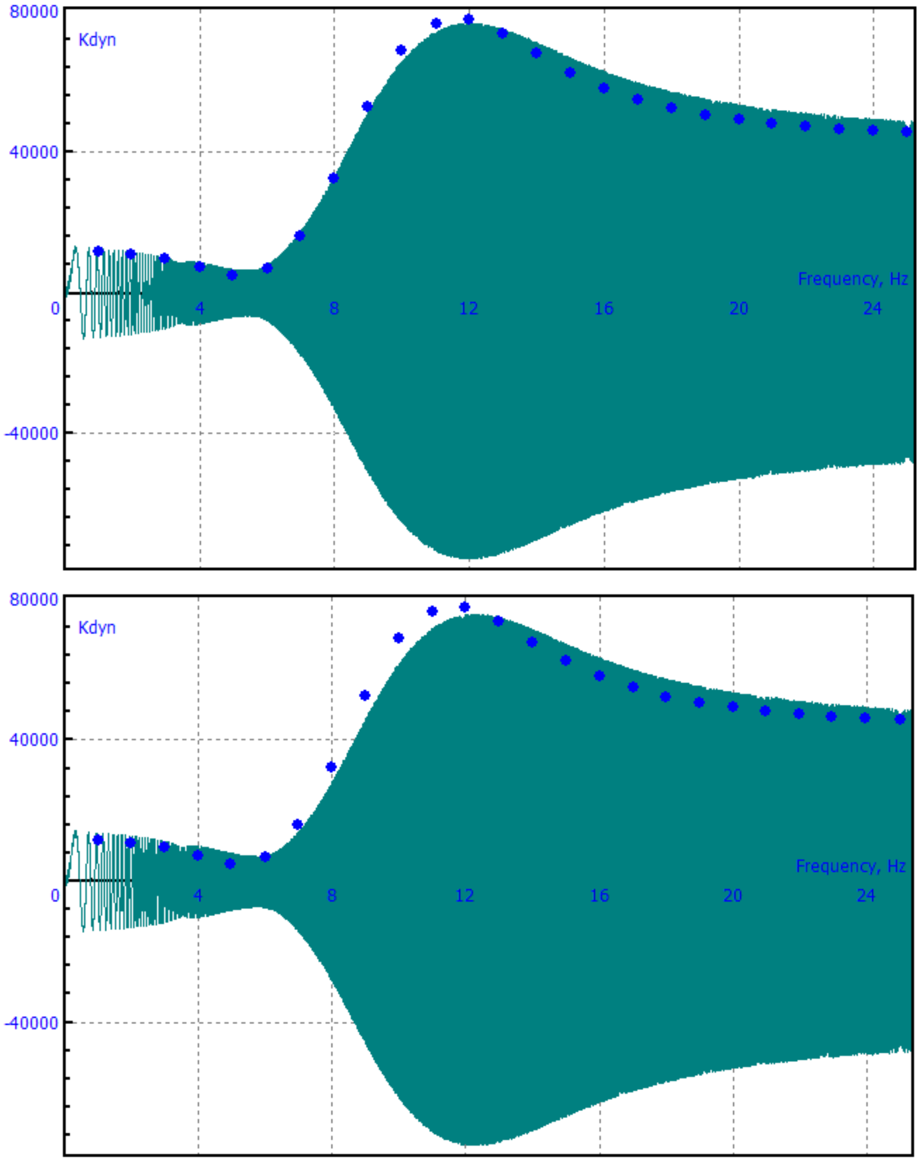


Figure 1.86. Dynamic stiffness vs. frequency: comparison of simulation and experiment: amplitude 1mm, polytropic index for auxiliary chamber n=1.2 for the upper and n=1.38 for the lower plot.

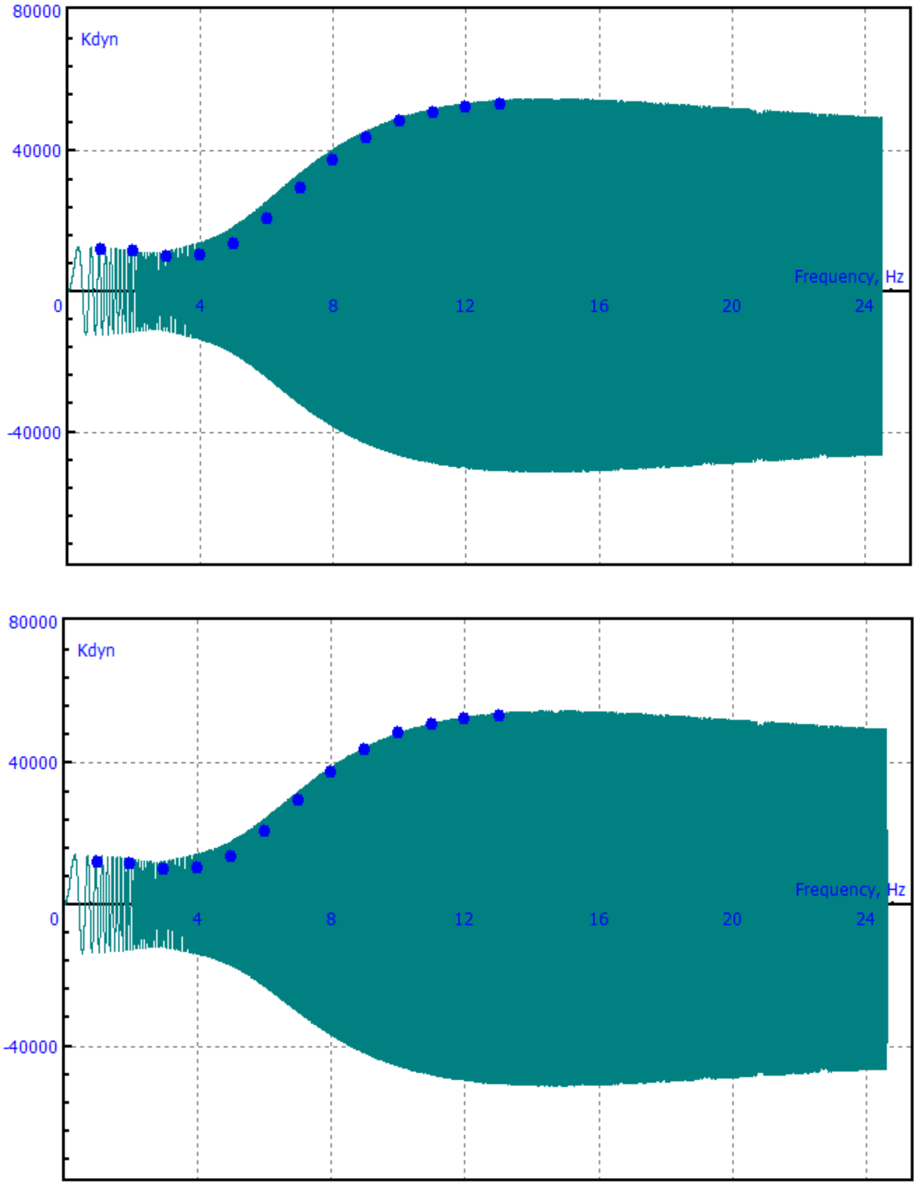


Figure 1.87. Dynamic stiffness vs. frequency: comparison of simulation and experiment: amplitude 5mm, polytropic index for auxiliary chamber n=1.2 for the upper and n=1.38 for the lower plot.

Comparison of UM simulation results on dynamic stiffness with the experimental data from paper [17] are shown in Figure 1.86, Figure 1.87. To fit better the experimental data, we recommend the standard polytropic index n=1.38 for the air spring volume and the lower value 1.2 for the auxiliary chamber. Anyway, coincidence seems to be very good.

The experimental results shown in figures by markers are located in the files

1mm (experiment).txt,

5mm (experiment).txt

and can be used for repeating tests with the UM model. The excitation amplitude can be changed in the list of variables, Figure 1.88.

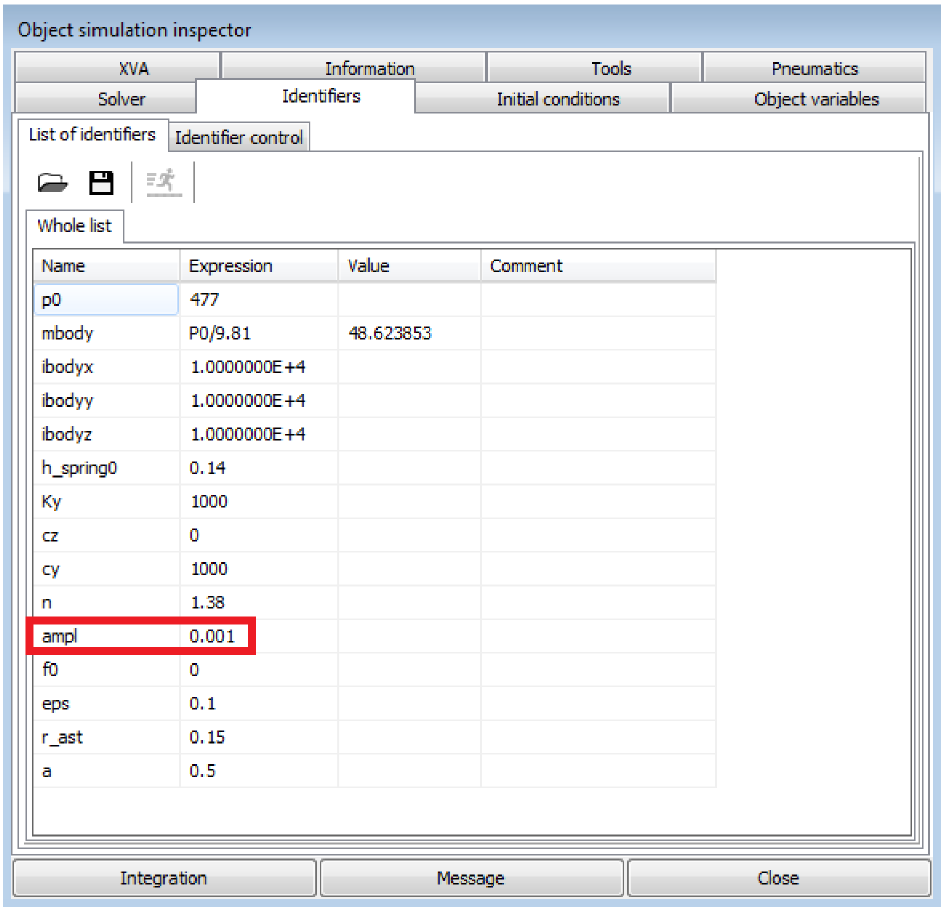


Figure 1.88. Change of excitation amplitude

Finally, comparison of stationary and time domain models in Figure 1.89 confirms that the stationary model of a long pipe can be used for the slow processes only.

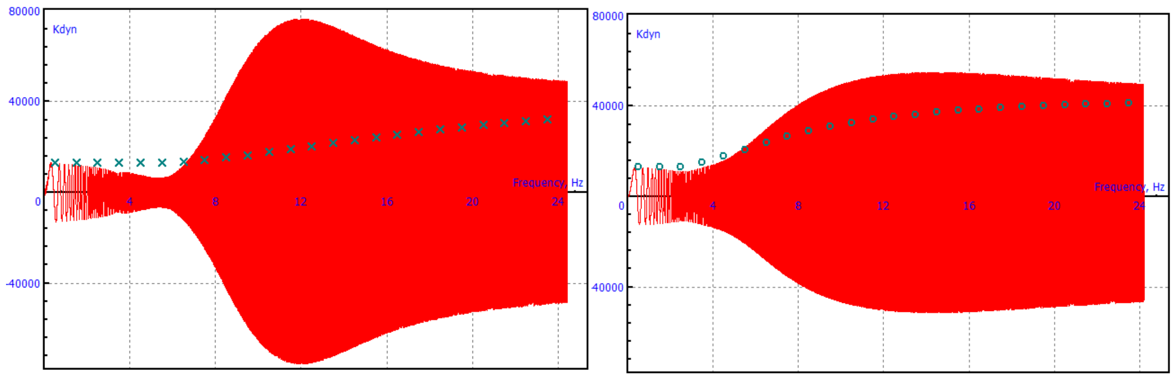


Figure 1.89. Comparison of stationary (marker) and time domain models

1.4.2.2. Case 2: Air spring connected by orifice with auxiliary chamber

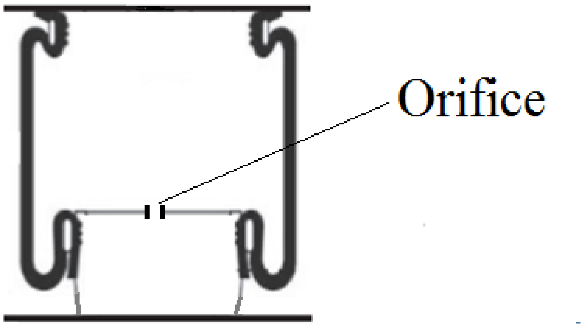
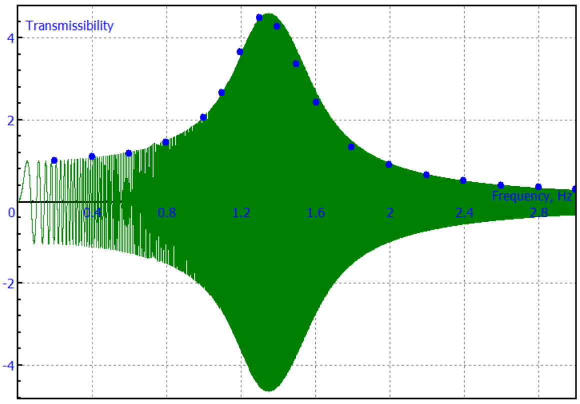


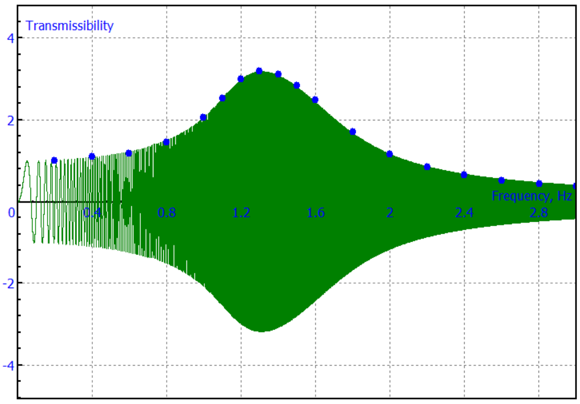
Figure 1.90. Air spring and auxiliary chamber

The test corresponds to the experimental data presented in paper [18]. In the test, an air spring is connected with an auxiliary chamber by an orifice, Figure 1.90. The paper includes the dependences of the effective area and volume of the air spring on its height, which allow us to develop the AS model, Sect. 1.2.3.1.3.5 *Creating tabular data by effective area*. The experiment consists of the harmonic excitation of the air spring foundation and the measurement of the dead weight oscillations. The UM model is

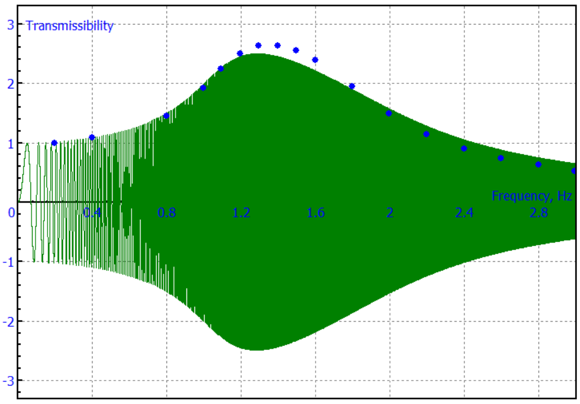
{UM Data}\SAMPLES\ Pneumatics\Orifice test



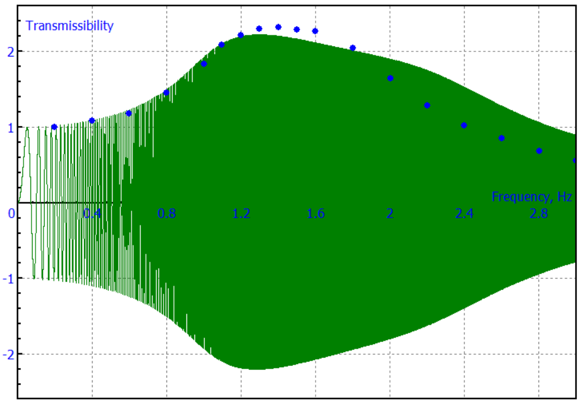
a = 1mm



a = 2.5mm



a = 5mm



a = 7.5mm

Figure 1.91. Comparison of simulation and experimental results

We compared simulation results for the static absolute pressure 280 kPa with experiments obtained in [18] for different excitation amplitudes, Figure 1.91. The plots show dependencies of the transmissibility on the frequency for different excitation amplitudes *a*. The transmissibility is the ratio of the response amplitude to the excitation amplitude *a*. The "Nozzle" orifice model is used.

The experimental results from paper [18] shown in figures by markers are located in the files

Transmissibility 1mm.txt,

Transmissibility 2.5mm.txt,

Transmissibility 5mm.txt,

Transmissibility 7.5mm.txt,

and can be used for repeating tests with the UM model. The excitation amplitude can be changed in the list of variables similar to Figure 1.88.

1.4.3. Models with air springs

1.4.3.1. Testing stand with 3 air springs

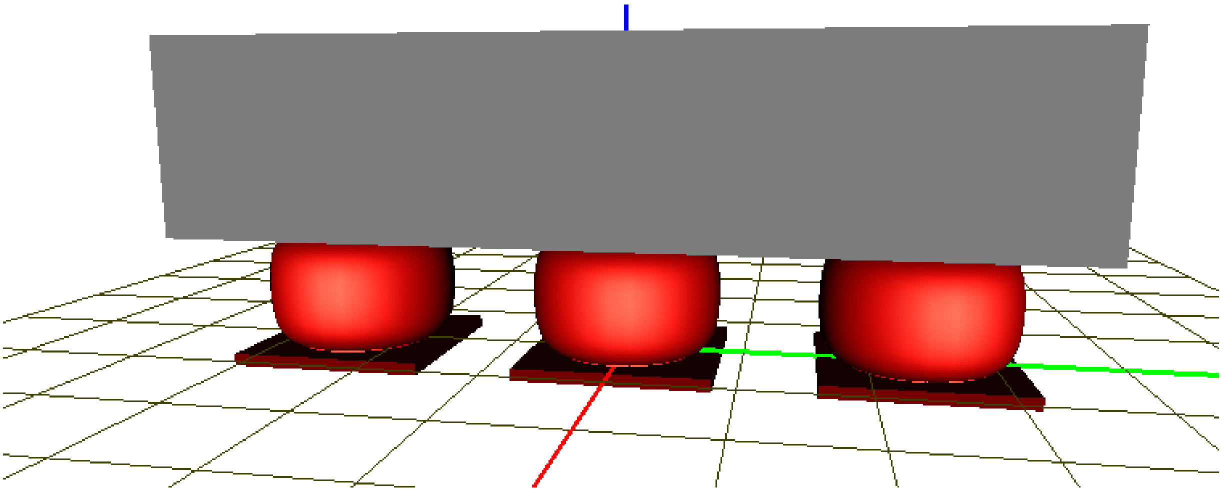


Figure 1.92. Testing stand with three AS

The stand model is located in
{UM Data}\SAMPLES\ Pneumatics\test_3as

The model includes three air springs supporting a rigid body, which has 3 d.o.f. in the vertical plane, Figure 1.92. Positions of three plates under each of the AS are parameterized by the identifiers *z_as*1, *z_as*2, *z_as*3, Figure 1.94.

The model has been developed for testing a suspension with air springs interconnected by pipelines, Figure 1.93. The pipelines are connected by a T-junction, which is modeled in UM PS by a simple node, Sect. 1.2.4 *Simple nodes* (**Node 1** in Figure 1.49).

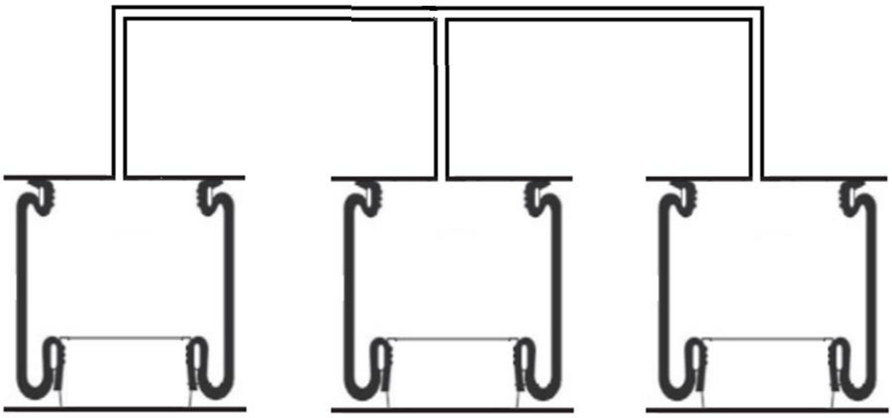


Figure 1.93. Interconnected air springs

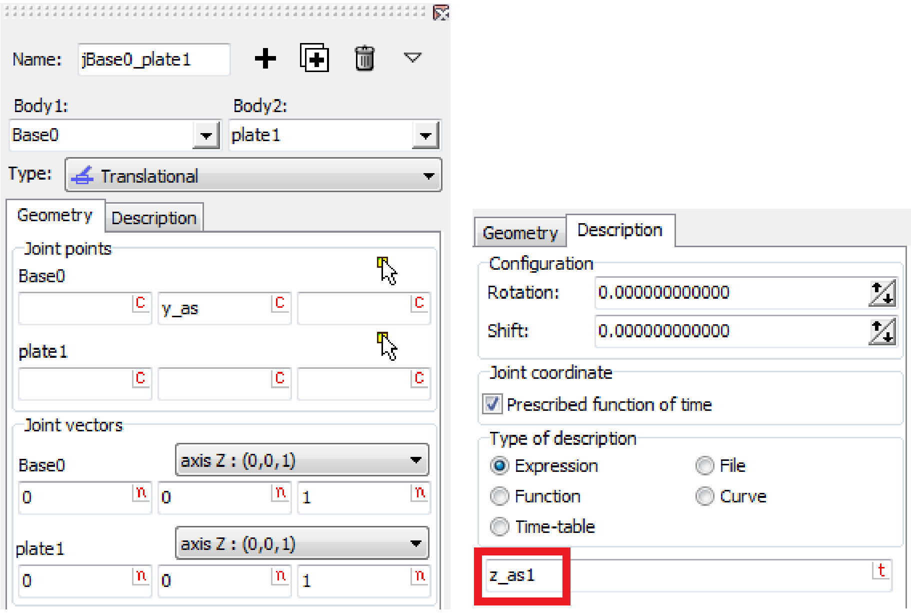


Figure 1.94. Joint for Plate1

The user can describe the motion of the plates under each of the AS with the **Identifier control** tool, Figure 1.95. As examples, we prepared two excitations for the plate1: step and harmonic functions, Figure 1.96, Figure 1.97.

To create a step function of time, we used the curve editor, see Figure 1.96. The harmonic function was made with the **Wizard of variables** and dragged into the **Assigned variable** box of the **Identifier control** window, Figure 1.97. We used identifiers for the excitations frequency (*freq*) and amplitude (*ampl*), so the user can change their values in the list of identifiers of the model.

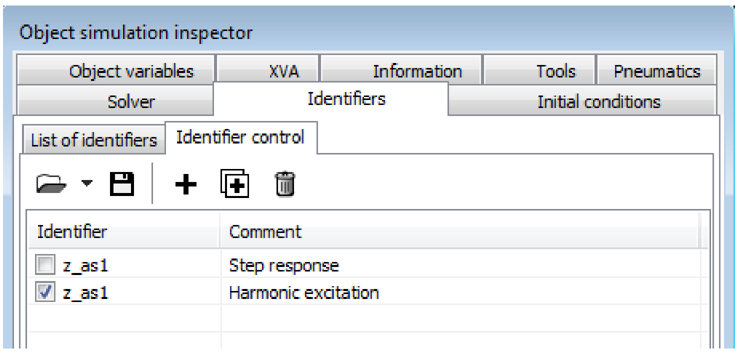


Figure 1.95. Examples of identifier control for vertical position of Plate1

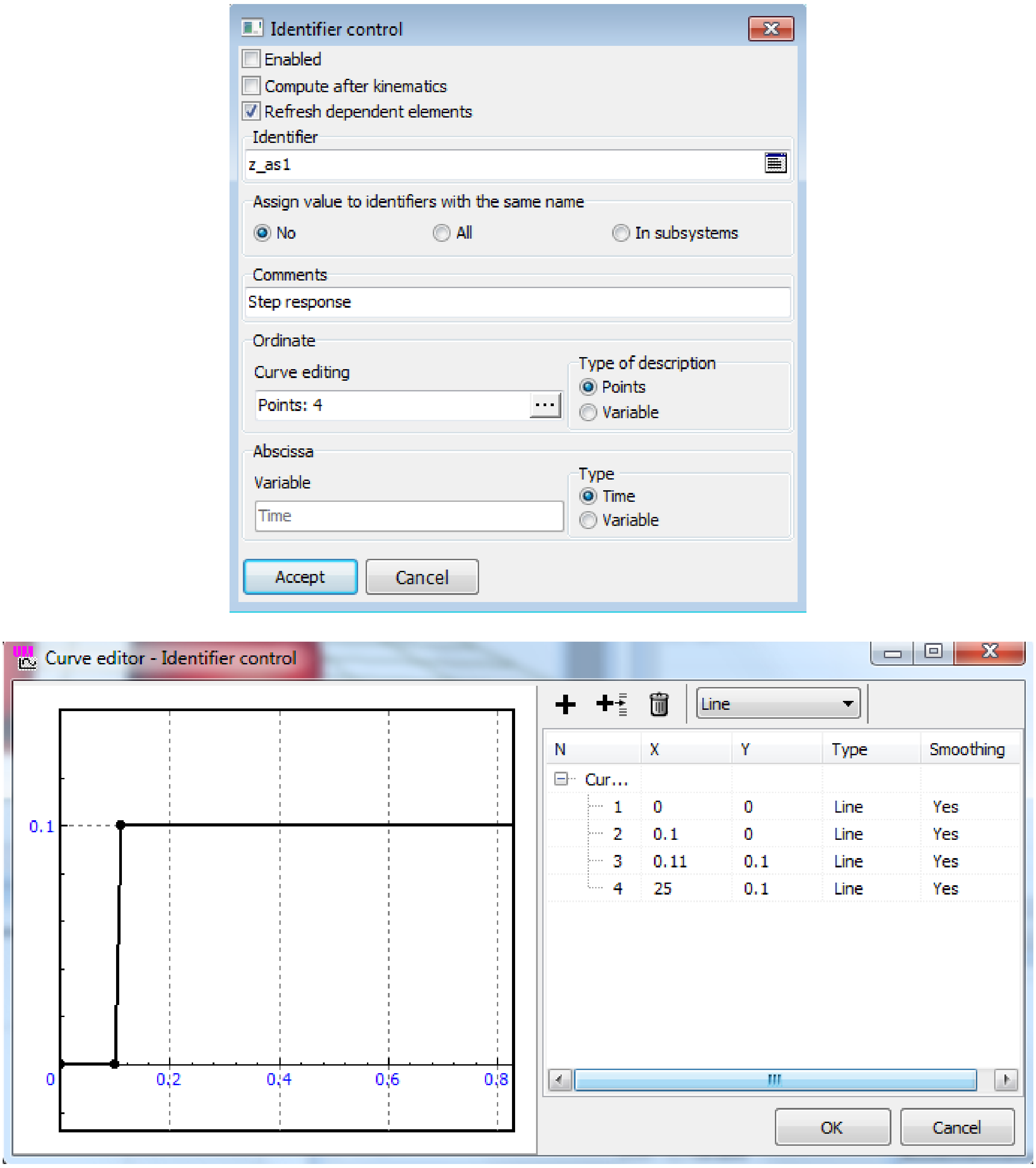
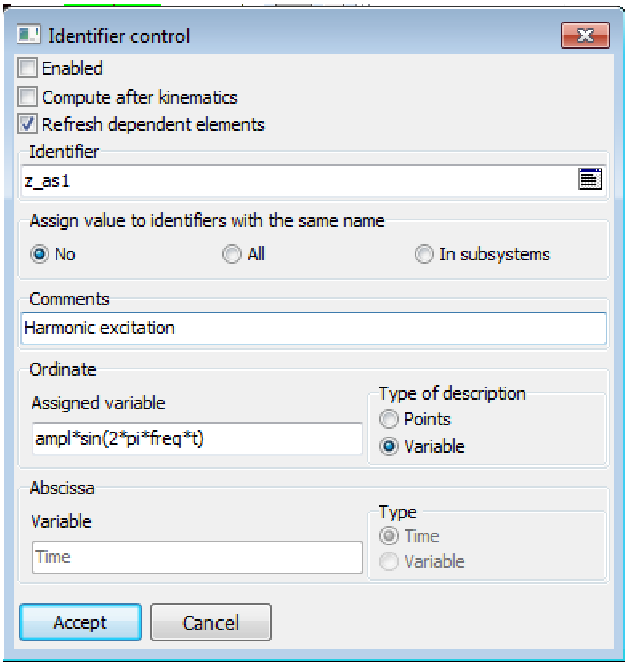


Figure 1.96. Step function for identifier z_as1



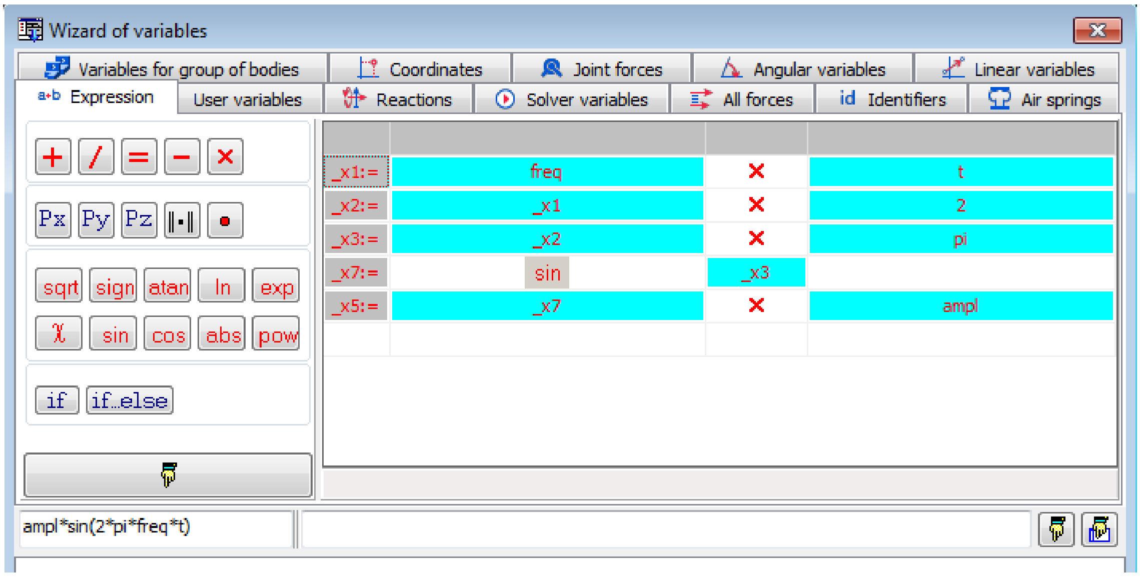


Figure 1.97. Harmonic function for identifier control

1.4.3.2. Testing stand with 6 air springs

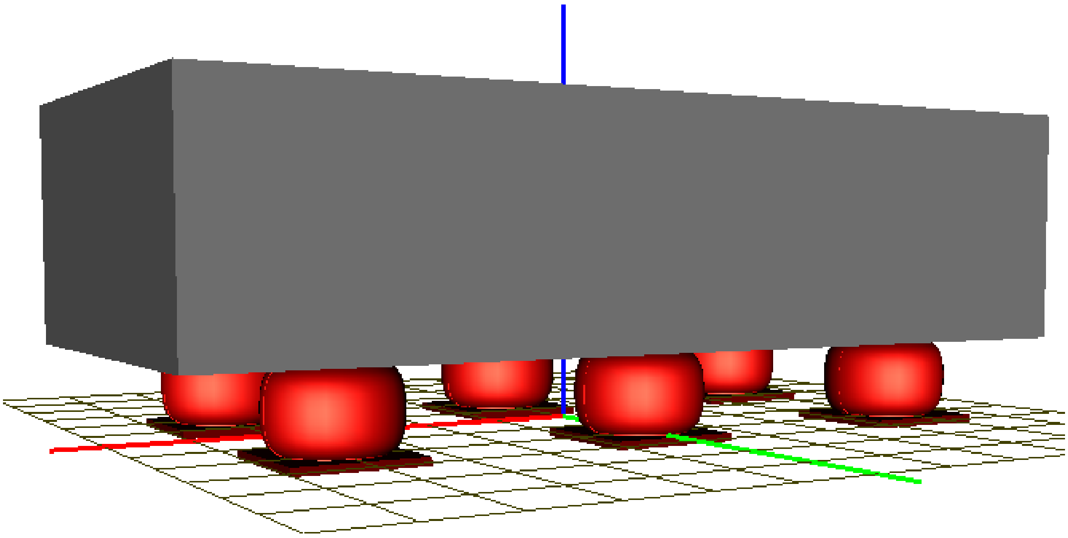


Figure 1.98. Testing stand with six AS

The stand model is located in
{UM Data}\SAMPLES\ Pneumatics\test_6as

The model includes six air springs supporting a rigid body, which has 6 d.o.f., Figure 1.92. Positions of six plates under each of the AS are parameterized by the identifiers *z_as*1*l*, *z_as*2*l*, *z_as*3*l*, *z_as*1*r*, *z_as*2*r*, *z_as*3*r*.

The model has been developed for testing suspensions with air springs interconnected by pipelines.

We developed two types of AS connections.

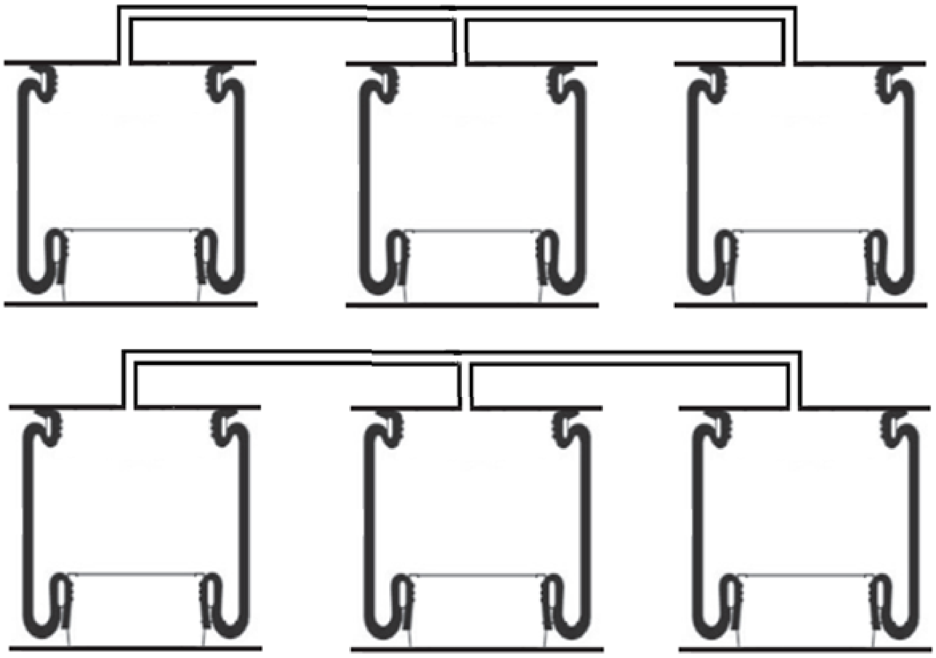


Figure 1.99. PS 1 scheme

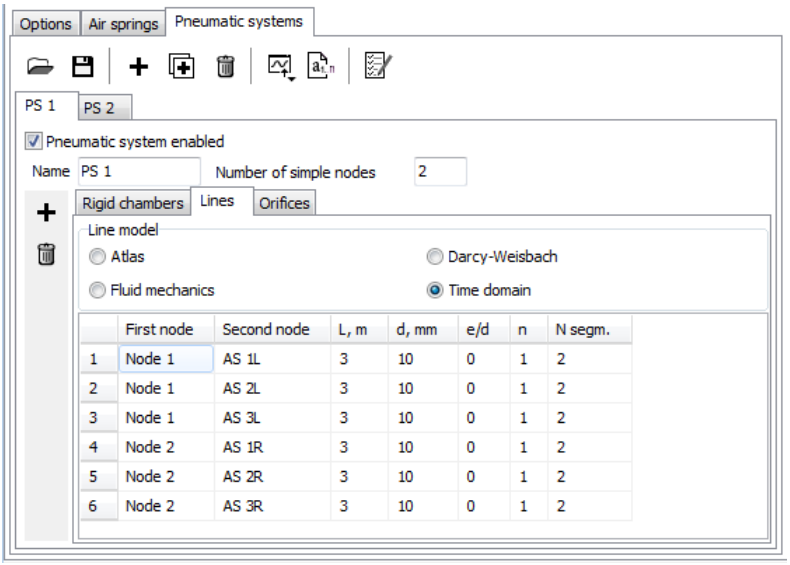


Figure 1.100. PS 1 connections

PS1, Figure 1.99: Left and rights AS are connected independently by two T-junctions, Node 1, Node 2 in Figure 1.100.

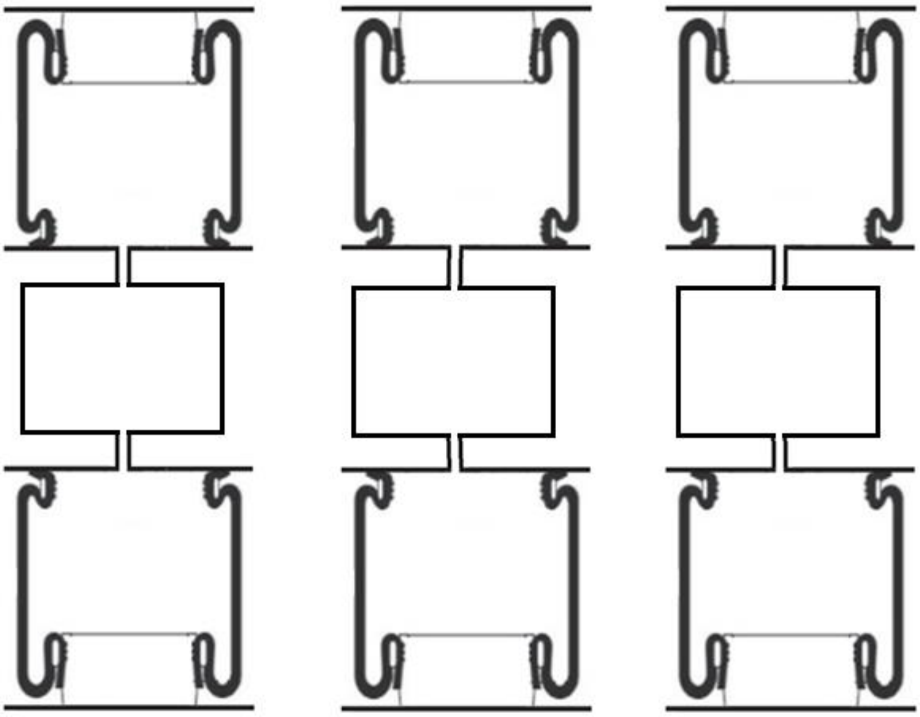


Figure 1.101. PS 2 scheme

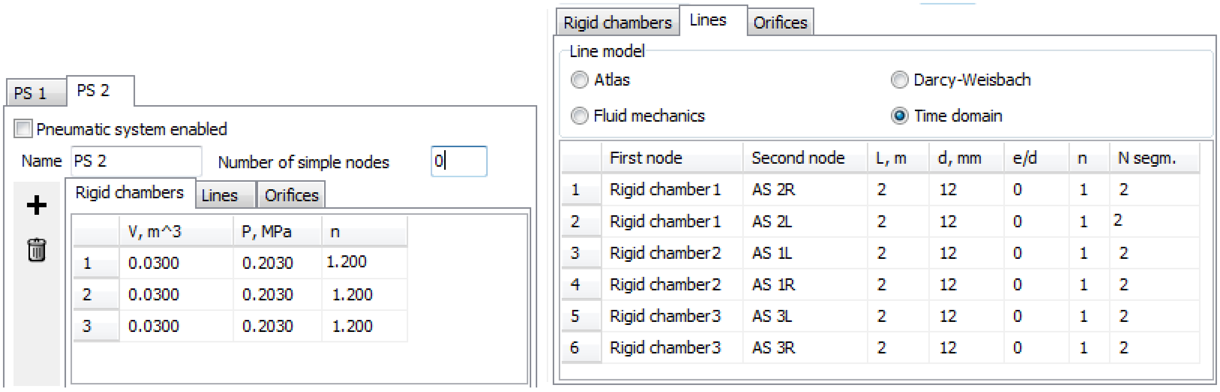


Figure 1.102. PS 2 connections

PS2, Figure 1.101: Left and rights AS are connected independently to three rigid chambers, Figure 1.102.

The stand excitation functions are created as variables of time, Figure 1.97, Figure 1.103. The variables are stored in the *Excitation functions.var* file, which can be read by the user in a list of variables. Use the **Tools | List of variables** menu command to open the list form, and then the button to open the file, Figure 1.104.

The variable approximating the step function depends on two identifiers:

- *h_step* is the step height;

- *t_step* is the time constant specifying the rate of the function growth.

The use can use these and other variables to assign them to the identifier control like in Figure 1.105.

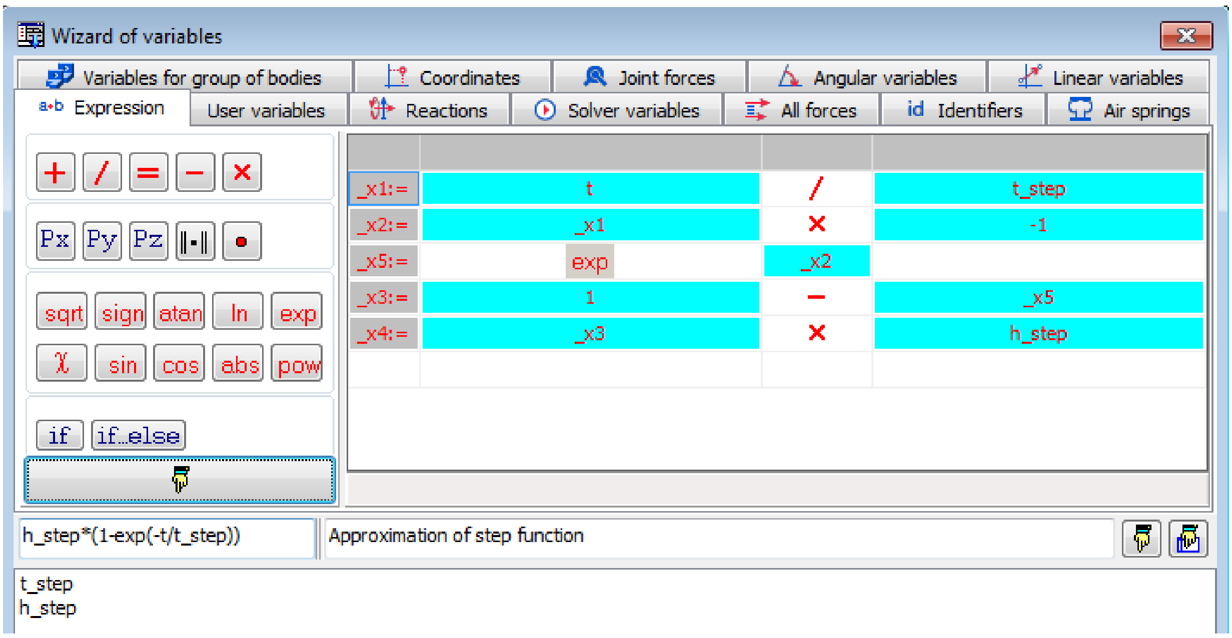


Figure 1.103. Variable approximating step function

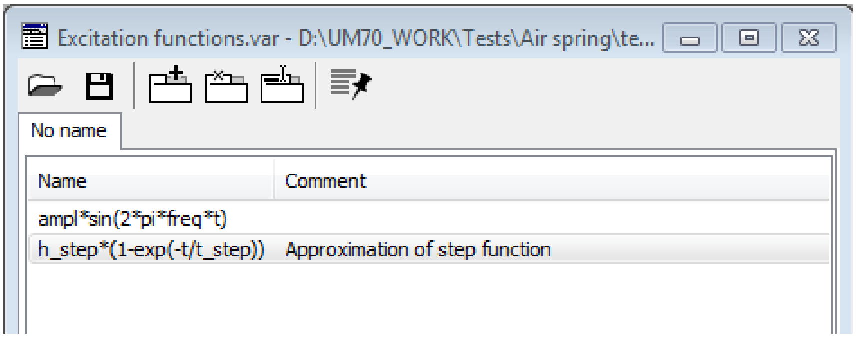


Figure 1.104. List of excitation variables

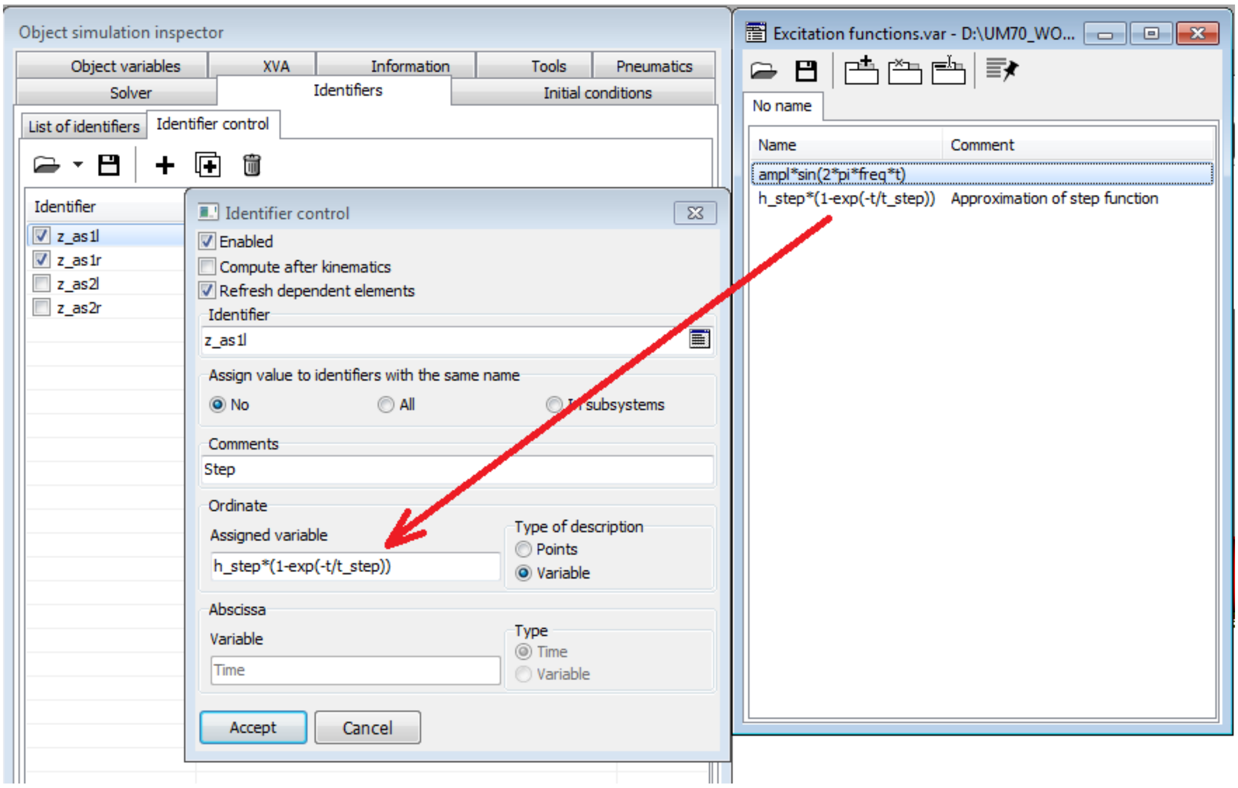


Figure 1.105. Assignment of excitation variables to identifier control

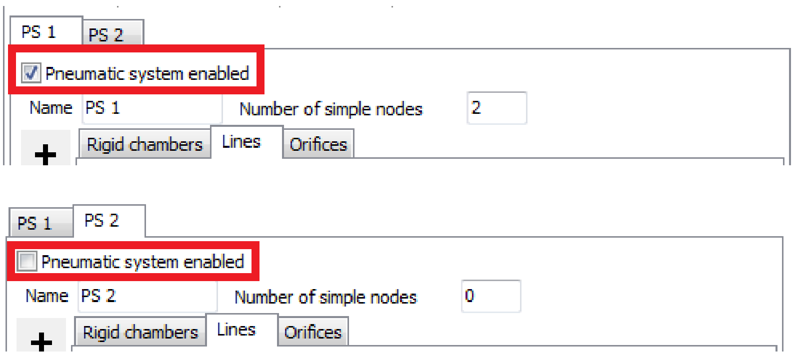


Figure 1.106. Enabled and disabled PS

The user can activate (enable) one of two PS before simulation start, Figure 1.106. If none of the PS is enabled, the air springs are considered as independent ones.

1.4.3.3. Test model: High speed railway motor car

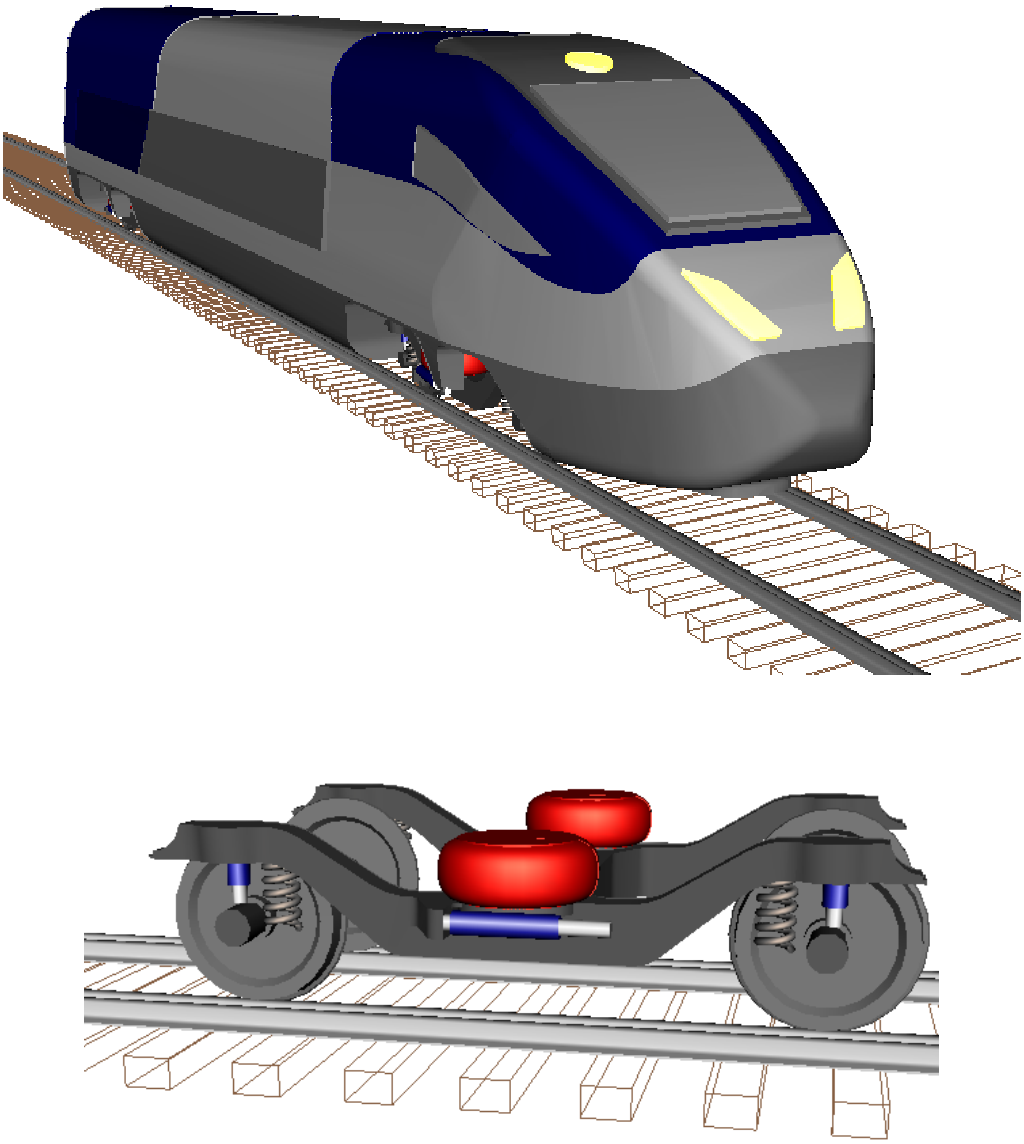


Figure 1.107. UM model of motorcar

The simplified model of a motorcar of a high speed train is located in {UM Data}\SAMPLES\ Pneumatics\motorcar

The secondary suspension of the motorcar includes two air springs for each of the bogie, Figure 1.107. In the model we used data for the YI-FT 1710-38-324, ENIDINE Incorporated air spring [19], Figure 1.108.

With this model the user can compare simulation results for two cases:

Case 1: Isolated air spring

The pneumatic system is disabled, and vertical dampers in secondary suspension are enabled.

Case 2: Air springs connected with auxiliary chamber by pipelines, Figure 1.109.

The pneumatic system is enabled, and the secondary vertical dampers disabled.

To load the simulation cases, open the model and use one of the **File | Load configuration | Auxiliary chambers/Isolated air spring** menu commands.

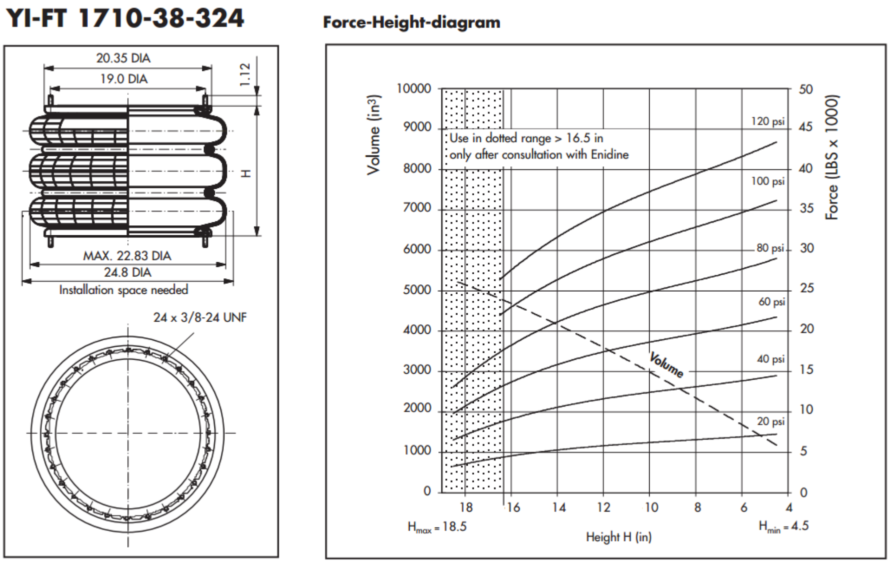


Figure 1.108. Force-height diagram for YI-FT 1710-38-324

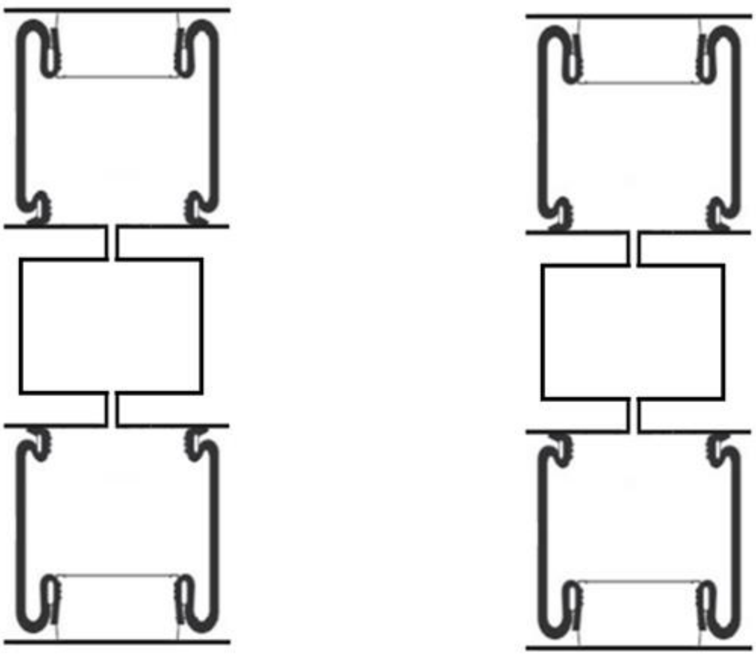


Figure 1.109. Air spring connections for bogies

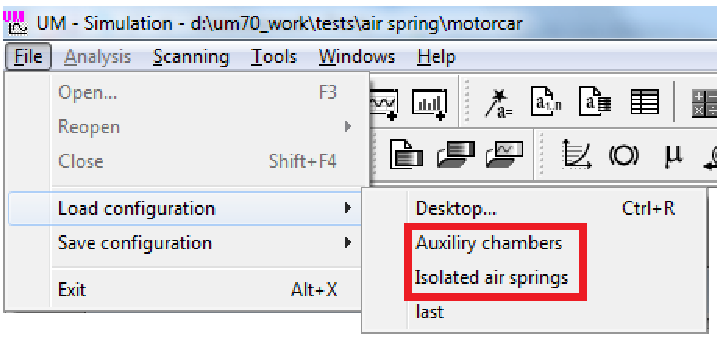


Figure 1.110. Selection of model configuration

1.4.4. Model with HCV

This example is based on the model described in Sect. 1.4.3.1 *Testing stand with 3 air springs*. The model is located in the directory

{Data UM}\SAMPLES\ Pneumatics\test_3as HCV

1.4.4.1. Adding bodies, joints and force elements to stand

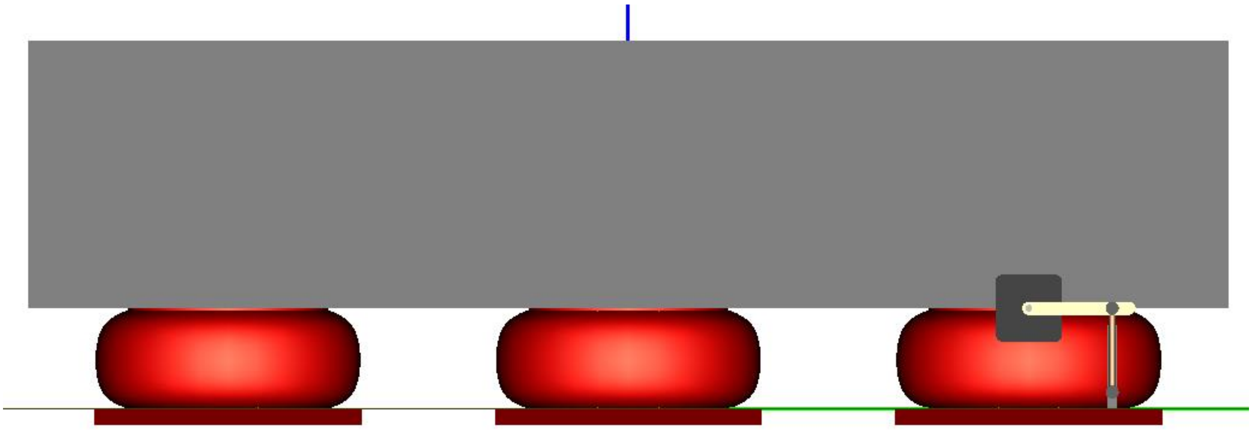


Figure 1.111. Model of stand with height control valve

Basic elements of the model are described in Sect. 1.4.3.1 *Testing stand with 3 air springs*. We added a simplified model of a HCV including the casing, control arm, and a force element connecting the arm with the first platform, Figure 1.111. This mechanism allows computing the rotation angle of the control arm, which will be used in the HCV control.

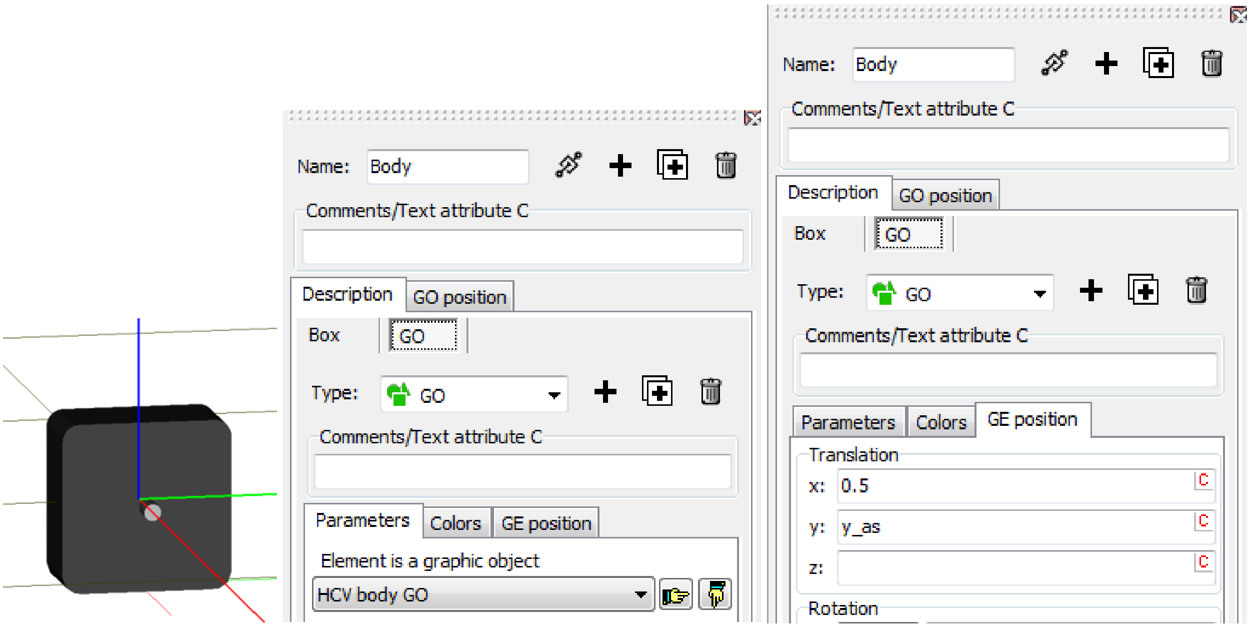


Figure 1.112. Image of HCV casing (left picture), reference to it in the Body graphic object (center) and the image shift (right)

The valve casing is rigidly connected with *Body*, which models a load suspended on three air springs. No special body is assigned to the casing, and its image is simply attached to the

Body graphic object as a reference to *HCV body GO* with an additional shift to the desired position, Figure 1.112.

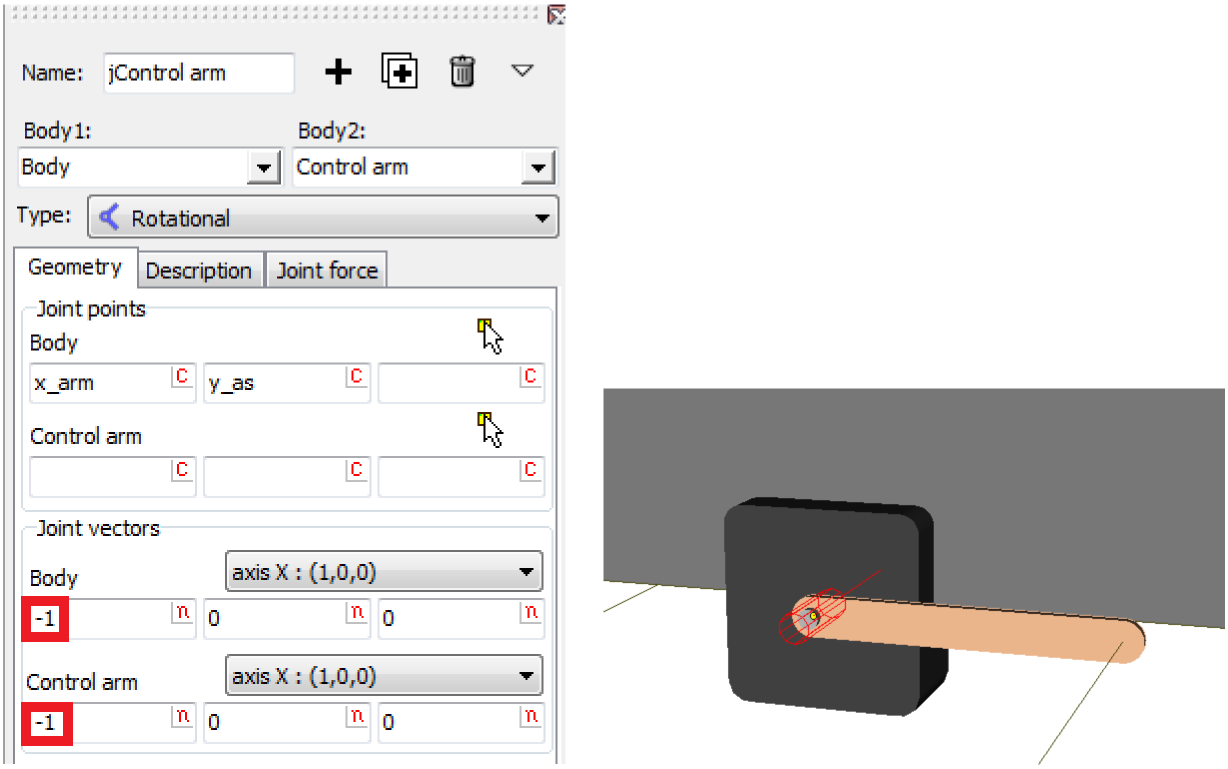


Figure 1.113. Rotational joint connecting control arm with casing

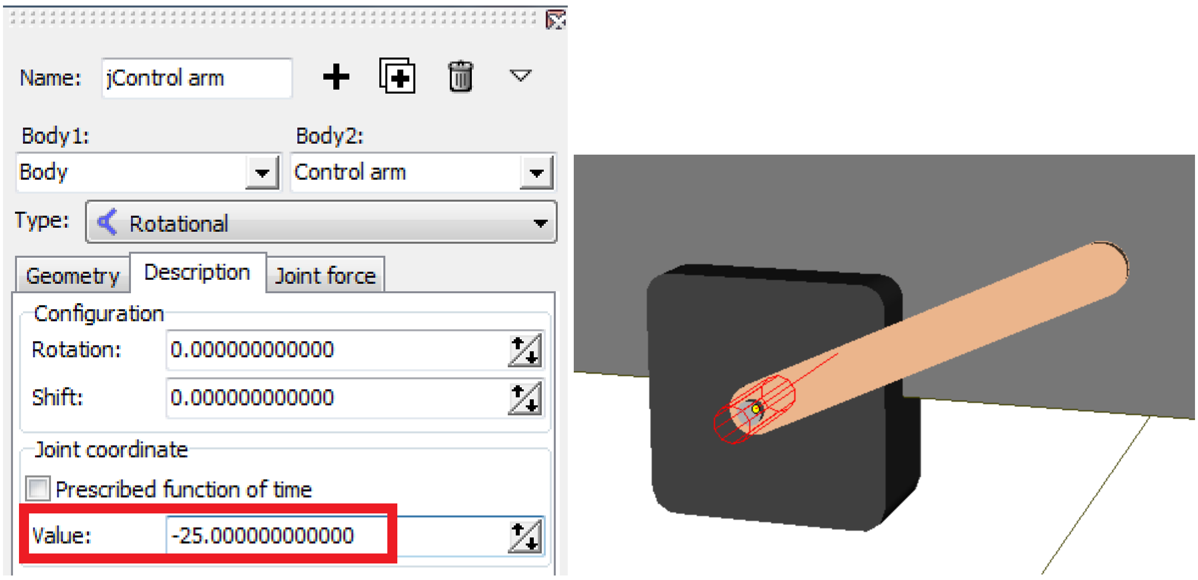


Figure 1.114. Negative coordinate value corresponds to supply

The **Control arm** is modeled by a body with the same name. The arm is connected to *Body* by a rotational joint, Figure 1.113. The joint coordinate will be used for the valve control. Thus it is important that it corresponds exactly to the abscissa of the flow curve. Firstly, zero value of the coordinate must coincide with zero of abscissa. Secondly, the sign of the coordinate must coincide with the sign of abscissa; otherwise the valve will connect the suspension with exhaust port instead of the supply and vice versa. In the example of the flow rate curves in Figure 1.36

the supply corresponds to the negative values of abscissa. To achieve this property for the coordinate, we have changed the directions of the joint vectors, Figure 1.113. By default the vectors are oriented in positive direction of the X axis, but the correct direction is opposite to X. Note that we can easily create a variable in UM Simulation with an opposite sign, so the user can correct the variable before the simulation if necessary.

An element linking the control arm with the platform in modeled by a linear bipolar force element *Control arm linkage*, Figure 1.115. It is important to assign correct values of the element attachment points for the neutral arm position, when the air spring height is equal to the desired value (the desired air spring height is parameterized by the identifier *h_spring0*):

- the linkage is vertical;

- the linkage is not deformed, i.e. the distance between the attachment points is equal to the length of undeformed force element (the identifier *link_length*).

The second condition is achieved by the expression for Z coordinate of the second attachment point *h_spring0-link_length*.

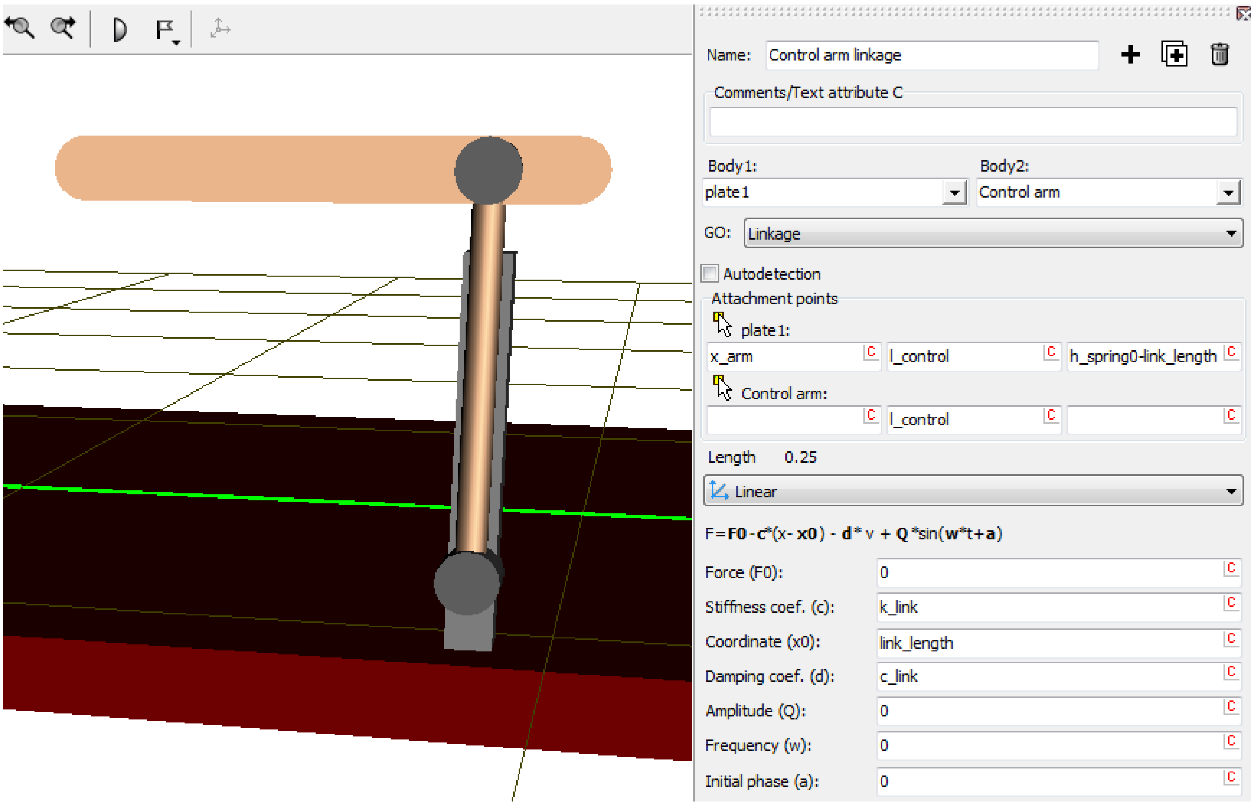


Figure 1.115. Linkage of control arm with platform

For the convenience of the user, the elements of the valve model are saved in a separate file

{UM Data}\SAMPLES\ Pneumatics\HCV\input.dat.

It is assumed in this file that the valve is located in the XZ plane; the images and joint axes are corrected correspondingly.

To add the valve elements to model of a truck or a rail vehicle, open the model in UM Input and use the button to select the file

{UM Data}\SAMPLES\ Pneumatics\HCV\input.dat.

As a result, all elements and identifiers from this file will be added to the user's model. After that the user should assign bodies, which the elements are assigned to. The attachment points must be corrected as well. If necessary, the direction of the joint vectors for the control arm joint must be changed.

1.4.4.2. Model of pneumatic system with HCV

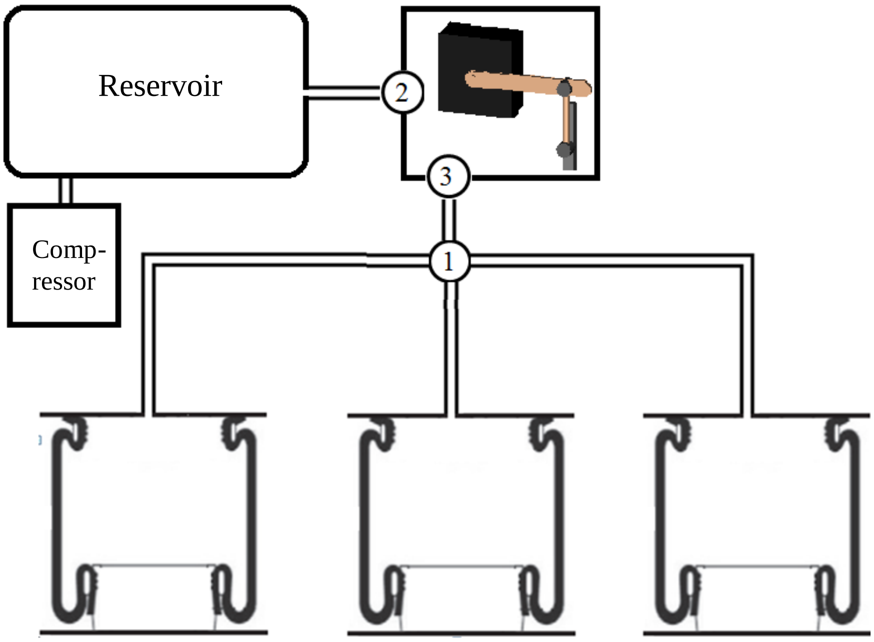


Figure 1.116. Model of pneumatic system with HCV. Indices of nodes are shown in circles

In comparison with the PS described in Sect. 1.4.3.1 *Testing stand with 3 air springs*, the following elements are added to the model, Figure 1.116:

- reservoir (a chamber with constant volume);

- compressor connected to the reservoir;

Rigid chambers | Lines | Orifices | HCV | Compressors

	Port 1	Port 2	HCV model	Angle var.	State	Identifier	Ang.max.	Ang.min.	Window(s)
1	Node 2	Node 3	Hendrickson	HCV arm angle	1	hcv_state	15	3	5

Figure 1.117. Description of HCV model

- HCV, Figure 1.117;

- two simple nodes (2 and 3) corresponding to Ports 1 and 2 of the valve;

- two pneumatic lines connecting the reservoir with Port 1 (Node 2) and Node 1 with Port 2 of the valve (Node 3)

1.4.4.3. Variable: angle of control arm

Consider in details a process of creation and assignment to HCV model of a variable, which is equal to the angle of rotation of the control arm.

- Open the wizard of variables on the **Coordinates** page and check the coordinate in joint *jControl arm*, Figure 1.118. The coordinate is measured in radians, and we must convert it to degrees.

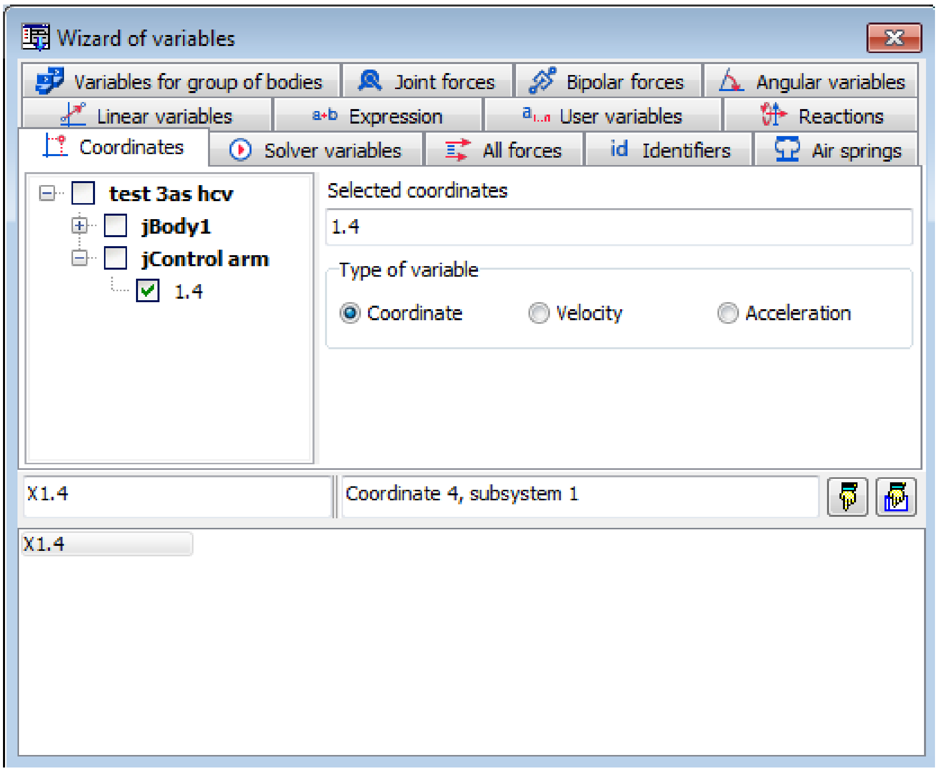


Figure 1.118. Angle of rotation of control arm in radians

- Open the **Expression** page in wizard. Create a multiplication operation by the  button. Drag the variable X1.4 from the container to the fist operand. Write *rtod* as the second operand, this is the standard UM identifier for conversion of radians to degrees, Figure 1.119.
- If the coordinate has a wrong sign, change it to the opposite one in the next multiplication as it is shown in Figure 1.120.
- Rename the variable to *HCV arm angle*, send it to the container and drag by the mouse into the table with HCV description, Figure 1.119.

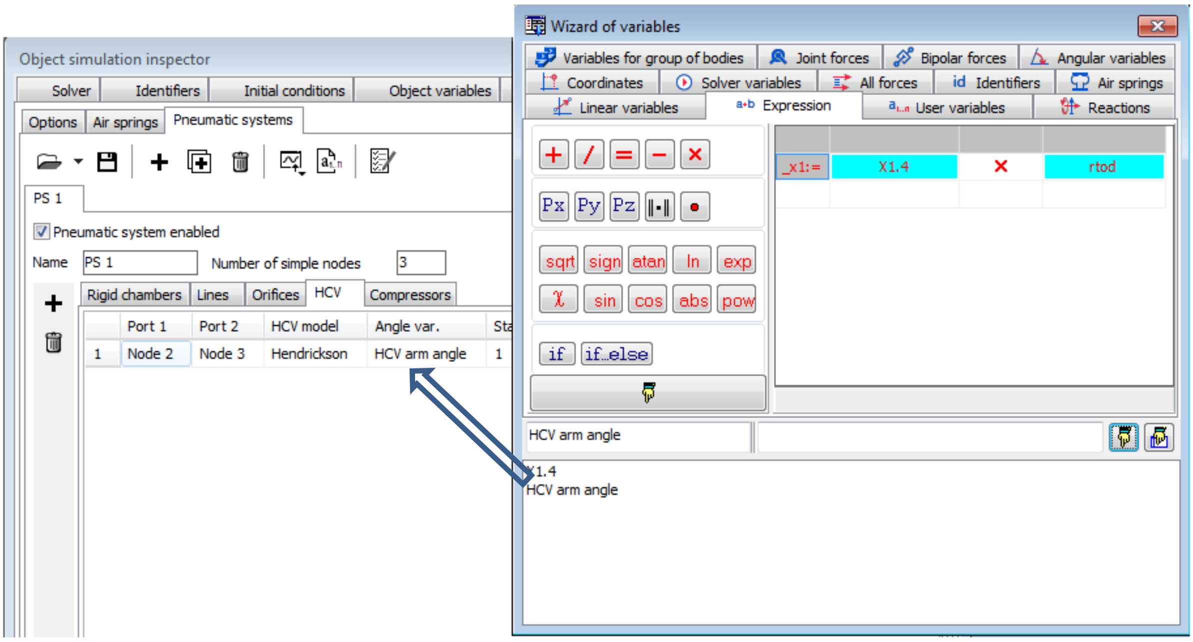


Figure 1.119. Angle of rotation of control arm in degrees and its shift to the table with HCV description

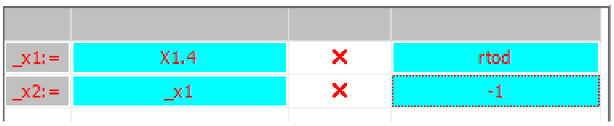


Figure 1.120. Change of the variable sign

1.4.4.4. Dynamic tests with HCV

1.4.4.4.1. General information about tests

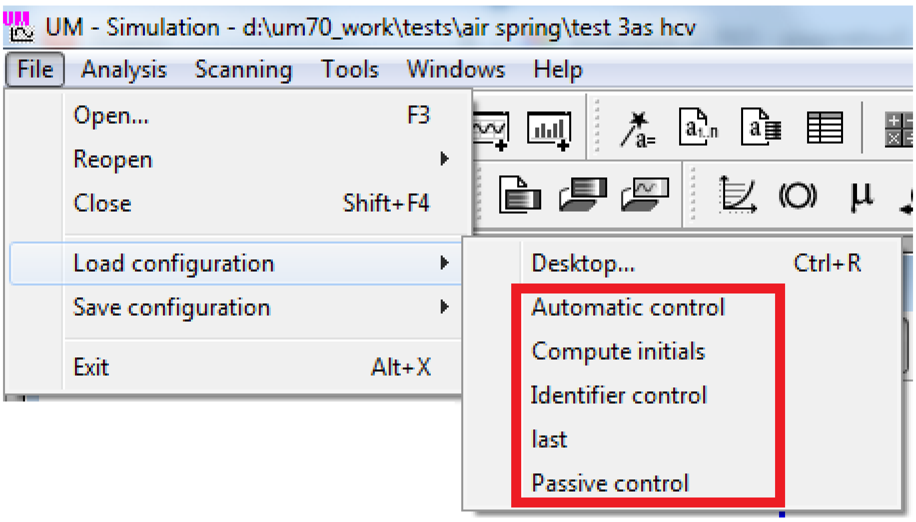


Figure 1.121. Test configurations

To clarify the use of the HCV in UM Pneumatics we prepared four tests. Open the model

{Data UM}\SAMPLES\ Pneumatics\test_3as HCV

in UM Simulation program and use the menu command **File | Load configuration | {Test name}** to read one of four configurations (Figure 1.121):

Passive control

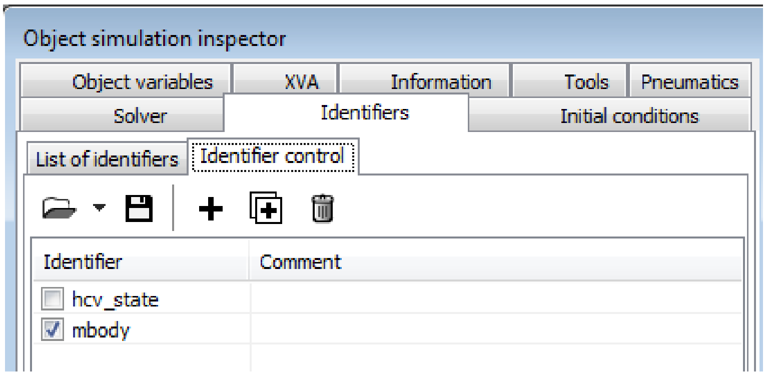
Automatic control

Identifier control

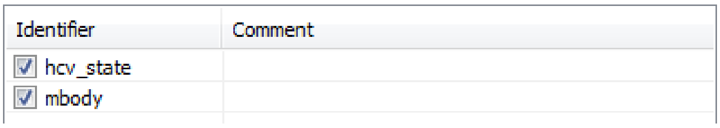
Compute initials

In all four tests, the model simulation starts from the equilibrium position where the spring height is less than the desired value *h_spring0*=0.5m. This means, the AS pressure is lower than it is necessary.

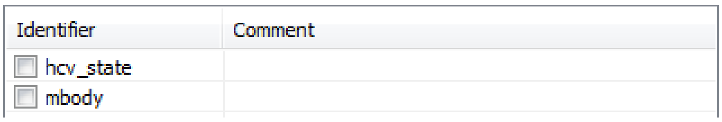
1.4.4.4.2. Tests with control



Tests **Passive control** and Automatic control



Test **Identifier control**



Test **Compute initials**

Figure 1.122. Identifier control for different tests

Let us consider three control tests.

The **Passive control** test corresponds to the constantly turned on valve. The state parameter is equal to 1.

The **Identifier control** test shows how the valve turning on/off can be controlled by the identifier *hcv_state*. The state parameter value is switched 0/1 by this identifier.

The **Automatic control** test illustrates the program ability to turn on/off the valve according to a simple algorithm. The state parameter is equal to 2.

The **Identifier control** page in inspector contains two records: the dependence on time of the load mass *mbody* and the HCV state identifier *hcv_state*, Figure 1.122.

The load mass is changed in all three control tests (Figure 1.123). The load mass decreases from 7.5 to 4.5 tons starting from 50th second.

The dependence on time of the state identifier *hcv_state* is active in the test **Identifier control** only, Figure 1.122. The identifier *hcv_state* dependence on time is synchronized with the mass change, Figure 1.124. The valve is turned on at t=4s to set the desired height when the load is 7.5 tons. The valve is turned off at t=50s. The load decreases and the height of suspension increases. The valve is turned on again at t= 55s to connect the suspension with the exhaust. Similar switching on and off of the valve in the **Automatic control** test occurs automatically according to the algorithm described in Sect. 1.3.2.2.1 *List of height control valves*.

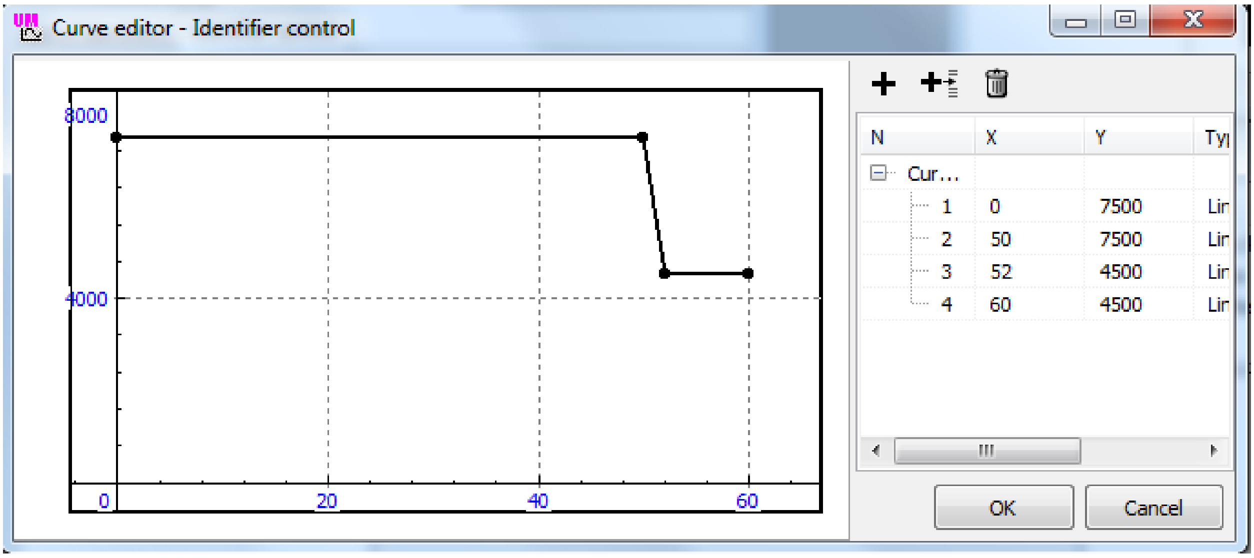


Figure 1.123. Load mass vs. time

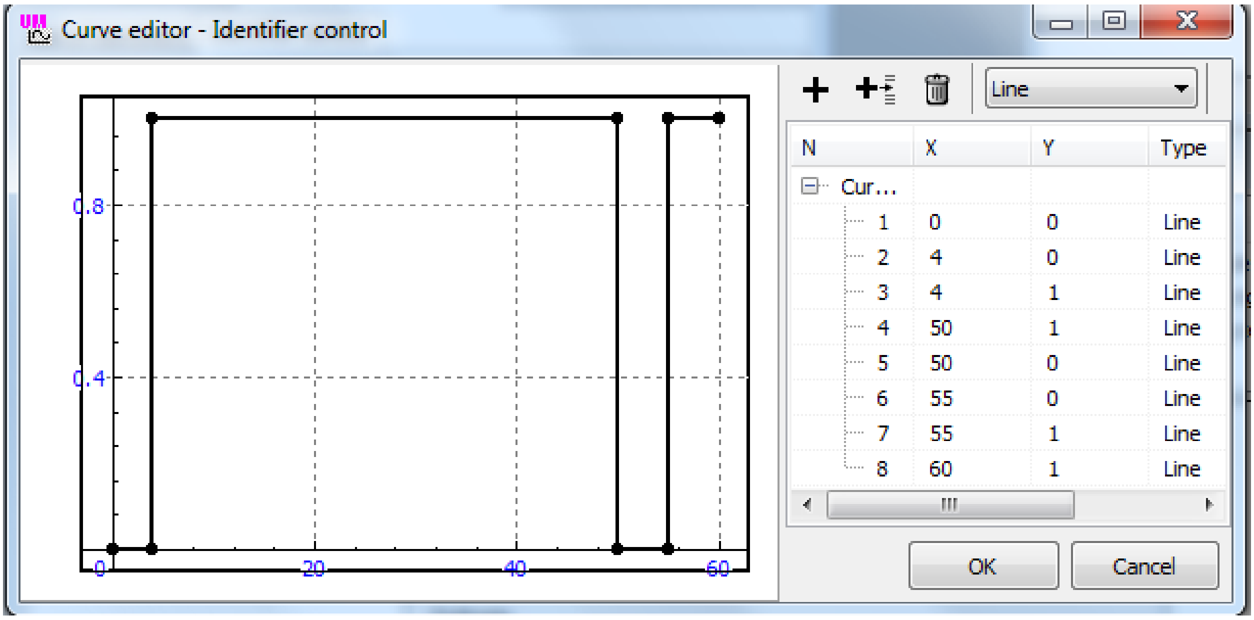


Figure 1.124. HCV state vs. time

Some results of the control tests are shown in Figure 1.125 - Figure 1.127.

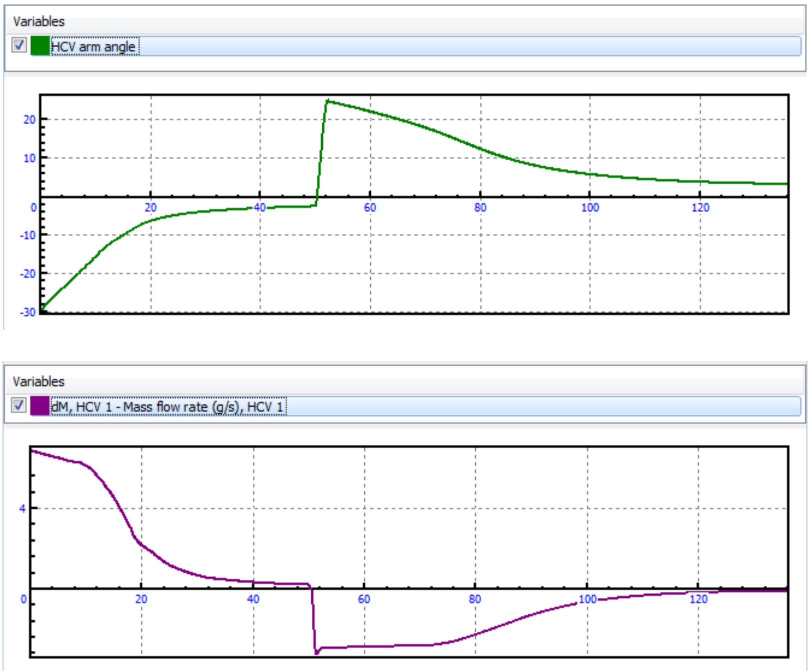


Figure 1.125. Test **Passive control**

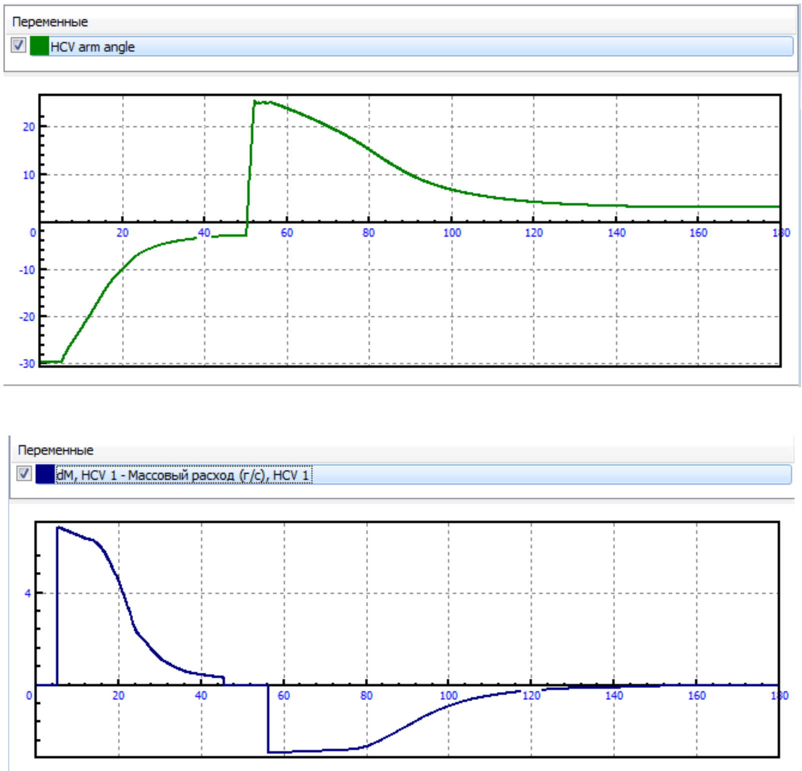


Figure 1.126. Test **Automatic control**

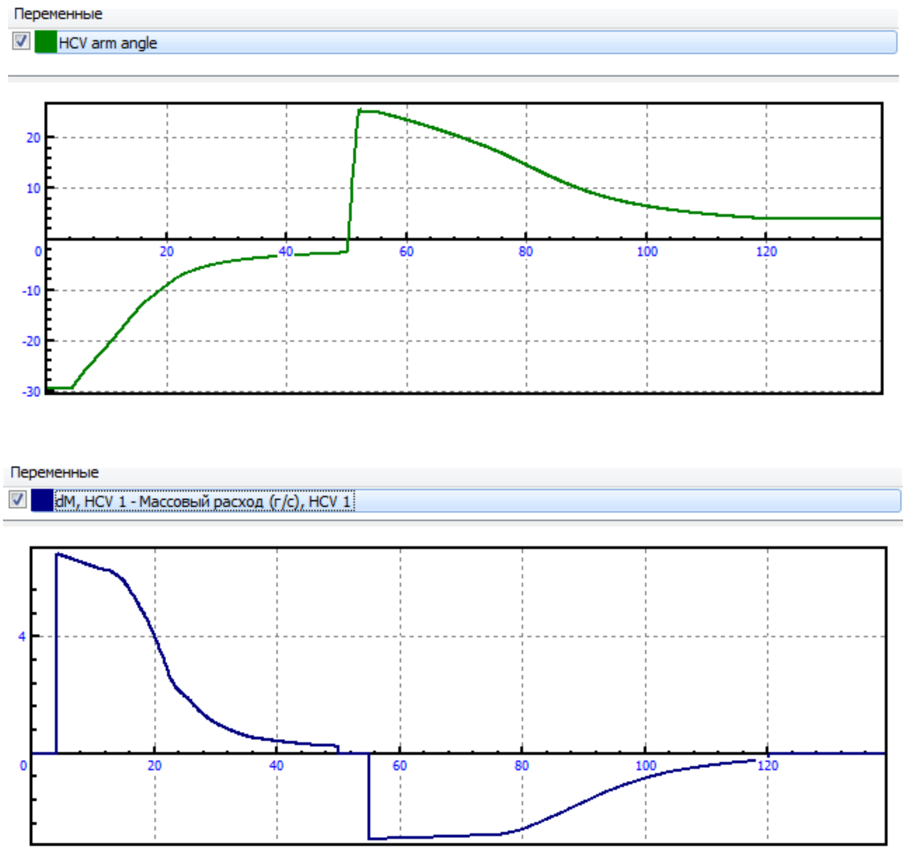


Figure 1.127. Test **Identifier control**

1.4.4.4.3. Test: computation of initial positions and pressures

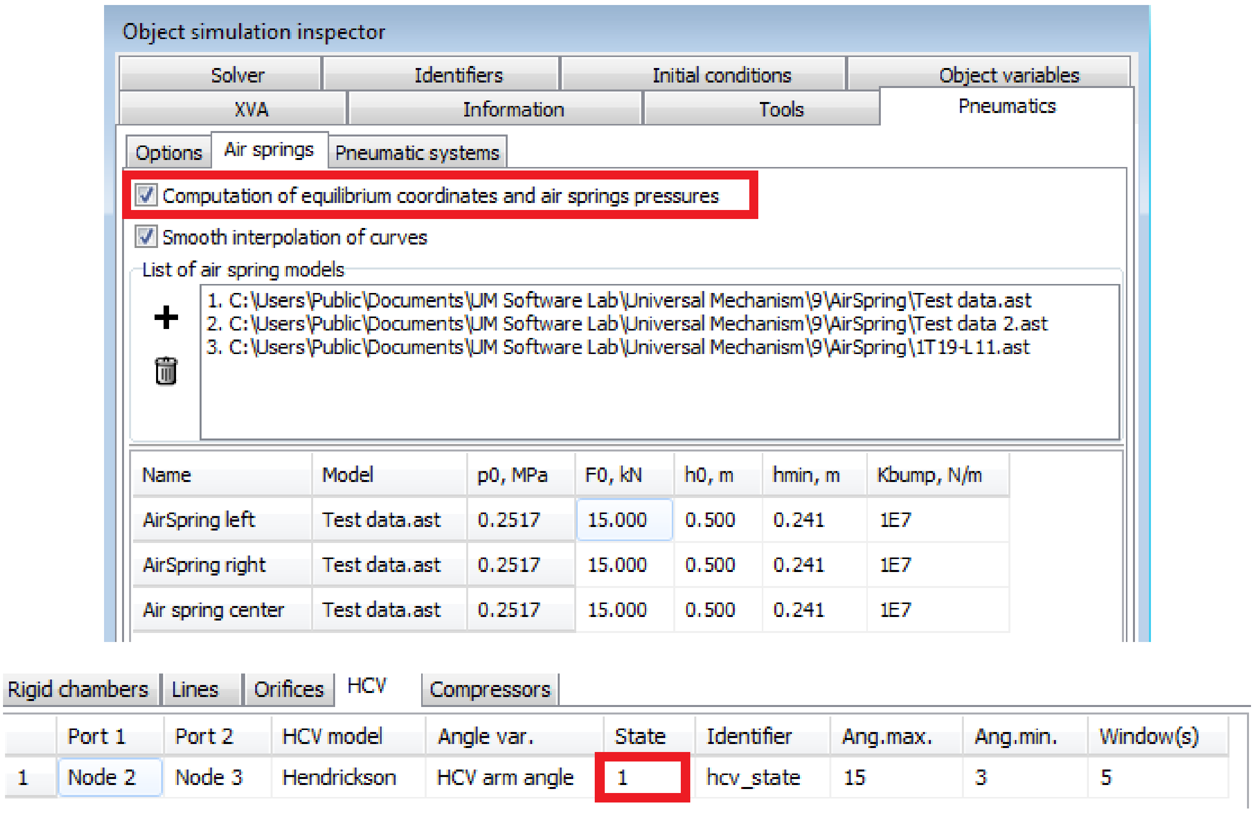


Figure 1.128. Options of **Compute initial** test

The **Compute initial** test shows how the user can compute and store the initial equilibrium position and pressure in air springs for the given values of load and suspension height. The computed initial conditions can be used in successive simulations.

In the case of automotive and railway models the computation must be run for zero speed value.

The test specific options are selected in Figure 1.128:

- The option **Computation of equilibrium coordinates and air spring pressures** is checked.
- HCV **state** parameter is equal to 1.
- The control for the identifier *hcv_state* is disabled, Figure 1.122.

Simulation should be run until the suspension height value approaches the desired value 0.5m. After finishing the simulation, the computed values must be either accepted or rejected by the user, Figure 1.129. New values of pressures are shown in Figure 1.130.

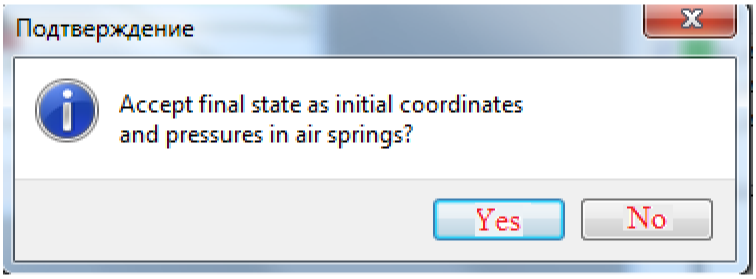


Figure 1.129. Accepting test results

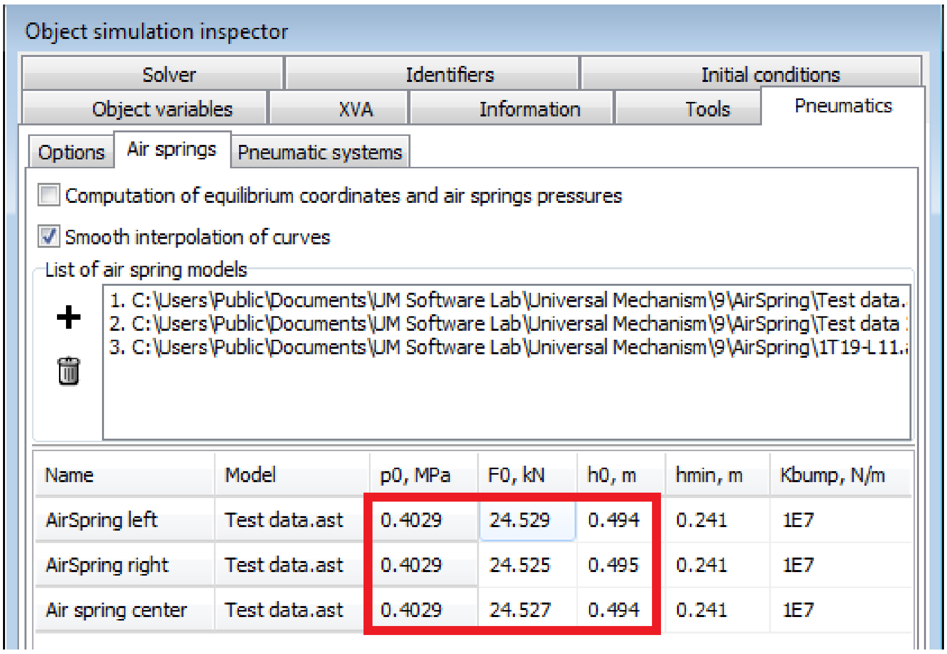


Figure 1.130. Computed values of pressure, height and force

1.5. Error messages

Here we consider messages related to preparing PS models and simulation process.

1.5.1. Errors in pneumatic system model

PS Model: Node(s) not assigned "Name"
One or two nodes are not assigned to a pipeline of an orifice.

PS Model: Equal nodes are assigned "Name"
Nodes assigned to a pipeline or an orifice must be different.

PS Model: Table model for air spring "Name" not assigned
Files with models should be assigned to all of the tabular air springs, Sect. 1.3.1 *Parameters of tabular air springs*.

PS Model: Air spring "Name" included in several enabled pneumatic systems
Tabular air spring can be included in **one** enabled PS only. Usually this error occurs when the user described several alternative pneumatic systems, only one of which must be active. The not active PS must be disabled, see Sect. 1.3.2.1 *List of pneumatic systems*.

PS Model: False static values of force and height, air spring "Name".
Static force value is out of the table data interval for the given AS height, Sect. 1.3.1 *Parameters of tabular air springs*. Change height and/or force value (F_0, h_0), Figure 1.45.

PS Model: Force table not correct
The force table must include data for at least two pressure and two height values.
The height and pressure must increase with index of row and column.
See Sect. 1.2.3.1.2 *Tabular data format*.

PS Model: Volume table not correct
The volume table must include data for at least one pressure and two height values.
The volume value must increase with the growth of both the pressure and the height.
The height and pressure must increase with index of row and column.
See Sect. 1.2.3.1.2 *Tabular data format*.

1.5.2. Errors during simulation process

PS Sim: Iterations do not converge
Solving nonlinear pneumatic equations fails. Try to change the pipeline model.

PS Sim: Negative pressure. Interruption
Negative pressure in one of the nodes detected. Simulation cannot be continued. Try to change the pipeline model. If the error appears anyway, please contact UM developers.

Integration step too small. Interruption

Numerical methods diverge. If the dynamic (time domain) model of pneumatic lines is used, the following steps are recommended:

- increase the parameter values **Valve switching time constant** and **Maximal number of iterations when dynamic lines**, Sect. 1.3.3 *General options in simulation of pneumatic systems*;

- use the stationary models for pneumatic lines;

- contact UM developers.

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