APPENDIX A: HYDRO-PNEUMATIC SUSPENSIONS

A.1 Hydrolastic / Hydragas (Moulton & Best 1979, 1980)

The Hydrolastic suspension system is one of the first interconnected suspensions. This suspension made use a rubber for the springing medium, with a fluid interconnection. The Hydragas suspension is the product of a 15-year evolution of the Hydrolastic suspension. The Hydragas suspension makes use of Nitrogen gas instead of rubber and a fluid interconnection. Figure A-1 shows the Hydragas suspension unit.

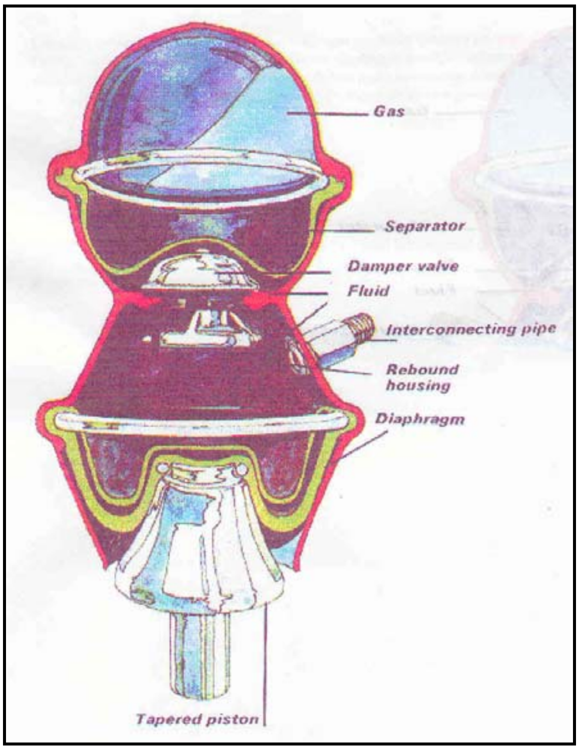


Figure A-1: Hydragas suspension unit

The reason for interconnecting the front and the rear suspension is to reduce the pitch frequency. More detail on interconnected suspensions is available in (Moulton & Best 1980).

A.2 Cadillac Gage Textron

Cadillac Gage Textron has a large range of hydro-pneumatic suspension units. Presented here are some of their products. The 6K unit (see Figure A-2) unit is designed for light AFV's and can be fitted to vehicles such as the M2/M3 Bradley and the USMC's AAV7A1 armoured amphibious assault vehicle.

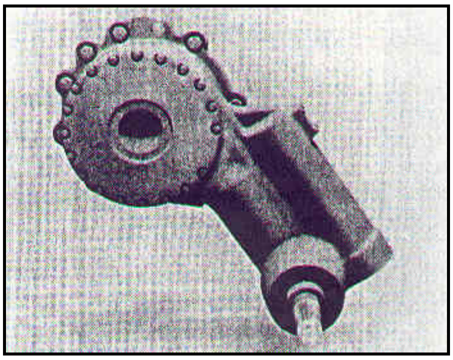


Figure A-2: 6K in-arm suspension

The 10K unit (see Figure A-3) can be fitted to AFV's such as the M48, M60, Centurion and the T-series MBT.

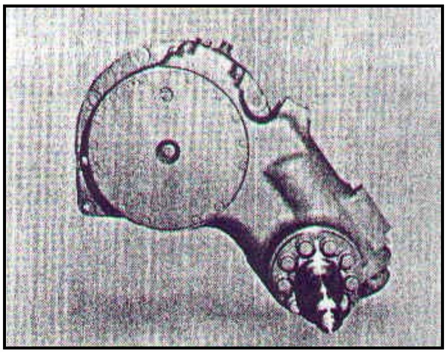


Figure A-3: 10K in-arm suspension

The 14K unit (see Figure A-4) is designed for installation on heavier MBT's such as the M1A1 and Leopard 2.

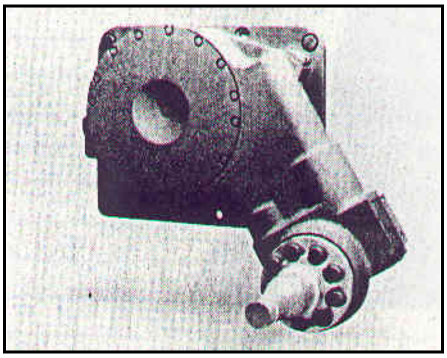


Figure A-4: 14K in-arm suspension

A.3 Citroen Xantia Activa

The Citroen Xantia Activa employs the Hydractive suspension system. This system was recently upgraded with active roll control. Figure A-5 shows a photograph of the Citroen Xantia Activa.

Figure A-5: Citroen Xantia Activa

The working principle of the active roll control is illustrated in Figure A-6.

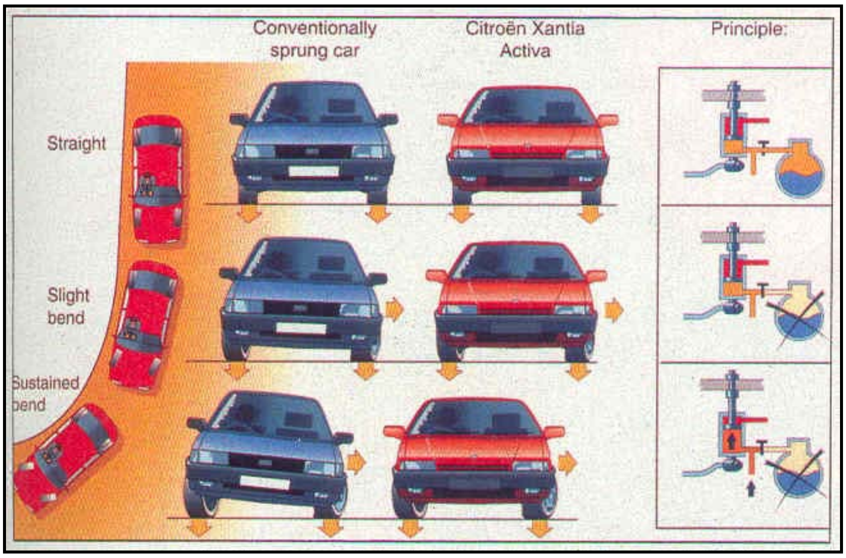


Figure A-6: Citroen's active roll control

A.4 Hydrostrut (Horstman Defence Systems)

The hydrostrut is manufactured by Horstman Defence Systems in the UK. This strut is a telescopic unit, which combines a nitrogen gas spring and a hydraulic oil damper in a single unit.

Figure A-7: Airlog Hydrostrut

The gas and the oil are separated by a floating piston, as can be seen in Figure A-8.

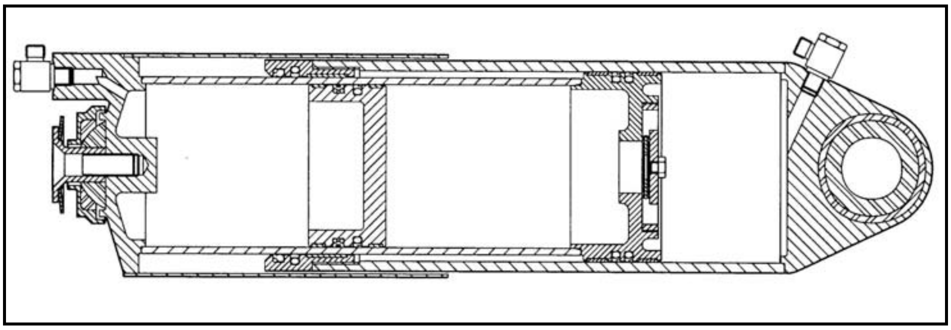


Figure A-8: Hydrostrut cut through

The hydrostut can also be equipped with additional features for increasing vehicle mobility. These includes variable ride height control (changing the amount of oil), load compensation (changing the amount of gas), suspension lock-out and roll and pitch compensation (interconnected struts).

A.5 SAMM, subsidiary company of Peugeot

SAMM produces various type of hydro-pneumatic suspensions, mainly for the military market. The following products are available:

a.) On-arm linear (translational) strut (for AFV and ATV)

- Vehicle weight: 10 to 30 ton
- Wheel travel: 330mm
- Natural frequency: 1Hz
- Damping factor: 0.4

- Maximum pressure: 420*bar*
- Weight: 25*kg*

b.) Twin cylinder (for MBT)

- Vehicle weight: 50 ton
- Wheel travel: -125*mm*, +300*mm*, 425*mm* total
- Natural frequency: 0.9*Hz*
- Maximum pressure: 900*bar* (225*bar* nominal)
- Weight: 250*kg*

c.) Mac Pherson (for wheeled vehicles)

- Static force per element: 25*kN*
- Maximum force: 110*kN*
- Static pressure: 50*bar*
- Maximum pressure: 220*bar*
- Total stroke: 280*mm*

A.6 Teledyne Hydro-pneumatic Suspension System (HSS)

The Teledyne HSS was developed for use initially in military tracked vehicles. This suspension unit can be retrofitted to the Centurion, M60 and M48. Figure A-9 shows a cut through of the Teledyne HSS unit. From this figure, it can be seen that the damper valve is separated from the spring unit and that a floating piston arrangement is used. This suspension unit is successfully implemented on several military vehicles.

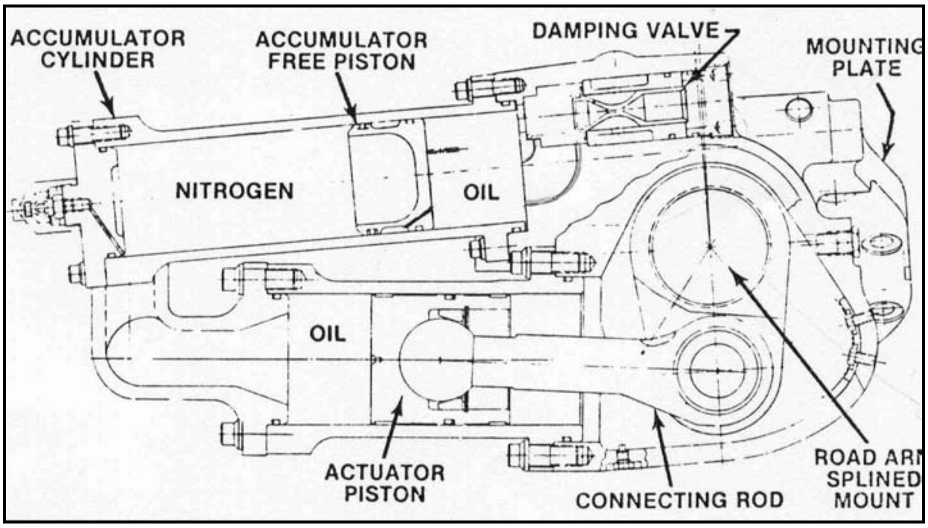


Figure A-9: Teledyne HSS unit

APPENDIX B: M-FILES AND SIMULINK MODELS

B.1 Simulink models

The strut characterisation and SDOF simulink models are supplied in this section. Table B-1 lists the figure numbers and Simulink model descriptions.

Table B-1: Simulink sub-systems

Figure no.	Simulink model description
Figure B-1	Characterisation main Simulink model
Figure B-2	SDOF main Simulink model
Figure B-3	SDOF spring sub-system
Figure B-4	0,3*l* Hydro-pneumatic spring sub-system
Figure B-5	0,3*l* BWR sub-system
Figure B-6	0,3*l* C_v sub-system
Figure B-7	0,3*l* Specific volume sub-system
Figure B-8	0,3*l* Temperature differential equation
Figure B-9	0,3*l* Sub-system
Figure B-10	0,7*l* Hydro-pneumatic spring sub-system
Figure B-11	0,7*l* BWR sub-system
Figure B-12	0,7*l* C_v sub-system
Figure B-13	0,7*l* Specific volume sub-system
Figure B-14	0,7*l* Temperature differential equation sub-system
Figure B-15	0,7l Sub-system
Figure B-16	Spring trigger sub-system
Figure B-17	Spring valve model sub-system
Figure B-18	Damper valve model sub-system

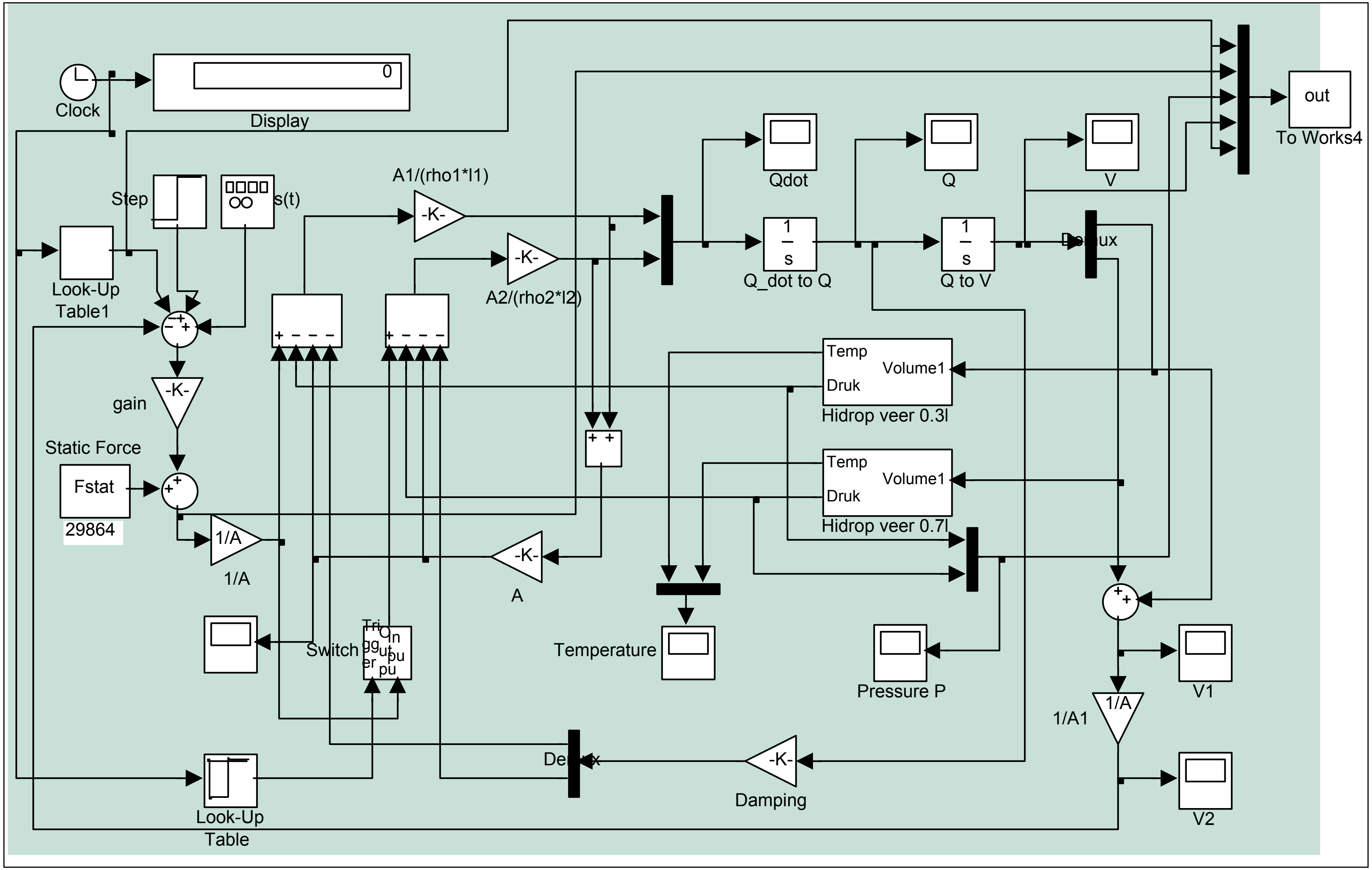


Figure B-1: Characterisation main Simulink model

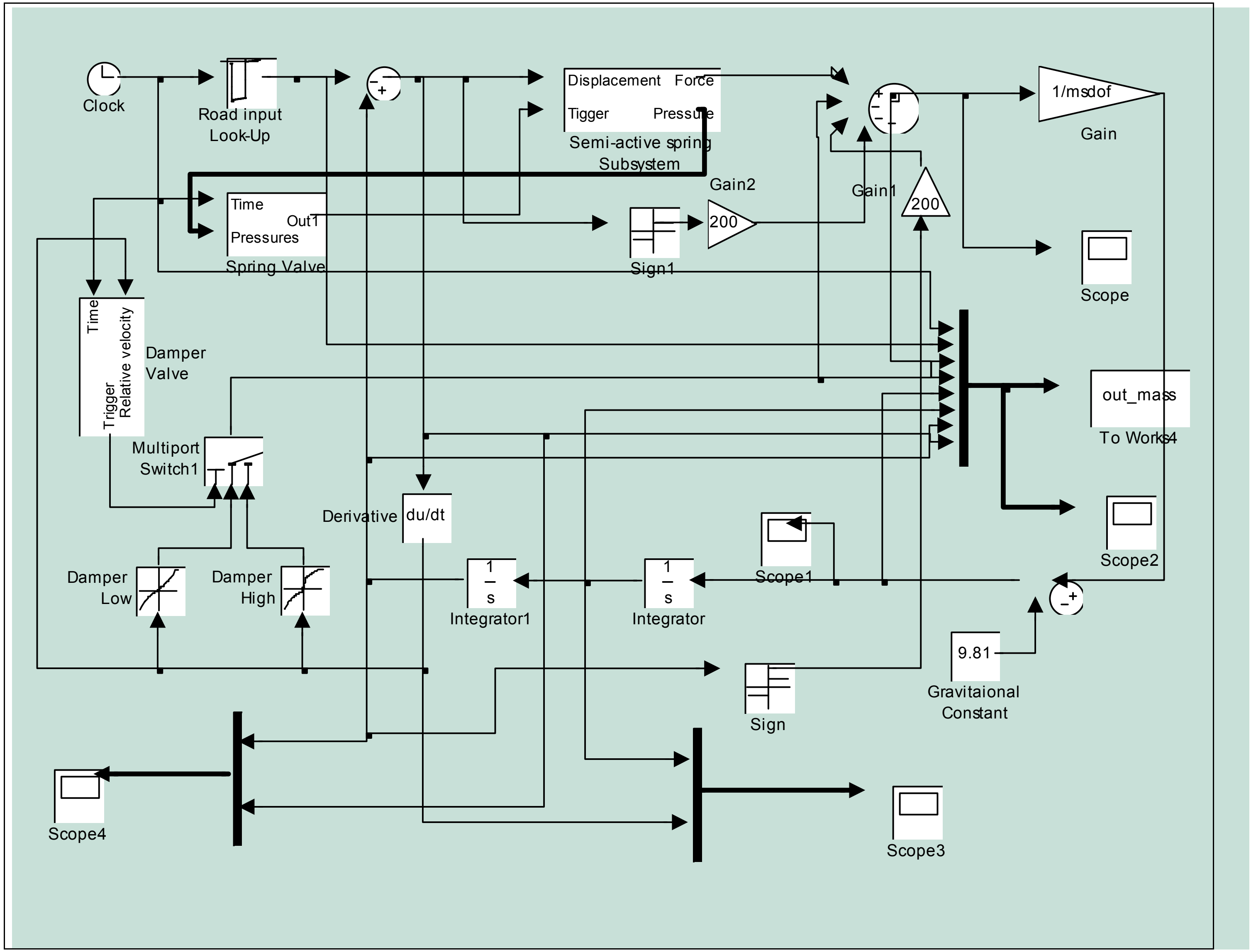


Figure B-2: SDOF main Simulink model

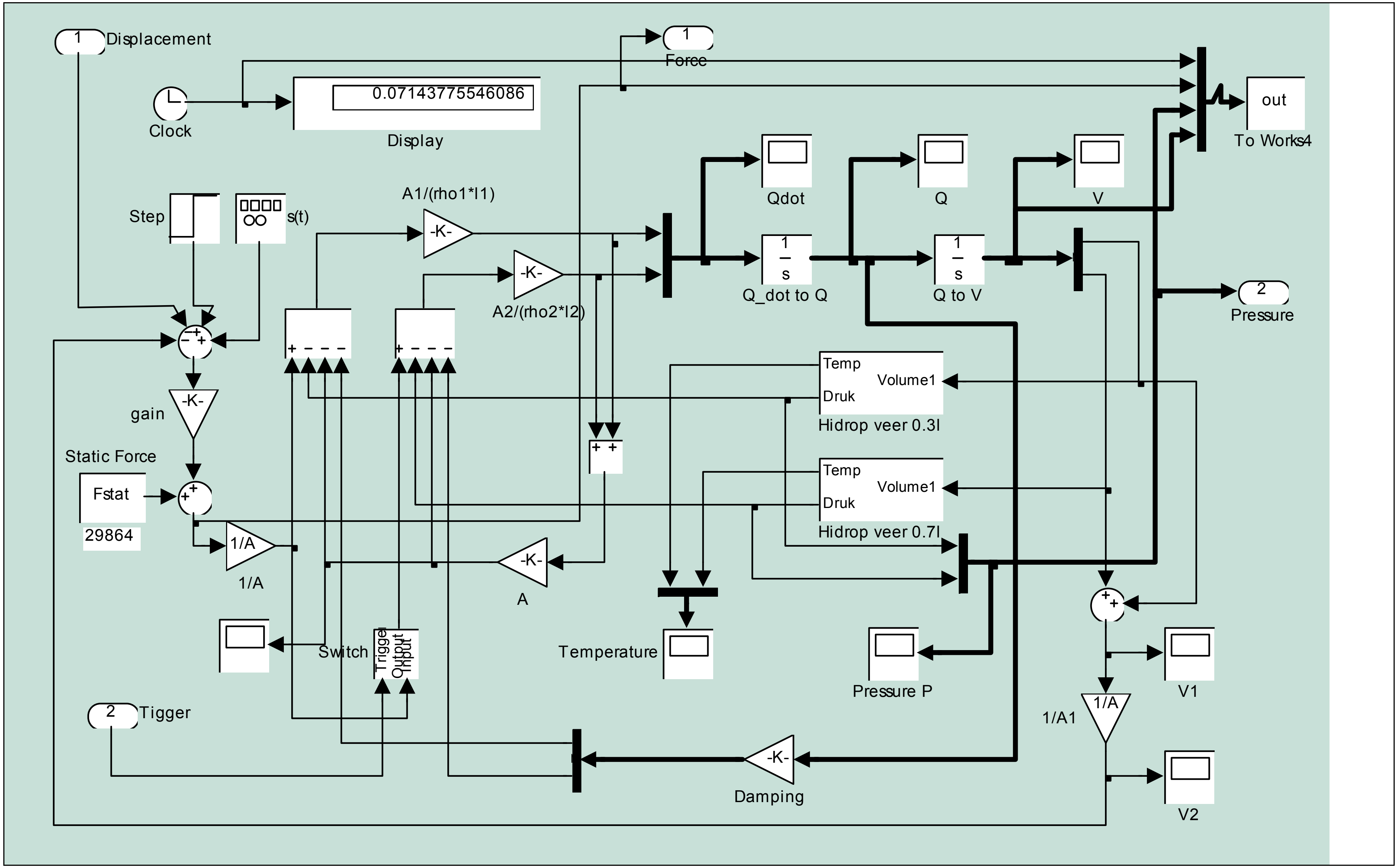


Figure B-3: SDOF spring sub-system

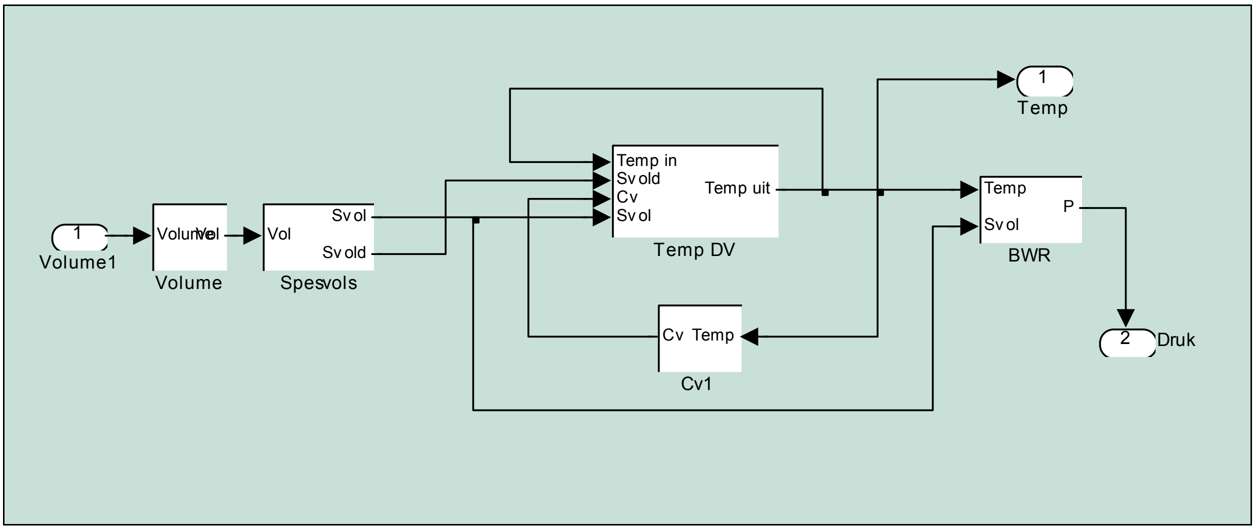


Figure B-4: 0,3*l* Hydro-pneumatic spring sub-system

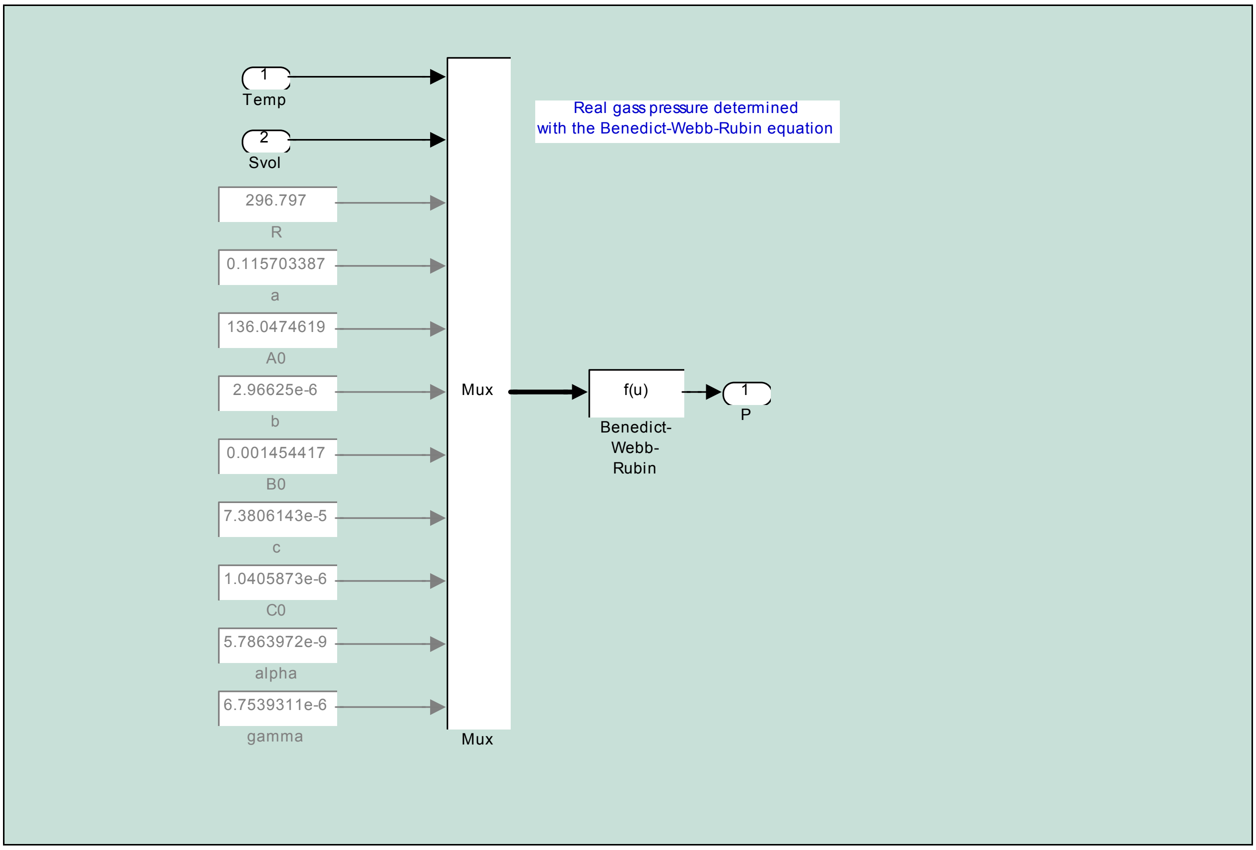


Figure B-5: 0,3*l* BWR sub-system

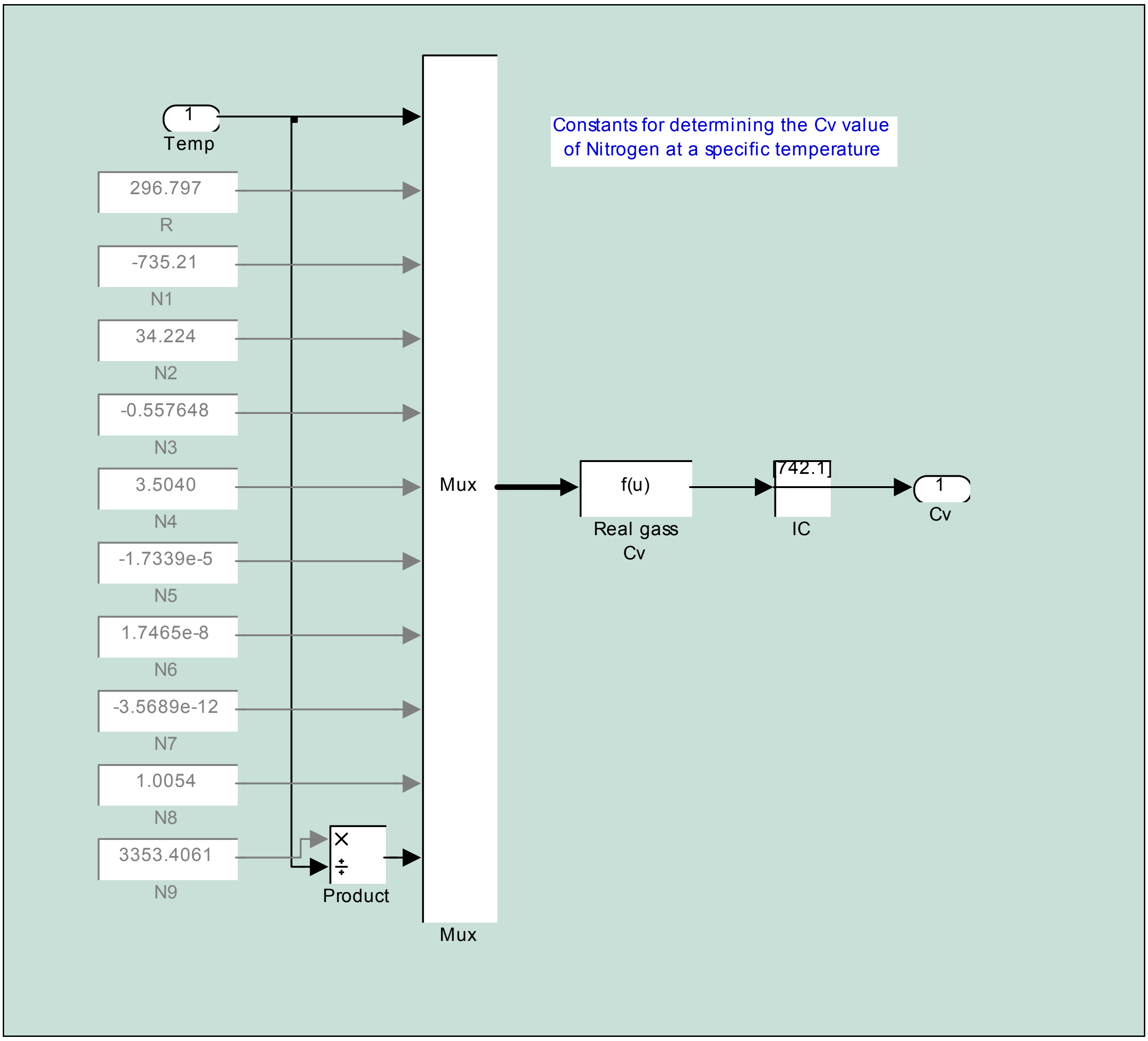


Figure B-6: 0,3*l* C_v sub-system

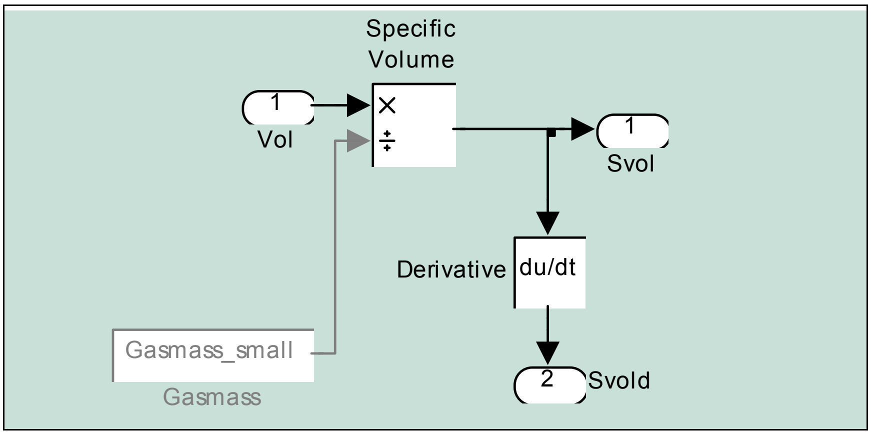


Figure B-7: 0,3*l* Specific volume sub-system

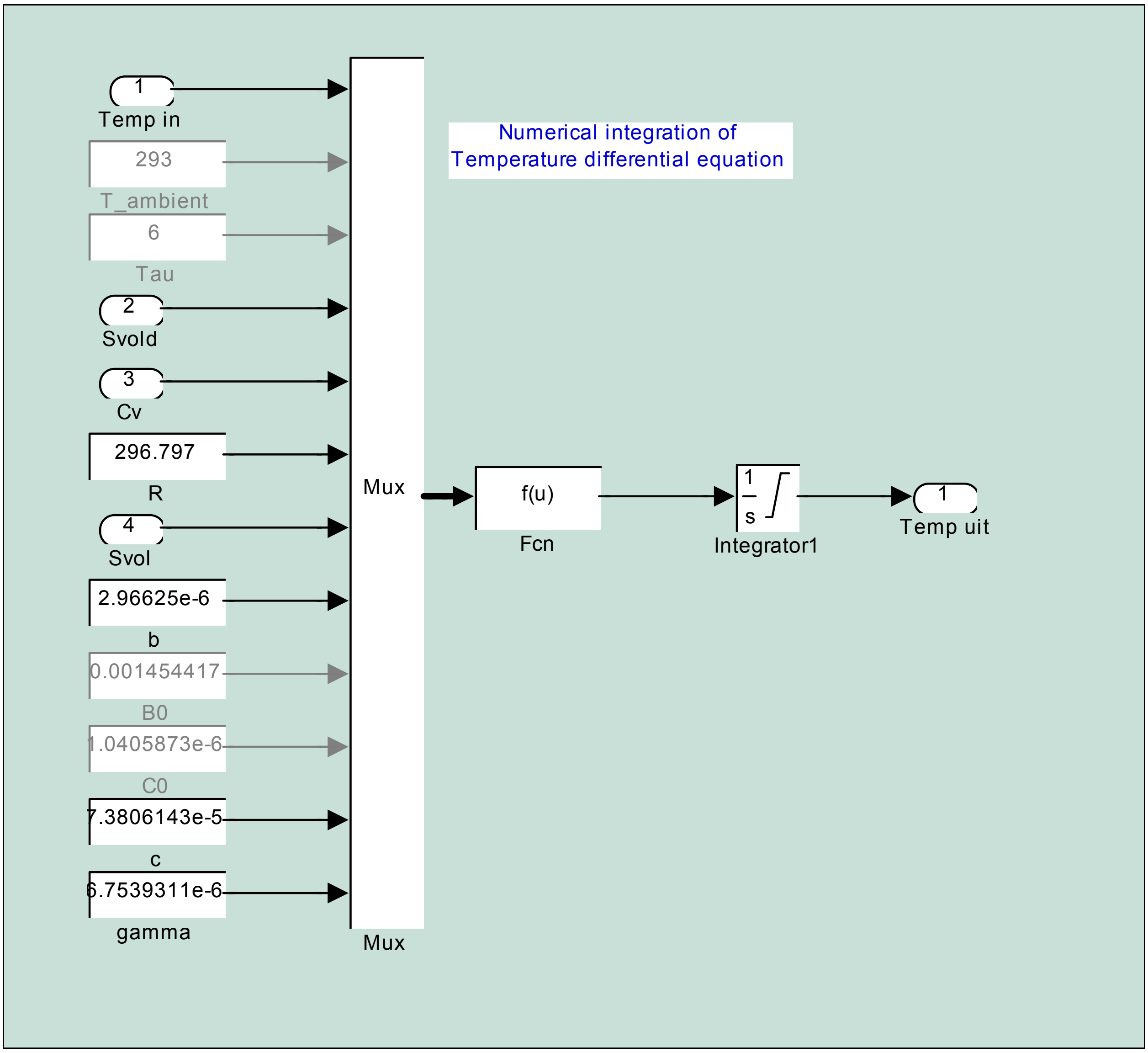


Figure B-8: 0,3*l* Temperature differential equation

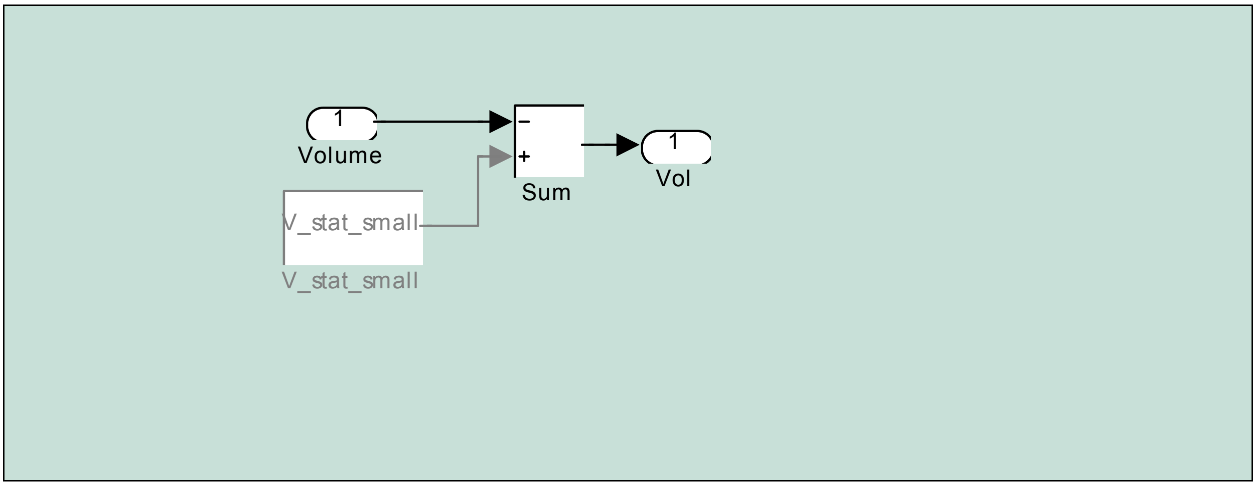


Figure B-9: 0,3*l* Sub-system

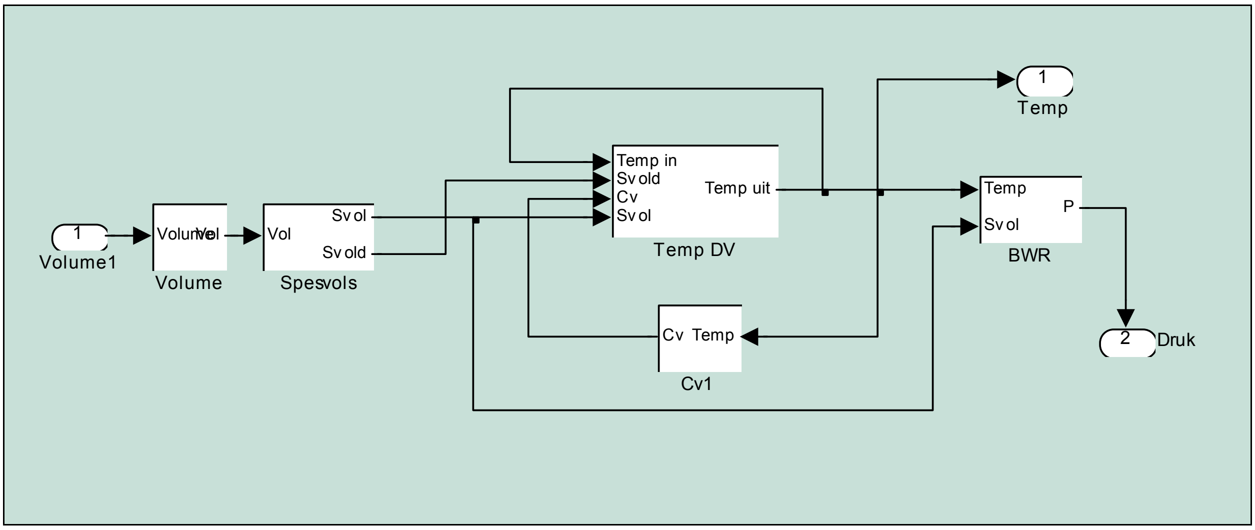


Figure B-10: 0,7*l* Hydro-pneumatic spring sub-system

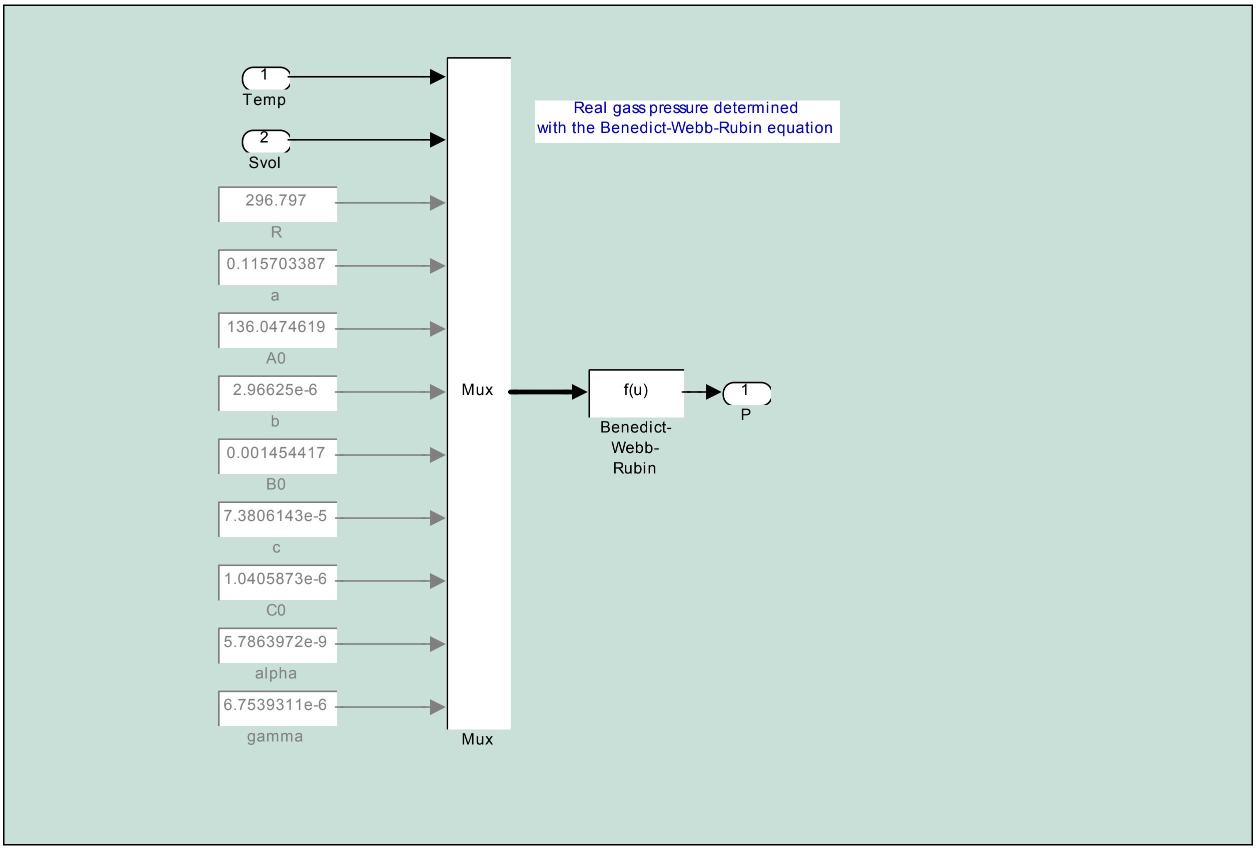


Figure B-11: 0,7*l* BWR sub-system

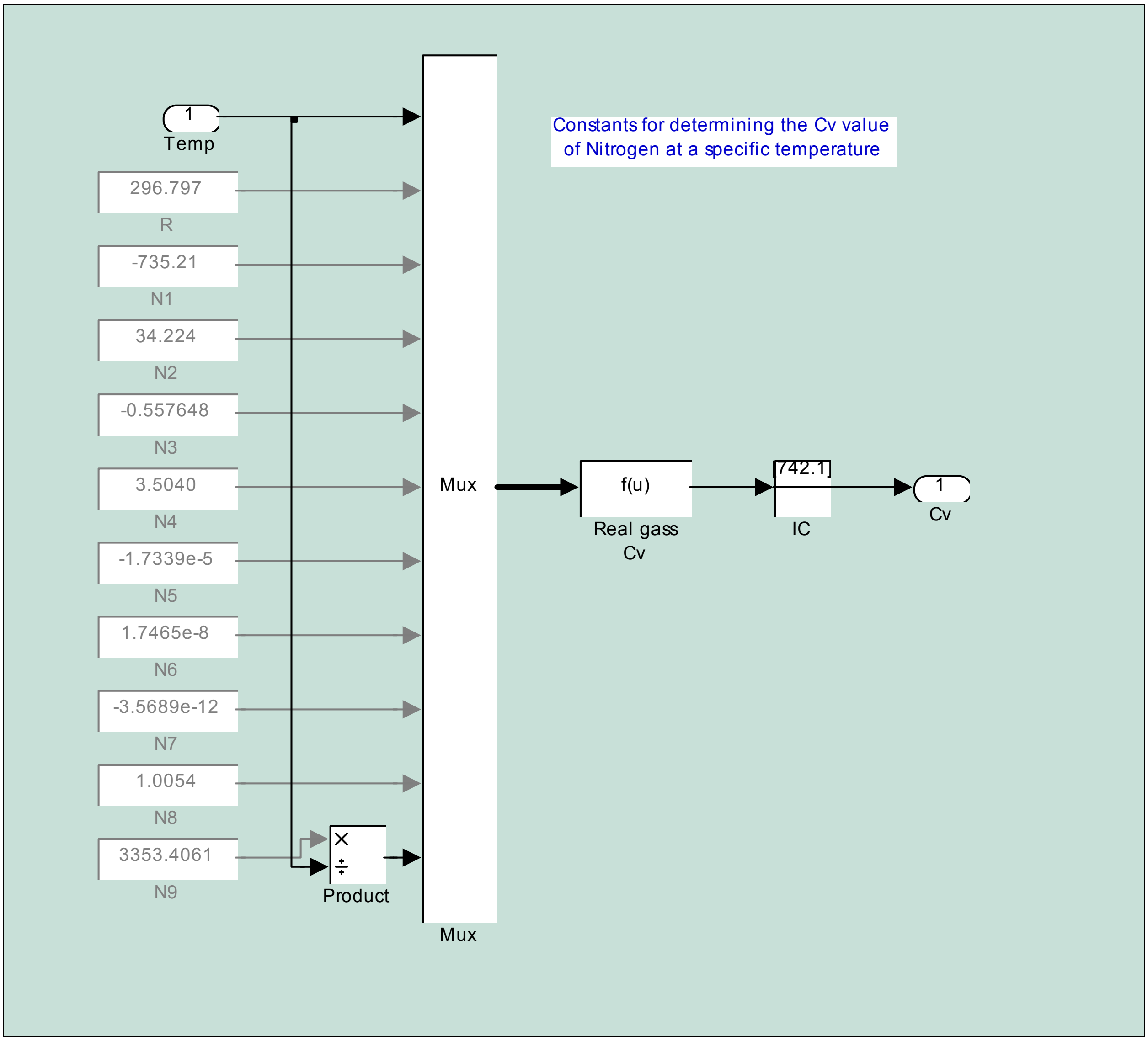


Figure B-12: 0,7*l* C_v sub-system

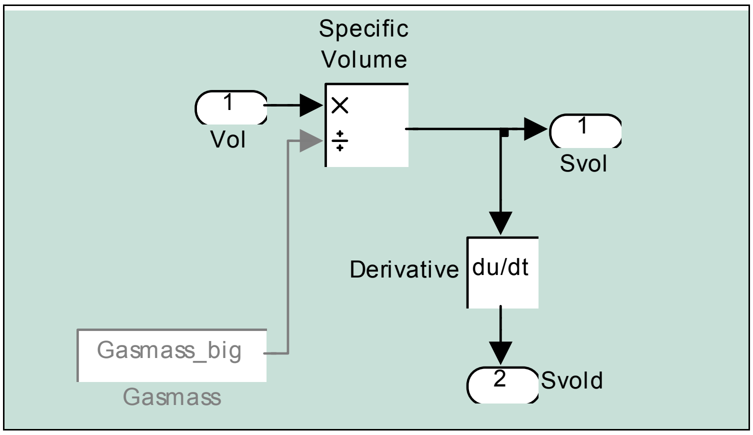


Figure B-13: 0,7*l* Specific volume sub-system

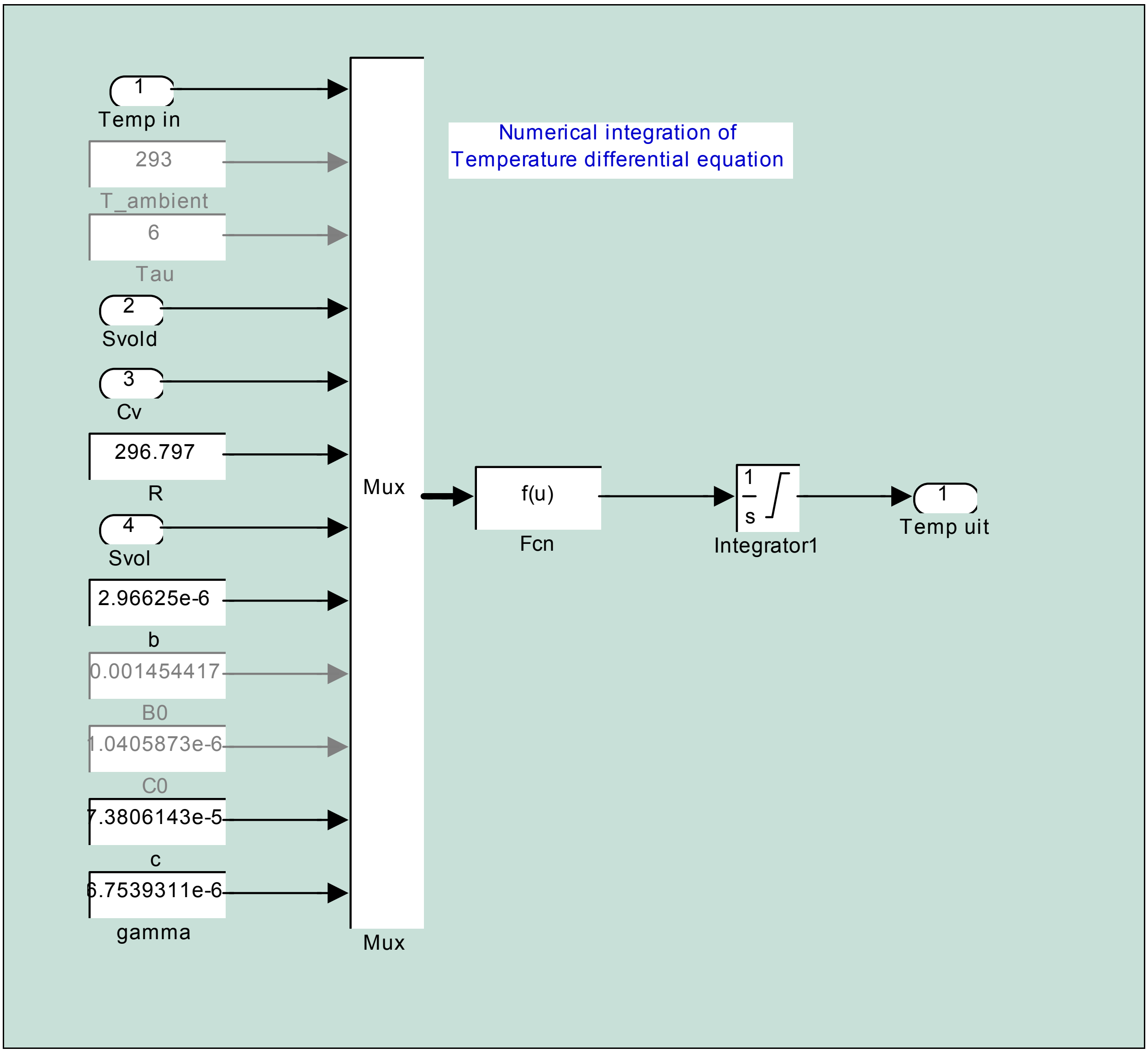


Figure B-14: 0,7*l* Temperature differential equation sub-system

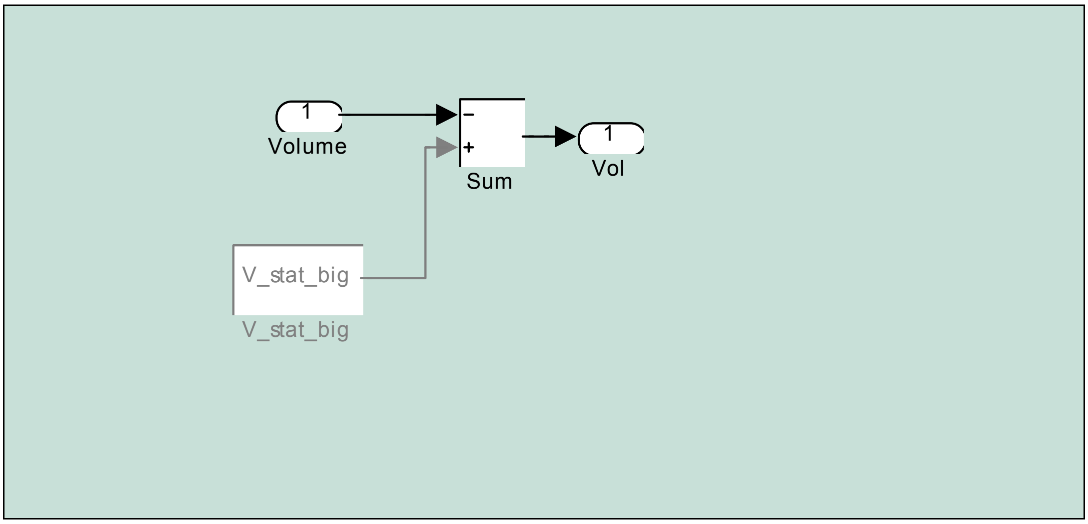


Figure B-15: 0,7l Sub-system

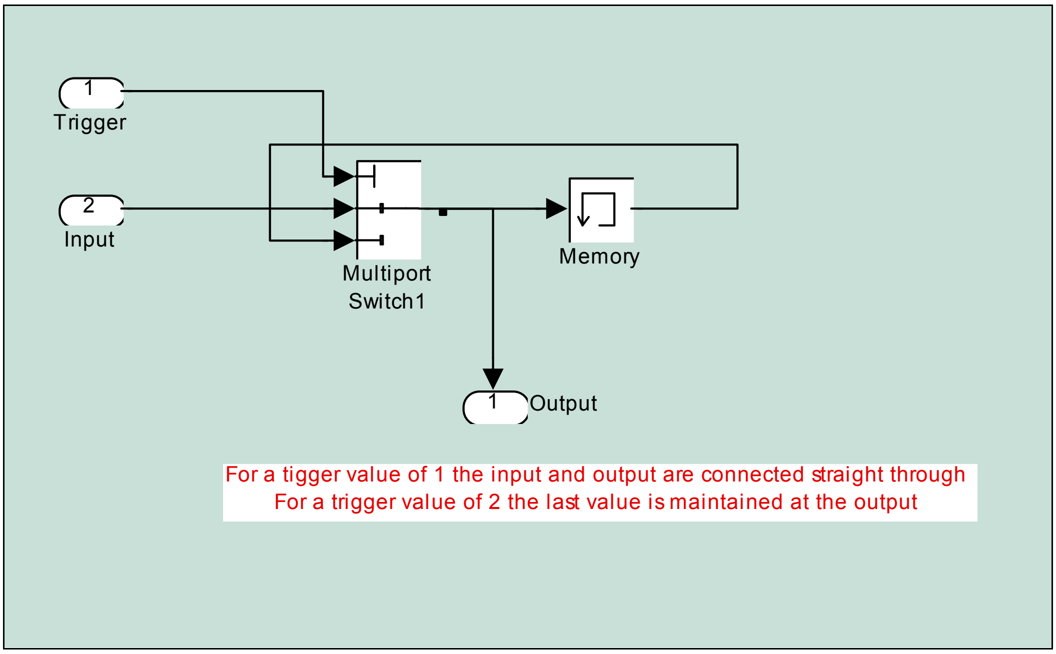


Figure B-16: Spring trigger sub-system

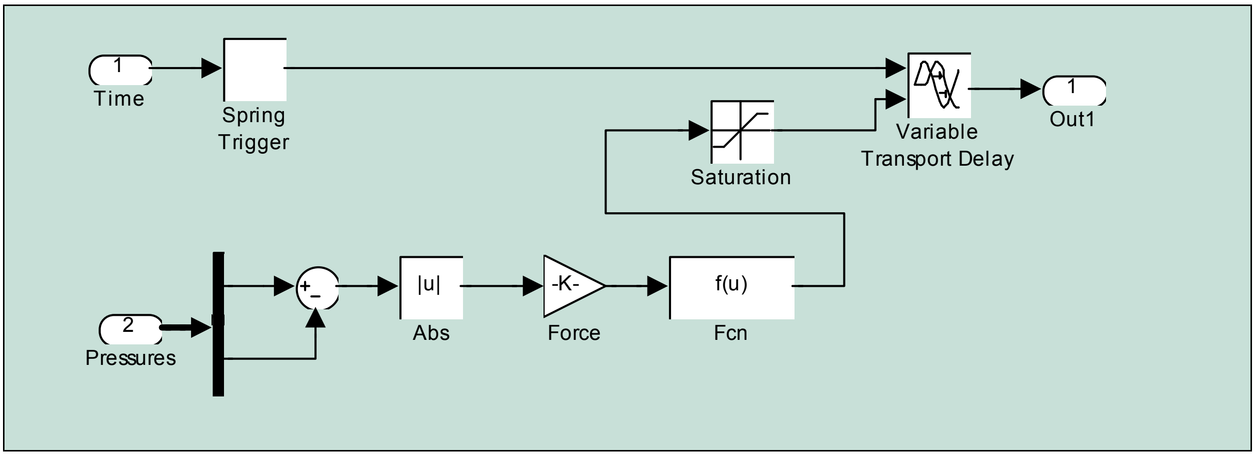


Figure B-17: Spring valve model sub-system

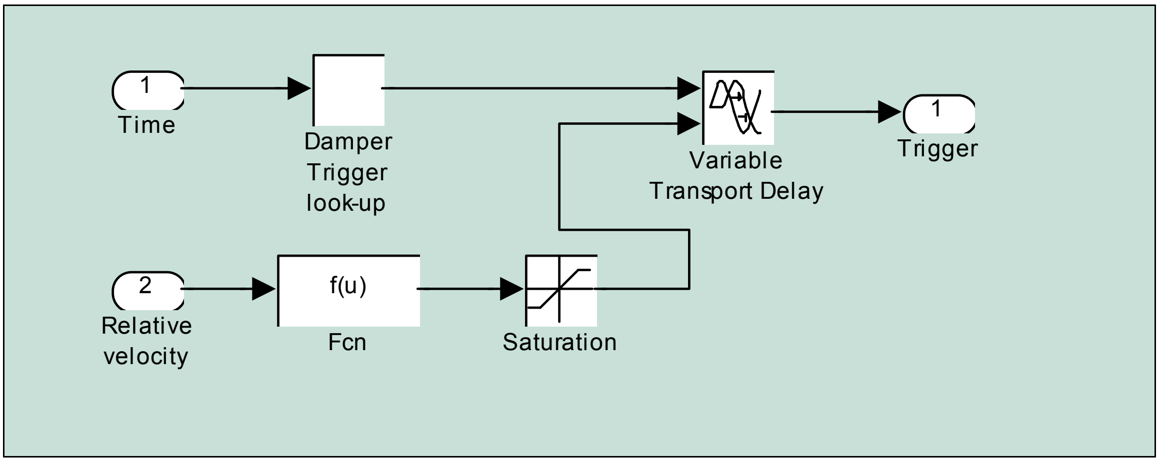


Figure B-18: Damper valve model sub-system

B.2 M-files

Two m-files were used in conjunction with the characterisation simulations (hidropsim.m) and the SDOF simulation (sdofsim.m). Numerous other m-files were also used to reduce measured and simulated data. The two m-files hidropsim.m and sdofsim.m are supplied below.

Hidropsim.m

```
% hidropsim.m
% 12/08/2000

clear all
close all

tic
%=== LOPIE KONSTANTES ===
load in_sig    %tfin = 1100
load in_sig2   %tfin = 110
load in_sig3   %tfin = 11
load karakteristieke.txt

%sinusvormige verplasing
in_sig4 = [karakteristieke(:,1) (-karakteristieke(:,2)/5)+2 karakteristieke(:,4)/1000];
q = find(in_sig4(:,2) <= 1.6);
w = find(in_sig4(:,2) >= 1.6);
in_sig4(q,2) = 1;
in_sig4(w,2) = 2;
in_sig4(1,2) = 1;

input_signal = in_sig4;
tfin = max(input_signal(:,1));
sample_time = .01;
%Fstat = 29864 - 8000 - 8000;
Fstat = 000;
Pstat = 6330000;
Tstat = 293;
%V_stat_small = 0.000365;  %0.000345 vir in_sig en in_sig2
V_stat_small = 0.00033;       %0.00032 vir in_sig4
V_stat_big = 0.0007;          %0.00069 vir in_sig en in_sig2 0.0007 vir in_sig4
Gasmass_small = gasmassa([Pstat,V_stat_small,Tstat]);
Gasmass_big = gasmassa([Pstat,V_stat_big,Tstat]);
%=== LOPIE KONSTANTES ===

%=== MODEL KONSTANTES ===
rho0 = 917;
rho1 = 917;
rho2 = 917;
rho = 917;
l0 = .3;
l1 = .3;
l2 = .3;
m = 10;
A = pi/4*(.065^2); %Piston area
A0 = pi/4*(.0245^2); %Pyp0 area
A1 = pi/4*(.0245^2);   %Pyp1 area
A2 = pi/4*(.0245^2);   %Pyp2 area
n = 1.4;
k1 = (1.35*9000000*(pi/4*.063^2)^2)/(.0003);
k2 = (1.35*9000000*(pi/4*.063^2)^2)/(.0007);
k1 = k1/(pi/4*.063^2)^2;
k2 = k2/(pi/4*.063^2)^2;
%=== MODEL KONSTANTES ===

%=== SIMULASIE ===
sim('chris1_1');
%=== SIMULASIE ===

%=== VERWERK RESULTATE ===
cd gemeet
load klepres4.txt
cd ..
```

```
t = linspace(0,length(klepres4(:,1)),length(klepres4(:,1)));

%plot(t,-klepres4(:,2),t,-klepres4(:,1)+25,out(:,1),out(:,2)/1000);
out([1 2 3],2) = 0;
karakteristieke(85:168,3) = karakteristieke(85:168,3)+2.5;
plot(karakteristieke(:,4),-karakteristieke(:,3),out(:,7)*1000,out(:,2)/1000);
grid on
zoom on
%=== VERWERK RESULTATE ===
toc
```

SDOFsim.m

```
% SDOFsim.m
% 12/08/2000

clear all
close all

tic
%=== LOPIE KONSTANTES ===
load dempkar
dempkar(:,2) = dempkar(:,2) * 1000;
dempkar(:,4) = dempkar(:,4) * 1000;

plot(dempkar(:,1),dempkar(:,2),'*',dempkar(:,3),dempkar(:,4),'*')
hold on
dempkar(:,2) = dempkar(:,2)-dempkar(:,1)*745.3;
dempkar(1:28,2) = dempkar(1:28,2)+2500;
dempkar(:,2) = dempkar(:,2)*1;
dempkar(:,4) = dempkar(:,4)*1;
plot(dempkar(:,1),dempkar(:,2),'*r',dempkar(:,3),dempkar(:,4),'*y')
grid on
zoom on

filename = {'trp30_1','trp30_2','trp30_3','trp30_4','trp30_5','trp30_6','trp30_7','trp30_8',...
      'belg1','belg2','belg3','belg4','belg5','belg6','belg7','belg8','belg9','belg10',...
      'sin15_1','sin15_2','sin15_3','sin15_4','sin15_5','sin15_6','sin15_7','sin15_8',...
      'trp60_1','trp60_2','trp60_3','trp60_4'};
% TRAP30 1 - 8
% BELG 9 - 18
% SINE 19 - 26
% TRAP60 27 - 30

for i = 1:30
   i
   cd gemeet
   switch i
   case 1
      load trp30_1.txt
      file = trp30_1;
   case 2
      load trp30_2.txt
      file = trp30_2;
   case 3
      load trp30_3.txt
      file = trp30_3;
   case 4
      load trp30_4.txt
      file = trp30_4;
   case 5
      load trp30_5.txt
      file = trp30_5;
   case 6
      load trp30_6.txt
      file = trp30_6;
   case 7
      load trp30_7.txt
      file = trp30_7;
   case 8
      load trp30_8.txt
      file = trp30_8;
   case 9
```

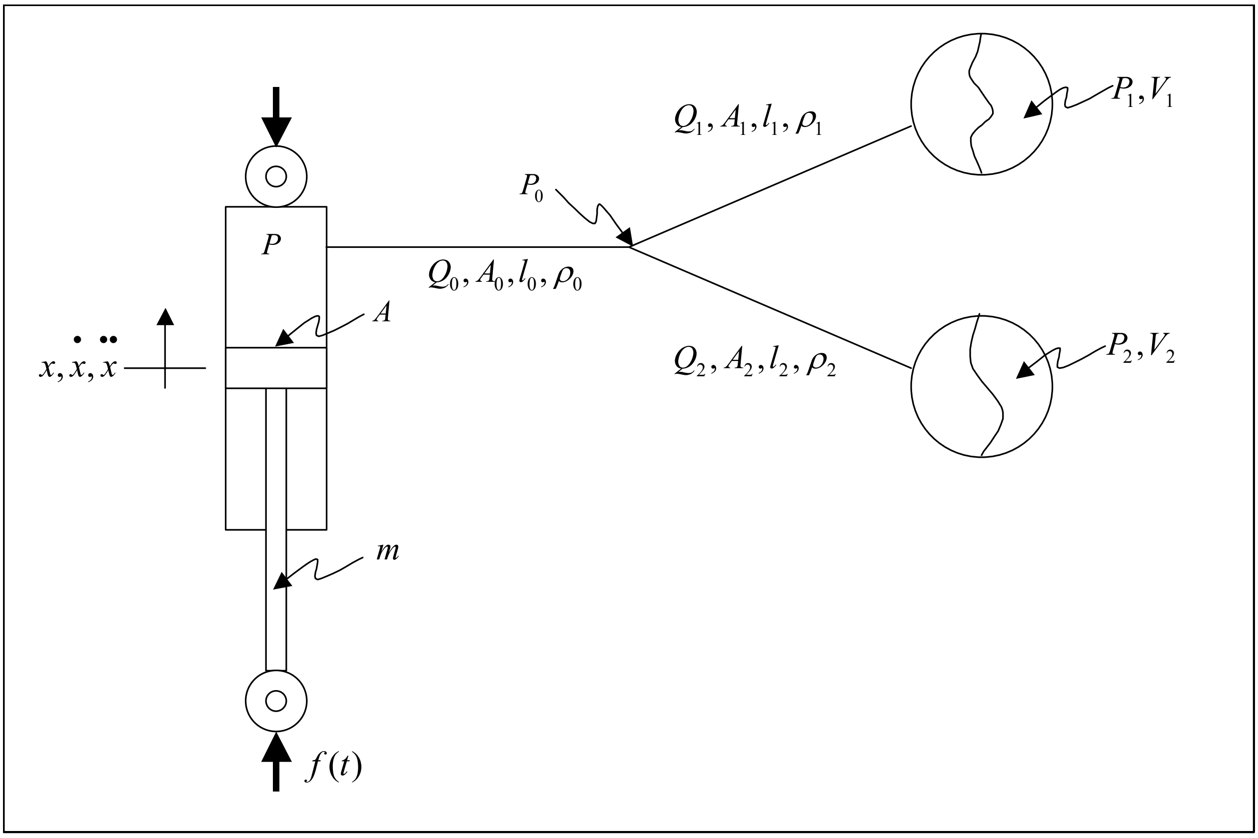
```
      load belg1.txt
      file = belg1;
   case 10
      load belg2.txt
      file = belg2;
   case 11
      load belg3.txt
      file = belg3;
   case 12
      load belg4.txt
      file = belg4;
   case 13
      load belg5.txt
      file = belg5;
   case 14
      load belg6.txt
      file = belg6;
   case 15
      load belg7.txt
      file = belg7;
   case 16
      load belg8.txt
      file = belg8;
   case 17
      load belg9.txt
      file = belg9;
   case 18
      load belg10.txt
      file = belg10;
   case 19
      load sin15_1.txt
      file = sin15_1;
   case 20
      load sin15_2.txt
      file = sin15_2;
   case 21
      load sin15_3.txt
      file = sin15_3;
   case 22
      load sin15_4.txt
      file = sin15_4;
   case 23
      load sin15_5.txt
      file = sin15_5;
   case 24
      load sin15_6.txt
      file = sin15_6;
   case 25
      load sin15_7.txt
      file = sin15_7;
   case 26
      load sin15_8.txt
      file = sin15_8;
   case 27
      load trp60_1.txt
      file = trp60_1;
   case 28
      load trp60_2.txt
      file = trp60_2;
   case 29
      load trp60_3.txt
      file = trp60_3;
   case 30
      load trp60_4.txt
      file = trp60_4;
   end
cd ..

input_signal = [file(:,1) file(:,2)/1000 file(:,8)+1 file(:,9)+1];
input_signal(1:40,4) = ones(40,1);
input_signal(1:40,2) = zeros(40,1);

figure(2)
%plot(input_signal(:,1),input_signal(:,2:4));
plot(input_signal(:,1),input_signal(:,2),'LineWidth',1.5);
zoom on
grid on
```

```
xlabel('Time [s]')
ylabel('Displacement [m]')
title('Step response actuator displacement')

tfin = max(file(:,1));
sample_time = .01;
%Fstat = 29864 - 8000 - 8000;
msdof = 3186;
Fstat = 000;
Pstat = 9420000;
Tstat = 293;
V_stat_small = 0.00035;    %0.000345 vir in_sig en in_sig2
V_stat_big = 0.0006;       %0.00069 vir in_sig en in_sig2
Gasmass_small = gasmassa([Pstat,V_stat_small,Tstat]);
Gasmass_big = gasmassa([Pstat,V_stat_big,Tstat]);
%=== LOPIE KONSTANTES ===

%=== MODEL KONSTANTES ===
rho0 = 917;
rho1 = 917;
rho2 = 917;
rho = 917;
l0 = .3;
l1 = .3;
l2 = .3;
m = 10;
A = pi/4*(.065^2); %Piston area
A0 = pi/4*(.0245^2); %Pyp0 area
A1 = pi/4*(.0245^2);   %Pyp1 area
A2 = pi/4*(.0245^2);   %Pyp2 area
n = 1.4;
k1 = (1.35*9000000*(pi/4*.063^2)^2)/(.0003);
k2 = (1.35*9000000*(pi/4*.063^2)^2)/(.0007);
k1 = k1/(pi/4*.063^2)^2;
k2 = k2/(pi/4*.063^2)^2;
%=== MODEL KONSTANTES ===

%=== SIMULASIE ===
%sim('chris2_2');
sim('chris2_4')
%=== SIMULASIE ===

%=== VERWERK RESULTATE ===
switch i
   case 1
      trp30_1_out = out_mass;
      save trp30_1_out trp30_1_out
   case 2
      trp30_2_out = out_mass;
      save trp30_2_out trp30_2_out
   case 3
      trp30_3_out = out_mass;
      save trp30_3_out trp30_3_out
   case 4
      trp30_4_out = out_mass;
      save trp30_4_out trp30_4_out
   case 5
      trp30_5_out = out_mass;
      save trp30_5_out trp30_5_out
   case 6
      trp30_6_out = out_mass;
      save trp30_6_out trp30_6_out
   case 7
      trp30_7_out = out_mass;
      save trp30_7_out trp30_7_out
   case 8
      trp30_8_out = out_mass;
      save trp30_8_out trp30_8_out
   case 9
      belg1_out = out_mass;
      save belg1_out belg1_out
   case 10
      belg2_out = out_mass;
      save belg2_out belg2_out
   case 11
      belg3_out = out_mass;
      save belg3_out belg3_out
```

```
    case 12
       belg4_out = out_mass;
       save belg4_out belg4_out
    case 13
       belg5_out = out_mass;
       save belg5_out belg5_out
    case 14
       belg6_out = out_mass;
       save belg6_out belg6_out
    case 15
       belg7_out = out_mass;
       save belg7_out belg7_out
    case 16
       belg8_out = out_mass;
       save belg8_out belg8_out
    case 17
       belg9_out = out_mass;
       save belg9_out belg9_out
    case 18
       belg10_out = out_mass;
       save belg10_out belg10_out
    case 19
       sin15_1_out = out_mass;
       save sin15_1_out sin15_1_out
    case 20
       sin15_2_out = out_mass;
       save sin15_2_out sin15_2_out
    case 21
       sin15_3_out = out_mass;
       save sin15_3_out sin15_3_out
    case 22
       sin15_4_out = out_mass;
       save sin15_4_out sin15_4_out
    case 23
       sin15_5_out = out_mass;
       save sin15_5_out sin15_5_out
    case 24
       sin15_6_out = out_mass;
       save sin15_6_out sin15_6_out
    case 25
       sin15_7_out = out_mass;
       save sin15_7_out sin15_7_out
    case 26
       sin15_8_out = out_mass;
       save sin15_8_out sin15_8_out
    case 27
       trp60_1_out = out_mass;
       save trp60_1_out trp60_1_out
    case 28
       trp60_2_out = out_mass;
       save trp60_2_out trp60_2_out
    case 29
       trp60_3_out = out_mass;
       save trp60_3_out trp60_3_out
    case 30
       trp60_4_out = out_mass;
       save trp60_4_out trp60_4_out
    end
%=== VERWERK RESULTATE ===
end
toc
```

APPENDIX C: MATHEMATICAL FLOW MODEL

The derivation of the hydraulic flow model is supplied in this appendix.



The following five states are defined:

$$x_1 = V_1$$
$$x_2 = V_2$$
$$x_3 = Q_0 = Q_1 + Q_2$$
$$x_4 = Q_1$$
$$x_5 = Q_2$$

therefore

$$\dot{x}_1 = \dot{V}_1 = Q_1 = x_4$$
$$\dot{x}_2 = \dot{V}_2 = Q_2 = x_5$$

The relationship between strut piston displacement and flow is:

$$A\dot{x} = Q_0 = Q_1 + Q_2$$

The force balance on the strut piston is as follows:

$$m\ddot{x} = f(t) - AP$$

but

$$\ddot{x} = \frac{\dot{Q}_0}{A} = \frac{1}{A}(\dot{Q}_1 + \dot{Q}_2)$$

therefore

$$\mathrm{m}/_{\mathrm{A}}\,(\dot{Q}_1 + \dot{Q}_2) = f(t) - AP$$

$$\because \mathrm{m}/_{\mathrm{A}}\,\dot{Q}_0 = f(t) - AP$$

Rearranging the above equation gives:

$$\mathrm{P} = \mathrm{f(t)}/_{\mathrm{A}} - m/_{A^2}\,\dot{Q}_0 \qquad \ldots(1)$$

Considering the oil in the pipes, the following equations can be written:

According to Newton's second law

$$\sum \mathrm{F} = \mathrm{m}\ddot{\mathrm{x}}$$

Therefore

$$\rho_0 l_0 \dot{Q}_0 = A_0(P - P_0) \qquad \ldots(2)$$

$$\rho_1 l_1 \dot{Q}_1 = A_1(P_0 - P_1) \qquad \ldots(3)$$

$$\rho_2 l_2 \dot{Q}_2 = A_2(P_0 - P_2) \qquad \ldots(4)$$

Replace P in (2) with (1)

$$\rho_0 l_0 \dot{Q}_0 = A_0\left(f(t)/_{A} - m/_{A^2}\,\dot{Q}_0 - P_0\right)$$

Rearranging the above equation gives:

$$P_0 = f(t)/_{A} - \rho_0 l_0 \dot{Q}_0/_{A_0} - m/_{A^2}\,\dot{Q}_0$$

Substitute the above equation into equations (3) and (4)

From (3)

$$\rho_1 l_1 \dot{Q}_1 = A_1\left({}^{\rho_0 l_0 \dot{Q}_0}\!\Big/_{A_0} + {}^{f(t)}\!\Big/_{A} - {}^{m}\!\Big/_{A^2}\, \dot{Q}_0 - P_1 \right)$$

From (4)

$$\rho_2 l_2 \dot{Q}_2 = A_2\left({}^{\rho_0 l_0 \dot{Q}_0}\!\Big/_{A_0} + {}^{f(t)}\!\Big/_{A} - {}^{m}\!\Big/_{A^2}\, \dot{Q}_0 - P_2 \right)$$

Rearrange the above to two equations to isolate the flow terms:

Therefore:

$$\frac{\rho_1 l_1}{A_1}\dot{Q}_1 + \left(\frac{\rho_0 l_0}{A_0} + \frac{m}{A^2}\right)\dot{Q}_0 = \frac{f(t)}{A} - P_1$$

and

$$\frac{\rho_2 l_2}{A_2}\dot{Q}_2 + \left(\frac{\rho_0 l_0}{A_0} + \frac{m}{A^2}\right)\dot{Q}_0 = \frac{f(t)}{A} - P_2$$

These equations can be written in state-space format as follows:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \left(\frac{\rho_0 l_0}{A_0} + \frac{m}{A^2}\right) & \frac{\rho_1 l_1}{A_1} & 0 \\ 0 & 0 & \left(\frac{\rho_0 l_0}{A_0} + \frac{m}{A^2}\right) & 0 & \frac{\rho_2 l_2}{A_2} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \dot{Q}_0 \\ \dot{Q}_1 \\ \dot{Q}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ Q_0 \\ Q_1 \\ Q_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ {}^{1}\!/_{A} \\ {}^{1}\!/_{A} \\ 0 \end{bmatrix} f(t) + \begin{bmatrix} 0 \\ 0 \\ P_1 \\ P_2 \\ 0 \end{bmatrix}$$

with the algebraic equation

$$Q_0 = Q_1 + Q_2$$

APPENDIX D: TEST RESULTS

D.1 Step response

The results for the step response tests are presented in this paragraph. The spring/damper configuration definitions are supplied in Table D-1.

Table D-1: Spring/damper configuration for step response tests

Figure number	Input	Spring state	Damper state
Figure D-1	30mm step	OFF	OFF
Figure D-2	30mm step	ON	OFF
Figure D-3	30mm step	OFF	ON
Figure D-4	30mm step	ON	ON
Figure D-5	30mm step	ON	Karnopp
Figure D-6	30mm step	OFF	Karnopp
Figure D-7	30mm step	ON	Hölscher & Huang
Figure D-8	30mm step	Maximum strut force summary	
Figure D-10	30mm step	Maximum strut displacement summary	
Figure D-11	30mm step	Maximum sprung mass acceleration summary	

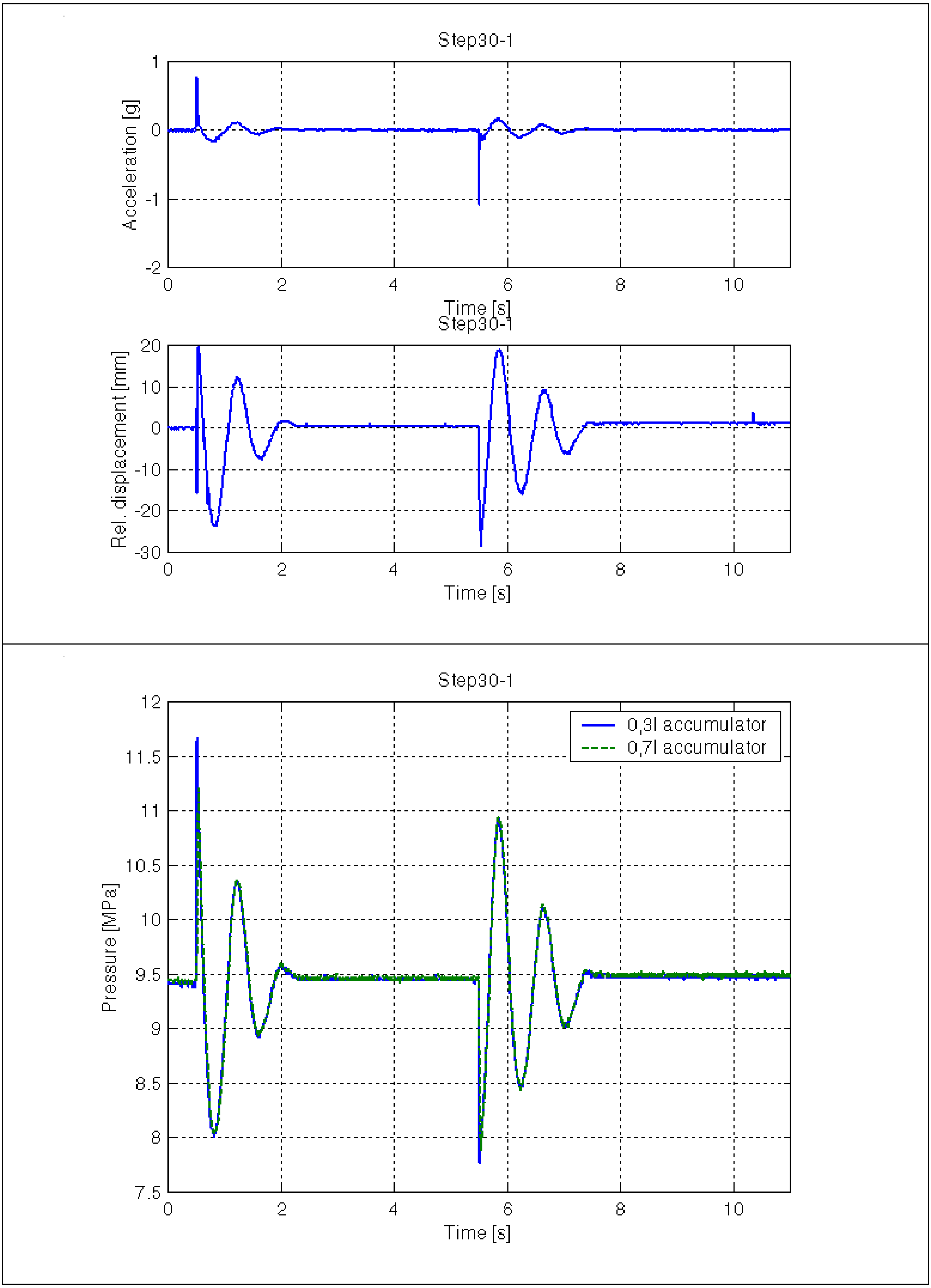


Figure D-1: 30mm step response (Spring – OFF, Damper - OFF)

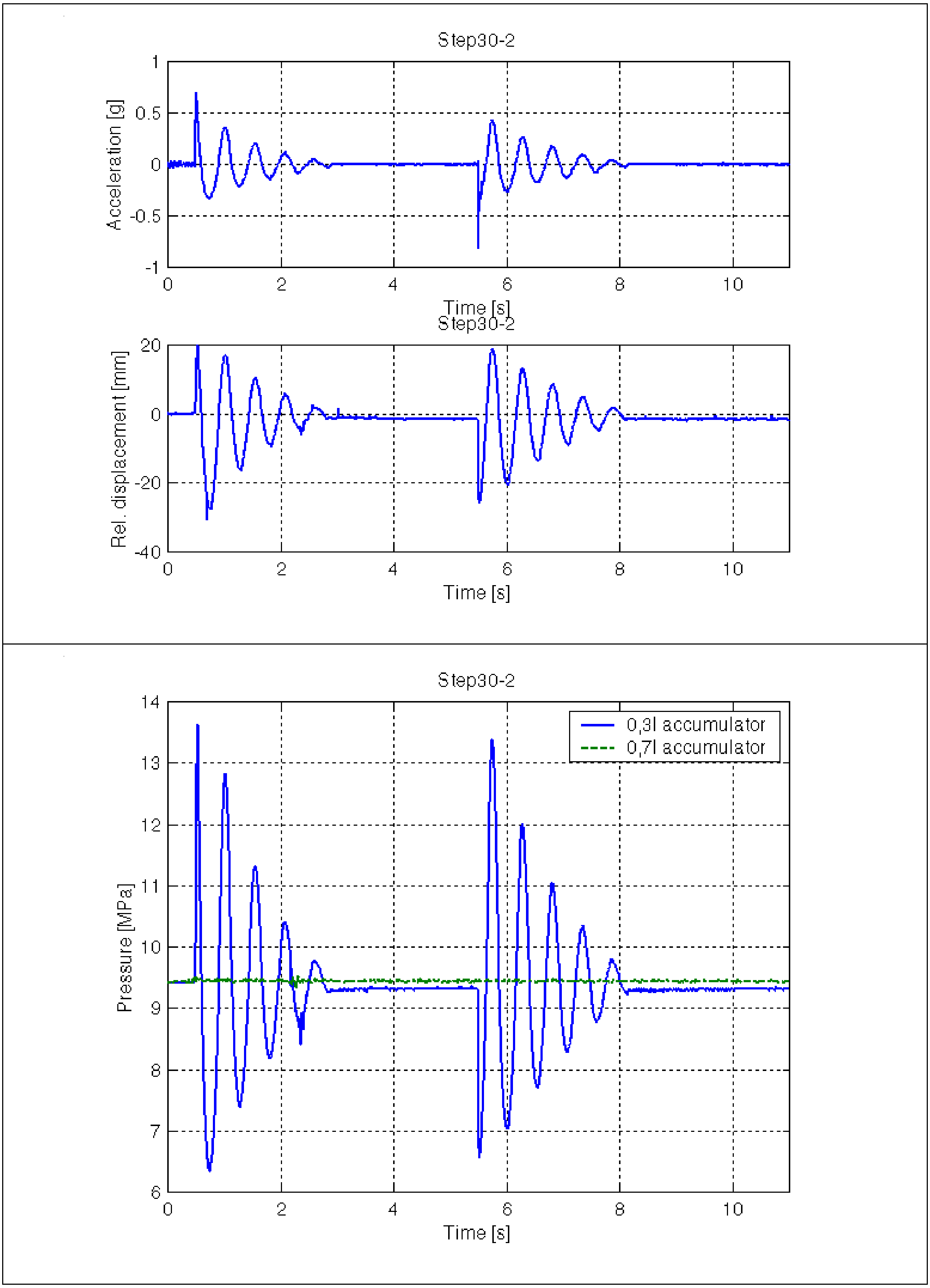


Figure D-2: 30mm step response (Spring – ON, Damper - OFF)

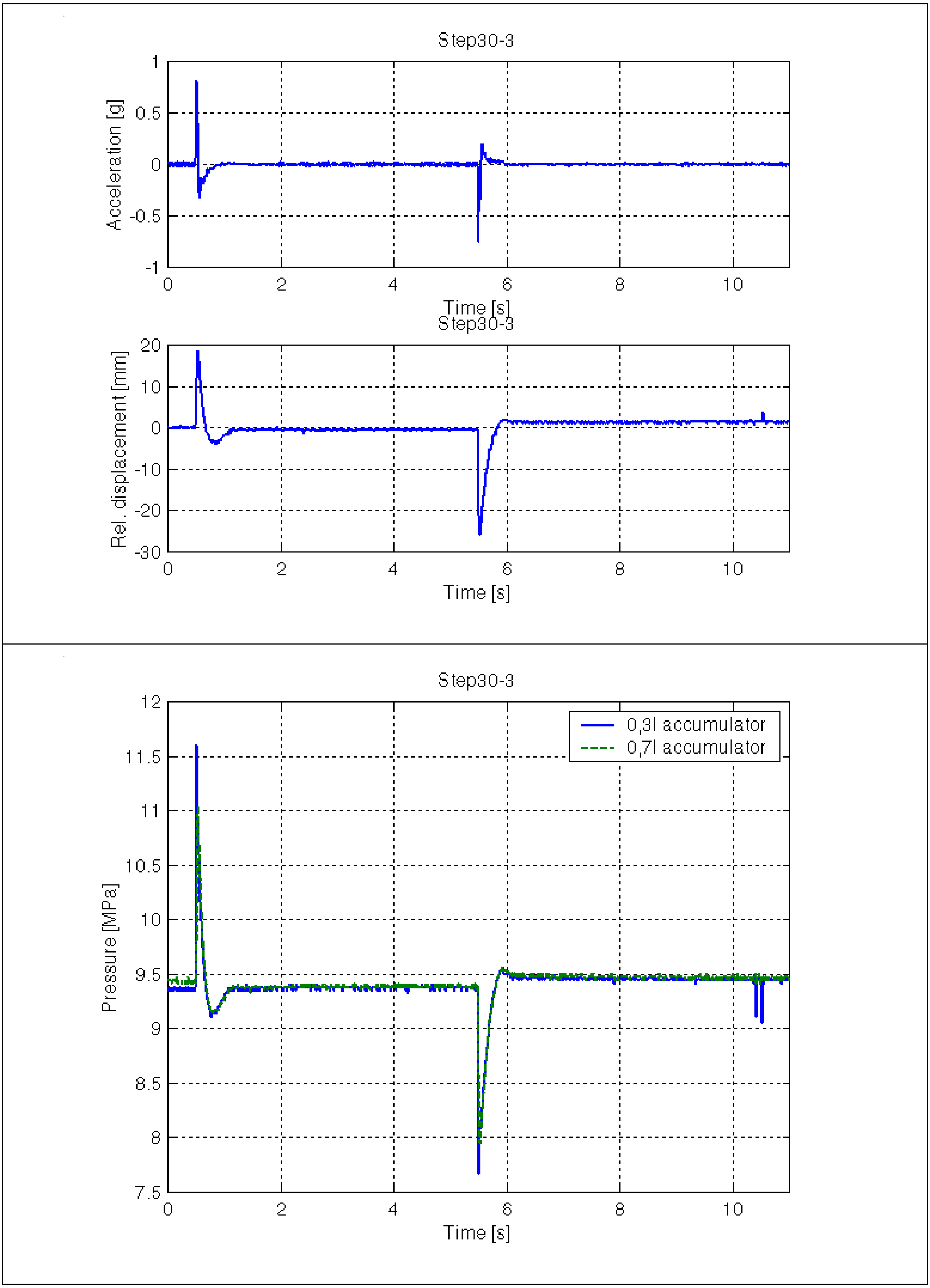


Figure D-3: 30mm step response (Spring – OFF, Damper - ON)

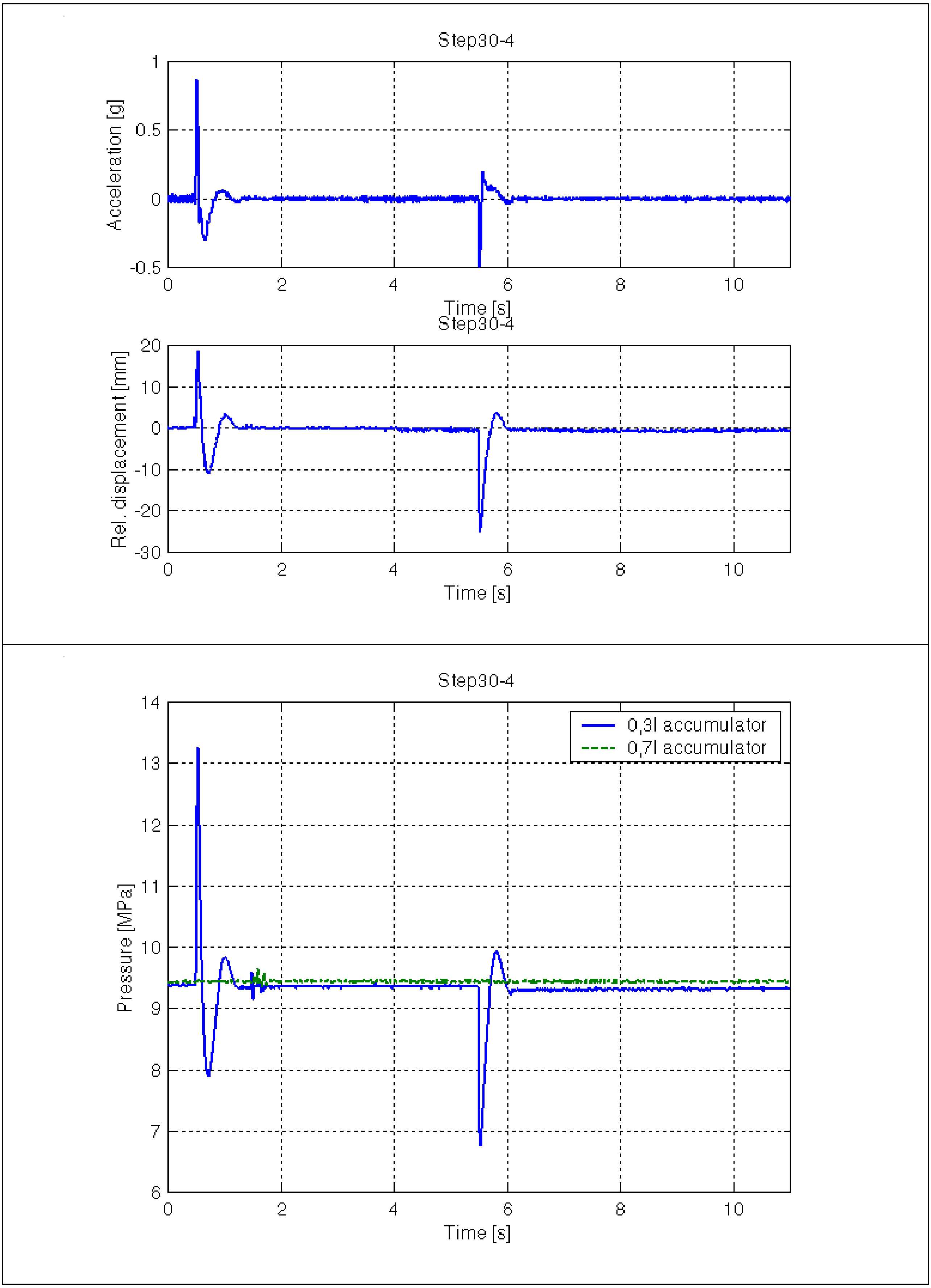


Figure D-4: 30mm step response (Spring – ON, Damper - ON)

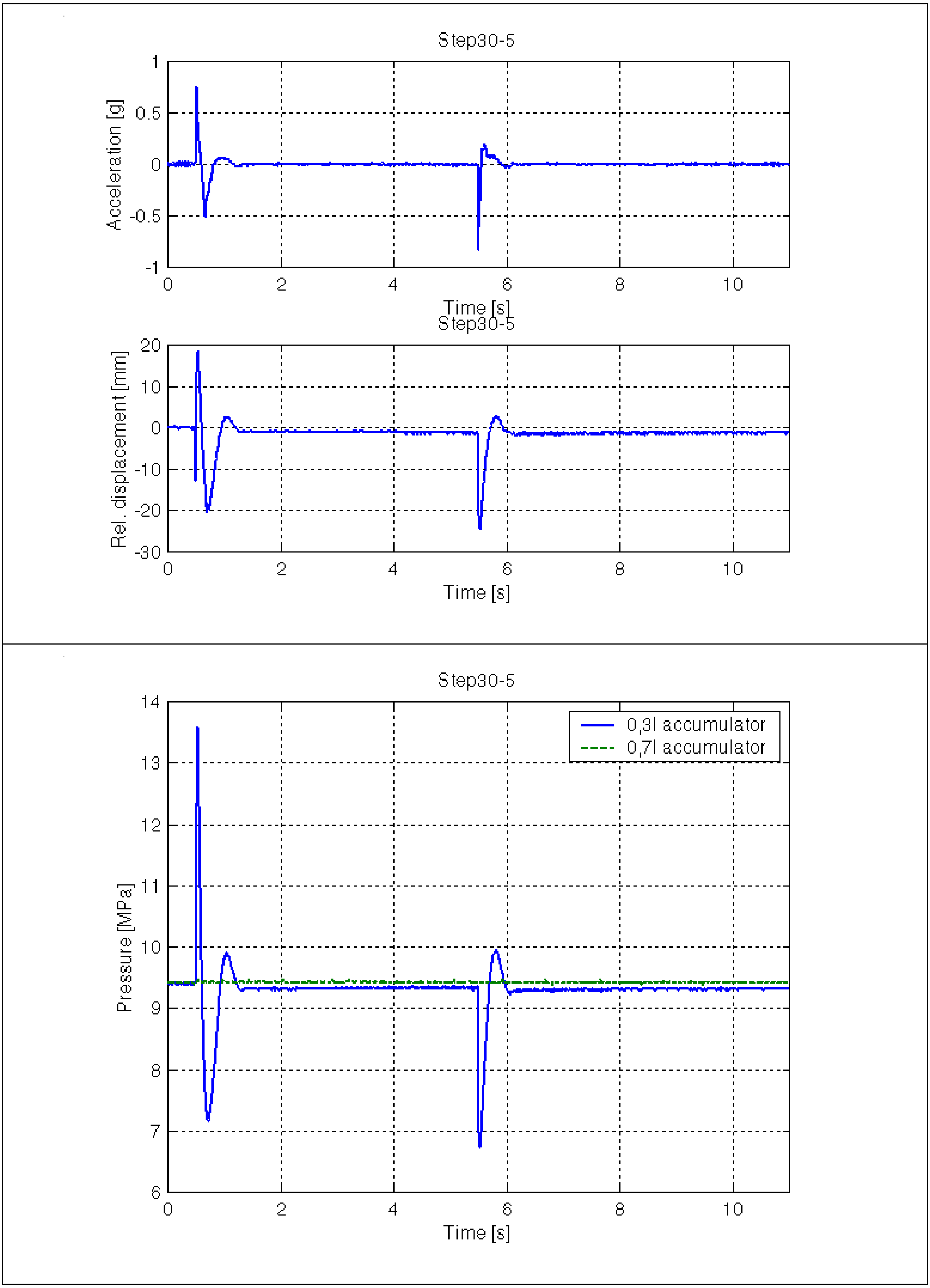


Figure D-5: 30mm step response (Spring – ON, Damper - Karnopp)

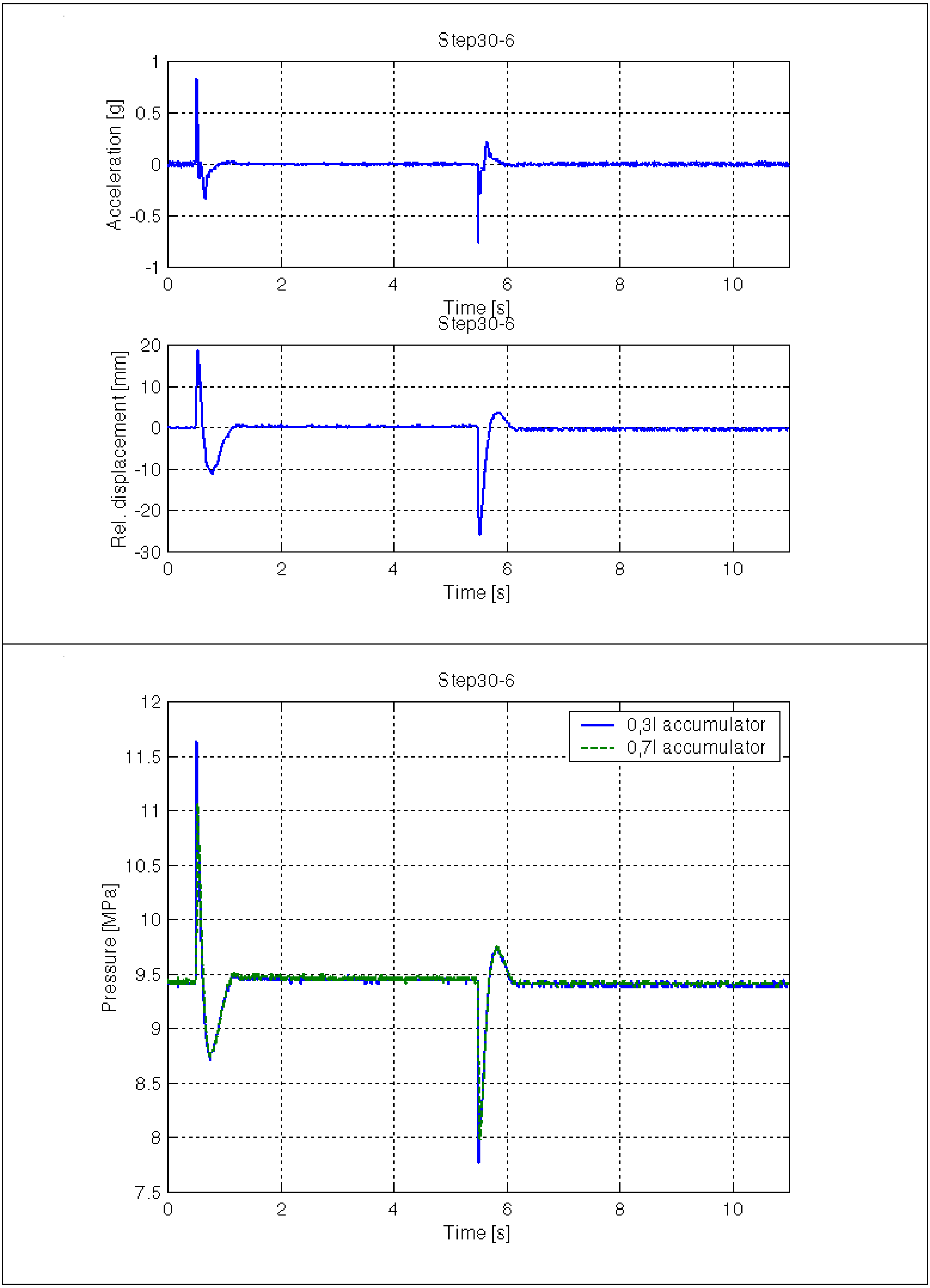


Figure D-6: 30mm step response (Spring – OFF, Damper - Karnopp)

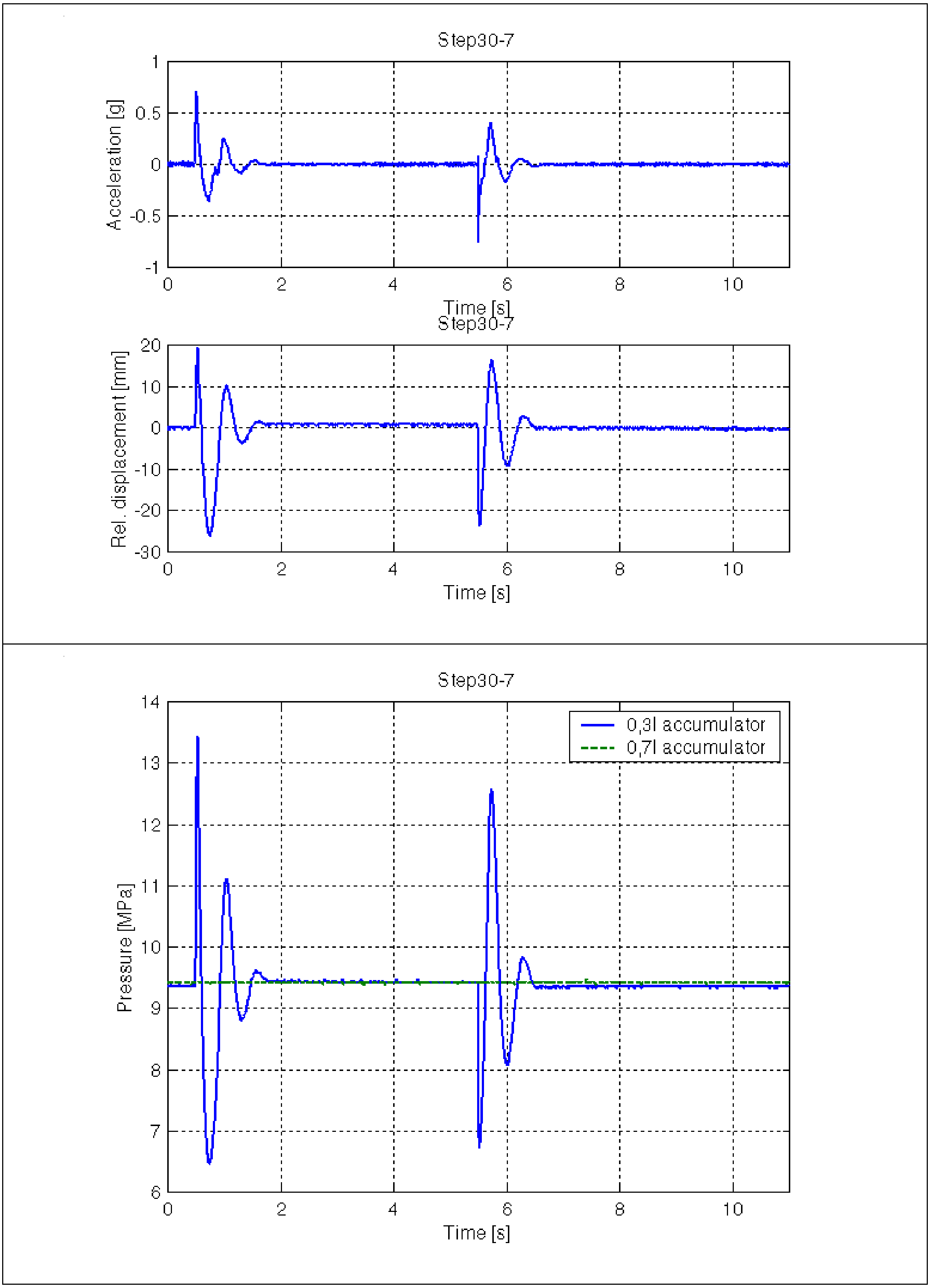


Figure D-7: 30mm step response (Spring – ON, Damper – Hölscher & Huang)

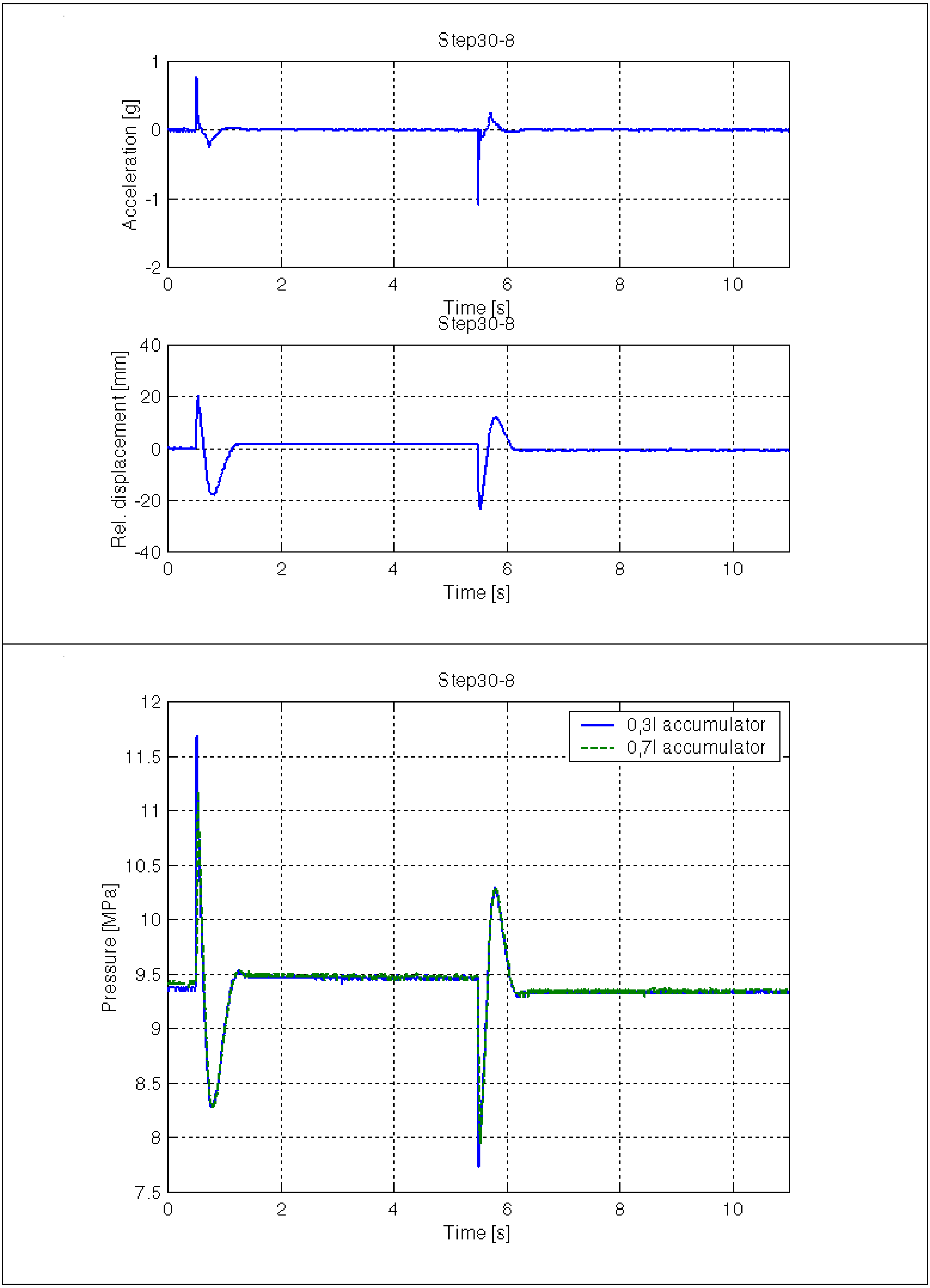


Figure D-8: 30mm step response (Spring – OFF, Damper – Hölscher & Huang)

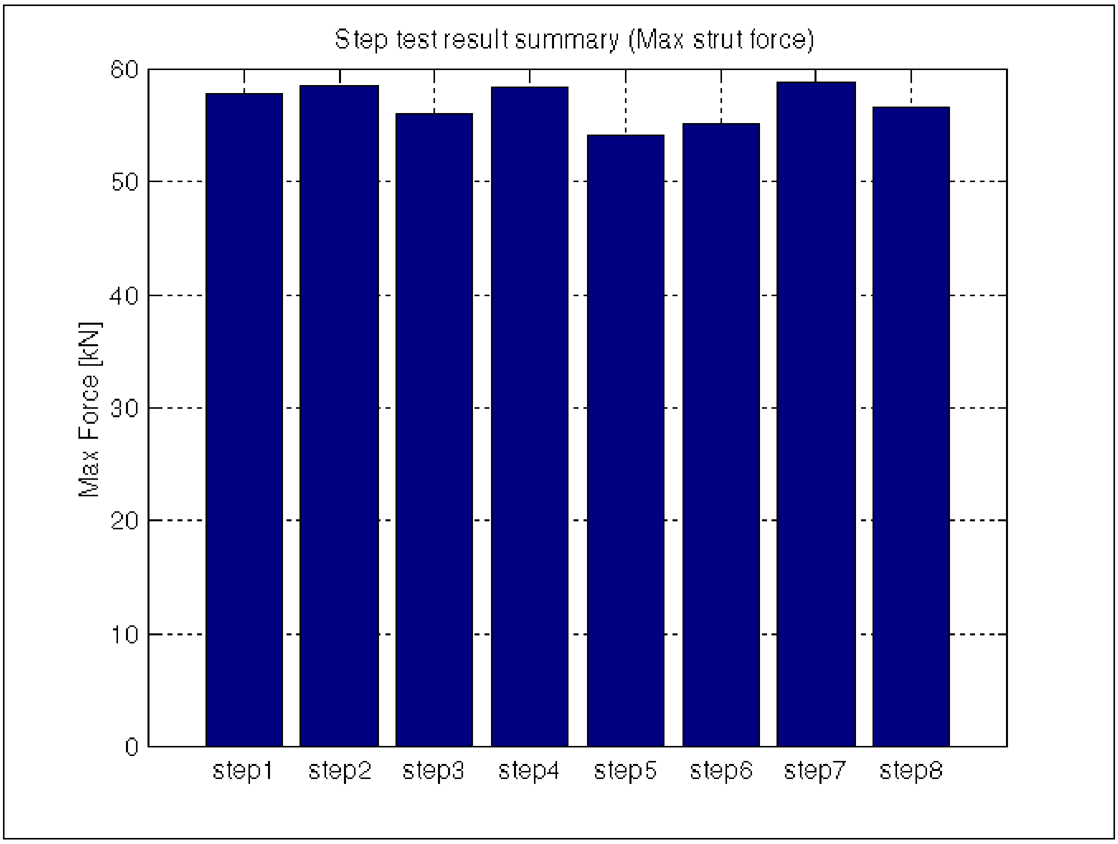


Figure D-9: 60mm step response (Spring – OFF, Damper - OFF)

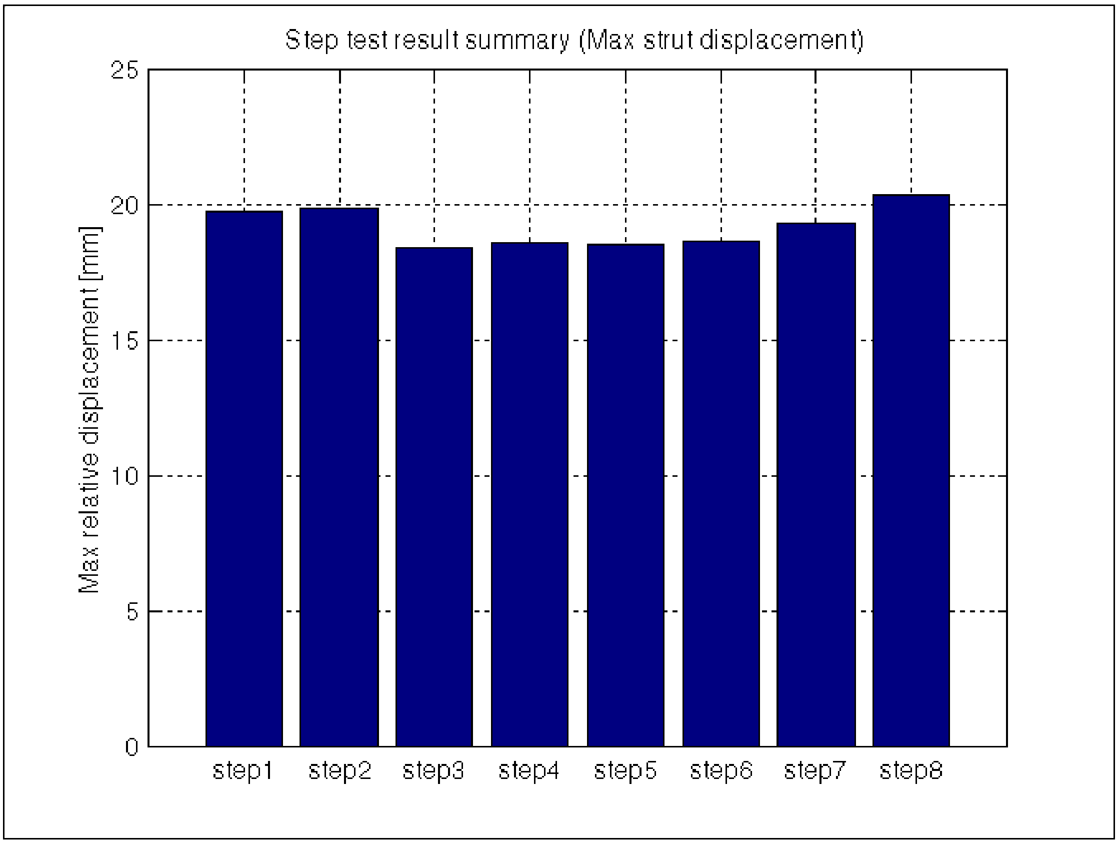


Figure D-10: 60mm step response (Spring – OFF, Damper - OFF)

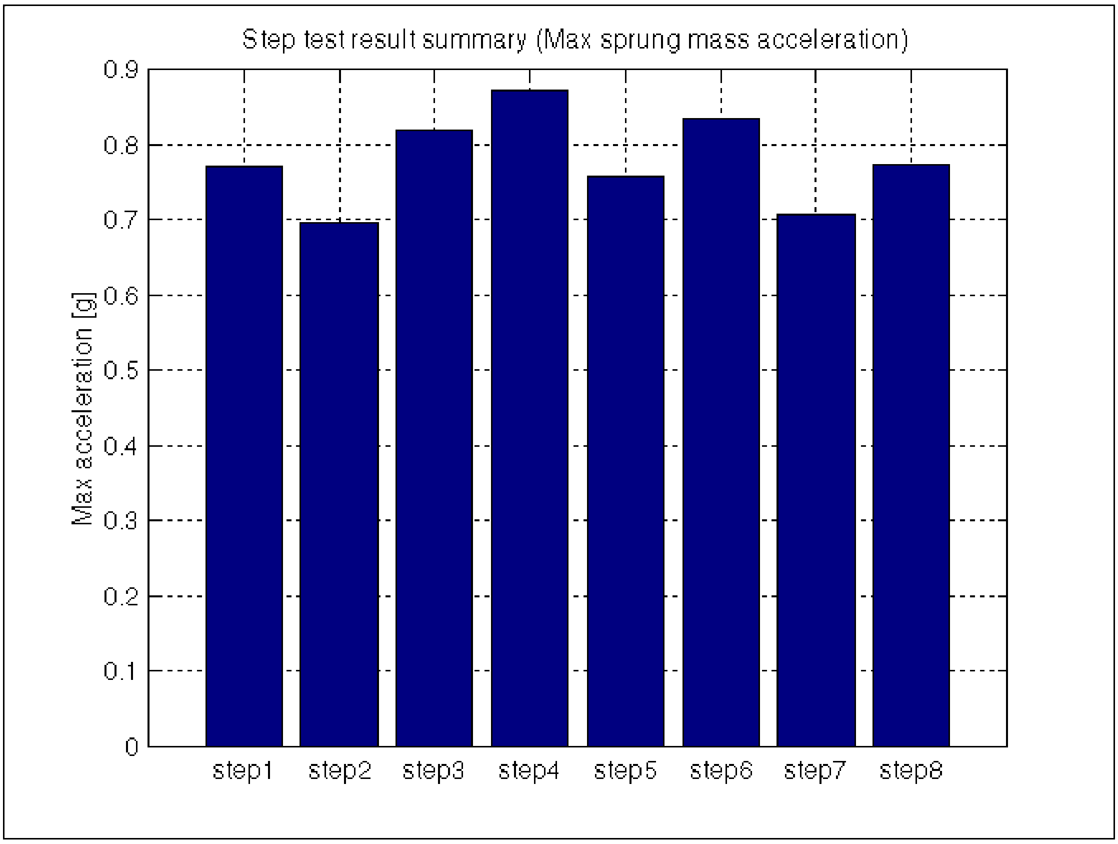


Figure D-11: 60mm step response (Spring – OFF, Damper - OFF)

D.2 Belgian paving test results

For the random input response tests, the left-hand lane of the Belgian paving track at the Gerotek Vehicle Testing Facility was used. Different spring and damper settings were tested and the figures in this section indicate the test results. Table D-2 indicates the spring and damper setting for each of the graphs presented in this section.

Table D-2: Spring/damper configuration for random input tests

Figure number	Input	Spring state	Damper state
Figure D-12	Belgian paving	OFF	OFF
Figure D-13	Belgian paving	ON	OFF
Figure D-14	Belgian paving	OFF	ON
Figure D-15	Belgian paving	ON	ON
Figure D-16	Belgian paving	ON	Karnopp
Figure D-17	Belgian paving	OFF	Karnopp
Figure D-18	Belgian paving	ON	Hölscher & Huang
Figure D-19	Belgian paving	OFF	Hölscher & Huang
Figure D-20	Belgian paving	RMS strut force summary	
Figure D-21	Belgian paving	RMS displacement summary	
Figure D-22	Belgian paving	RMS sprung mass acceleration	

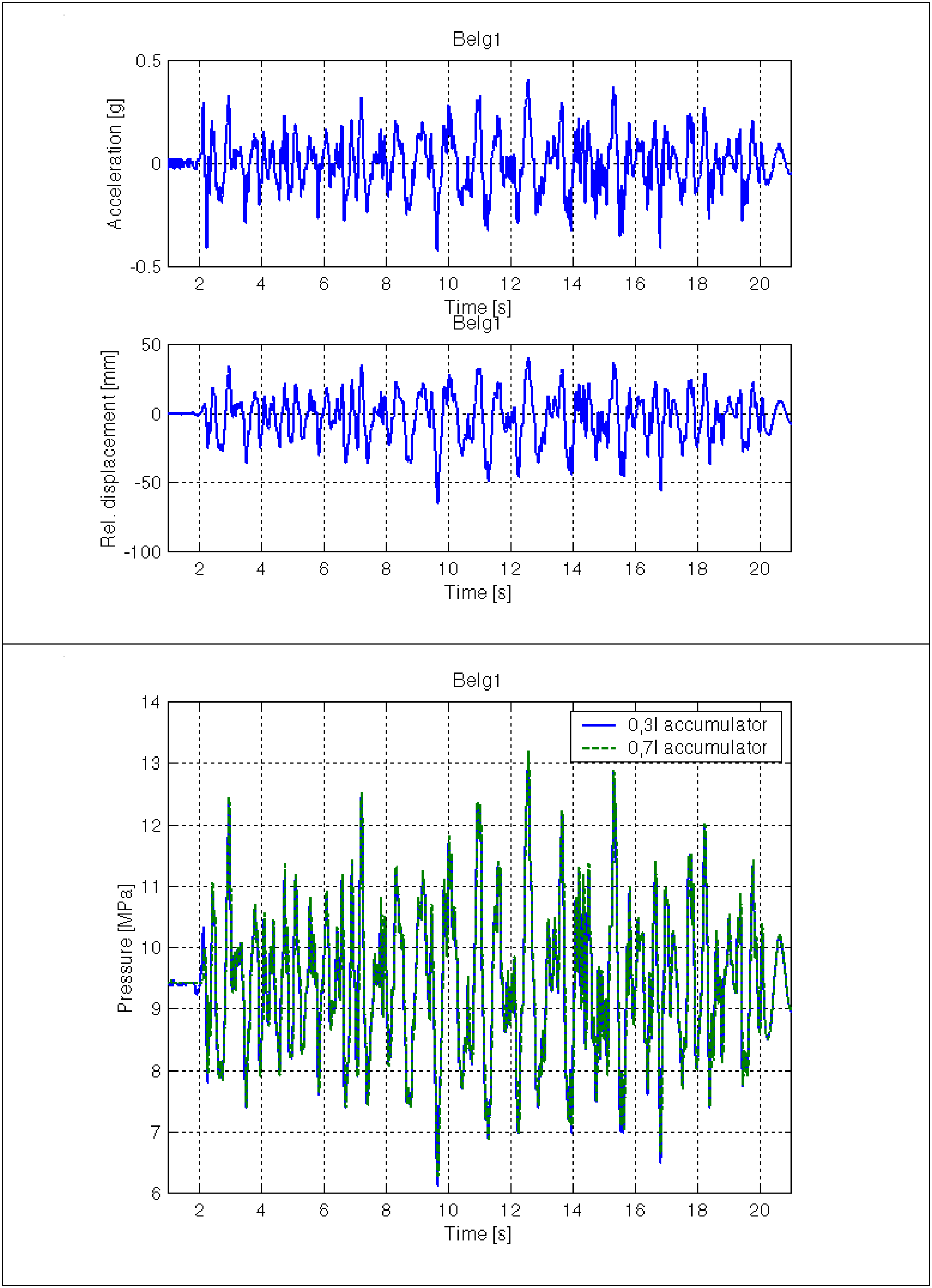


Figure D-12: Random input test (Spring – OFF, Damper – ON)

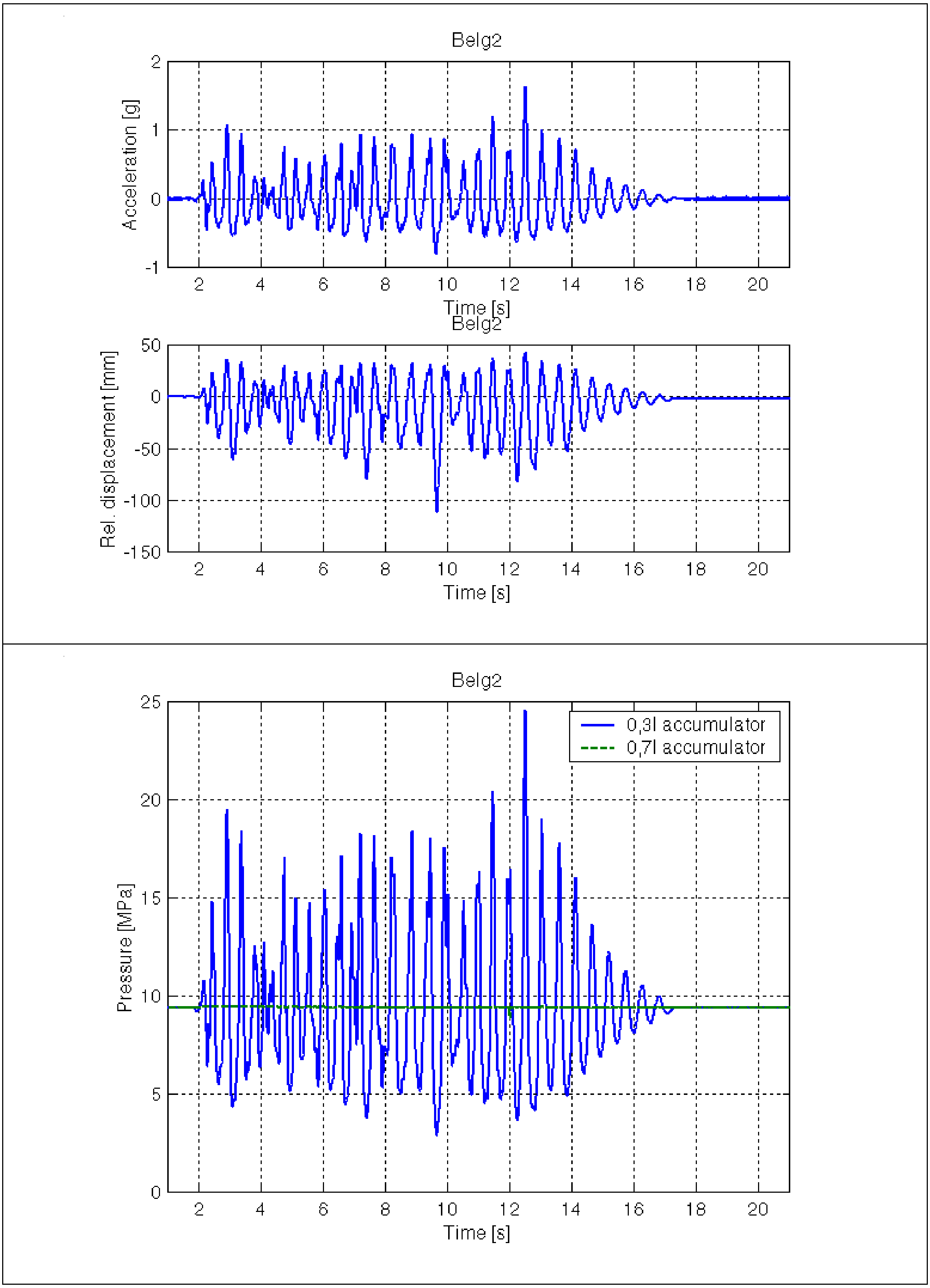


Figure D-13: Random input test (Spring – ON, Damper – OFF)

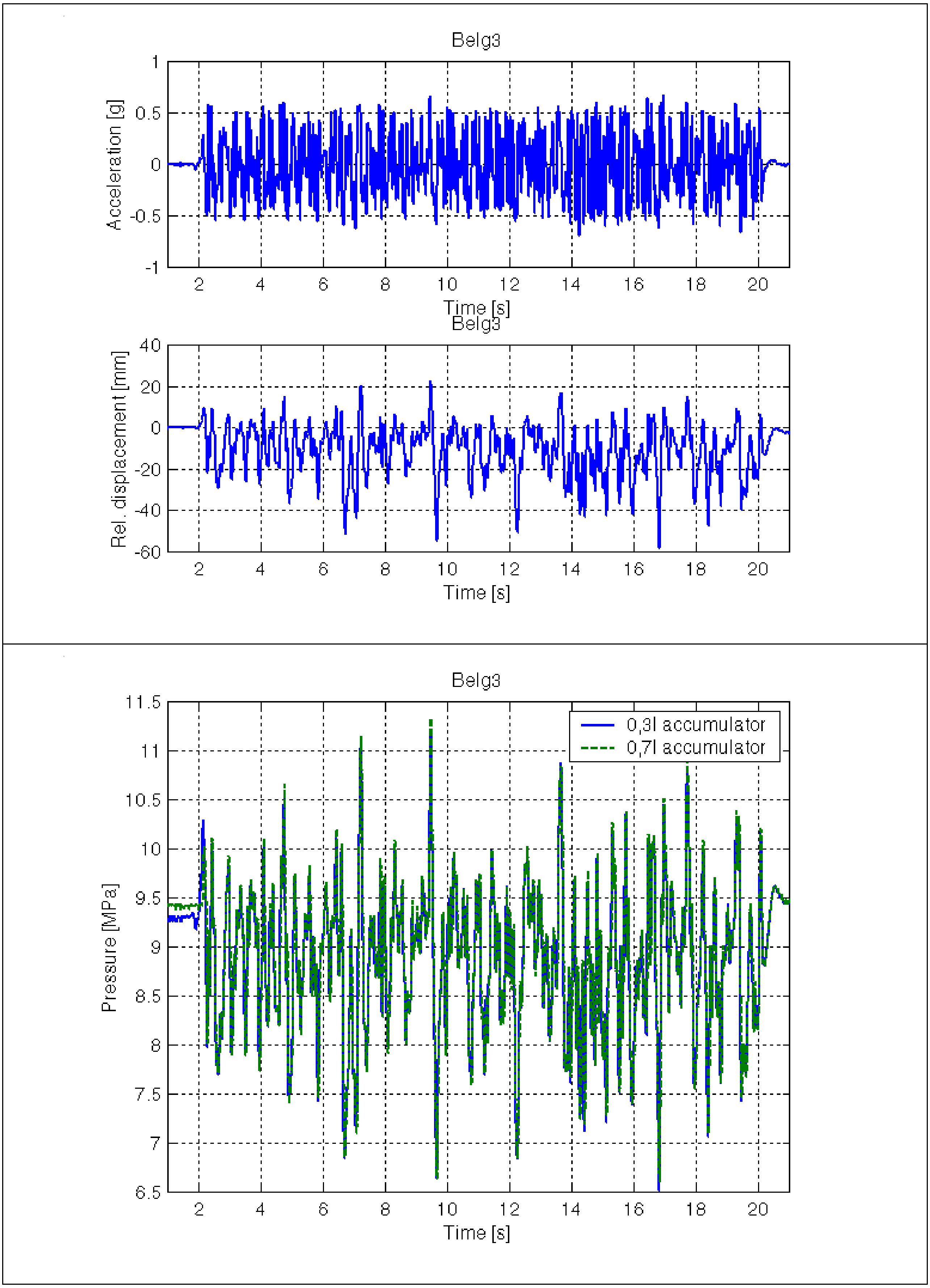


Figure D-14: Random input test (Spring – OFF, Damper – ON)

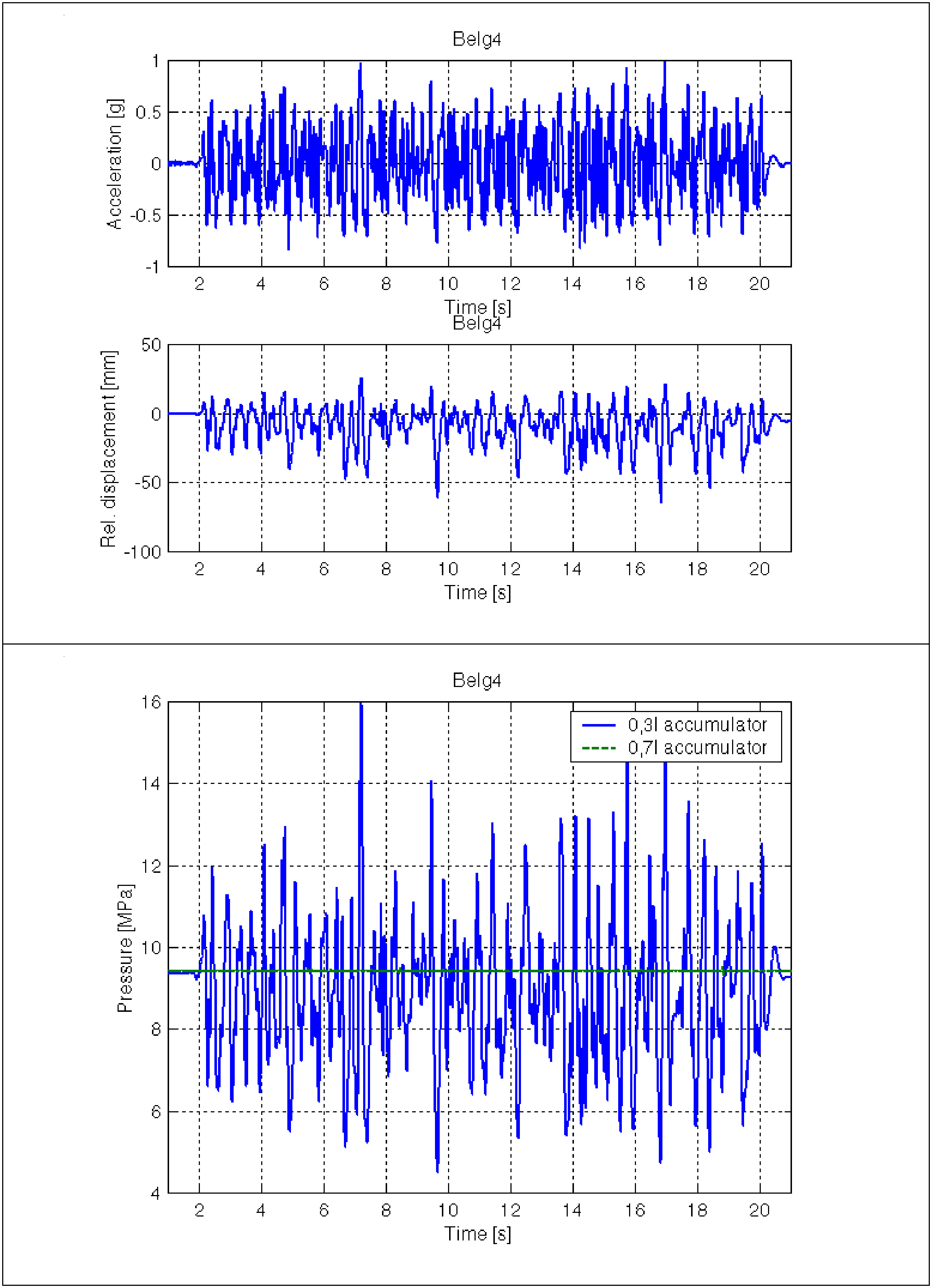


Figure D-15: Random input test (Spring – ON, Damper – ON)

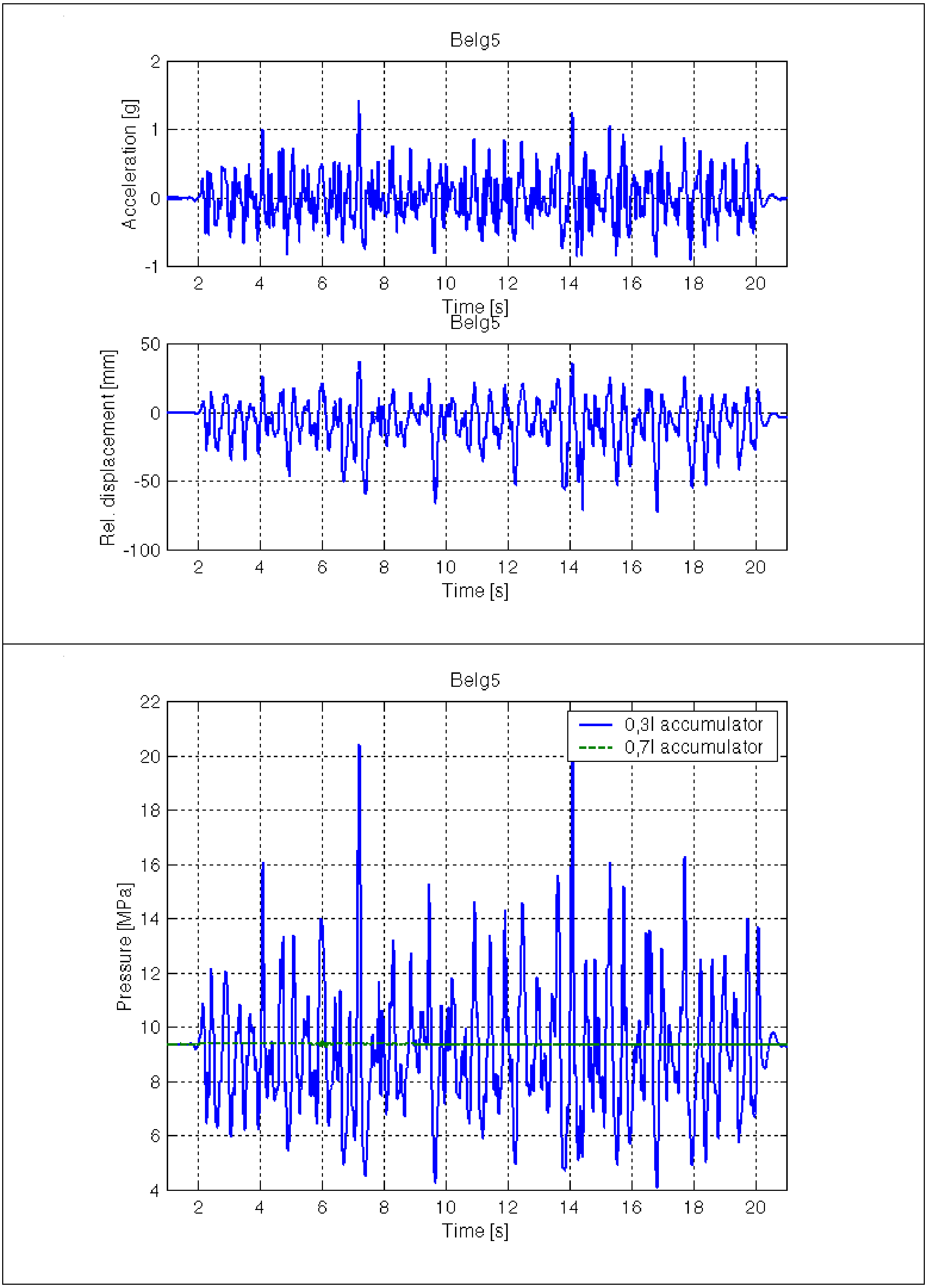
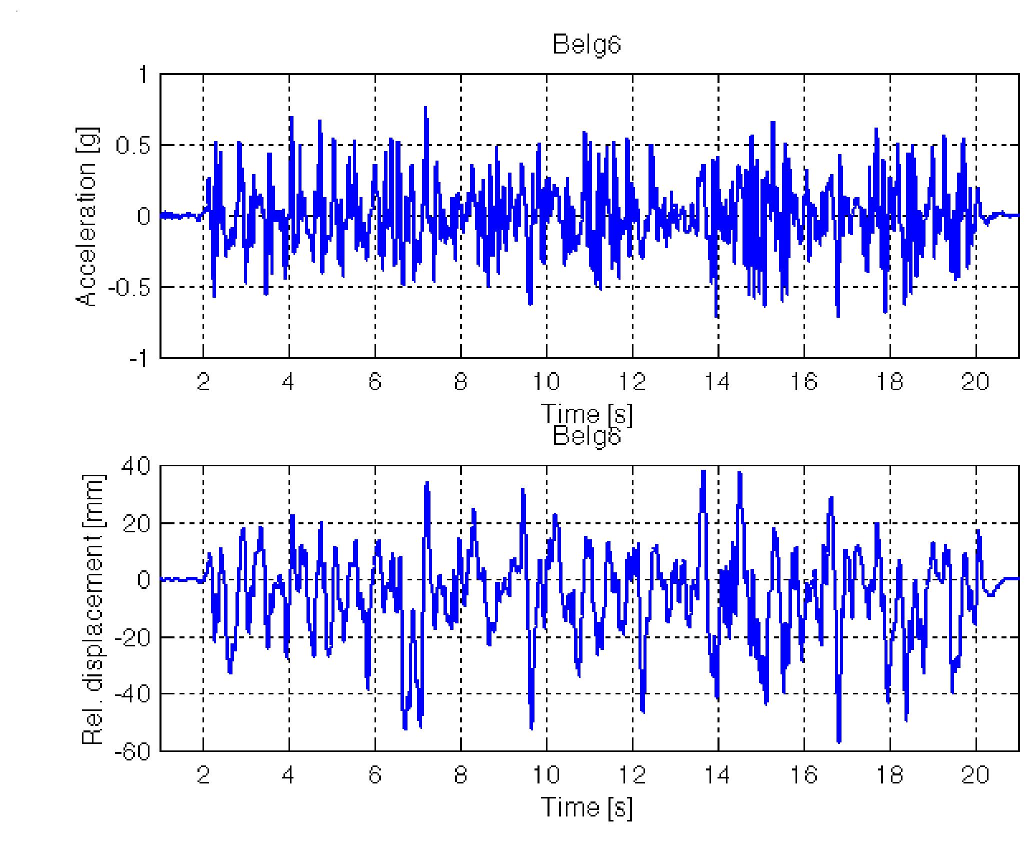


Figure D-16: Random input test (Spring – ON, Damper – Karnopp)



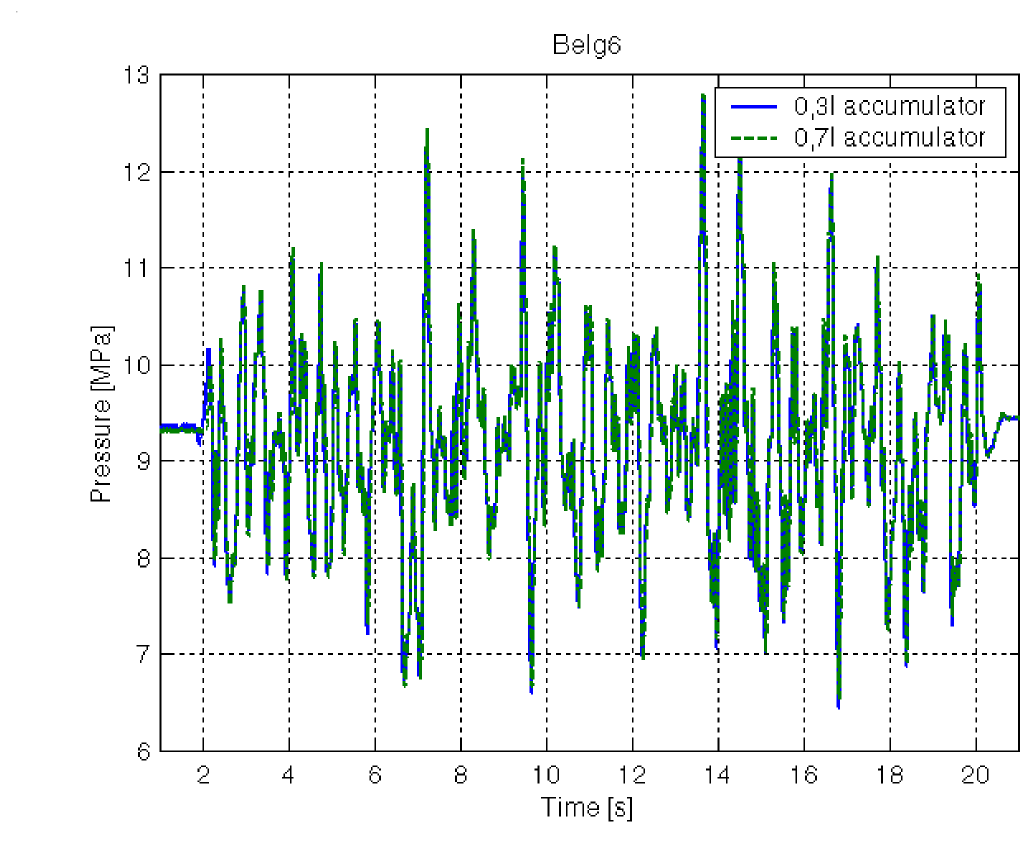


Figure D-17: Random input test (Spring – OFF, Damper – Karnopp)

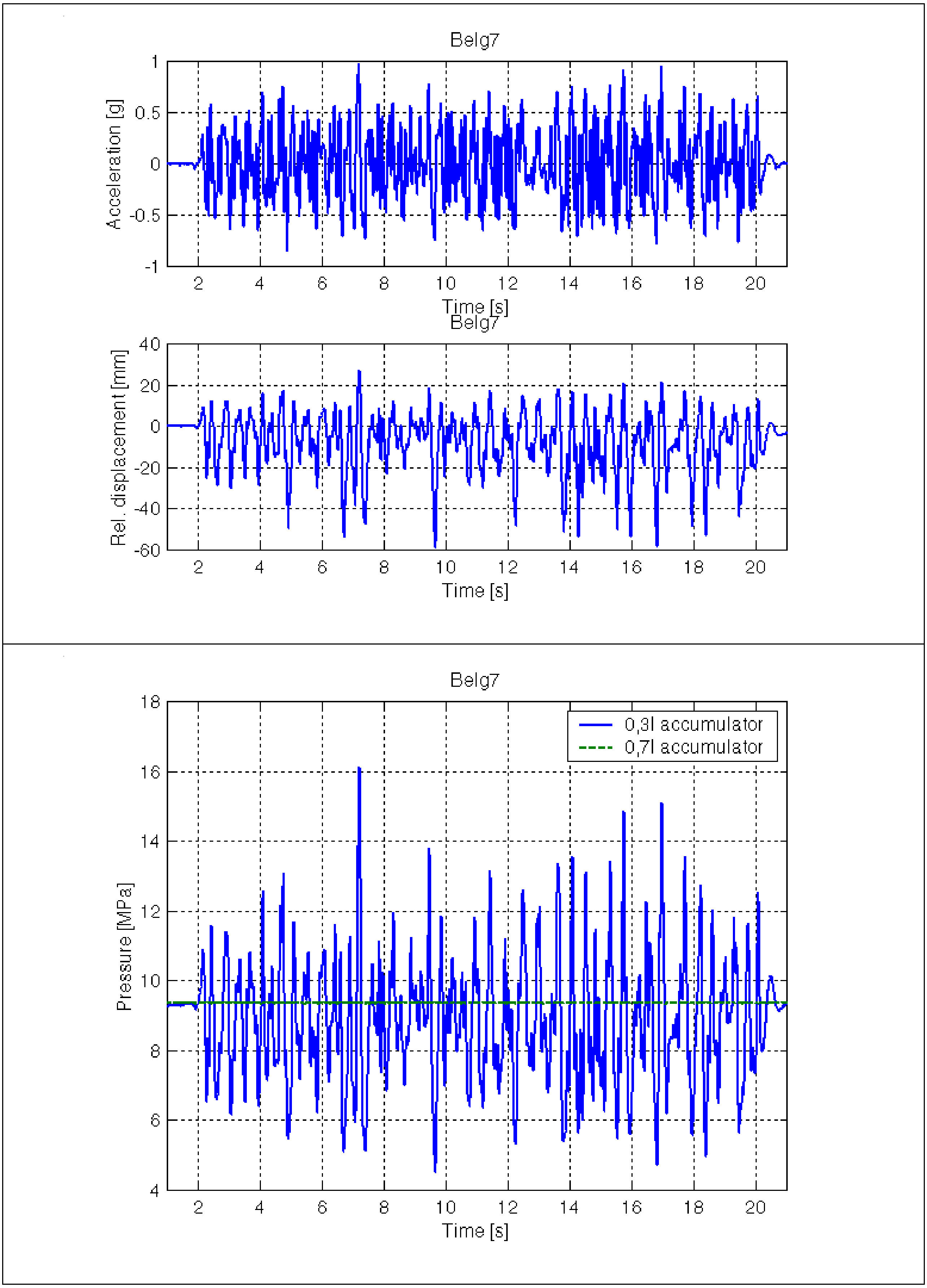


Figure D-18: Random input test (Spring – ON, Damper – Hölscher & Huang)

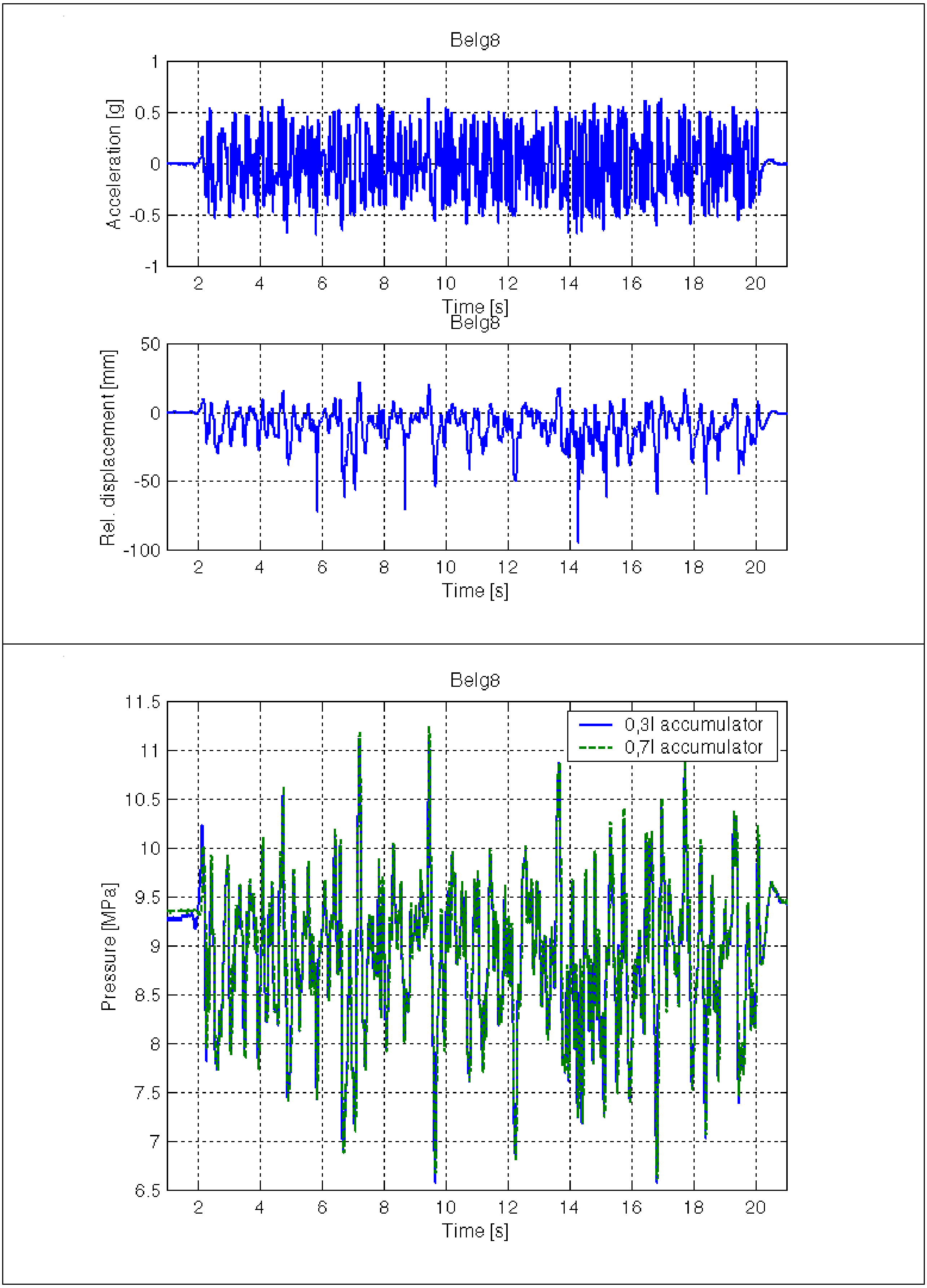


Figure D-19: Random input test (Spring – OFF, Damper – Hölscher & Huang)

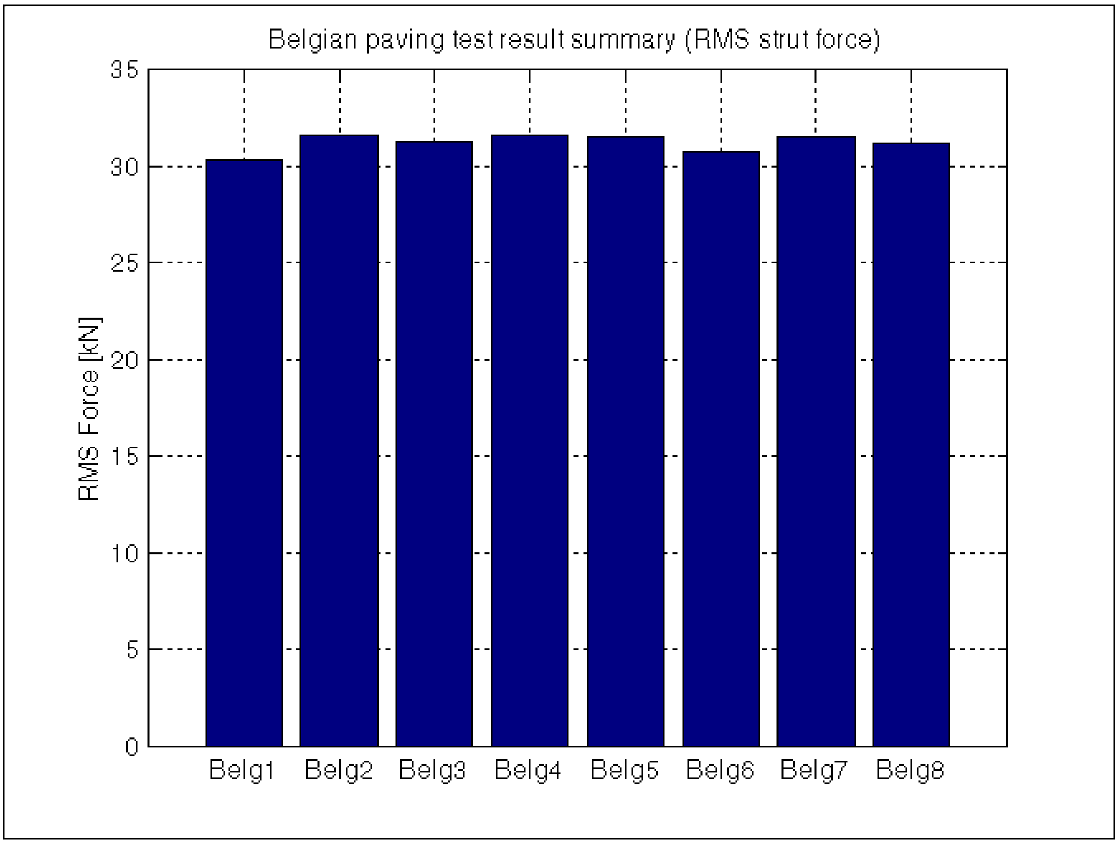


Figure D-20: Random input test (Spring – Height adjustment, Damper – OFF)

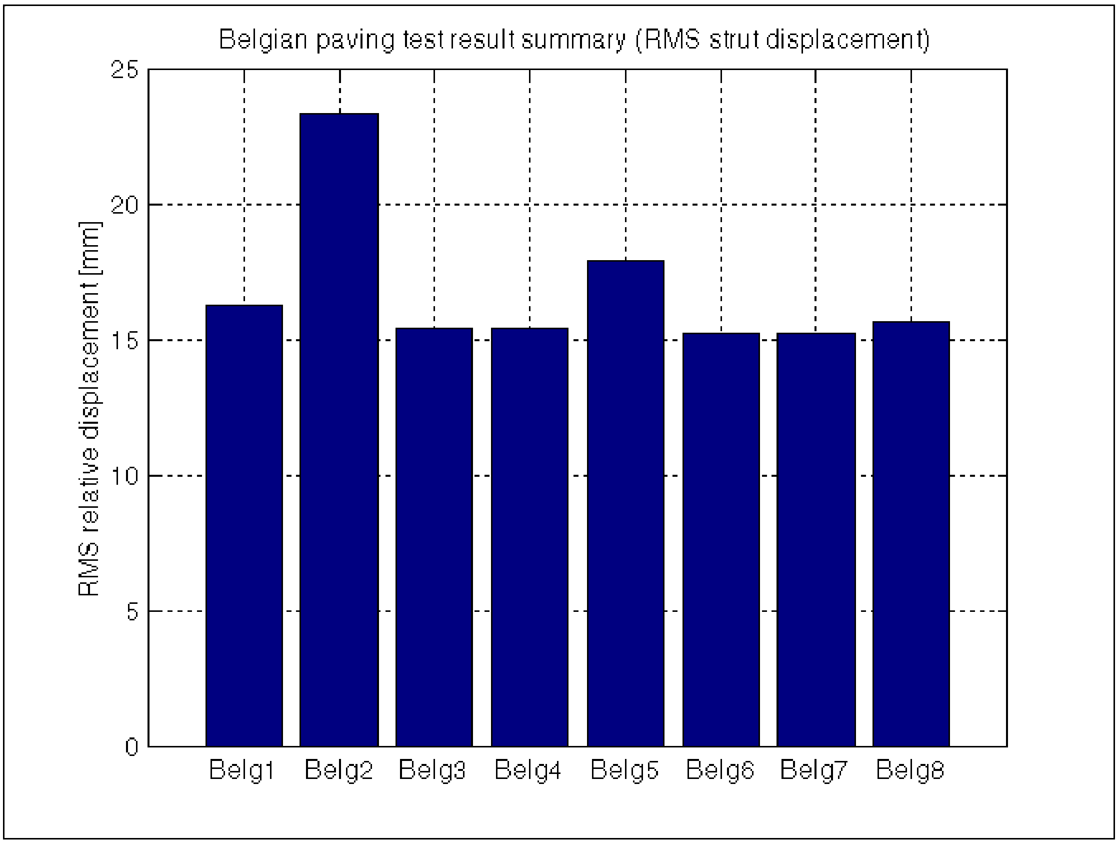


Figure D-21: Random input test (Spring – Height adjustment, Damper – ON)

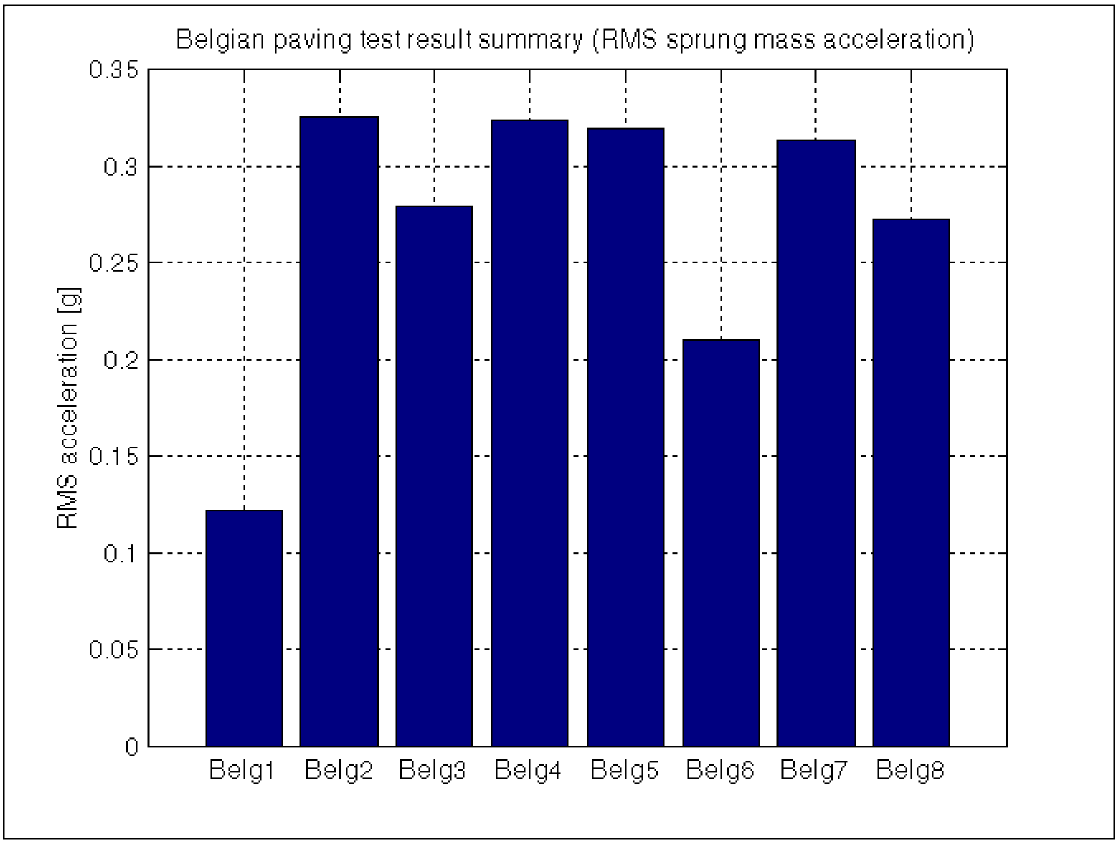


Figure D-22: Belgian paving test summary (Minimum and maximum)

D.3 Sine sweep test results

For the sine sweep tests, a sine displacement input was supplied to the actuator. The sine wave had a constant amplitude of 15*mm*, while the frequency was linearly adjusted from 0.1*Hz* to 15*Hz* in 78*s*. Table D-3 supplies a list of figures and the corresponding spring and damper settings for different graphs. Figure D-31 shows an example of the measured actuator displacement, relative strut displacement, as well as the sprung mass displacement. From this figure, it is clear that the frequency response of the actuator is not sufficient to follow the input signal at the higher frequencies. Figure D-32 indicates the transmissibility of for the configurations listed in Table D-3.

Table D-3: Spring/damper configuration for sine sweep tests

Figure number	Input	Spring state	Damper state	Filename
Figure D-23	Sine sweep (15mm amplitude)	OFF	OFF	Sin15-1
Figure D-24	Sine sweep (15mm amplitude)	ON	OFF	Sin15-2
Figure D-25	Sine sweep (15mm amplitude)	OFF	ON	Sin15-3
Figure D-26	Sine sweep (15mm amplitude)	ON	ON	Sin15-4
Figure D-27	Sine sweep (15mm amplitude)	ON	Karnopp	Sin15-5
Figure D-28	Sine sweep (15mm amplitude)	OFF	Karnopp	Sin15-6
Figure D-29	Sine sweep (15mm amplitude)	ON	Holsher & Huang	Sin15-7
Figure D-30	Sine sweep (15mm amplitude)	OFF	Holsher & Huang	Sin15-8

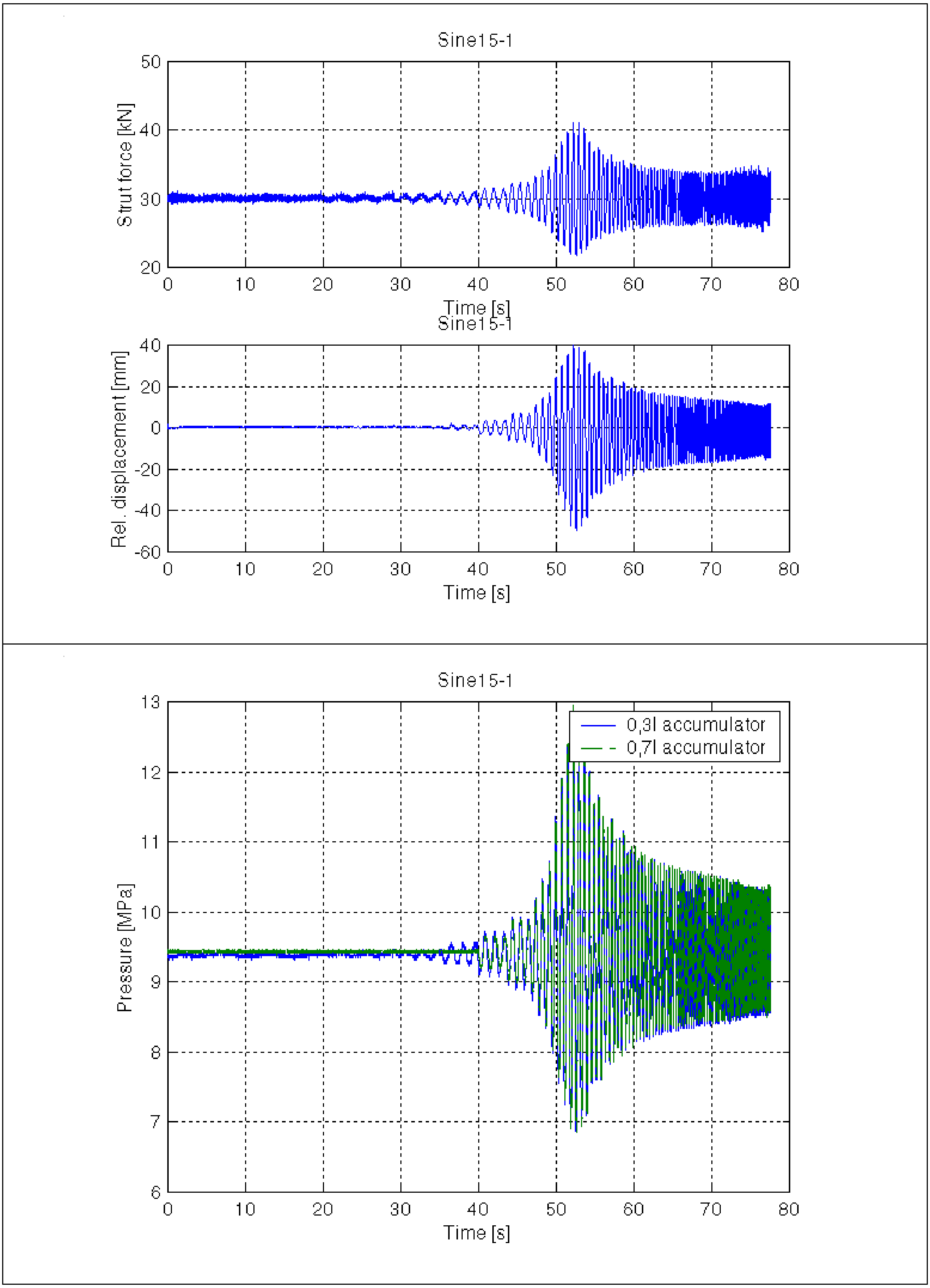


Figure D-23: Sine sweep (Spring - OFF, Damper - OFF)

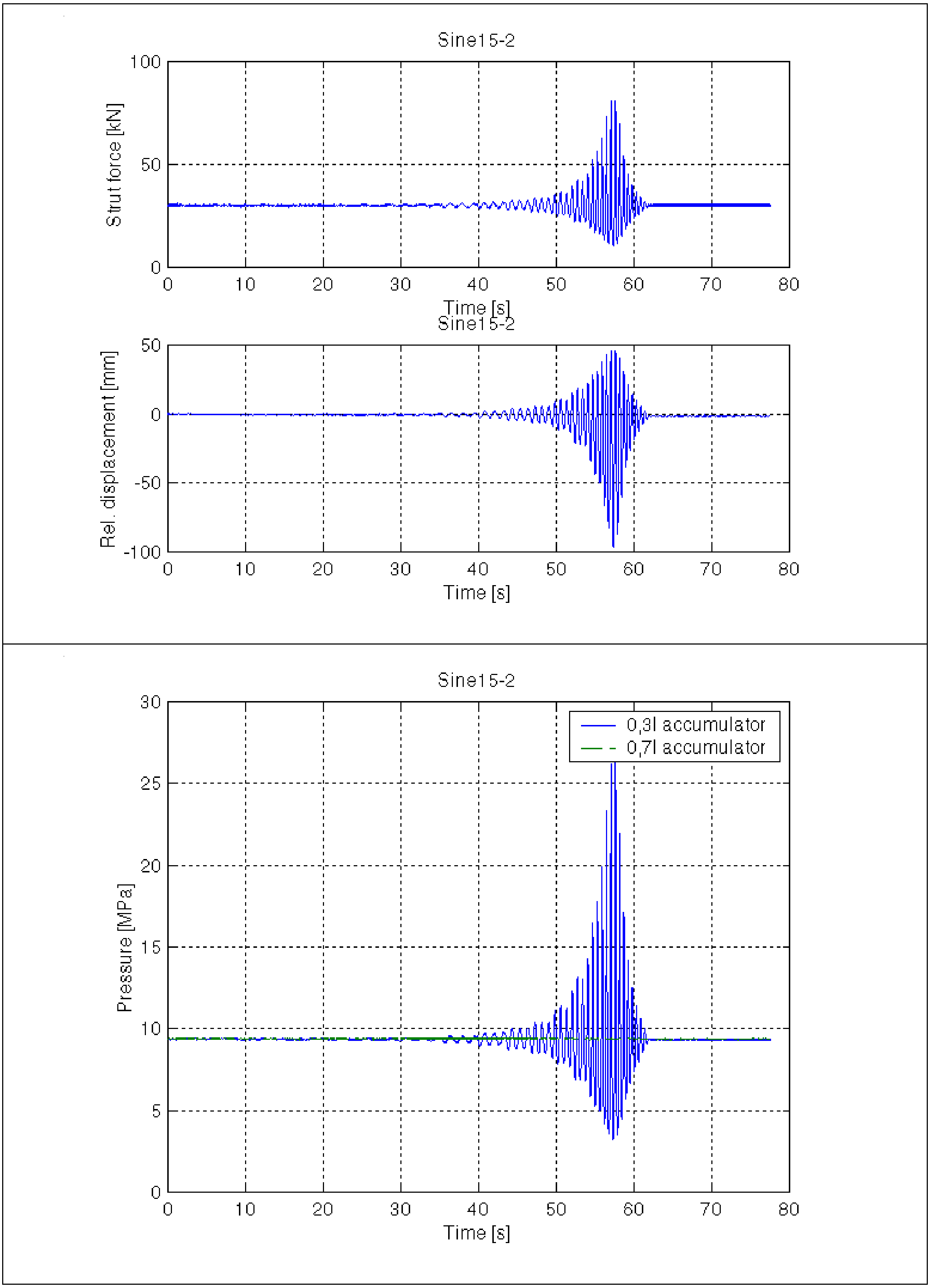


Figure D-24: Sine sweep (Spring - ON, Damper - OFF)

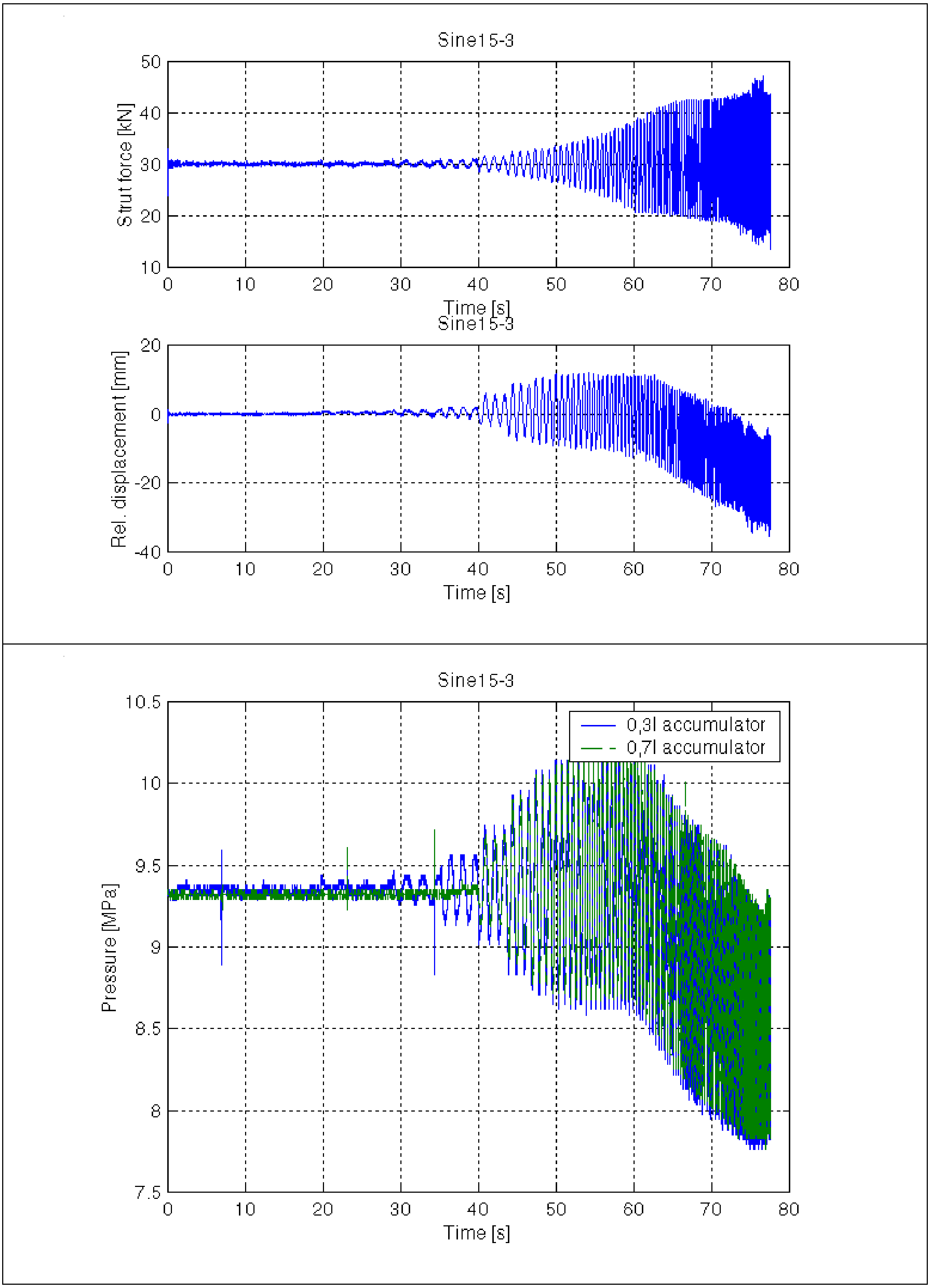


Figure D-25: Sine sweep (Spring - OFF, Damper - ON)

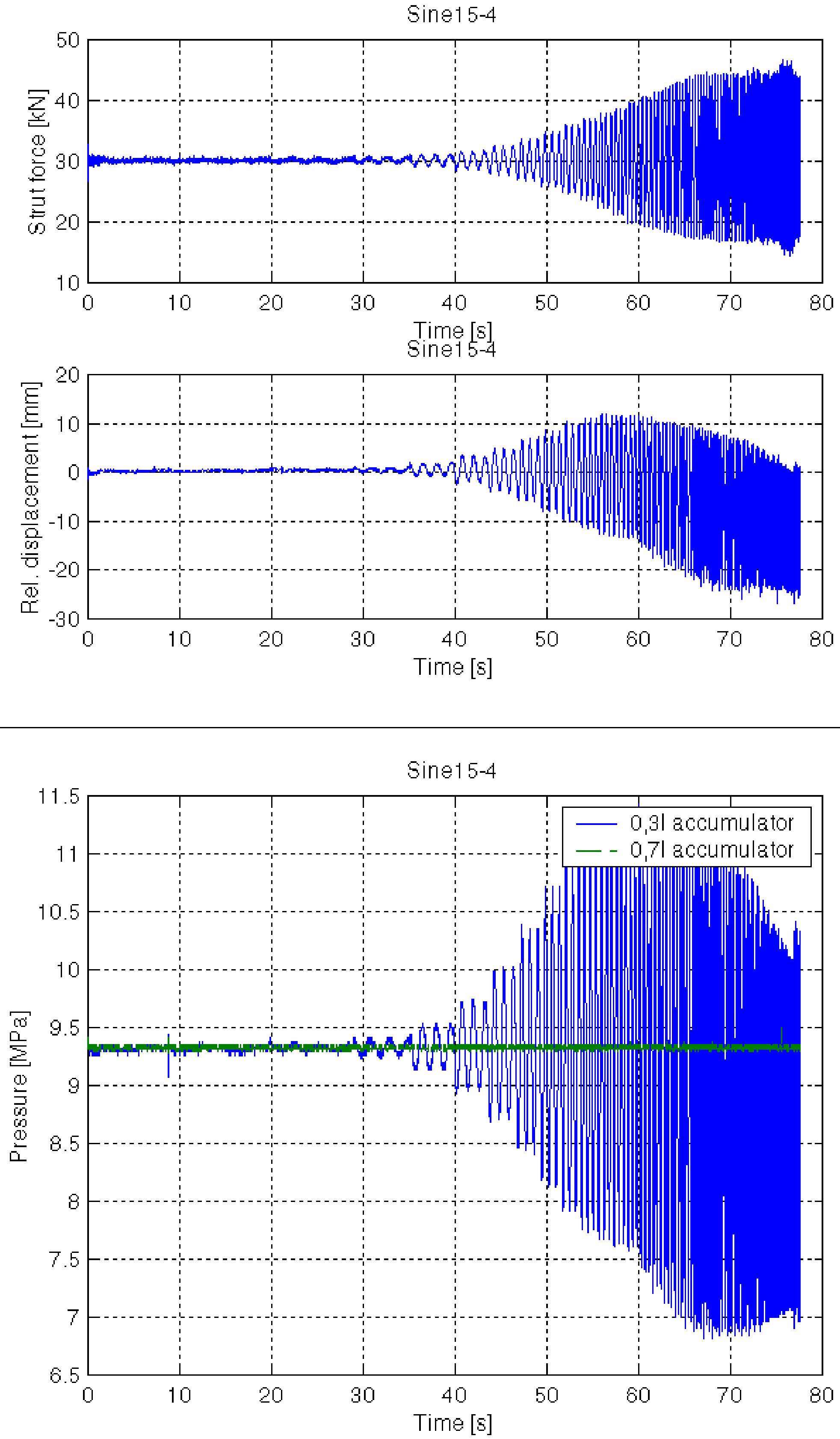


Figure D-26: Sine sweep (Spring - ON, Damper - ON)

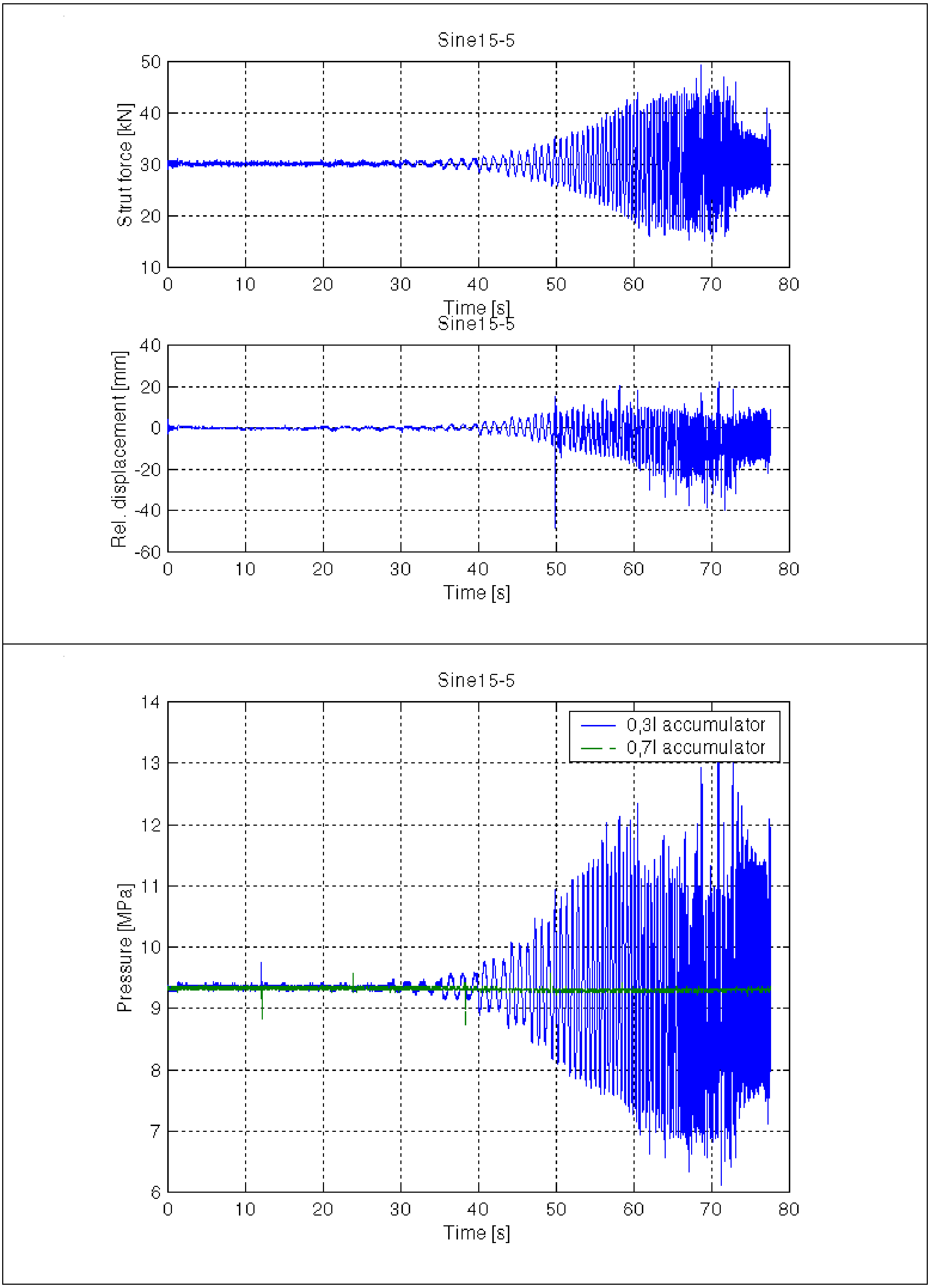


Figure D-27: Sine sweep (Spring - ON, Damper - Karnopp)

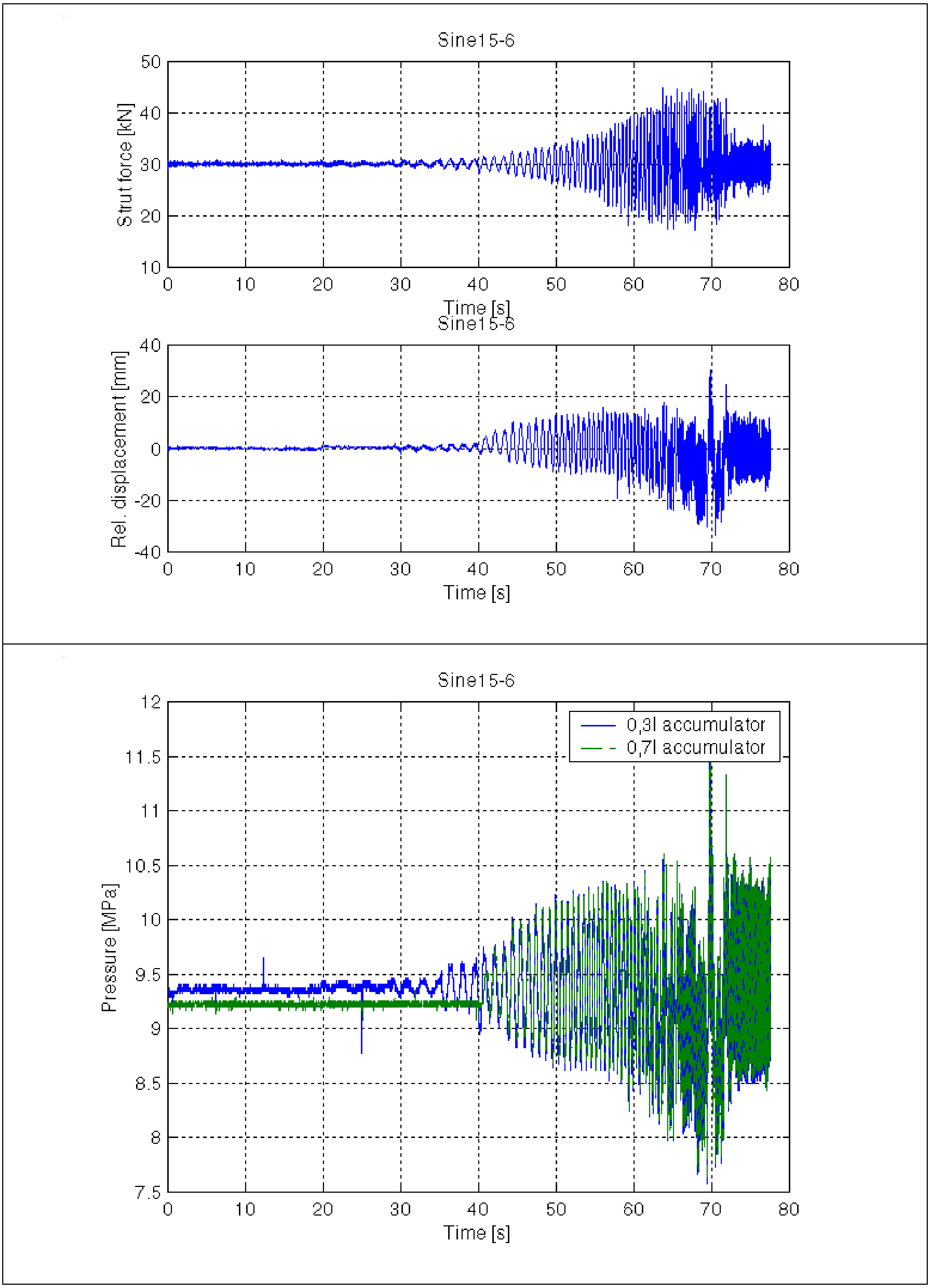


Figure D-28: Sine sweep (Spring - OFF, Damper - Karnopp)

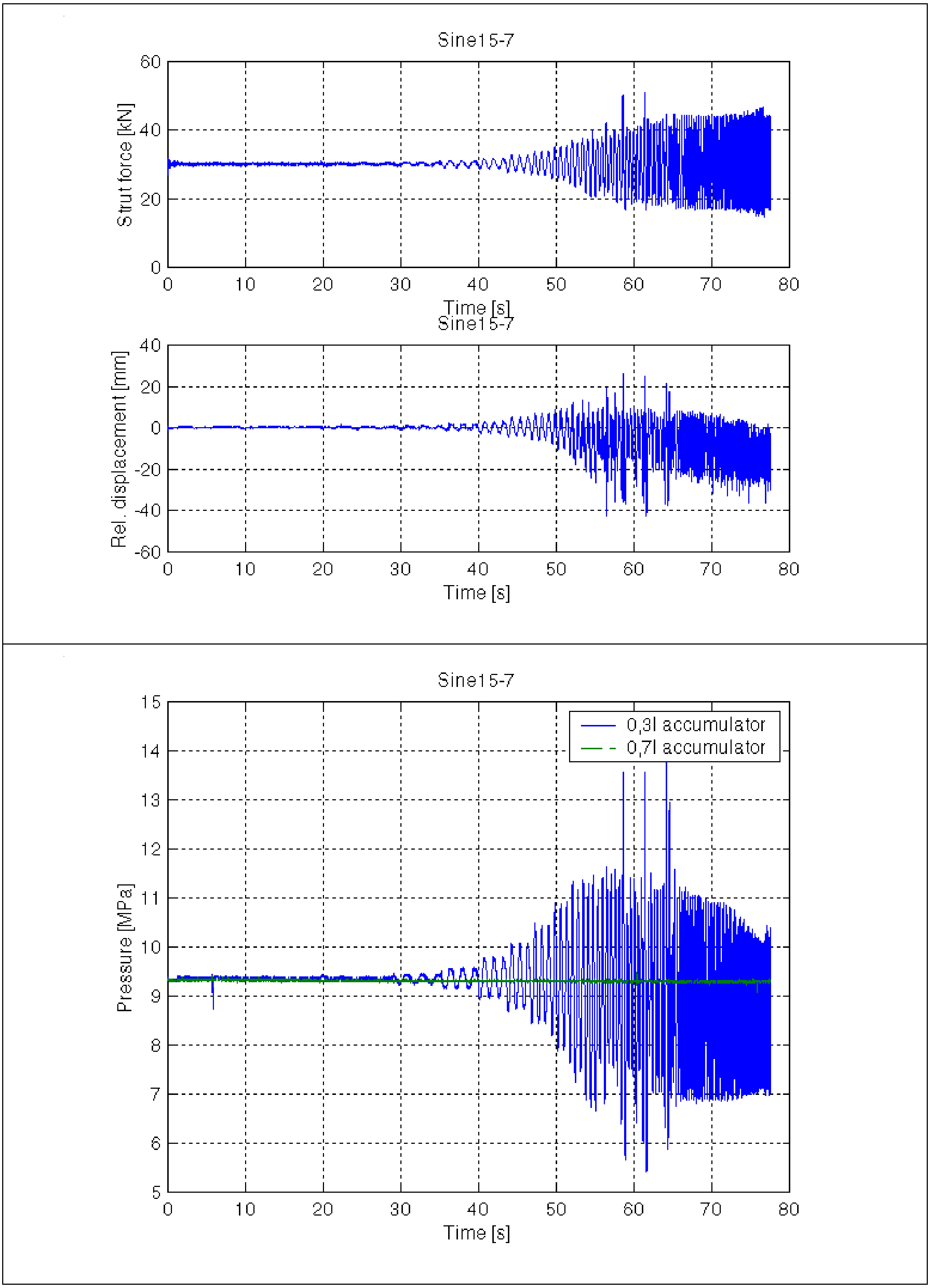


Figure D-29: Sine sweep (Spring - ON, Damper - Hölscher & Huang)

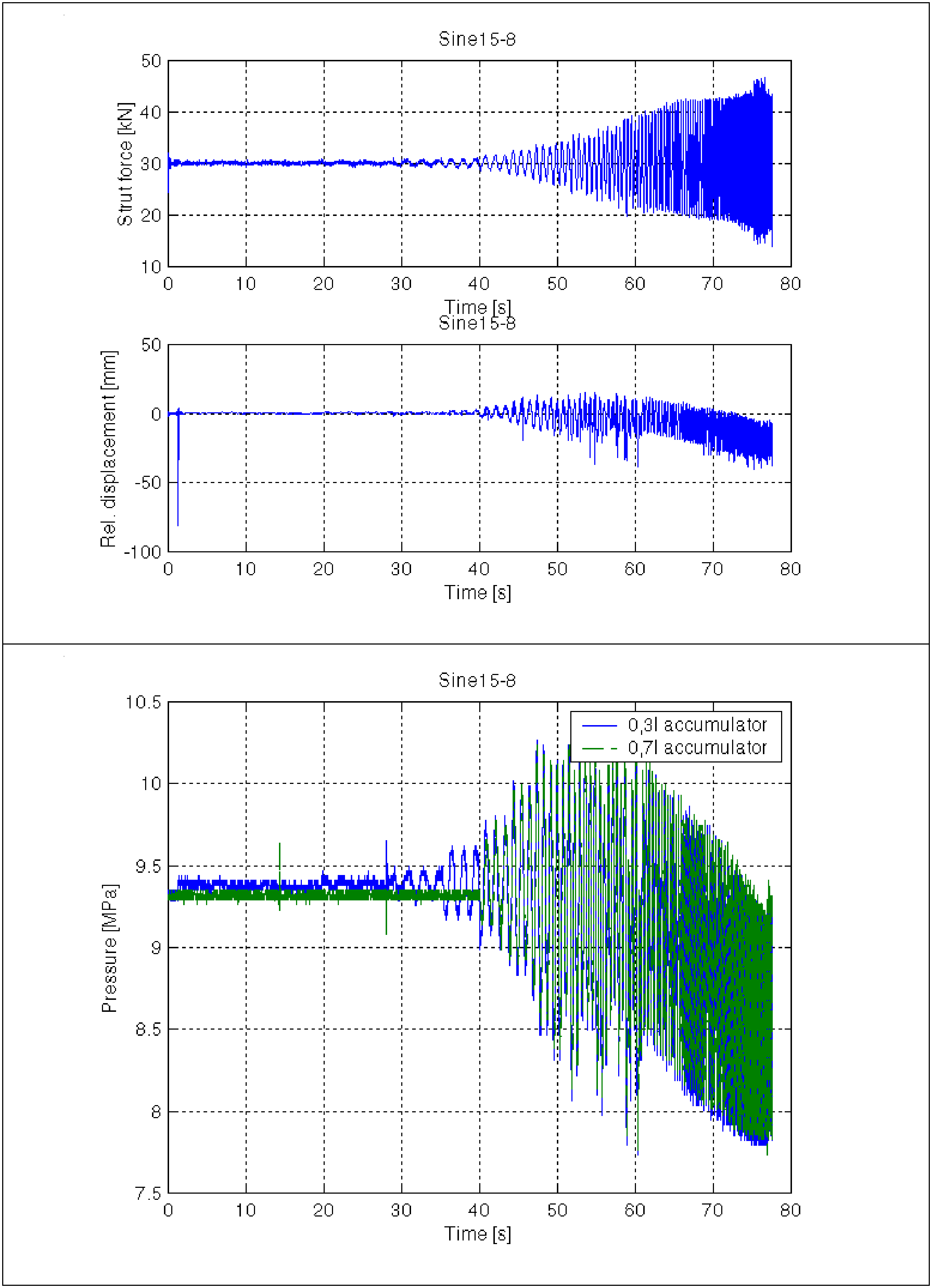


Figure D-30: Sine sweep (Spring - OFF, Damper - Hölscher & Huang)

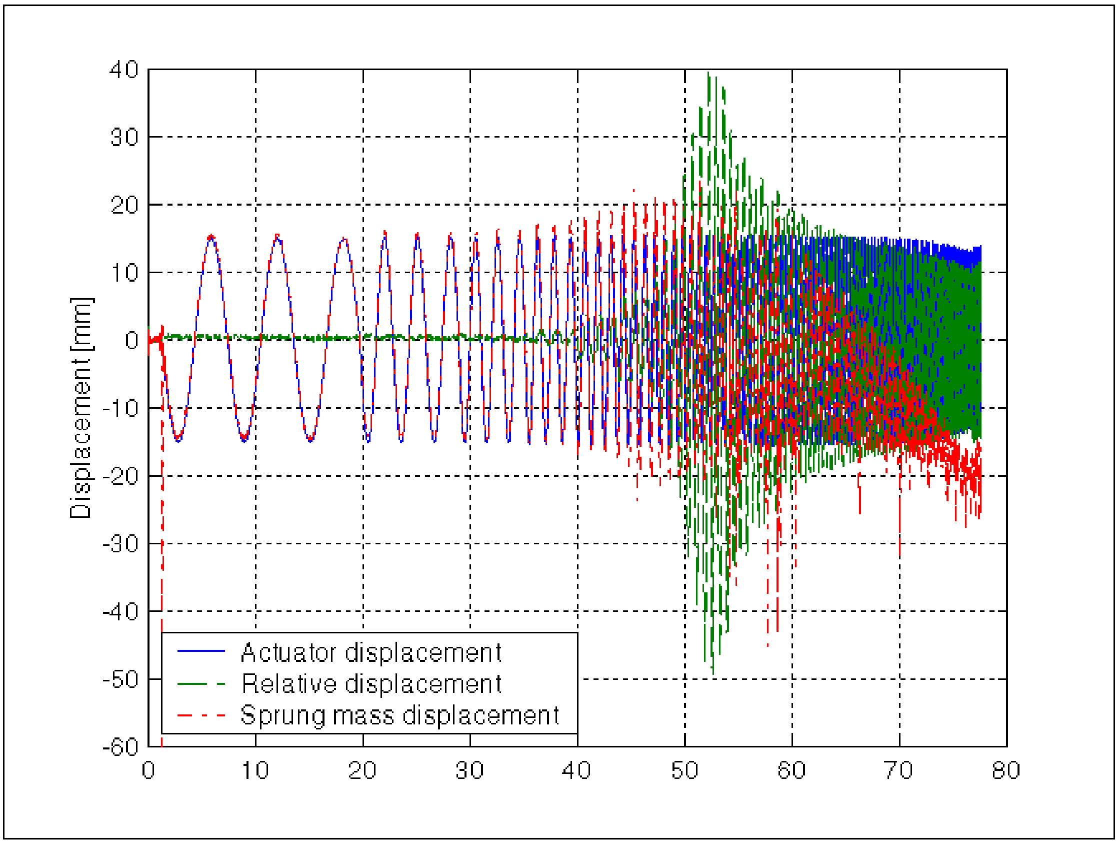


Figure D-31: Transmissibility plot (Spring - OFF, Damper - OFF)

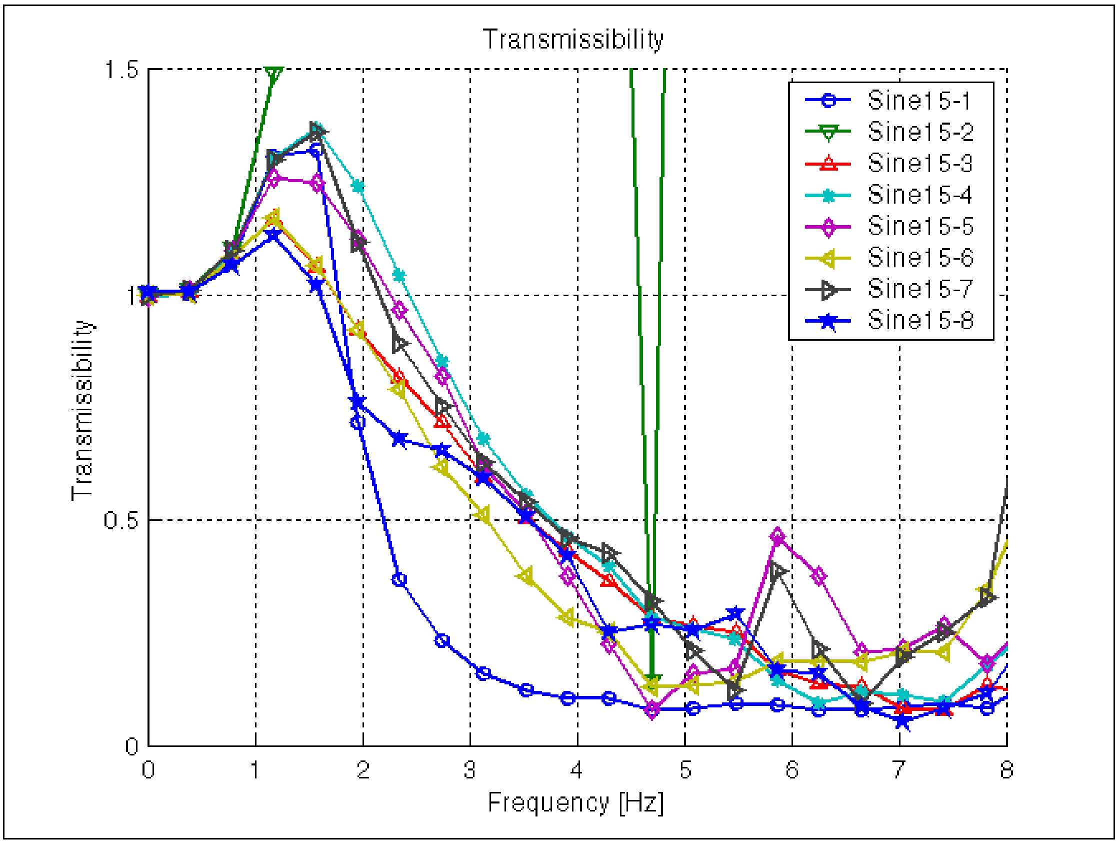


Figure D-32: Transmissibility plot