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Modeling and Digital Simulation of Hydraulic Systems in Design and Engineering Education using Modelica and HyLib.

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Modeling and Digital Simulation of Hydraulic Systems in Design and Engineering Education using Modelica and HyLib

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ABSTRACT

While a decade ago electronic calculators and trial and error were the most often used tools to design a hydraulic drive this has changed considerably in the last years. Using modern simulation tools like Modelica and HyLib it is possible to build a mathematical model of a system and simulate the behaviour during a couple of hours. And it doesn't necessarily require an expert in numerical analysis. At the Department of Mechanical Engineering - Automation of the Universität - GH Paderborn this is part of a set of laboratory experiments for third year students.

The objective of the project is to understand the behaviour of a (rather old) universal testing machine that has a conventional hydraulic control system for a constant pull velocity. To test material with a varying load the machine has to be modified using an electro-hydraulic valve. In both cases digital simulation provides valuable insight.

Introduction

Whenever a mechanical engineer starts designing he needs models for the behaviour of the used materials. A simple model is the assumption of an uniform stress distribution in a rod, leading to $\sigma = F / A$. When the acting forces are know or calculated a maximum permissible value for the stress σ has to be found to compare the actual stress with the permissible stress. To find this parameter a tensile test can be carried out where the force F is slowly increased until the specimen breaks. The resulting stress-strain diagram describes how the material reacts under load and can be used to determine the maximum permissible stress. For this kind of testing so called universal testing machines have been used for a long time.

When the load is not static but periodic another parameter for the reaction of the material is needed. And the method of testing has to be modified too. Instead of a static, slowly increasing force a alternating or pulsating force is needed. Typical universal testing machines are not designed for this kind of test and the purpose of this project is to determine what kind of modifications are needed to adapt them to those tests and what kind of performance can be achieved with these machines.

Hydraulic Drive

The hydraulic circuit diagram of the universal testing machine in the laboratory is given by Fig. 1.

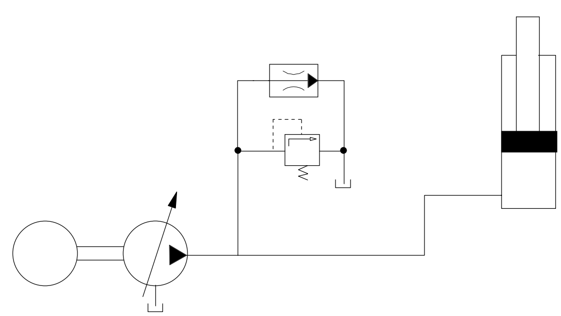

Fig. 1 Hydraulic circuit of universal testing machine

The machine is powered by a small AC Motor with 0.8 KW that via a V belt drives the variable displacement pump, which has a displacement volume of 2 cm³. By setting the displacement volume of the pump via a lever the amount of oil that flows into the cylinder can be controlled by hand. For a fine adjustment the series flow control valve can be used. It is also used to lower the piston after an experiment has been performed. For safety reasons and some kind of experiments where a constant force (i. e. pressure) is needed the relief valve is added.

It is worth to note that to reduce friction at the piston a small constant oil flow is present at the sealing.

Digital model of the universal testing machine

A good way to model this kind of system is to follow the oil flow. This means that first a model for the pump is selected, then the necessary valve models and at last the cylinder with the mechanical load. All these components are standard components for hydraulic circuits and can be obtained from many manufacturers. Models of all of them are contained in the hydraulics library for Modelica, HyLib. These mathematical models include both standard textbook models [e. g. Merrit 1967, Viersma 1980, Dransfield 1981] and the most advanced published models that take the behaviour of the real components into account [e. g. Will 1968, Schulz 1979]. An example is the pump model where the output flow is reduced if pressure at the inlet port falls below atmospheric pressure. Numerical properties were also considered when selecting a model [Beater 1999].

After opening the library the main window is displayed (Fig. 2). A double click on the pumps icon opens the selection for all components that are needed to originate or end an oil flow (Fig. 3). For the universal testing machine the AC

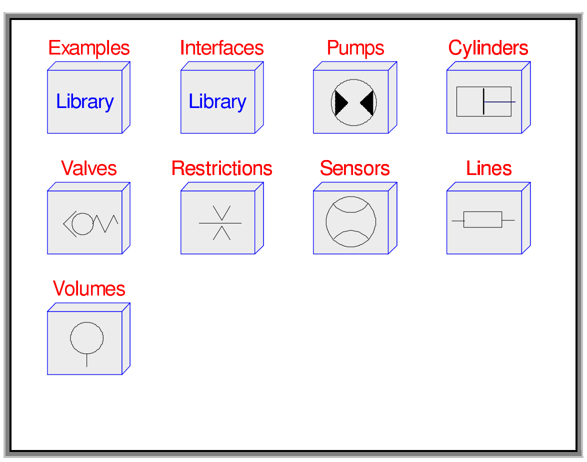

Fig. 2 Overview of Hydraulics library HyLib

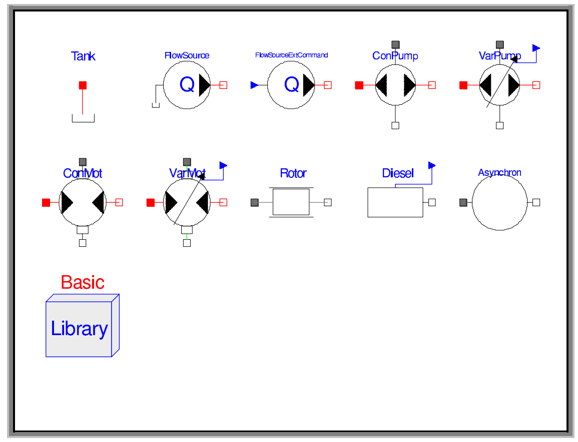

Fig. 3 Pump models in HyLib

motor and the variable displacement pump are selected. Both could be connected directly but the machine has a V belt transmission with a transmission ratio of 1.57. Therefore the model "ideal gear" from the standard Modelica mechanics library is used. To model the position of the lever that sets the displacement volume of the pump a constant block from the standard Modelica block library is used.

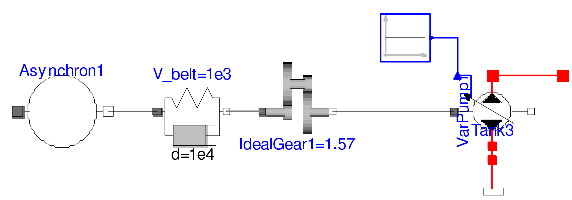

Fig. 4 Model of oil source

Many textbook models use only two equations to describe the behaviour of a real pump:

$$Q = n \cdot D$$

$$T = \frac{\Delta p \cdot D}{2\pi}$$

with Q volume flow rate
n shaft speed
D displacement volume per revolution
T torque at pump shaft
Δp pressure differential from port A to port B

But real pumps require a more detailed model. To model the mechanical, i. e. torque, losses a friction model is necessary. Simple models use speed proportional friction, other use nonlinear functions of the speed and the pressure at the ports. For pumps it is usually more important to model the volumetric losses, i. e. the leakage. In the literature there has been been a number of models proposed, starting from linear resistances to multi-dimensional look-up tables [Huhtala et al. 1995].

When simulating a system there is always a trade off between cost and performance. The costs result from the required effort to determine the parameters of the loss modell and the needed computing time to run it. What kind of performance is needed depends on the particular problem. In the library all the relevant effects are included.

The friction and the inertia of the rotating parts of the pump is modeled using the component Rotor that uses speed proportional friction. The cross port leakage is modeled as a linear function of the pressure differential at port A and port B with the component LaminarResistance. The external leakage is modeled by the components Tank that model a tank – if required with preload – and a laminar resistance. The oil volume that is contained in the pump and at the ports is modeled by VolumeA and VolumeB.

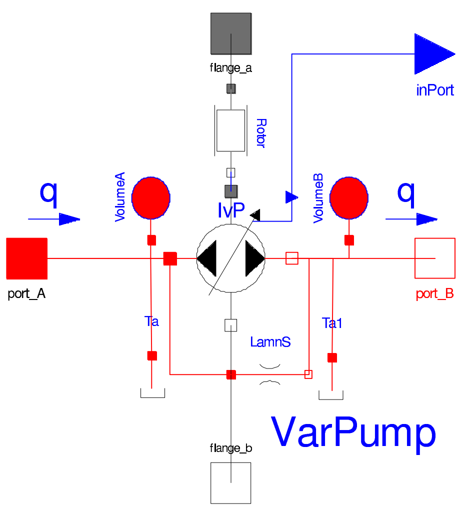

Fig. 5 Object diagram of libray model VarPump

The model of an ideal pump is contained in IvP and includes the two equations mentioned above.

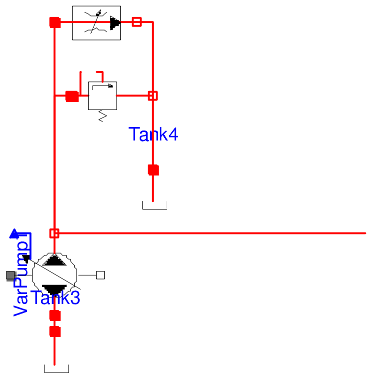

Fig. 6 Valve models of the universal testing machine

Beyond that there is an equation that reduces the flow rate at the output port if the pressure at the input port falls below atmospheric pressure. The series flow control valve and the relief valve are standard components that can be obtained from many manufacturers. They are both included in the HyLib library and the relief valve is used to show a typical valve model.

When first modeling a valve many engineers tend to build a large model that has all the details of the actual component. These models are very well suited if the focus of the study is on the behaviour of the valve itself. Otherwise a static input – output characteristic is usually sufficient [Chong and Dransfield 1979]. Important is that all relevant leakage flows are modeled and that there are no jumps in the curve.

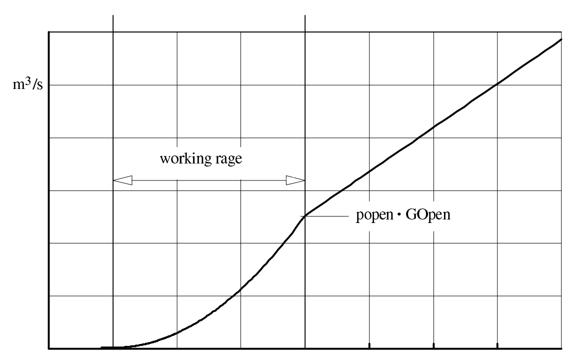

Fig. 7 Flow rate as a function of pressure for a relief valve

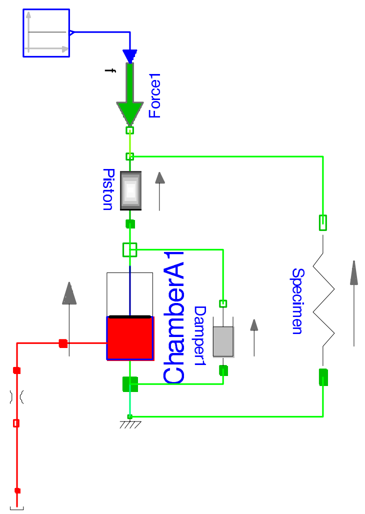

Fig. 8 Model of cylinder and load

The cylinder can be modeled with the library model ChamberA that describes the pressure build up. To account for the piston lubrication the laminar resistance is used. The Damper models velocity proportional friction. The complete mass of the moving parts is lumped into the model piston. The specimen is modeled by a linear spring from the standard Modelica mechanics library.

Typical model of the hydraulic library

The LaminarResistance is a typical example of a component that has two ports. To get a structured library it makes sense to start modeling this kind of component with a class that models a component with two ports and no energy storage, (s. Fig. 9). The modelica code looks like (graphical information omitted)

```
model TwoPortComp "Superclass of circuits with
       TWO hydraulic ports"
   Modelica.SIunits.Pressure dp "Pressure drop";
   Modelica.SIunits.VolumeFlowRate q "Flow rate
       through component";
   Modelica.SIunits.Pressure pA_limited;
   Modelica.SIunits.Pressure pB_limited;
   HyLib.Interfaces.Port_A port_A  "Port A, were oil
       flows into the component ";
   HyLib.Interfaces.Port_B port_B "Port B, were oil
       leaves the component";
  equation
   pA_limited = max(port_A.p,
            HyLib.Interfaces.FluidProp.pvapour);
   pB_limited = max(port_B.p,
            HyLib.Interfaces.FluidProp.pvapour);
   dp = pA_limited - pB_limited;
   q = port_A.q;
   port_A.q + port_B.q = 0;
end TwoPortComp;
```

The max operator limits the lower value of the pressure because the pressure of a technical fluid cannot fall below vapour pressure; a technical fluid can transmit only positive forces. This is a very crude model of the very complex effects of cavitation but is has proven helpful especially when starting a simulation.

Fig. 9 Object diagram of TwoPortComp

Using this class it is simple to model a laminar resistance. Only the equation that describes the relation between pressure drop Δp (already defined as dp and computed) and flow rate q has to be added. The key word for this inheritance is extends.

```
model LamResNoStates "Resistance with laminar
      flow."
   extends HyLib.Interfaces.TwoPortComp;
   parameter HyLib.Interfaces.HyLibUnits.
     Conductance G=4.2e-13
     "conductance of laminar resistance";
   equation
     q = G*dp;
end LamResNoStates;
```

The class TwoPortComp can also be used for the relief valve.

```
model ReliefValveNoStates "Ideal model of a relief
          valve."
    extends HyLib.Interfaces.TwoPortComp;
    parameter Modelica.SIunits.Pressure
       pclosed(final min=0) = 190e5
       "valve closed if dp smaller";
    parameter Modelica.SIunits.Pressure
       popen=205e5
       "valve wide open if dp higher";
    parameter HyLib.Interfaces.HyLibUnits.
       Conductance GLeak=1.111e-12
       "conductance of closed valve, i. e. leakage";
    parameter HyLib.Interfaces.HyLibUnits.
        Conductance GOpen=1.666e-9
        "conductance of wide open valve";
    Boolean closed(start=false)
      "closed: .true. => valve closed, only leakage";
    Boolean open(start=false)
      "open : .true. => valve wide open";
   equation
    closed = dp < pclosed;
    open = dp > popen;
    q = if closed then dp*GLeak else if open then
          (dp - pclosed)*GOpen + dp*GLeak
          else (dp - pclosed)^2*GOpen/(popen –
```

```
            pclosed) + dp*GLeak;

      assert(popen > pclosed, "Parameter popen
              MUST be greater than parameter
              pclosed.");

end ReliefValveNoStates;
```

The relief valve model uses an `assert` statement to make sure that the selected parameters make sense. The pressure that opens the valve completely must be greater than the pressure where the valve is completely closed. The discrete states `closed` and `open` help the user to determine the state of the valve during a simulation run. These kind of models can already be used to build a system and are contained in the Basic library windows. When connecting them to a system the user has to add manually lumped volumes to model the pressure dynamics, however.

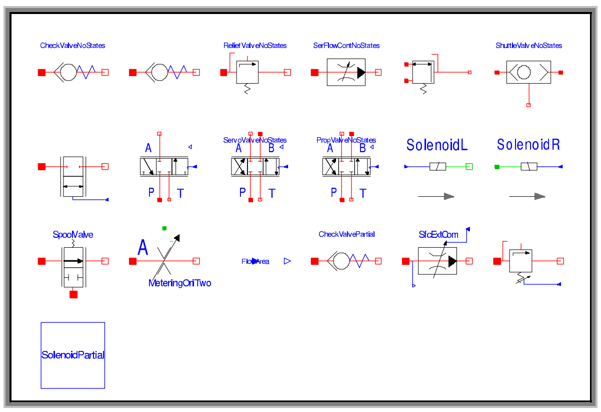

Fig. 10 Basic Library Window "Valves"

The ports of a real component are oil filled and therefore two lumped volumes are added at the ports for the main library model `LamRes` or `ReliefValve`.

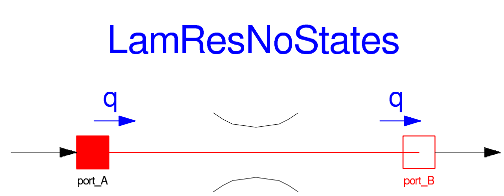

Fig. 11 LamResNoStates
Basic model no state

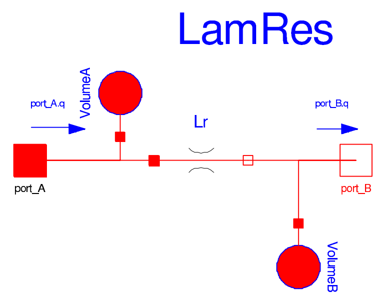

Fig. 12 Laminar Resistance. Main Model, two volumes (states) at the ports

This approach makes it very easy to build a model because the user only has to select components, parametrize and connect them. The user doesn't have to include lumped volumes as with other hydraulic simulation packages. The reason that it can be done this way is that Dymola can cope with the resulting higher index system. During the system anlysis Dymola finds volumes that are connected in parallel and lumps them together.

First simulation run of universal testing machine

A first simulation shows the expected results. The pressure builds up slowly and reaches the maximum given by the relief valve.

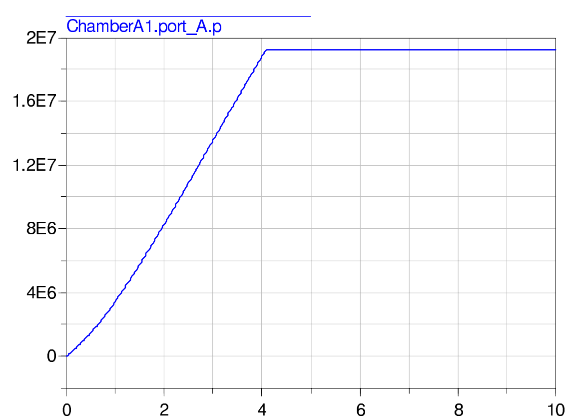

Fig. 13 Pressure in the chamber

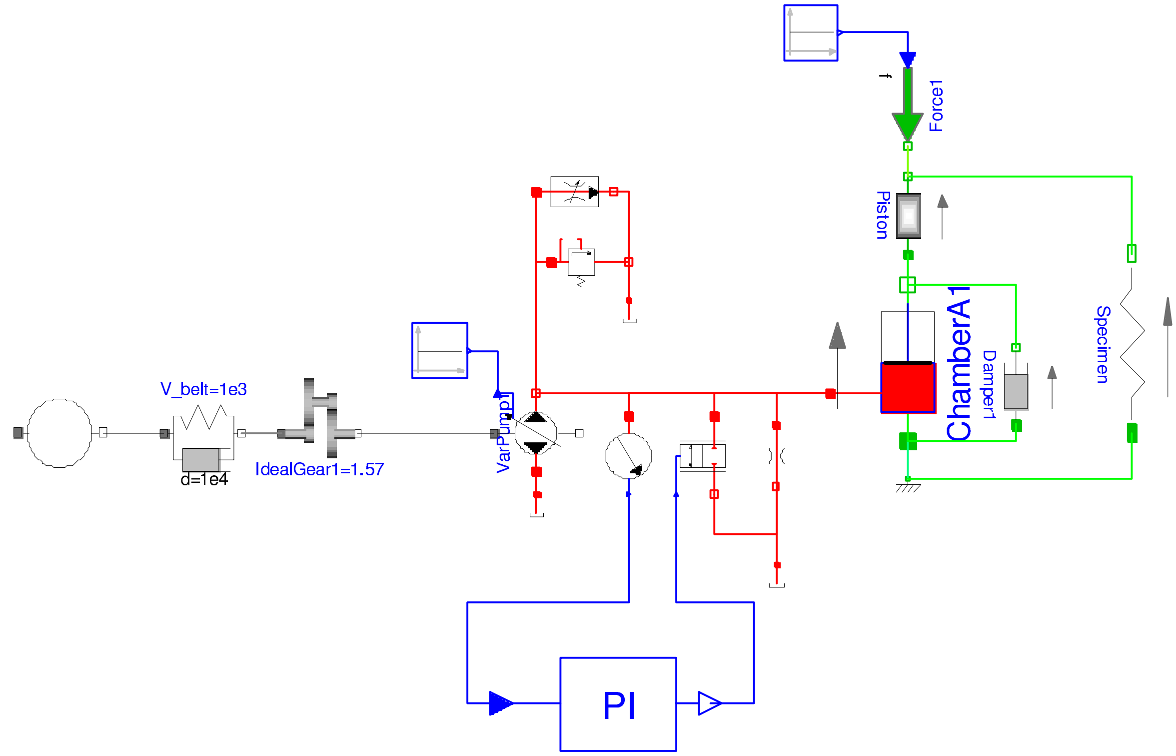

Fig. 14 Universal testing machine with elektro-hydraulic control

Electro-hydraulic control for dynamic testing

The goal of this study was to find ways for dynamic testing with the given universal testing machine. The simplest way would be to manually operate the lever and flow control valve. But for the required number of cycles and accurary this is not possible. When designing a complete new machine one could use a variable displacement pump with electronic command input. These pumps have been available for some years and have been very successfully used in injection moulding machines. Another approach could be the use of a double acting cylinder and a fast 4-port valve.

The approach that is used in this project is to use an elektro-hydraulic valve as a by-pass to the cylinder. Similar circuits have been shown to be very energy efficient [Backé 2000]. The control loop consists of a sine wave generator as reference signal and a PI-controller built from standard Modelica blocks.

This simulation model was used intensively to test the control scheme and find suitable parameters for the valve. It also helped to determine the maximum possible testing frequency before any hardware had to be purchased or installed.

Translation and running of the model is simply done by pressing the appropriate buttons. Then Dymola starts, giving the following message:

```
 - translateModel("utm2")
Translation started
DAE with 303 unknown scalars and 303 scalar equations.
5 constants found.
26 parameter bound variables found.
136 alias variables found.
136 remaining time dependent variables.
Finished
- simulate
Finished
```

More information is available by selecting the appropriate option in a Dymola window.

```
Logged connection equations:
  Asynchron1.flange_a.tau = 0 (unconnected)
  VarPump1.flange_b.tau = 0 (unconnected)
  2 default connections generated.
DAE with 303 unknown scalars and 303 scalar equations.
```

```
5 constants found.
26 parameter bound variables found.
136 alias variables found.
136 remaining time dependent variables.

Constraint equation found. Reduced state space.
  equation
  TwoWayValve1.VolumeB.port_A.p =
LamRes1.VolumeB.port_A.p;
Non-state variable chosen:
TwoWayValve1.VolumeB.port_A.p
Differentiated the equation
  TwoWayValve1.VolumeB.port_A.p =
LamRes1.VolumeB.port_A.p;
giving
  der(TwoWayValve1.VolumeB.port_A.p) =
der(LamRes1.VolumeB.port_A.p);

/* There are 13 continuous time states:
  TwoWayValve1.TWVnS.FIA.velocity
  TwoWayValve1.TWVnS.FIA.position
  VarPump1.VolumeA.port_A.p
  Asynchron1.Rotor.w
  V_belt.phi_rel
  VarPump1.Rotor.w
  VarPump1.IvP.flange_a.phi
  VarPump1.VolumeB.port_A.p
  ReliefValve2.VolumeB.port_A.p
  Piston.v
  Damper1.s_rel
  LamRes1.VolumeB.port_A.p
  PI_Regler.LimIntegrator1.y[1]
End of list of continuous time states. */
```

The required cpu time for translation is 14 s and 7.9 s for 4 s simulated time, using a Pentium III, 530 MHz. This fast execution allows many simulation runs for optimisation of the components before any hardware has to be purchased or installed.

Figure 15 gives a typical simulation result. After start up the force in the specimen is pulsating from 10^4 N to 9.5 10^4 N according to the required sine wave reference input. The frequency of exicitation is 0.65 Hz which is about the maximum frequency that can be realized with this hydraulic circuit.

Figure 16 shows that the selected valve has the appropriate size. During a cycle the valve is both completely closed and completely open.

Figure 17 shows that a higher excitation frequency should not be used. During the last part of the pressure build up phase (1.5 to 1.75 s) the pump cannot build up the pressure faster while at the pressure minimum (1.2 s) the valve cannot release more oil to the tank to decrease the pressure faster.

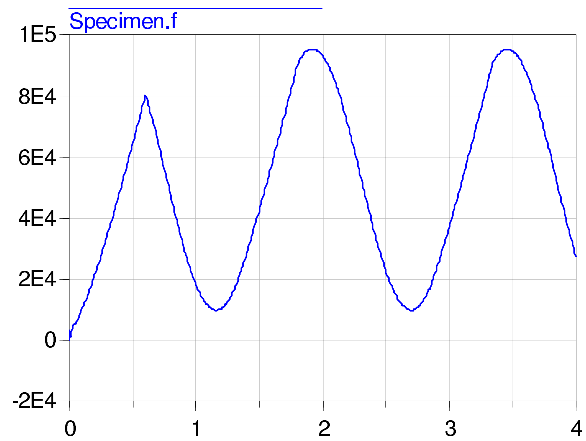

Fig. 15 Dynamic load: Force acting on the specimen.

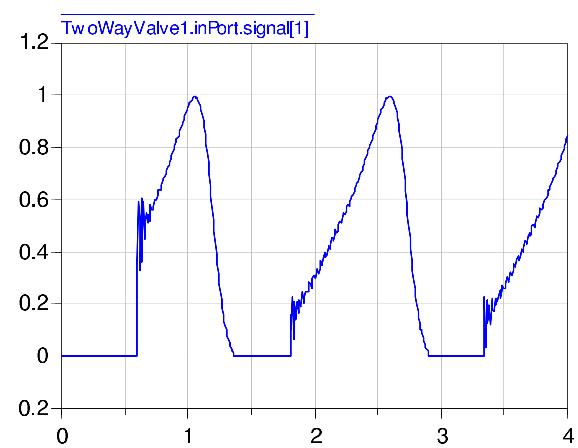

Fig. 16 Dynamic load: RelativeValve opening.

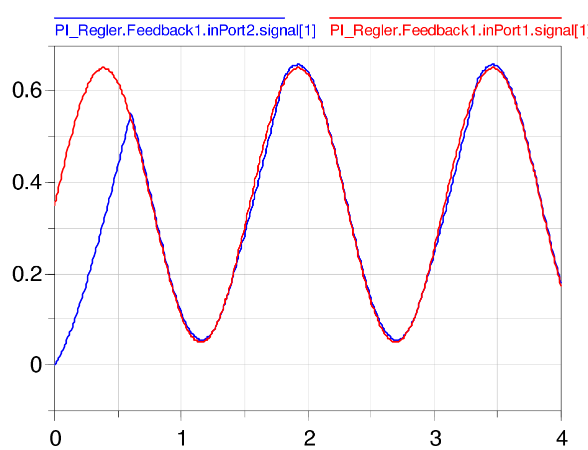

Fig. 17 Dynamic load: Actual and commanded pressure.

ACKNOWLEDGMENTS

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