Coupling of ADAMS with Pneumatic Systems Simulation Software

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Abstract

A method will be described to couple a software modul for pneumatic systems with ADAMS. The purpose is to simulate the dynamics of pneumatically actuated mechanisms. Some examples will be presented and a comparison of computed and measured results will be given.

Examples will be:

- a pneumatically actuated tool changer
- a handling system consisting of two servo pneumatically controlled cylinders.

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1. Introduction

In modern automation systems we will allways find mechanisms consisting of actuators, links, gears, etc. In most cases the method of multibody system simulation can be used to describe the dynamic behaviour of these mechanisms. Since 1992 FESTO uses **ADAMS** to simulate such systems.

In **ADAMS** as well as in other multibody system simulation packages, pneumatic actuators are not available as standard force elements. Thus it was necessary for FESTO to develop a method to provide a pneumatic force element. In this paper the *Coupling of ADAMS with Pneumatic Systems Simulation Software* is described.

2. The FESTO KG (limited partnership company)

- see slides

3. Application of ADAMS

- Support of FESTO sales department to design actuator systems and automation systems for our customers

  - ☐ How can we solve an automation task using FESTO pneumatic components?
    - selecting appropriate components (actuators, valves, flow controls, ...)
    - motion analysis (time of motion, minimum cycle time, air consumption, ...)
    - adjustment of the pneumatic damping unit
    - visualization

  - ☐ Improvement of existing solutions
    - improvement of the cycle time
    - use of smaller and cheaper actuators or valves if possible
    - improve pneumatic damping

  - ☐ Damage analysis
    - calculation of load used as input for structural mechanic calculations (FEM, analytical methods, ...)

  - ☐ Typical applications
    - tool changing mechanism
    - knuckle-joint press
    - packaging machine mechanisms

- Support of FESTO product development

  - ☐ Support of FESTO construction departments
    - feasibility studies (preliminary concept development)
    - load calculations on actuators, guide bearings, etc.
    - calculation of impact loads
    - calculations on assembly and handling units (multiaxis systems)

  - ☐ Damage analysis in cooporation with the FESTO testing department
    - calculation of load

- 1 licence **ADAMS/AVIEW**, **ADAMS/SOLVER**, on hardware platform Hewlett Packard 9000/715 - 50

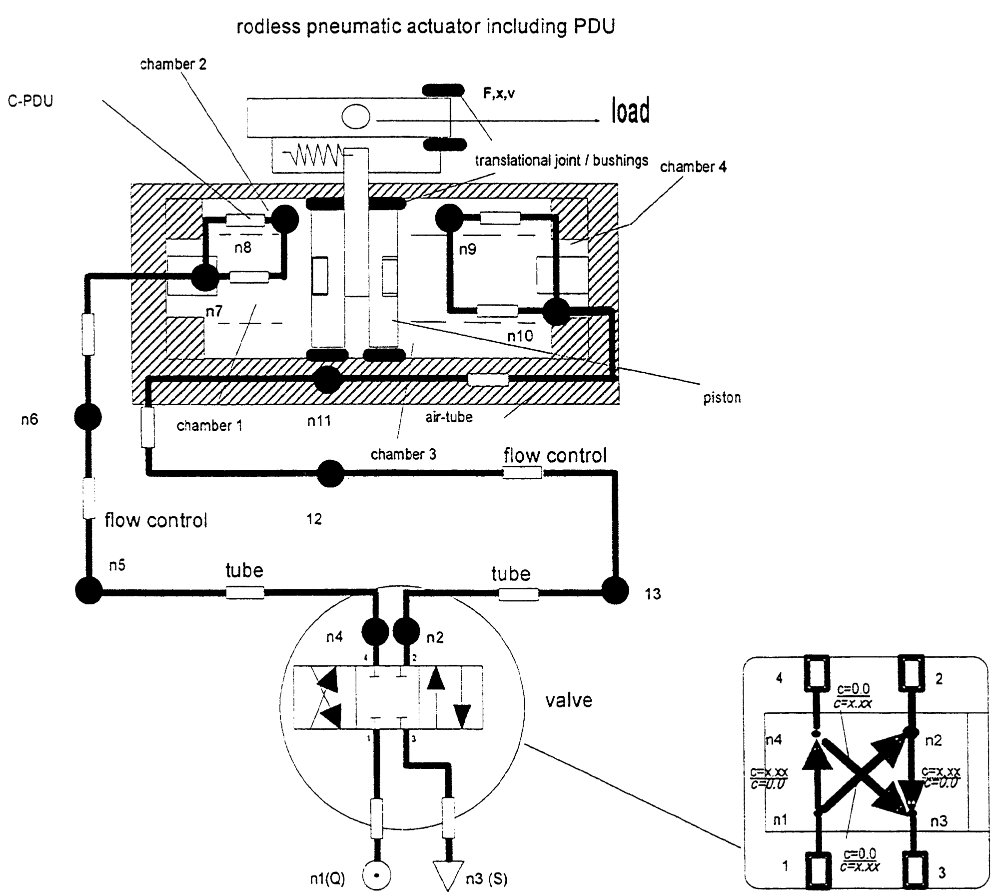
4. Pneumatic system simulation - multibody system simulation

4.1 Simulation of pneumatic systems and networks

Characteristics of pneumatic model:

- variation of fluid proporties with pressure and temperature (fluid compressibility)
- friction of actuators, described using measured data
- two dimensional flow (valves, flow dividers), described using measured data
- one dimensional actuator force (translational or rotational forces)
- direct controlled and servo controlled system

Example of a pneumatic network



- System equations of a pneumatic network

  Using the laws of mass conservation, energy conservation and the equation for an ideal gas we get the equations to describe the pneumatic characteristics of the different model elements as shown below.

model element	equations
volume	$\dot{p}_i = \frac{n_i}{V_i}\left[R\sum_j q_{ij}T_{ij}^* - p_i\frac{dV_i}{dt} + \frac{n_i-1}{n_i}\frac{dQ_i}{dt}\right]$ $\dot{T}_i = \frac{n_i T_i}{p_i V_i}\left[R\sum_j q_{ij}(T_{ij}^* - \frac{T_i}{n_i}) - \frac{n_i-1}{n_i}p_i\frac{dV_i}{dt} + \frac{n_i-1}{n_i}\frac{dQ_i}{dt}\right]$
flow divider	$0 = \left[R \cdot \sum_j q_{kj} \cdot T_{kj}^* + \frac{n_k-1}{n_k} \cdot \frac{dQ_k}{dt}\right]$ $0 = \left[R \cdot \sum_j q_{kj} \cdot (T_{kj}^* - \frac{T_k}{n_k}) + \frac{n_k-1}{n_k}\frac{dQ_i}{dt}\right]$
pressure supply	$0 = p_l - p_{l(t)}$ $0 = T_l - T_{l(t)}$
moving mass	$\frac{dx_m}{dt} = \dot{x}_m = v_m$ $\frac{dv_m}{dt} = \frac{1}{M_m}\left[F_m^P + F_m^R + F_m^A + F_m^E + F_m^{St}\right]$

Abbreviations used:

i,j,k,l,m	identifiers
p	pressure element i
t	temperature element i
$\dot{}$	differentiation with respect to time
n_i	polytropic coefficient
R	specific gas constant of air
ρ	mass densitiy
V_i	volume of element i (depending on x_m)
Q_i	thermal flow
c_{ij}	C-value between i und j (conductance, depending on time, ...)
b_{ij}	b-value between i und j (flow quality)
T_{ij}^*	$= T_{ji}^* = T_i$ if $p_{ij}^* = p_i$; T_j if $p_{ij}^* = p_j$
x_m	piston displacement/angle
v_m	piston speed/angular velocity
M_m	mass/moments of inertia
F^P_m	pressure force
F^R_m	friction force (piston or external)
F^A_m	sum of external forces
F^E_m	forces pneumatical damping unit
F^{St}_m	impact forces
q_{ij}	mass flow between i und j
p_{ij}^*	$= p_{ji}^* = \max(p_i, p_j)$
p_{ij}^{**}	$= p_{ji}^{**} = \min(p_i, p_j)$

$$q_{ij} = \pm C_{ij} \cdot \rho_{ref} \cdot \sqrt{\frac{T_{ref}}{T_{ij}^*}} \cdot p_{ij}^* \cdot \Phi\left(\frac{p_{ij}^{**}}{p_{ij}^*}, b_{ij}\right)$$

$$\Phi\left(\frac{p_{ij}^{**}}{p_{ij}^{*}}, b_{ij}\right) = 1 \qquad \text{if } 0 < \frac{p_{ij}^{**}}{p_{ij}^{*}} < b_{ij}, \text{ critical flow}$$

$$\Phi\left(\frac{p_{ij}^{**}}{p_{ij}^{*}}, b_{ij}\right) = \sqrt{1 - \frac{\left(\frac{p_{ij}^{**}}{p_{ij}^{*}} - b_{ij}\right)^2}{(1-b_{ij})^2}} \qquad \text{if } b_{ij} < \frac{p_{ij}^{**}}{p_{ij}^{*}} < 1, \text{ non choked flow}$$

The dynamic behaviour of a pneumatic system including an actuator is described by a coupled system of differential and algebraic equations. In addition there may be a control system which changes specific parameters influencing the flow (i.e switching valve or servo valve)

4.2 System equations to describe a multibody system (as used in ADAMS)

ADAMS uses the variables and equations described below ("Analysis Methods and Model Representation in **ADAMS"**, T. Wielenga, MDI Inc.)

variables		equations
$\underline{V} = [v_x, v_y, v_z]^t$	velocities	$M\dot{\underline{V}} - \underline{Q}_R + \underline{C}_R = 0$
$\underline{R} = [x, y, z]^t$	displacements	$\underline{V} = \dot{\underline{R}}$
$\underline{P}_R = [P_\psi, P_\phi, P_\theta]^t$	momenta	$\dot{\underline{P}}_R - \partial E/\partial\underline{\gamma} - \underline{Q}_\gamma + \underline{C}_\gamma = 0$
$\underline{\omega}_e = [\omega_\psi, \omega_\phi, \omega_\theta]^t$	angular velocities	$\underline{P}_r = \underline{B}^t \underline{J}\, \underline{B}\, \underline{\omega}_e$
$\underline{\gamma} = [\psi, \phi, \theta]^t$	euler angles	$\underline{\omega}_e = \dot{\underline{\gamma}}$

4.3 Coupling relations

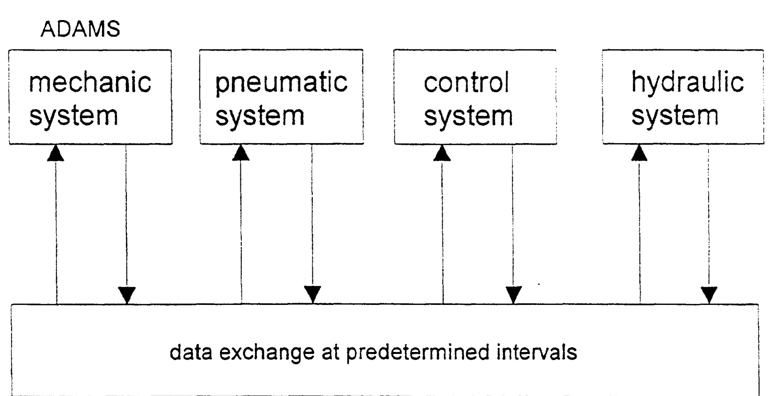
The relations that couple the multibody system equations with the pneumatic system equations are for a linear pneumatic actuator:

	coupling relation
pressure force pneumatic actuator	$F_m^P = \Delta p \cdot A_{Cyl.} = Q_{R,m,z}$
volume (cylinder chambers)	$V_{i,m} = A_{Cyl.} \cdot r_{m,z}$
change in volume (cylinder chambers)	$\frac{dV_{i,m}}{dt} = A_{Cyl.} \cdot v_{m,z}$
friction forces	$F_m^R = f(r_{m,z}, v_{m,z})$
piston positions	$x_m = r_{m,z}$
piston velocitys	$\dot{x}_m = v_{m,z}$
piston accelerations	$\ddot{x}_m = \dot{v}_{m,z}$

Summarizing section 4.1 and 4.2 the equations describing a multibody system and a pneumatic actuator are coupled only via the relative displacement, velocity and acceleration of the piston (rotational or translational). These variables determine the the evaluation of forces (pressure force, friction forces, ...) to be returned to **ADAMS** as well as the numerical integration of the differential equations for the pneumatic elements (i.e. volume flow, volume, change in volume). They also influence the control system.

5. Methods of simulator coupling

- Importing the functionality to describe the fluid power system into **ADAMS** using **GSExx** statements and **GSESUB** (as for example done by C. W. Richards, Imagine)
  - ☐ Automatically introducing a DAE-system into **ADAMS** which describes the fluid system and the control system. Integration of the united system equations is done using the **ADAMS**-Integrator.
  - ☐ Automatic definition of the dependencies and coordination of state variables
- VHDL (NOT yet available)
  - ☐ standardized and tool independent language to exchange simulation models
- "Simulator Backplane"
  - ☐ Running each simulation separately using different integrators for multibody system and for pneumatic system (including control system)
  - ☐ Exchanging information at predetermined intervals



6. Implemented method of simulator coupling

6.1 Reasons to use the "simulator backplane" method

- Existing FESTO simulation software tools are used to do almost 80 % of the calculations concerning pneumatically actuated mechanisms. These tools are

  - ☐ available at many FESTO-companies without licence fees
  - ☐ well known software tools within FESTO (acceptance and experience)
  - ☐ to be developed and maintained in the future

- Only few variables have to be exchanged. In contrast, the dependencies within the pneumatic system and the control system simulator are considerable.

- The interface is almost independent from the multibody system simulation program (also tested with **SIMPACK** and **SDFAST**)

- Each type of equation is handled by a specially adapted solver.

- "Uncoupling coupled equations -- numerically realistic"

- Easy to implement and to maintain

6.2 Aspects NOT to use the "simulator backplane" method

- Time interval to exchange data with sufficient accuracy depends on the problem

- Some data may be redundant i.e. initial conditions of the actuator must be specified and checked in either simulation programm

- "Uncoupling coupled equations -- physically unrealistic" (C.W. Richards, Imagine)

- Large executables (up to 10 Mb)

- Computation costs

Summarized with respect to the needs of FESTO we decided to use the simulator backplane method in order to couple **ADAMS** with Pneumatic Systems Simulation Software.

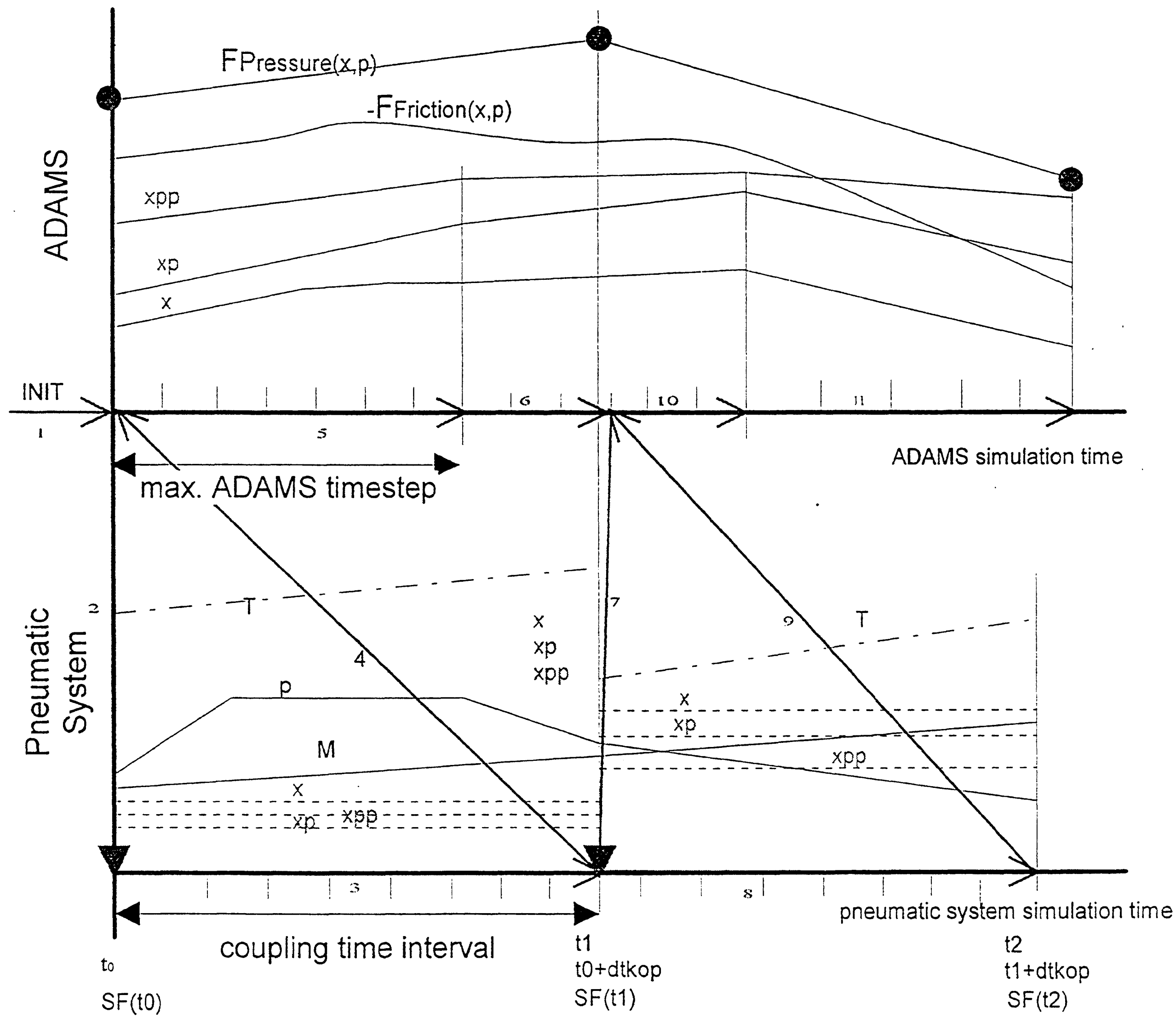
6.3 Main problems

- Use of consistent state variables ⇨ use **timget** function to get state variable values of the last successful integration step and remember these values until next successful time step is completed.
- Handling of predictor-corrector and/or integrator failure (looking from the pneumatic system simulation software it might happen that time seems to go backwards i.e before the last successful pneumatic time step).
- Pneumatic system simulation software has to ignore equations of motion but provide friction and impact forces if used in a simulation coupled with ADAMS.
- Stiffness of pneumatic system (small timesteps depending on volumes, conductance values, valve transmission behaviour, ...).
- Handling of discontinuities (switch valves, mechanical stops, ...).
- Handling the sampling time of controllers (used in servo pneumatics). The controller determines the time interval to exchange information between **ADAMS** and pneumatic system simulation software ⇨ simulation time increases in some cases.
- Handle aborting and restarting the program

6.4 Method of data exchange

- the **SFORCE**-Statement is used to exchange Marker-IDs, actuator types, force values
- **SYS** function requests of **ADAMS** are used to provide the piston displacement, velocity and acceleration of a pneumatic actuator depending on the actuator type (translational or rotational).
- **Pressure forces** (generated by the pressure difference between the cylinder chambers) are calculated at the beginning and at the end of the coupling interval. If the actuator force is requested within this interval a linear force interpolation is used, else a new pneumatic time interval is calculated or the value at the beginning of the interval is returned if the integrator fails.
- **Friction forces** of the pneumatic cylinders are evaluated at any SFORCE-request (static friction !)
- **Impact forces** and other forces externally acting on the pneumatic actuator are evaluated at any SFORCE-request if they are not handled within **ADAMS** using **IMPACT**- or **BISTOP**-statements

Simulator coupling
ADAMS - Pneumatic System Simulation Software



——— variable values of ADAMS system of differential equations

- - - - - consistent values of ADAMS-equations system used to integrate pneumatic system and evaluate pressure forces (last succesful timestep)

——▶ calls to Pneumatic System Integrator

——— pneumatic system variables

● pressure force values used for interpolation

——— curve of evaluated pressure force

——— friction and other forces evaluated at any time requested

SFORCE-value returned to ADAMS: Σ(FPressure, FFriction other Forces)

6.5 Steps to successful coupled simulations

a) Modelling the pneumatic system, resulting in a description of the

- □ system components
- □ topological dependencies of the system components
- □ coordination of pneumatic actuators and **ADAMS** force elements
- □ initial conditions of the pneumatic system
- □ control system including its initial conditions

b) Modelling the mechanical system using **ADAMS/AVIEW** resulting in a description of the

- □ multibody system including
  - parts representing the housing of the pneumatic cylinder
  - the moving parts of the cylinder (piston rod and piston)
  - the joints between the piston rod and the load of the cylinder
  - the joints between the housing and other parts
  - markers to calculate the state of the cylinder.
- □ user defined force elements (SFORCE statements)
- □ initial conditions of the pneumatic actuators

c) Initialize **Callable ADAMS Solver** and the pneumatic system simulator in a first call to the user written subroutine **SFOSUB**. Within this subroutine we have to provide **SFORCE**-values at any request of **ADAMS** corresponding to the given actuator identifiers as long as the simulation time does not exceed the last simulation time reached by the pneumatic system integrator. Therefore it is necessary to

- □ watch for consistent system state variables using the **timget** function.
- □ evaluate (interpolate) pneumatic force
- □ evaluate friction forces
- □ evaluate forces induced by external mechanical stops
- □ return the sum of the above force values to **ADAMS**

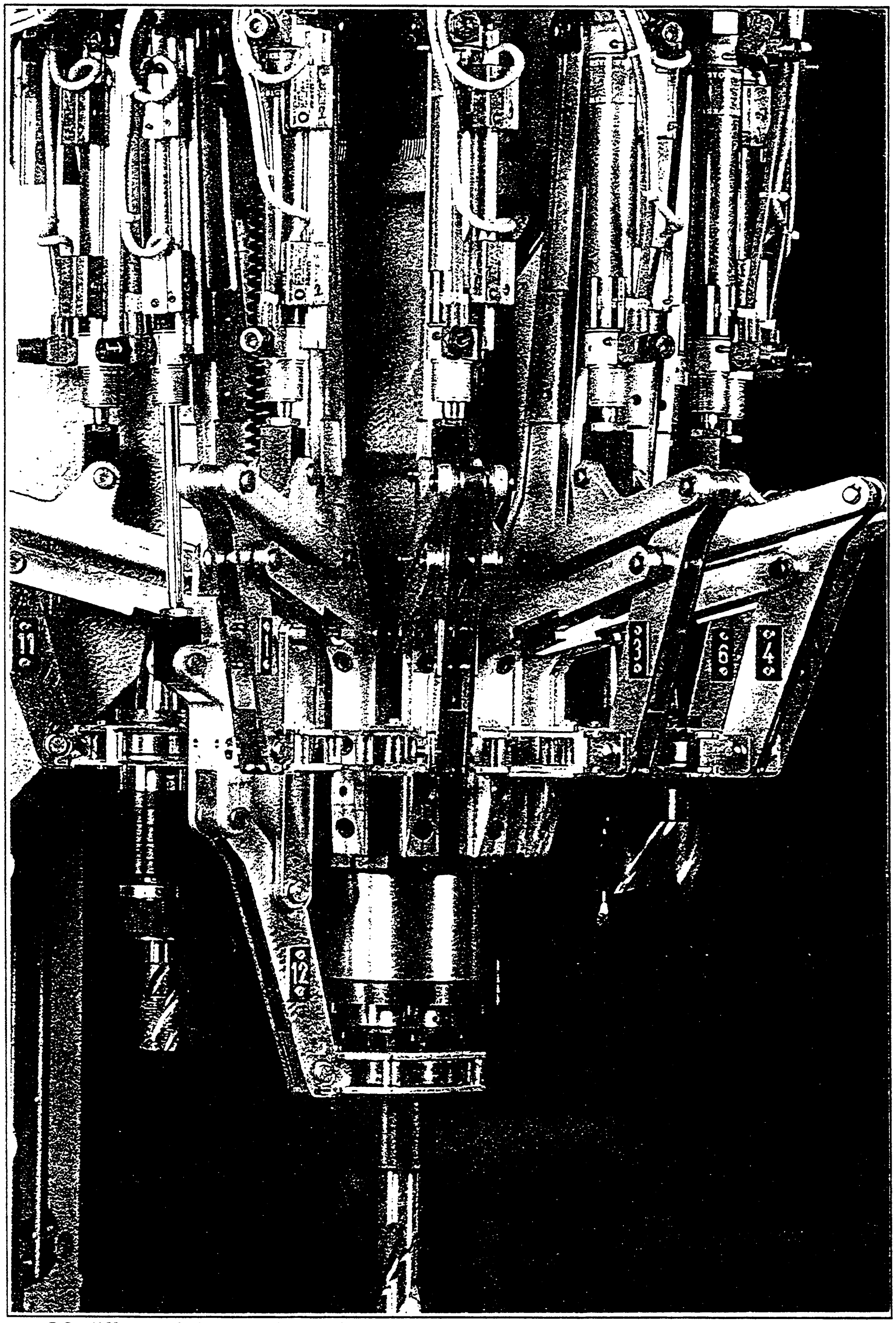
d) If the **ADAMS** simulation time exceeds the time reached by the "pneumatic system simulator" start a new pneumatic time interval using the last consistent values of the system state variables.

- □ update volume values
- □ integrate algebraic and differential equations of the pneumatic system
- □ evaluate new pressure forces, friction and impact forces

e) Do the last two steps c) and d) until the simulation is complete

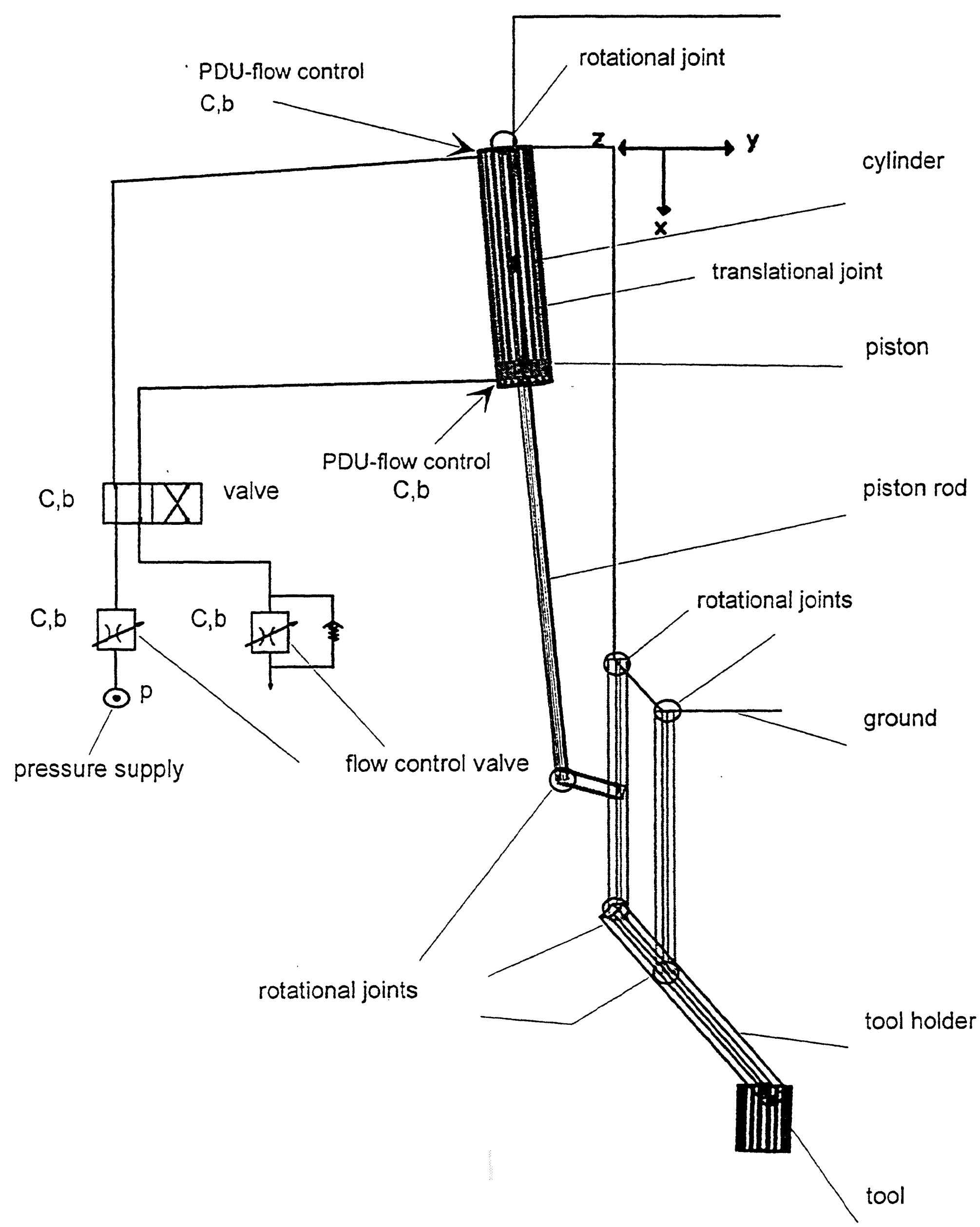
7. Examples

7.1 Pneumatically actuated tool changer



- 28 differential equations describing the pneumatic system
- 6 ADAMS parts, 1 DOF

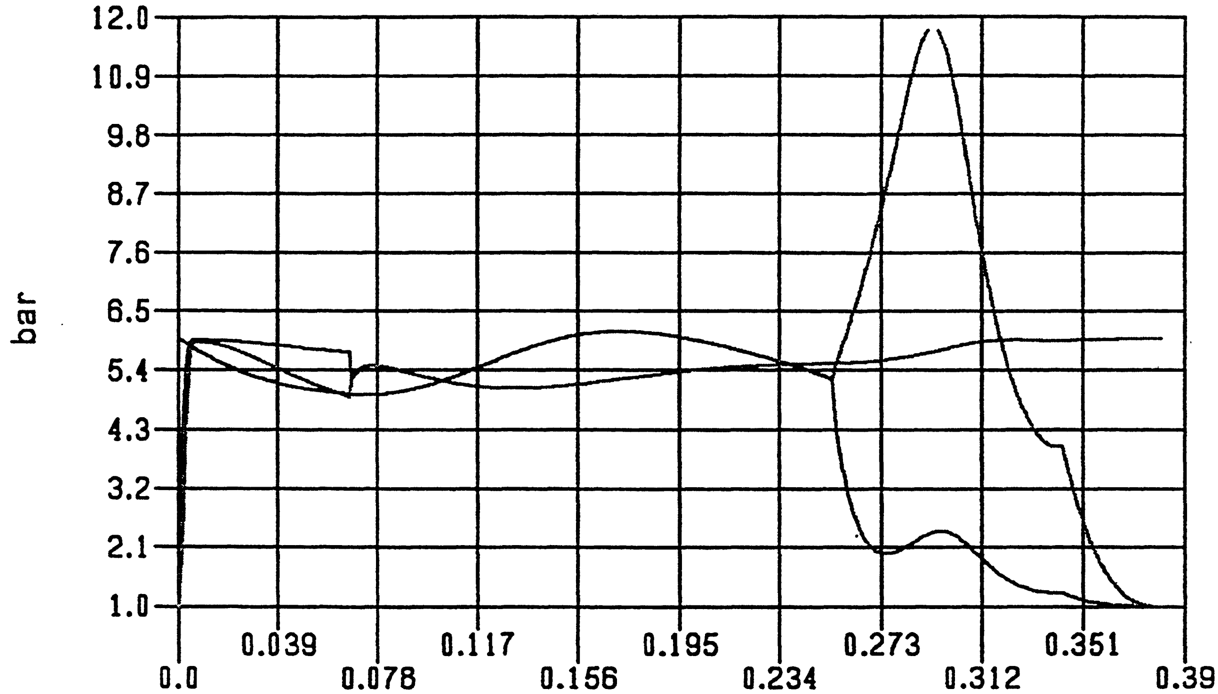
Simulation Model of the Tool Changer



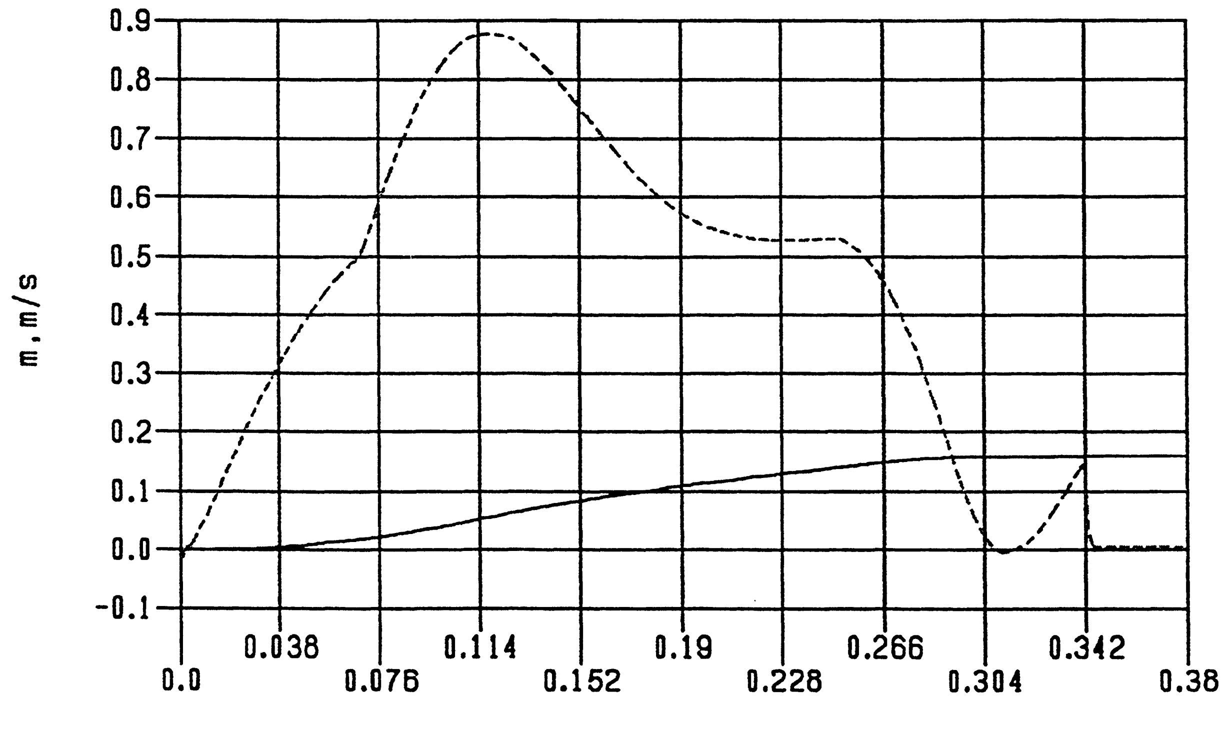
mechanism in end position

Results tool changer

Pneumatic system - pressure cylinder chambers

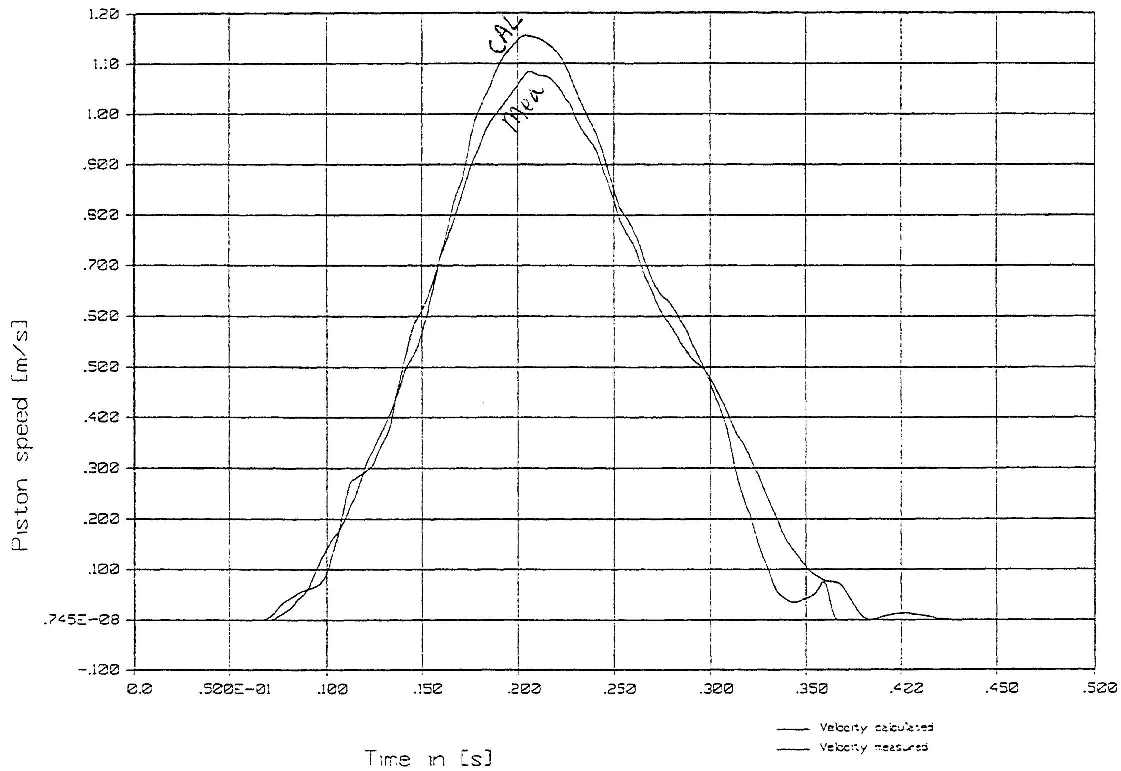


Mechanical system - piston position and velocity



Results tool changer

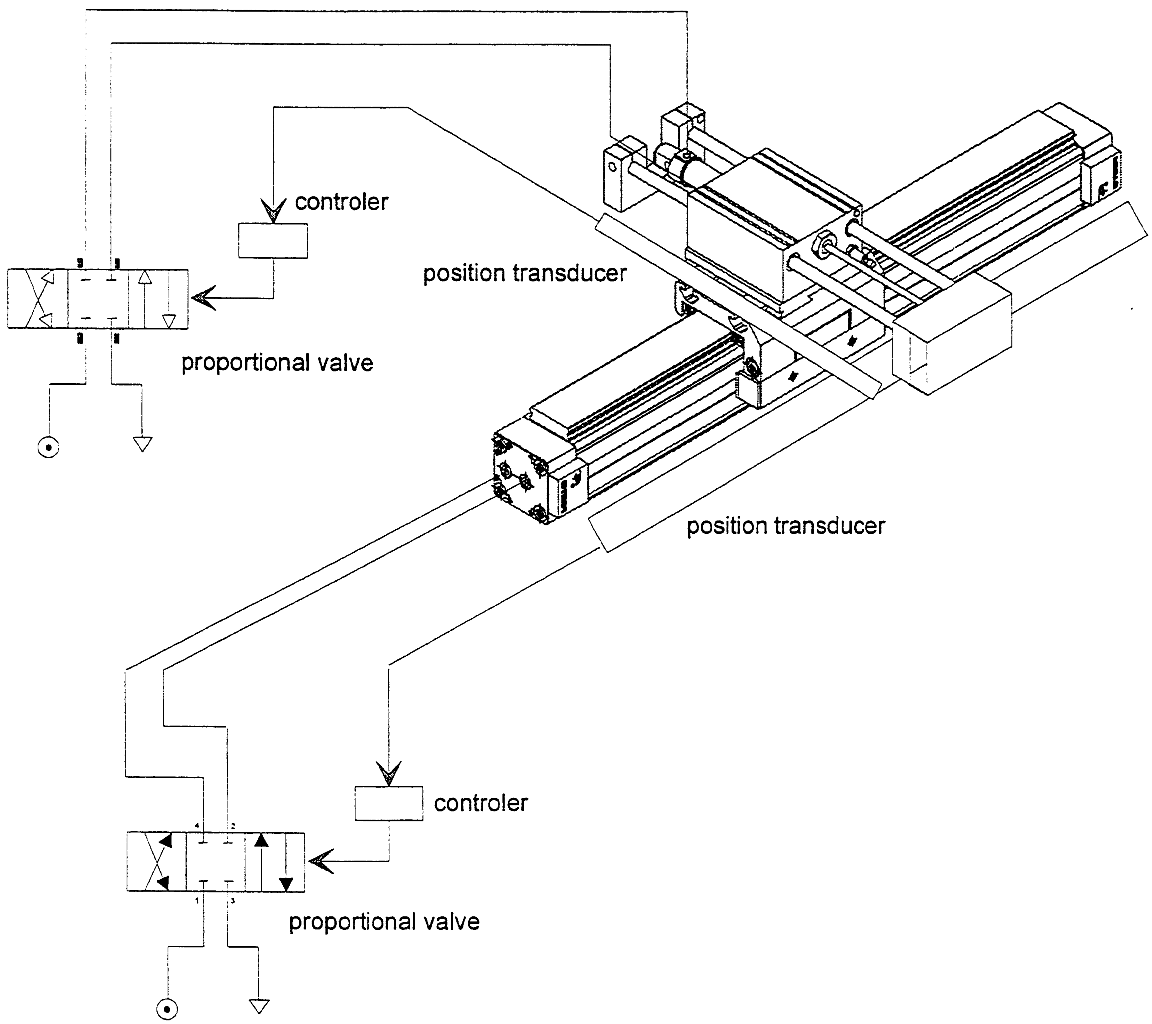
piston velocity (calculated results - measured results)



Benefits

- reduced amount of testing devices
- optimum pneumatic damping by insertion of fixed diameter flow controls for specific mass ranges
- minimum motion time

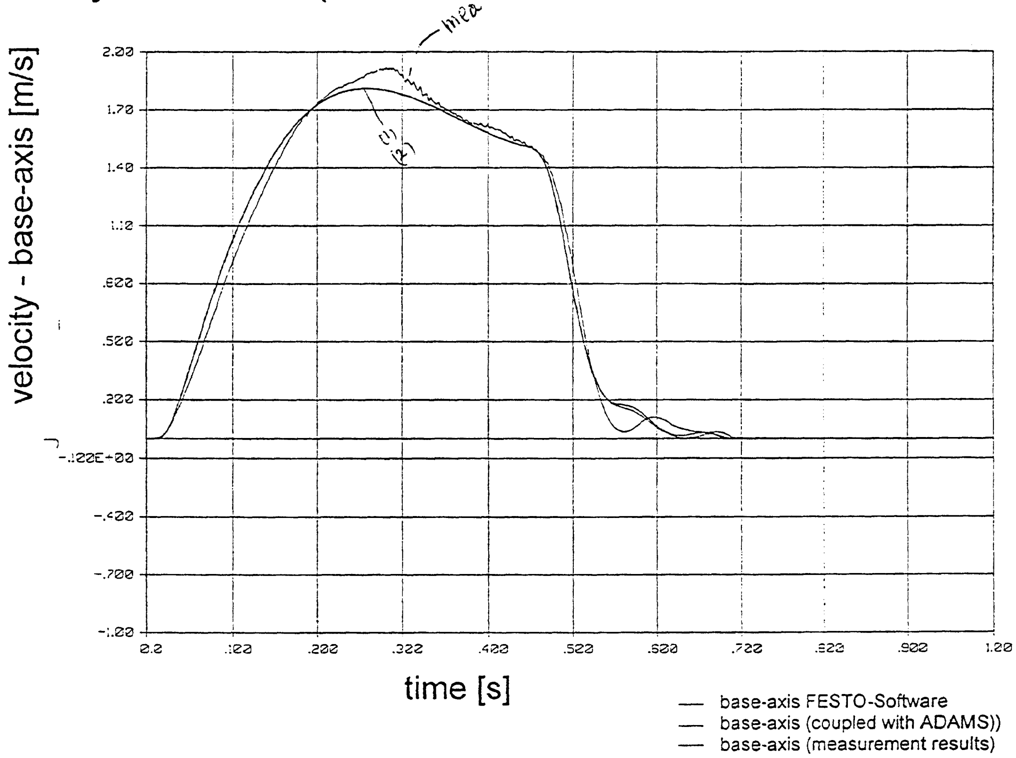
7.2 Servo controlled two axis system



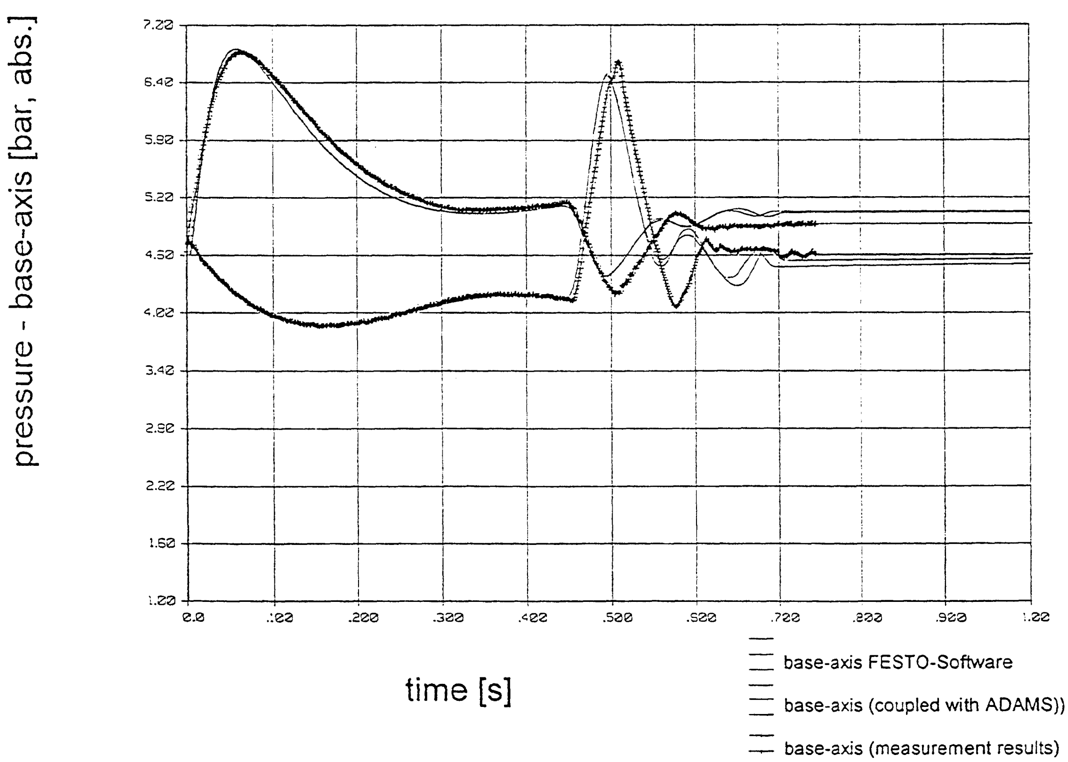
- 46 differential equations describing the pneumatic system
- 7 ADAMS parts, 4 DOF

Results two axis system

Velocity base-axis(calculated results - measured results)

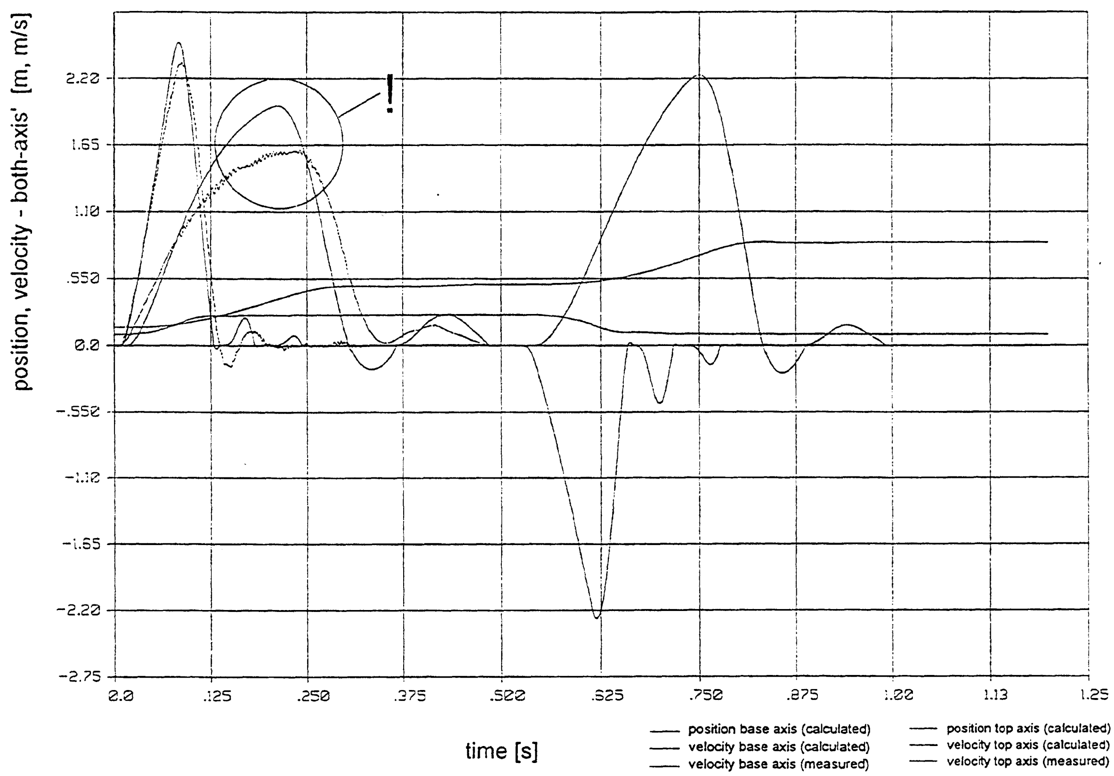


Pressure base-axis(calculated results - measured results)



Results two axis system

Velocity both axis moved simultanously
(calculated results - measured results)



Encountered problems

- friction of the base axis was found to be depending on the acceleration of the top axis due to clamping effects

Benefits

- support of the FESTO product development by calculation of load on all parts of the actuators
- calculation of the displacements of the tool center point (static formulas - load calculated by ADAMS)
- evaluation of the system performance

8. Conclusions

- The interface to couple pneumatic system simulation software with **ADAMS** using the simulator backplane method proved to be a successful way to provide a pneumatic actuator force element in **ADAMS**.
- The results achieved for single axis applications using a coupled simulation of **ADAMS** and pneumatic system simulation software are almost identical with the stand-alone simulation with the pneumatic system simulation software.
- The calculated results compared to measurement data are good. The calculation of cycle time and joint forces of a pneumatically actuated nonlinear mechanism is possible with sufficient accuracy.
- The interface between **ADAMS** and pneumatic system simulation software has been tested with mechanisms containing up to five linear pneumatic actuators (extension with rotary actuators is planned).
- This interface is easy to implement and to maintain.
- This software solution is a powerful tool for FESTO to dimension pneumatically actuated mechanisms and systems for its customers and to develop new and better actuators.

9. Acknowledgements

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