Characterization of the dynamic behaviour of material testing machines

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Abstract

Material test results may depend strongly on the dynamic properties of the used testing machines. Unique methods and parameters for characterisation and validation of force or displacement controlled testing machines are still missing. In the presented paper a study of the control behaviour of a spindle driven uniaxial machine is carried out using a piezoelectric translator for generating the disturbance variable. The typical responses of the systematically optimized machine are compared to simulations of simplified controller systems. Some parameters concerning the time behaviour are discussed in terms of a systematic characterisation of the machine's dynamic properties and the experimental set up used.

Introduction

The specific response of the tested materials requires highly stiff machines achieved by controlling the machine relating to the displacement of the specimen. However, reaction time and therefore dynamic characteristics of the machine like overshooting, control deviation and settling time are important with respect to the quality of the test results. These characteristics are investigated systematically with a view of proposing test procedures and specifying parameters. It is shown that piezoelectric actuators with moderate slew rates may serve for this purpose. Some earlier investigations and details of the experimental set-up can be find elsewhere [1].

Experimental

The set-up is represented schematically in Fig 1. The used **piezoelectric translator (PZT)** that is tightly linked to a highly stiff force transducer was loaded in a 10 kN spindle driven

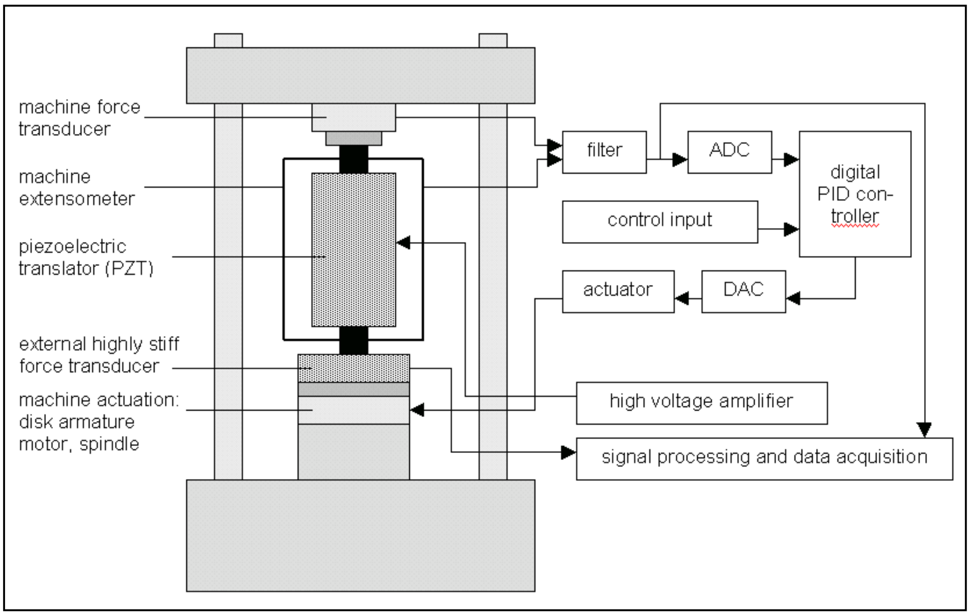

Fig. 1: Schematic representation of the force and displacement controlled materials testing machine and the used experimental set-up.

testing machine using a highly stiff connecting adapter. Data of the PZT are given in Tab. 1 below. Signal processing was performed by dc amplifiers (bandwidth ca. **4 kHz**). The data logging frequency was 4800 Hz.

Tab. 1 : Static and dynamic properties of the experimental set-up.

Piezoelectric translator P-246.50 (PI)	**specifications**
Maximum displacement at F = 0 N	80 µm
Maximum displacement at F = 5000 N	63 µm
Stiffness	295 N μm^{-1}
Unloaded resonance frequency	4 kHz
system stiffness	**experimental values**
stiffness k_s of the machine including fixing and force transducer of the simulator	≈ 76 N/µm
stiffness k_b of the entire system including machine, fixing and entire simulator	≈ 56 N/µm
system slew rates	**experimental values**
system slew rate at voltage step (100V) of the PZT (change of disturbance)	≈ 67 N/ms or ≈ 1 µm/ms
system slew rate at programmed force change (4200 N) of the machine (change of control input) at typical PI-parameters	≈ 70 N/ms
max. system slew rate of the machine force change at max. velocity of the spindle	≈ 250N/ms
max. velocity of the spindle displacement	≈ 4,5 µm/ms*

* calculated concerning the system stiffness of 56 N/µm

The actuation of the INSTRON 8562 consists of a spindle and controlled disk armature motor that distinguishes itself by low inertia. Therefore the machine is designed for intermediate control velocity but particularly for highly accurate displacement control. It works with a digital PID controller. Hence the analog to digital convertion (ADC) leads probably to dead times of about 0,5 to 1 ms in the signal processing that influence the control behaviour moderately. The controller input for the extensometer or force transducer is followed by a 100 Hz low pass filter. The machine was investigated in force as well as in displacement control mode.

Concerning the type of PZT the measurements were carried out solely in the pressure force mode. On principle the measurements and results are applicable to the tensile mode of the machine without restriction. Some essential relations between system stiffness values and properties of the PZT are given below. Because of the PZT hysteresis [2] no exact relations can be written.

$$\Delta F_t \approx \Delta L(U)\,\frac{k_t\,k_s}{k_t + k_s} \qquad\qquad k_s \approx \frac{1}{\dfrac{\Delta L}{\Delta F} - \dfrac{1}{k_t}} \qquad (1)$$

$$\Delta s_t \approx \Delta L(U)\,\frac{k_t}{k_t + k_s} \qquad (2)$$

ΔF_t : force step generated by the voltage driven PZT of step U

Δs_t : elongation of the fixed PZT that works against the stiffness of a static system (no additional external force generation)

$\Delta L(U)$: intrinsic elongation of the PZT depending on the supply voltage U .

k_t : stiffness of the PZT

k_s : stiffness of the rest of the system

Fig. 2 represents the rise behaviour of the PZT at static operation of the machine (prestress-ed by the spindle). The PZT was driven by a sharply rise voltage step. The rise of the force and displacement (not shown) signal is linear. The slew rates are represented in Tab. 1 as well as the other dynamic data of the PZT-machine system determined experimentally .

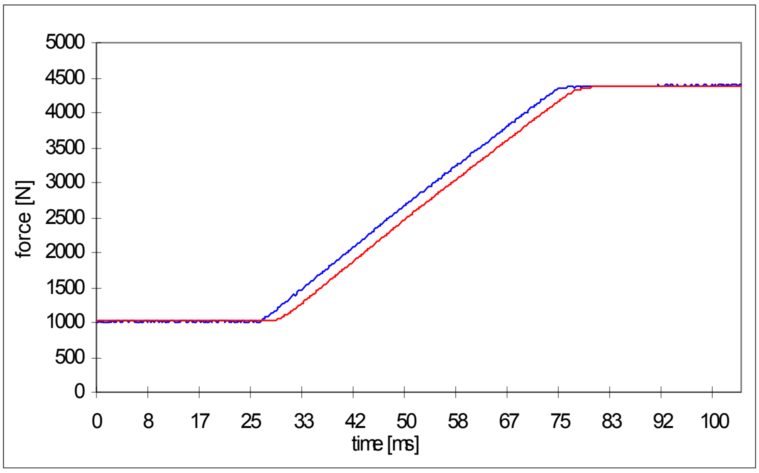

Fig. 2
Force rise of the system as a respond of a voltage step (800V) of the PZT. The system shows a constant slew rate of ≈ 67 N/ms (signal of external force transducer and delayed signal of machine force transducer)

Results

On principle two different methods can be applied to investigate the behaviour of a controller system: variation of the disturbance i. e. in this case variation of the behaviour of the specimen or variation of the control input. The first method that was applied within this study provides the direct comparison with respect to the conditions that effect the tested specimens.

In general the PID parameters may be optimized by the so called method of Ziegler-Nichols [3]. However this leads to ca. 10% overshoot that is not acceptable generally. To eliminate largely the overshooting the PI parameters were modified carefully so that the overshoot was limited to a few percents at sharp rise or fall of the control input. For testing machines the differentiation parameter (D parameter) has no importance.

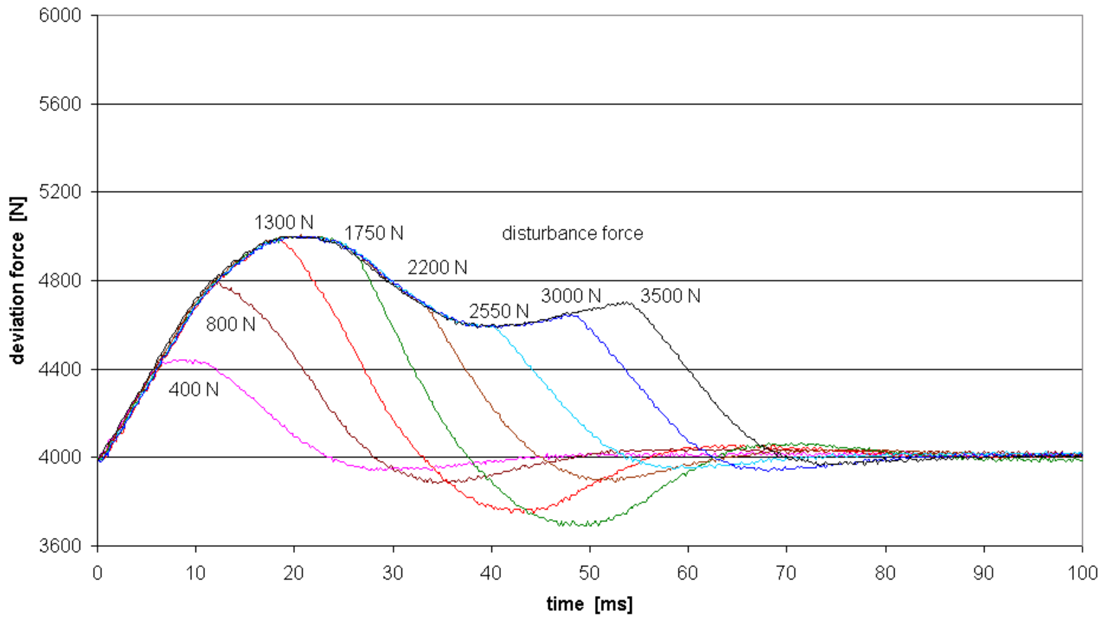

Fig. 3 Force control. Controlled variable vs. increasing disturbance force with linear increasing rise time from 6 ms (400 N) up to 55 ms (3500 N). At the end of the disturbance' rise (at beginning of constancy) the deviation decreases rapidly.

Force control
Fig. 3 shows the recorded force signal in force controlled mode at increasing force rises generated by the PZT that range from ≈400 N up to ≈3500 N (experimental values related to the voltage steps that range form 100 V up to 800 V). Because of the linear rise of the PZT force

the rise time of disturbance increases from ≈6ms (100 V/400 N) up to ≈55 ms (800 V/3500 N) at increasing levels of the force steps. During the rise the deviation force increases, stagnates and falls rapidly after reaching the constant disturbance value. After prepulsing the deviation is reduced to zero. The signal shows positive and negative overshooting. Equivalent behaviour is obtained at negative force steps (negative disturbance).

The automatic controller action of the machine is characteristic and can be simulated simplified by a simple spring mass element called PT2 element in the following. Fig. 4 gives a schematic representation of the simplified controller system that considers 100 Hz input filter, dead time element (analog to digital converter, dead time: ca. 0,5 ms) besides the PI controller (P=7; I=0,1 s) and the PT2 element (gain=1,8; time constant=20ms; damping=2,2). The disturbance is simulated by a linear ramp of constant slew rate (67 N/ms) and of different max. forces of the disturbance ranging from 400 N up to 3500 N.

Fig. 5 shows the simulation of the system response with respect to the linear rising disturbance forces from 400 N up to 3500 N of constant slew rate (~67 N/ms). The simulation is in good qualitative correspondence with the experimental results. It should be mentioned that this qualitative correspondence is not attainable without using a PT2 element of represented characteristics.

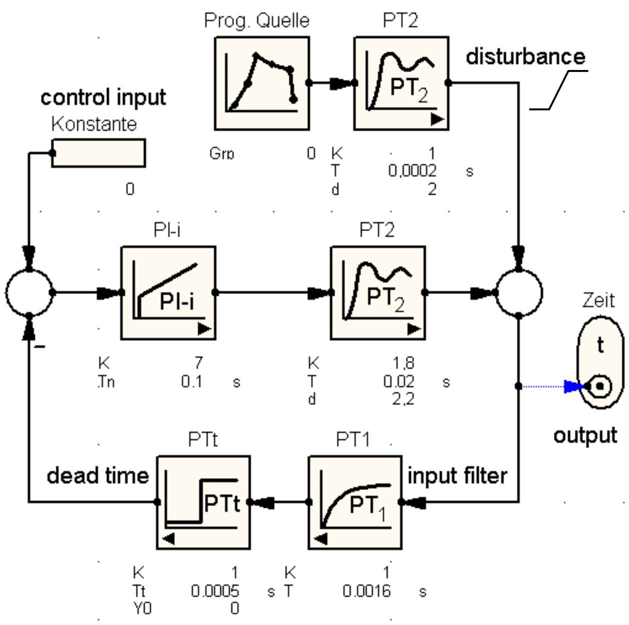

Fig. 4 Block diagram of the controller system. Simulation of the experimental results by a simplified controller system. Force control: 100Hz input filter; 0,5ms dead time element representing ADC; PI controller (P=7, I=0,1s) and PT2 element (gain=1,8; time constant=20 ms; damping=2,2). The disturbance is simulated by a ramp of constant slew rate = 67 N/ms that get constant at the chosen force level.

Displacement control

In the case of displacement control a much greater propensity to oscillation of the system is apparent that arises during optimization of the PI parameters. This should be due to the mechanical and therefore dynamic properties of the extensometer. Consequently this restricts the choice of PI parameters considerably and merely a lower dynamic of the system is attainable. The settling time (5%) had increased up to ca. 650 ms using the optimized PI parameters (optimization by sharp rise and fall of the control input, avoiding overshooting).

Fig. 6 shows the recorded displacement deviation using displacement control with the optimized parameters P=22, I=0,8s. The PZT had been loaded by the machine and the PZT driving voltage up to 9000 N, respectively. Then the disturbance was generated decreasing the PZT voltage abruptly. Displacement steps of the PZT were generated that ranged from ca. -6 µm up to ca. -29 µm (experimental values related to the voltage steps that range form 100 V up to 500 V).

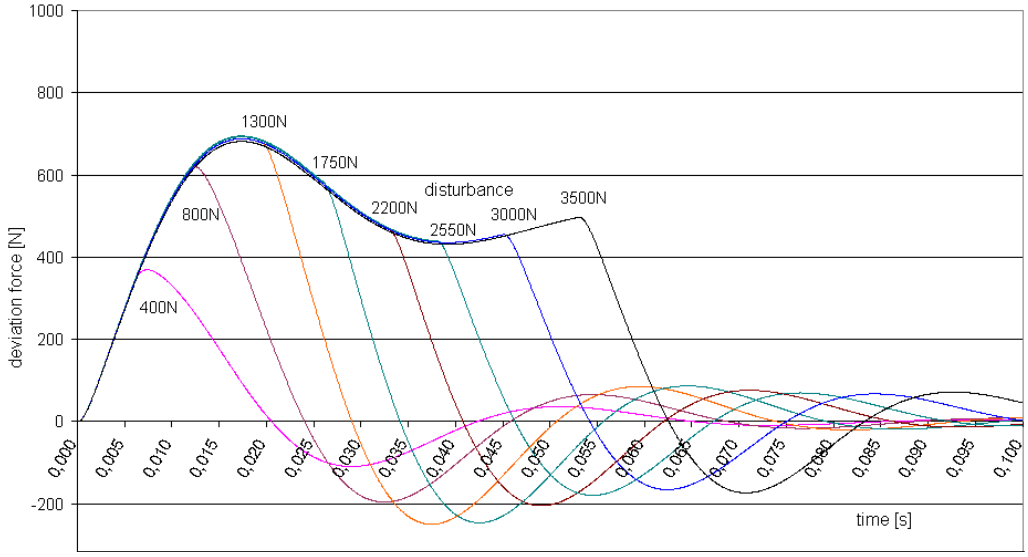

Fig. 5 Force control. Simulation of the system using the equivalent circuit shown in Fig. 3. The simulated input parameters correspond to the experimental conditions.

The rise of the displacement deviation reflects largely the rising behaviour of the PZT (linear ramp), respectively, without indications of control. After reaching the constant region of the disturbance signal the displacement deviation decreases exponentially with decay times in the range of $\tau_m \approx 100 \ldots 115$ ms. This behaviour is characteristic for a strong damping within the controller system and has to be ascribed to the properties of the machine extensometer. The upper part of Fig. 6 shows the decrease of the system force.

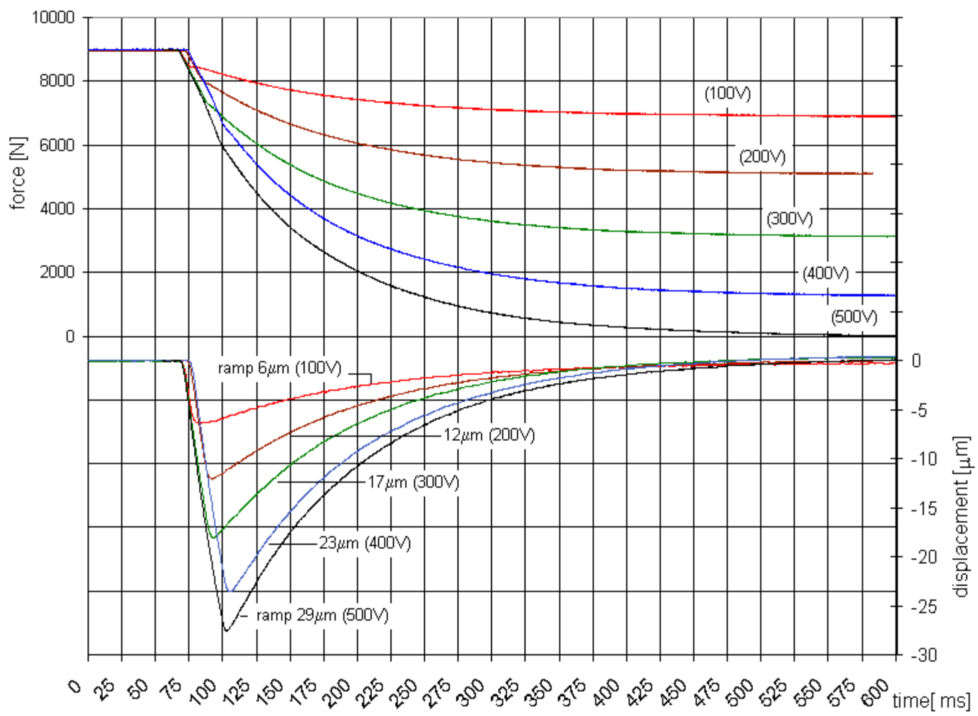

Fig. 6 Displacement control. Lower curves: Controlled variable vs. increasing disturbance ranging from ≈6 µm (rise time ≈6 ms, 100V step of PZT) up to ≈29 µm (rise time ≈33 ms, 500V step of PZT). The optimized parameters of the PI controller were: P=22, I=0,8s.
Upper curves: Corresponding changes of force. The initial force was set to 9000 N.

Fig. 7 shows the time simulation of the system using a linear ramp of the disturbance ranging from 6 µm (100V step of the PZT) up to 29 µm (500V step of the PZT) with constant slew rate ≈1 µm/ms. To attain the characteristic mono exponential decay and the experimental decay time of about 105 ms (see above) a damping element with a high damping factor of ≈30 was necessary.

The simplified model of the controller system corresponds essentially to the block diagram represented in Fig. 4. The elements and parameters were: 100Hz Input filter; 0,5ms dead time element representing ADC; PI controller (P=22, I=0,8s) and PT2 element with low gain and prevailing damping (gain=0,036; time constant =1 ms; damping=30). The disturbance is simulated by a ramp of constant slew rate=1 µm/ms that get constant at the chosen displacement level. The simulation is in good qualitative correspondence with the experimental results that can not be attained without the use of a strong damping element.

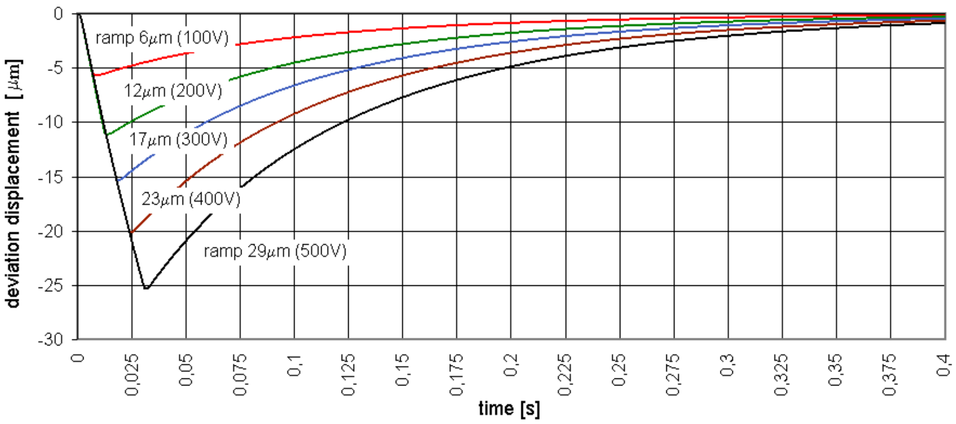

Fig. 7 Simulation of displacement control. The linear rise that follows largely the rise of disturbance and the mono exponential decay is attributed to a low gain / strong damping element within the controller system.

Aspects of specifying the control behaviour based on system stimulation by disturbance ramp

Maximal overshoot and settling time (to 5- or 2-percent limit) are commonly used as specifications for the control behaviour in conjunction with a steep ramp stimulation of the controller system [3]. The results are highly dependant on the slew rate of the stimulation and therefore of limited application for generalized specifying. Furthermore the inverse of the slew rate and the rise time up to the constant level of the stimulating variable have to be of the order of the system time constant. This can usually be achieved by using piezoelectric translators. In the presented case of force control the time constant of the controller system is approximately 20 ms (first overshoot in Fig.3). For detection of the overshoot maximum the stimulating ramp must have a rise time > 20 ms that is met by a step of ≥ 1750 N corresponding to ≈ 26 ms see Fig. 3.

The ratio of overshoot maximum OS_{max} and slew rate SR of the disturbance ramp may serve as a generalized parameter - here written as Q_{max} - that specifies the control behaviour of the system. This is supported by the results shown in Fig. 3 and deduced from time simulations of such systems varying systematically the system parameters. In the present case of force control Q_{max} is (OS_{max} = 1000 N ; SR = 70 N/ms = 70 kN/s, cf. Fig. 3 and Tab.1)

$$Q_{max} \text{ (force control)} = OS_{max} \ / \ SR = 0{,}014 \text{ s}$$

If no overshoot is detectable the commonly used settling time e. g. to 5% t_s(5%) or decay time τ_m may serve as a specifying parameter. In the present case of displacement control the settling time is estimated t_s(5%) ≈ 0,3 ... 0,4 s. Smaller values reflect higher dynamic of the system in both cases.

References

[1] Seiffert, Subaric-Leitis, Ullner, 'Device for Testing the Control Response of Highly Stiff Materials Testing Machines', Proc. EUROLAB Workshop, Dübendorf, Swizerland, 2001

[2] Physik Instrumente, Catalogue, Waldbronn, Germany, 1998

[3] Ogata, K., 'Modern Control Engineering', Prentice Hall, Englewood Cliffs, 1990