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Operating Manual PZ 77E

E-509

Position Servo Control Module

Calibration Procedures / Technical Reference

This Document is valid for these Products:

E-509.Lx	**Position Servo Control Module for LVDTs**
E-509.Sx	**Position Servo Control Module for SGS**
E-801.15	**SGS Sensor processing unit**
E-801.25	**LVDT Sensor processing unit**
E-802.5x	**Position Servo Control, sub PCBs**

Release: *2.10*
Release Date: *29 September 1999*

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Table of Contents :

1. Introduction

E-509 is a *PZT Actuator Position Servo Control Module*.

The module is used in the E-500 series electronics and allows to control the position (displacement) of piezoelectric devices with nanometer resolution.

The E-509 generates the input signal for the amplifier module according to the difference of target and actual position. Drift and hysteresis of PZT actuators are compensated. The stiffness of the actuator is significantly increased due to fast displacement control by adjusting the PZT operating voltage to maintain the displacement even when external forces are changed.

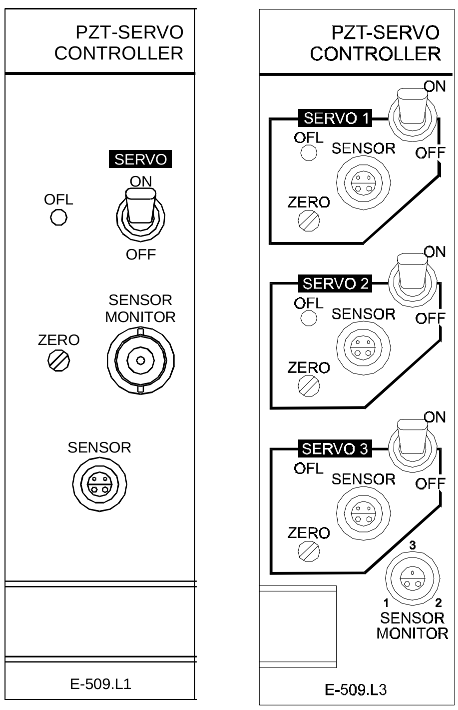
Position information is provided by high resolution sensors integrated in the mechanical stage or in the PZT actuator. Both strain gage sensors and LVDTs are supported by the E-509. Also capacitive sensors can be used with E-509.Cx modules (see PZ63E product documentation).

The E-509 need an external amplifier for the PZT operating voltage. Depending on the PZT type, high-voltage amplifiers (E-507) or low-voltage amplifiers (E-503, E-505,) are available.

Main parts of the E-509 are the *sensor signal processing circuit* and a *servo controller* with adjustable p-i filter and optional notch filter to allow operation close to the mechanical resonance frequency.

The hardware design of the module consists of one basic board and two small add-on boards for each channel, one for sensor processing the other for position servo control.

Front Panels :



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1.1. Product Survey :

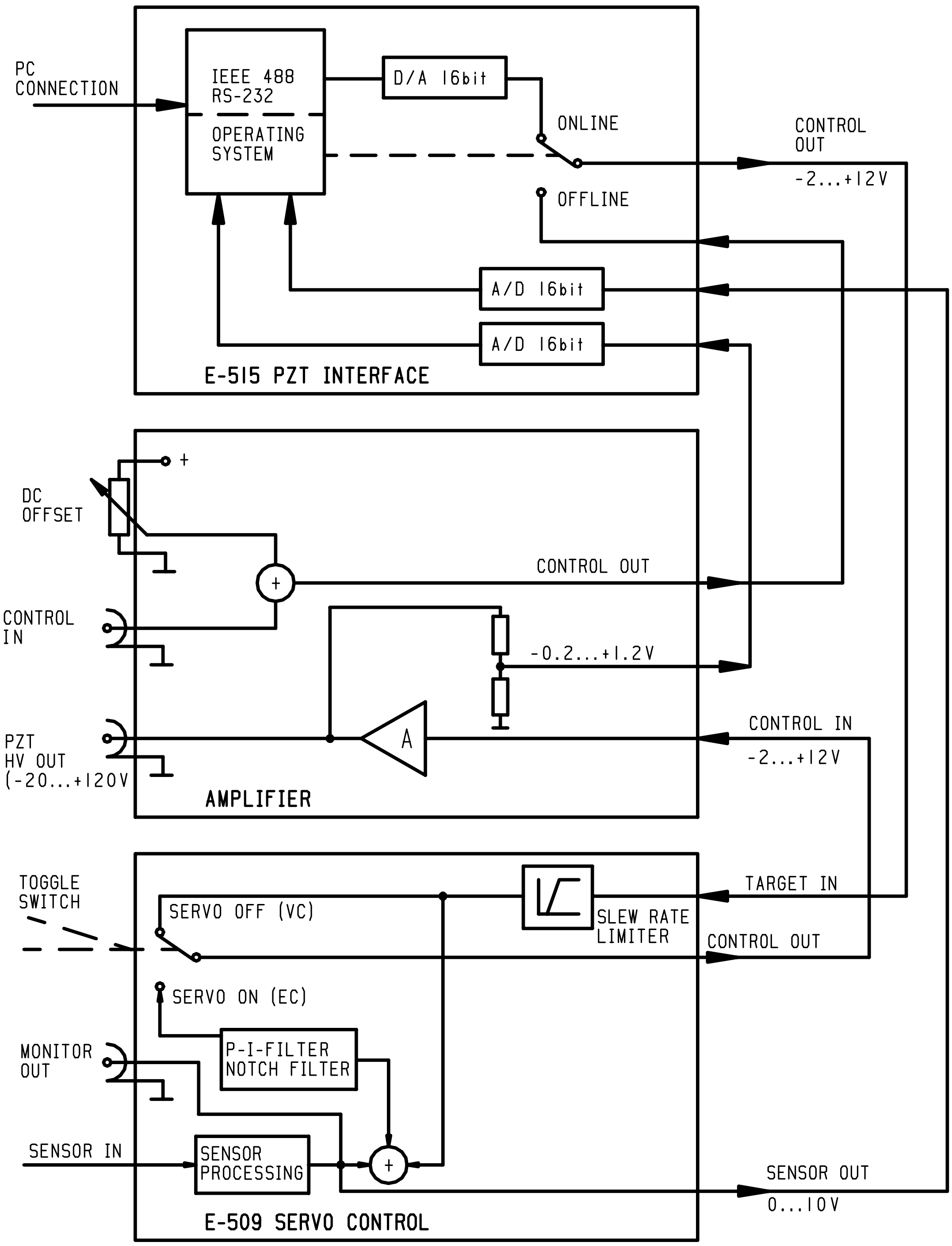
E-509.S1	PZT Servo Control Module, single channel, for strain gage sensors
E-509.S3	PZT Servo Control Module, three channels, for strain gage sensors
E-509.L1	PZT Servo Control Module, single channel, for LVDT sensors
E-509.L3	PZT Servo Control Module, three channels, for LVDT sensors
E-801.15	Sensor processing add-on board for SGS sensors
E-801.25	Sensor processing add-on board for LVDT sensors (Master)
E-801.26	Sensor processing add-on board for LVDT sensors (Slave)
E-802.50	Position Servo Control, sub PCB
E-802.51	Position Servo Control, sub PCB
E-802.52	Position Servo Control, sub PCB

Front panels of E-509.S1 and E-509.S3 modules are identical.

1.1. E-509 Technical Data

Function:	**PZT position servo controller with displacement sensor evaluation electronics**
Channels:	**1: (E-509.x1)** **3: (E-509.x3)**
Sensor types:	**SGS (Strain Gage): E-509.Sx** **LVDT (Linear Variable Differential Transformer) E-509.Lx**
Servo characteristics:	**P-I (analog)**
Rear connector:	**32-pin connector, DIN 41612**
Sensor socket:	**LEMO ERA.0S.304.CLL (E-509.Cx: LEMO EPL.00.250.NTD)**
Sensor monitor output socket:	**LEMO ERA.0S.303.CLL (3 channel versions)** **BNC (1 channel versions)**
Dimensions:	**plug-in module width: 7TE (1.4")**
Operating voltage:	**+/- 15V, 0.2A** **E-530 power supply, part of the E-500 chassis**

1.2. Signal Path Diagram



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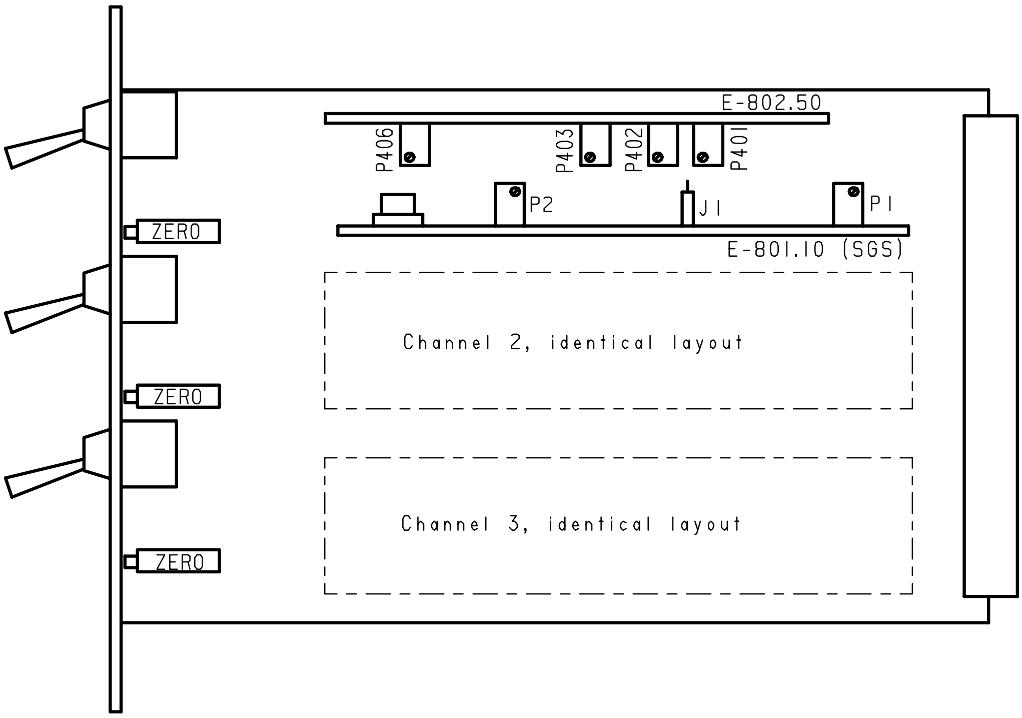
2. E-509 Design

2.1. E-509.S3

PZT Position Servo Control Module for 3 channels with strain gage sensors.

Host System: E-500 chassis

E-809.S3



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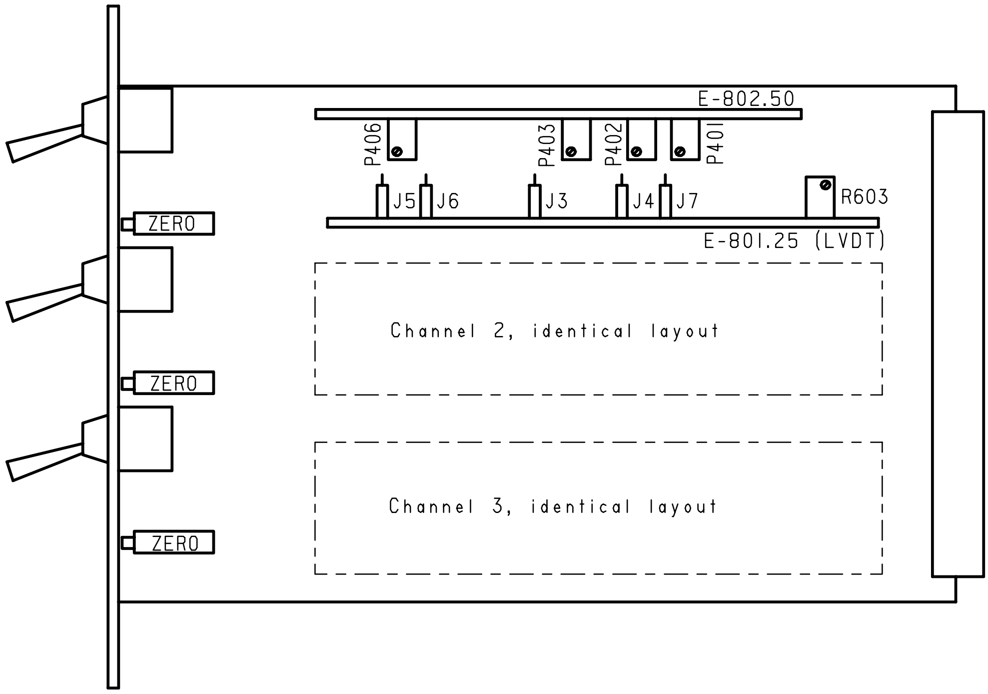
2.2. E-509.L3

PZT Position Servo Control Module for 3 channels with LVDT sensors.

Host System: E-500 chassis

E-509.L3



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3. Board Functions and Layouts

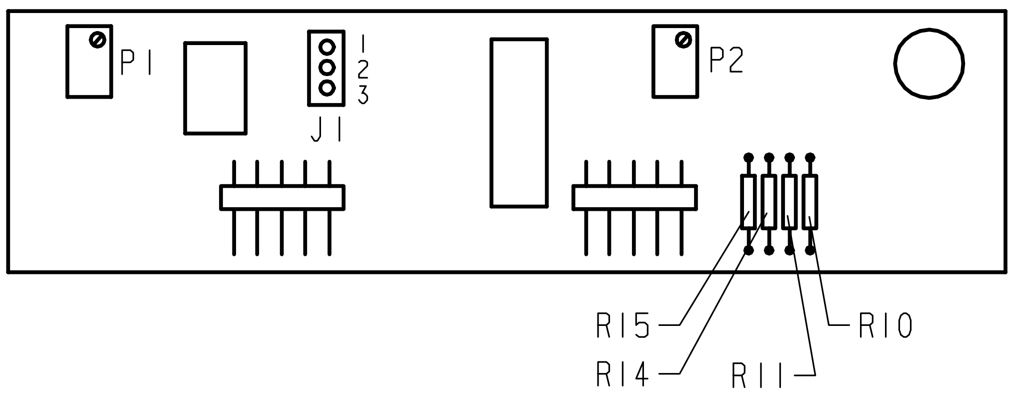
3.1. E-801.15

Processing Board for Strain Gage Sensors

E-801.15 sub-modules are used for excitation and evaluation of strain gage sensors (SGS). It is designed as an add-on board for the E-509 servo control module.

The strain gage is excited with DC signals and the evaluated signal is proportional to the expansion of the gage.

E-801.15



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Adjustment Controls:

P1: Sensor Gain

P2: Zero PZT

J1: Jumper for 100 Hz filter
<u>1-2: Filter disabled</u>, 2-3: Filter enabled

The resistors R10 to R15 are used with half-bridge SGS configurations to complete the full bridge. R10/R11 and R14/R15 are in parallel to allow to assemble the required value.

R10: 703 Ohms if half-bridge sensors are used

R11: optional

R14: 703 Ohms if half-bridge sensors are used

R15: optional

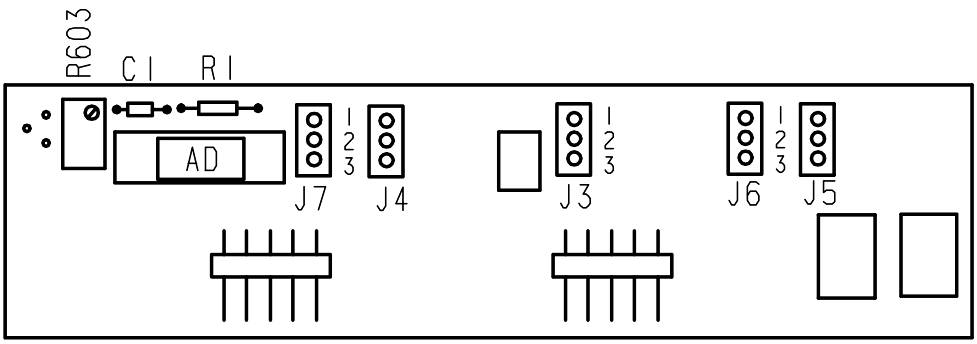
3.2. E-801.25, E-801.26

Processing Board for LVDT Sensors

E-801.25 (master module) and E-801.26 (slave module) are used for excitation and evaluation of LVDT sensors. They are designed as add-on boards for E-509 servo control modules. For multi channel E-509 modules, one of the E-801 add-on boards has to be a master, the other have to be slave versions.

The LVDT sensor is supplied with AC signals. On-board pre-amplifiers and filters allow to adapt the module to different PZT mechanics and amplifiers.

E-801.25, E-801.26



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Adjustment Controls

R603:	Sensor Gain
J3:	Jumper: Internal bridge completion 1-2: installed, **2-3: not installed**
J4:	Jumper: Excitation C-coupled 1-2: C installed, **2-3: C not installed**
J5:	Jumper: Gain pre-amplifier #1 **1-2: high gain**, 2-3: low gain
J6:	Jumper: Gain pre-amplifier #2 **1-2: high gain**, 2-3: low gain
J7:	Jumper: Excitation **1-2: direct**, 2-3: one side grounded
R1:	(only on E-801.25) Excitation signal amplitude
C1:	(only on E-801.25) Excitation signal frequency

3.3. E-802.50 / E-802.51 / E-802.52

Position Servo Control Boards

The **E-802.50** *Servo Position Control Board* is a small add-on PCB that generates the control signal for the high voltage or low voltage amplifier driving the piezoelectric translators.

The circuit compares the control voltage input and the sensor reference signal to generate amplifier control signal. Analog P-I filter performance and optional feed forward behavior combined with an adjustable notch filter to suppress mechanical resonances reflects the general capability of the E-802.

The circuit of the board is designed as a small add-on PCB to be used with the E-509.xx and E-809.xx servo position control modules.

The difference between both versions E-802.50 and E-802.51 is that the latter one has an additional adjustment potentiometer (P407) for fine adjustment of the monitor output

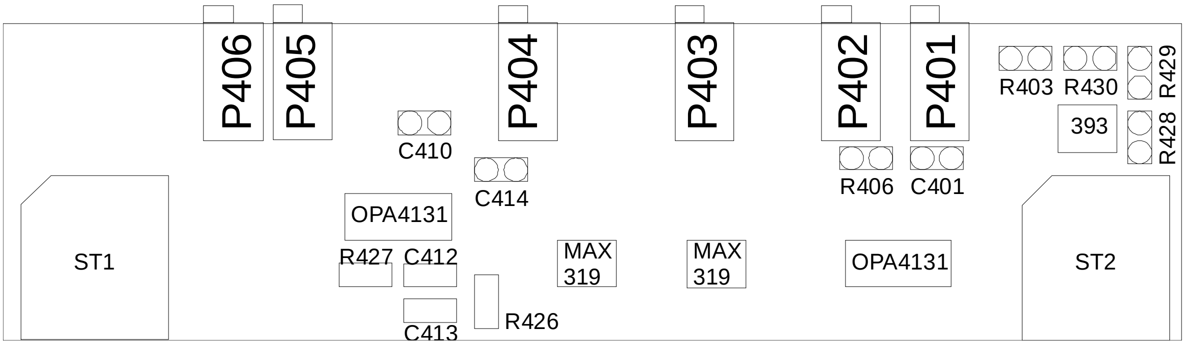
E-802.52 Module has an additional potentiometer for fine adjustment of dynamic properties. An additional time constant allows to compensate the position error caused by PZT creeping effects. Settling times can be increased significantly by these procedures. With this module, the adjustments for notch-Q-factor is no longer required.

3.3.1. Functionality

- Slew rate limitation of output signals can be set within the range of 15 V/ms up to 1500 V/ms.
- P-I control performance with individual settings of P- and I-terms.
- Optional notch filter allows to suppress mechanical resonances. The filter frequency and quality can be adjusted by trim potentiometers.
- Servo function can be enabled/disabled via TTL signals (low=servo ON, high=servo OFF).
- A feed-forward circuit can be installed optionally if extended dynamic performance is required. The feed-forward option allows to feed a variable portion of the control signal directly to the controller output (open loop concept). The advantage is a shorter rise time or higher cut off frequency, respectively. The price for these benefits is a reduced precision with step-like input signals (overshooting). Installed feed forward circuit has no influence on stability and precision of the static control performance.
- Excellent long term stability was accomplished by using exclusively low tolerance / small drift components. Residual errors in the range of 0.05% can be compensated by additional trimming components.

3.3.2. Component Maps / Adjustment Controls

E-802.50



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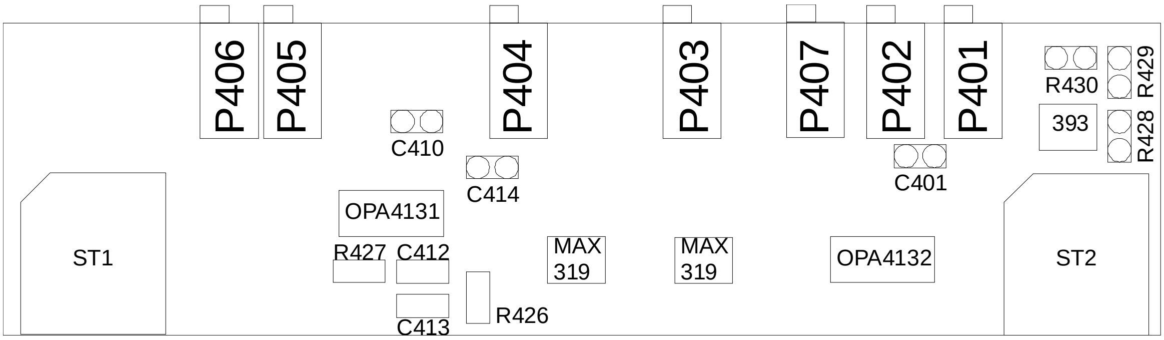
E-802.51 / E-802.52



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Adjustment Controls:

P401: Slew rate setting, has to be adjusted to the current supply capability of the amplifier.

P402: Proportional term of the servo loop (Loop gain)

P403: Integration term of the servo loop (i-Term)

P404: Feed forward gain setting of the servo loop. Not installed as standard.

P405: E-802.50, E-802.51: Q-factor of notch filter
E-802.52 : PZT drift compensation, fine adjustment

P406: Notch filter frequency, has to be adjusted to the first resonance of the PZT mechanics.

P407 Monitor output adjustment (only E-802.52)

C401: Range extension of slew rate (rise time), standard 47nF

C410: Range extension of integral term, not installed as standard

R403: Correction of a positive control deviation, 0 Ohms as standard, only on E-802.50

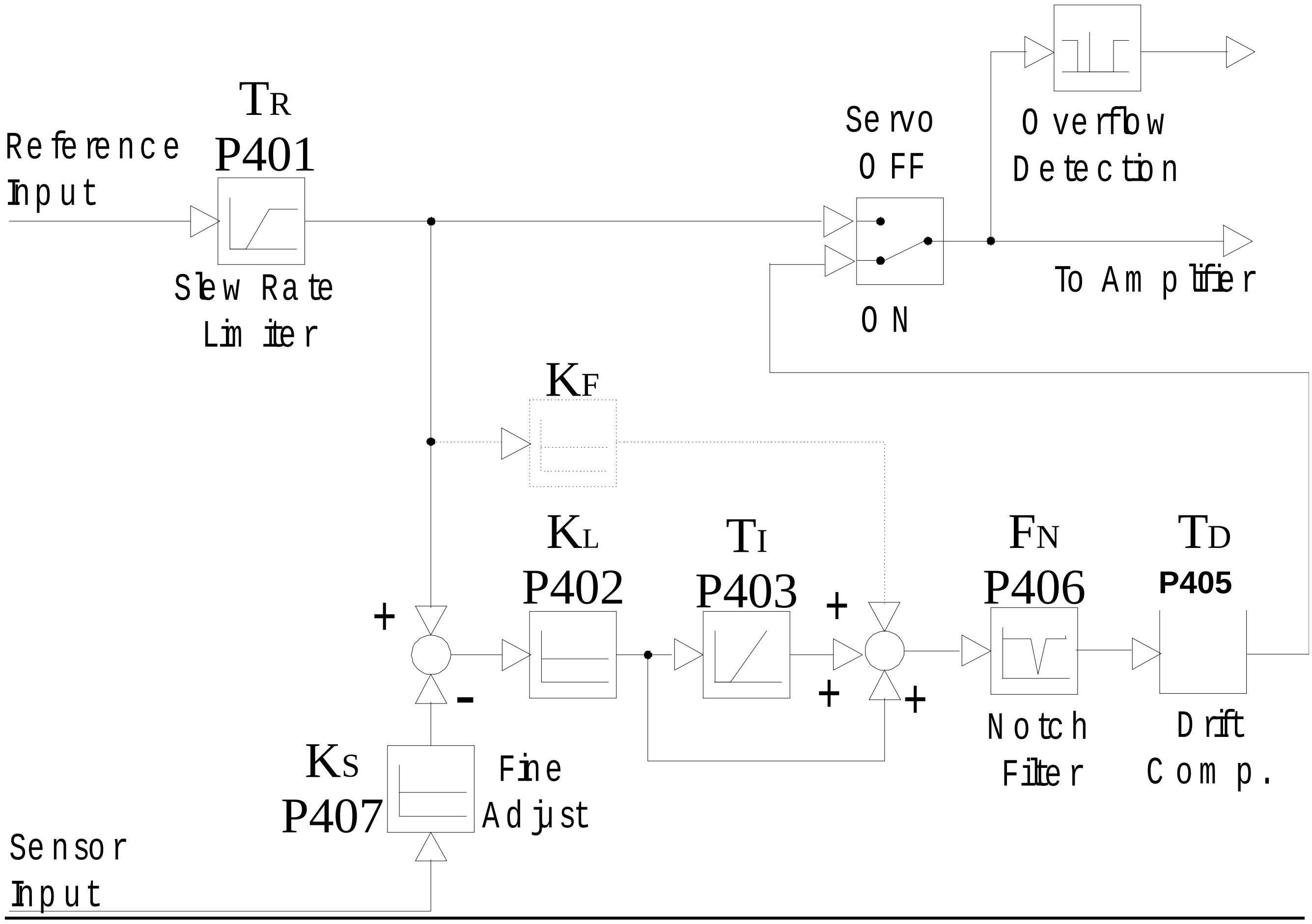
R406: Correction of a negative control deviation, 0 Ohms as standard, only on E-802.50

R428, R429, R430 Programming the over voltage limits. See table 1.

C412, C413, C414 Range for notch filter frequency. See table 2.

ST1, ST2 Connectors to main board

3.3.3. E-802.5x Block Diagram



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T_A	Slew rate limitation
K_P	Proportional term
T_I	Integration time constant
f_N	Notch filter
K_F	Feed forward (not used in regular case)
T_D	Drift Time Constant (E-802.52 only)

3.3.4. Voltage Ranges and Over Voltage Recognition Settings

Nominal Voltage Range /V	Actual Voltage Range / V	R428	R429	R430
NV, 0..100	-20 .. +120	3,01 K	14,0 K	13,0 K
HI, -1000 .. 0	-1120 .. -3	4,02 K	11,3 K	14,7 K
HII, -750 .. +250	-790 .. +265	7,15 K	10,5 K	12,4 K
HIII, -500 .. +500	-560 .. +560	9,53 K	11,0 K	9,53 K
HIV, -250 .. +750	-265 .. +790	12,4 K	10,5 K	7,15 K
HV, 0 .. +1000	+3 .. +1120	14,7 K	11,3 K	4,02 K

Table 1

Any more precise adjustments are not possible at this place, due to fact that the test voltage is derived from the operating voltage, which can vary about 1% from the nominal value. The same tolerance has to be taken into account regarding the over voltage recognition.

3.3.5. Notch Filter Setting for C-802.50 / .51

Bestückung des Notchfilters X2h, 17.04.96

Nennbereich Hz		Auswahl der Bauteilen – Optionen der Dämpfung: -25db					-20db				
f_{min}	f_{max}	C414+C413 /nF	C412 /nF	R426 /k	R427 /k	F_{f0}	C414+C413 /nF	C412 /nF	R426 /k	R427 /k	F_{f0}
40	90	100	820	22	22	6,57E+05	33	1500	47	47	8,00E+05
90	220	47	220	22	22	3,96E+06	18+2,2	680	47	47	3,92E+06
190	490	18	150	22	22	2,00E+07	6,8+2,2	330	47	47	1,81E+07
300	750	8,2+2,2	100	22	22	5,20E+07	3,3+2,2	220	47	47	4,45E+07
610	1600	3,3+2,2	47	22	22	2,08E+08	0,56+2,2	100	47	47	1,95E+08
1600	4100	2,20	18	22	22	1,36E+09	2,20	22	47	47	1,36E+09

Table 2

The indicated frequency range can be adjusted by potentiometer P406.

Extended frequency ranges can be selected by exchange of components as listed in the table.

3.3.6. Notch Filter Setting for E-802.52

Bestückung des Notchfilters xZh

Nennbereich Hz		Auswahl der Bauteilen		Optionen der Dämpfung -20db		-20db	
f_{min}	f_{max}	C413 /nF	C412 /nF	R426 /k	R427 /k	R426 /k	R427 /k
38	103	100	100	22	22		
80	219	47	47	22	22		
171	467	22	22	22	22		
377	1028	10	10	22	22		
802	2188	4,7	4,7	22	22		
1712	4674	2,2	2,2	22	22		

4. E-509 Calibration Routines

The analog *E-509 Position Servo Control Module* has to be adapted to the characteristics of amplifier, sensor and PZT mechanics.

Dynamic performance of the PZT system is determined by the maximum output current of the amplifier and by the mechanical properties of the PZT-mechanics like moving mass, damping and resonance frequencies.

In order to match the analog circuit and the mechanical characteristics to achieve the desired performance, the E-509 has to be adjusted for static and dynamic operations.

As the result of the static calibration, the E-509 controlled PZT system can be driven to absolute positions according to an external analog control signal ranging from 0 to +10 Volts. Dynamic calibration optimizes step response and suppresses resonance overshoots and oscillations.

The full calibration and adjustment procedure includes adjustment of zero point, sensor gain, slew rate and step response. All these basic adjustments are done in our lab before shipment. The PZT system is delivered ready for operation. Only the zero point has to be aligned from time to time to compensate temperature changes. Further adjustments are not required as long as system components are not exchanged or modified.

The PZT actuator has to be calibrated in conjunction with one E-509 control module, so both parts belong together. Any exchange of either one or the other part requires a new calibration run to get the specified system accuracy.

4.1. Equipment needed for calibration

Zero point adjustments can be performed without extra equipment if an E-515 display/interface is installed, otherwise an voltmeter is needed.

Static displacement calibration requires an external expansion gage with 0.1 µm resolution and a precision voltmeter.

Dynamic calibration procedures require an oscilloscope (a digital storage oscilloscope is recommended), frequency generator to output square and sine functions from 1Hz to 1 kHz, an Ohm-meter with a range from 0.1 to 100 kOhm and an 32-pin extension adapter board to give access to the trim-potentiometers on the E-509 while the board is installed in the E-500 chassis.

4.2. Preparations

Mount the PZT actuator in the same way and with the same mass as it will be operated in the application.

4.3. Zero point adjustment

The correct zero point adjustment allows the PZT to be used within the full displacement range without reaching the output voltage limits of the amplifier.

A proper zero point calibration ensures that in closed loop operation the full output voltage swing of the amplifier can be used and prevents overflow conditions.

Zero point adjustment procedure:

1. Set servo mode to SERVO OFF (E-509 module)
2. Turn DC-Offset potentiometer to zero (CCW) (amplifier module)
3. Read the SENSOR MONITOR signal and turn the ZERO potentiometer until the monitor signal reads zero.
4. Set servo mode to SERVO ON
5. If no E-515 module is installed, connect a voltmeter to the PZT operating voltage. Use a T-connector at the LEMO output to access the voltage.
6. Adjust the PZT operating voltage using the ZERO potentiometer.
   For HV-amplifiers: set voltage to -50 V
   For LV amplifiers: set voltage to 0 V

4.4. Static Gain Adjustment

The objective of the static gain adjustment procedure is to ensure that the PZT actuator expands to its nominal expansion at 10 Volt control signal input.

Preparations:

An adjustable voltage source from 0 to +10 Volts and a displacement gage with 0.1 µm resolution is needed. Instead of using an external voltage source, also the E-515 interface module can be used to output control voltages.

1. Switch SERVO ON using the toggle switch at the front panel of the E-509 module.
2. Turn DC-OFFSET potentiometer at the amplifier module to zero (CCW)
3. Verify whether the PZT oscillates. If so, you can't miss to hear it. In this case, dynamic gain adjustments have to be done prior to continue with static gain adjustment.
4. Apply 0V to the CONTROL INPUT at the amplifier module. If an E-515 interface is installed, the command "SOUR:POS 0" will also apply zero volts to control input.
5. Adjust the external position probe and set the expansion reading to zero.
6. Apply 10V to the CONTROL INPUT at the amplifier module. If an E-515 interface is installed, the nominal expansion of the PZT can be commanded. In this case, the command "SOUR:POS 20" would apply +10 Volts to control input.
7. Read the external gage. Turn potentiometer R603 (using LVDT sensors) or P1 (using SGS sensors) until the external gage reads nominal expansion, e.g. 20 µm with a PZT specified with 20 µm nominal expansion.
8. Repeat steps 3 to 6 several times until stable results are achieved.

4.5. Position Servo Error Adjustment (E-802.51)

The adjustment of the position servo error allows to equalize the input control signal and the sensor signal at the monitor output. The command value (control input) shall be the same like the measurement reading.

Set SERVO ON and tune P407 to equalize control input and monitor reading.

5. Dynamic Calibration

5.1. Finding Resonance Frequency and Define Notch Filter

Evaluate the resonance frequency of the actuator while installed at the operation site. For this purpose a square wave (≈10Hz, 1Vpp, Offset 5V) is applied to the BNC input. Set this channel to Servo OFF.

Connect the sensor monitor output with one channel of the oscilloscope and watch the step response. The resonance frequency of the system can be estimated by the induced oscillations. If, for example, the period of the oscillation is 3 ms, then the resonance frequency is 1/period length or 1/3 ms = 0.33 kHz or 330 Hz.

Based on this frequency, the dimensioning of the notch filter can be found in table 2. It may be required to add some components or to change some.

5.2. Step Response Optimization (empirical method)

5.2.1. Standard Tuning

For dynamic operation, the step response of the mechanical system is important. The amount of damping and overshooting can be optimized by tuning the differential and integral term of the amplifier. Either the empirical or the calculating method can be used.

Procedure :

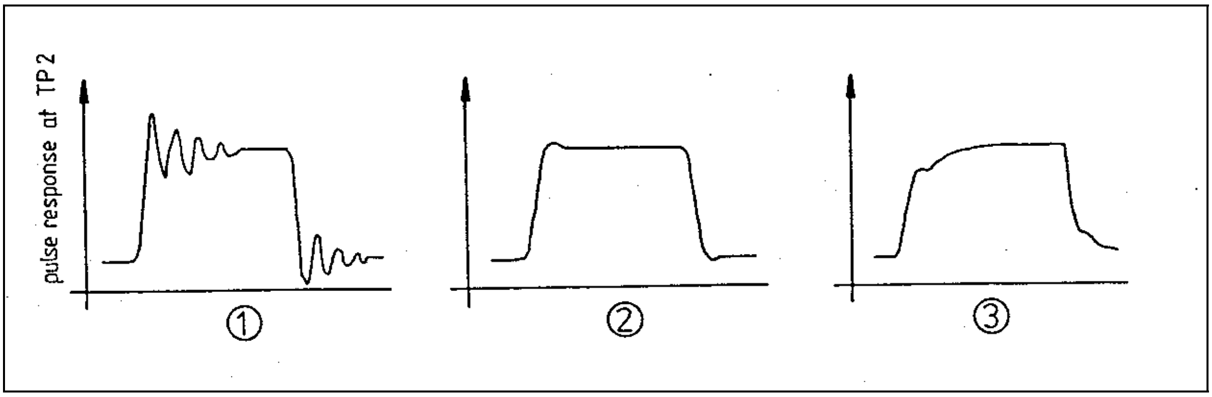
1. Mount the PZT at the place where it will be operated.
2. Set Servo ON
3. Use a square wave function generator and supply the BNC signal input with a square wave of 5 Vpp (set offset to 5V) and a frequency of 5 to 10 Hz.
4. Connect an oscilloscope to the monitor output.
5. Turn P402 until resonance frequency becomes visible
6. Turn P406 notch filter frequency until the oscillation amplitude becomes a minimum.
7. Turn P402 / P403 alternating to optimize step response.

The settling curve could look like the following :

Case 1 : Large overshoot, unstable

Case 2 : Optimal

Case 3 : Settling time too long



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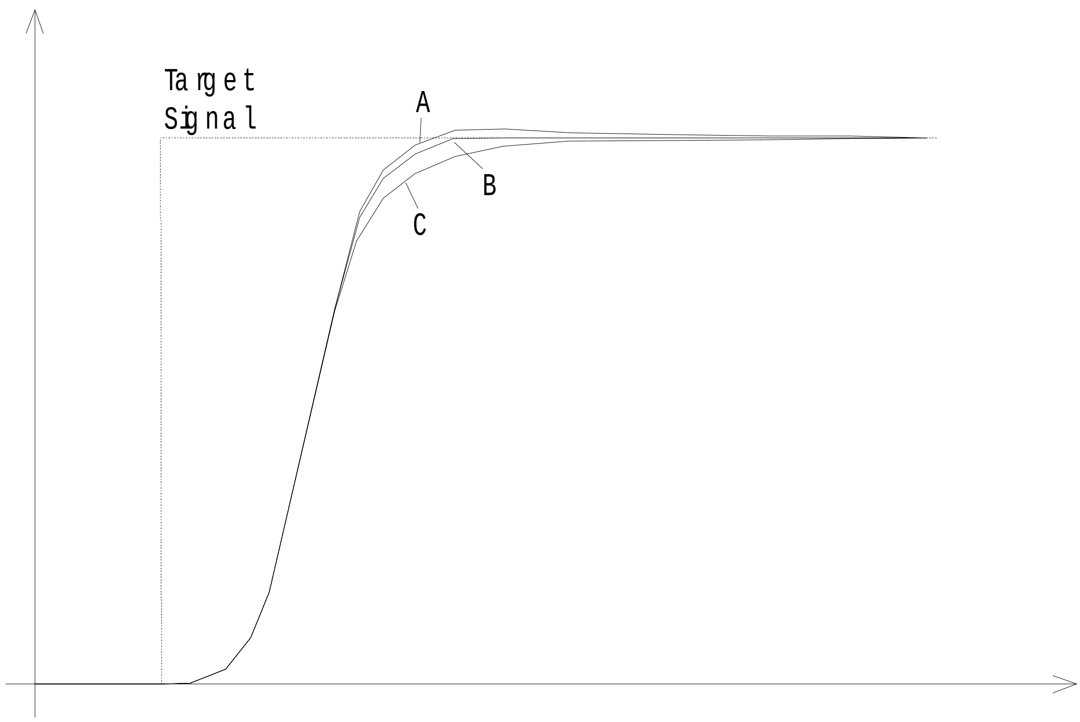
5.2.2. Fine Tuning



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The objective of the drift fine tuning is curve B of the diagram. Because the curve is exaggerated, an high resolution oscilloscope (12..14 bits) is required as well as a precise voltage generator.

At first the step response is to adjust without overshoot. Using P405 curves shapes A, B and C can be reached. If the overshoot can not be eliminated by using P405, the loop gain has to be reduced.

The result may be different at rising / falling edges, so a compromise has to be found.

5.3. Step Response Optimization, calculated method

5.3.1. Characterizing Servo Parameters

Servo loop parameters depend on each single component used in the system. Amplifier, PZT actuator and Sensor have to be handled as a system and the best way to determine the system servo parameters would be the use of a simulation program.

If no simulation program is available, typical assumptions can be made in order to get stable servo parameters, not optimized but good enough to work with.

Proportional term: $K_P = 0.3$

Integration time: $T_I = \frac{1}{2\pi f_{res}}$

Example: f_{res} = 330 Hz -> T_I = 0,48ms

Note: If the PZT resonance frequency is above 1 kHz, the system bandwidth is limited by the amplifier and the sensor. Do not use a higher frequency in any case.

5.4. Dimensioning Components

$$P_{402} = K_P \cdot 27400\Omega - 470\Omega;$$

$$P_{403} = \frac{T_I}{C_{410} + C_{411}} - 470\Omega; \quad [T_I] = s; \quad C_{410} = 0; \quad C_{411} = 22 \cdot 10^{-9} F;$$

Example:	K_p = 0.3	->	P_{402} = 7.75 kΩ;
	T_I = 0.48ms	->	P_{403} = 21,35 kΩ;

5.5. Apply calculated values in the circuit

If already the software simulation run found optimized values, theses values can be set immediately with the corresponding potentiometers.

The following procedure has to be used, if servo parameters are derived from arbitrary values (case 2):

1. Set potentiometer P401 to CCW hard stop (slew rate limitation)
2. Set P402 (p-term) to evaluated value using an ohmmeter.
3. Set P403 (I-term) to a value of 130 % of the calculated value (add 30% to the calculated value)
4. Power up the device and set SERVO ON. If you hear oscillation noise, set SERVO OFF immediately. Verify all values you have set.
5. Apply a square wave signal (10Hz, 10Vpp, 5V Offset) to the BNC input.
6. Turn potentiometer P403 (i-term) CW until a significant overshoot can be seen (2 to 5%)
7. Adjust P406 (notch filter) so that resonance impacts and overshooting are optimal damped.
8. Depending on the application, set P403 either for optimized settling or allow an overshoot of 5 to 10 %. The latter case allows a larger bandwidth.
9. Turn P401 (slew rate limitation) CW until the wobble comes to a minimum without having the raise time significantly enlarged.
10. Apply a sine wave with variable frequency, 10 Vpp, 5V offset. Check the sensor reading for amplitude and signal shape starting at 10 Hz up to the resonance frequency. If needed, repeat steps 8 and 9. If the bandwidth is too small, increase the i-term. (this also increases the overshoot amplitude for a step response). If signal distortions are already noticeable wide below the resonance frequency, decrease the i-term.

6. Correction of Control Deviations

This chapter refers to E-802.50.

Components with 0.1% tolerance are used in the circuits for slew rate limitation and signal comparison. Extended requirements for accuracy can be satisfied by adjusting the residual error. For this purpose the control signal at the control chip has to be probed. The second test value is the monitor signal of the sensor (U_{real}).

Calculate the factor

$\alpha = U_{real} / U_{target}$

if $\alpha = 1$, no adjustments are required.

If there is a deviation from 1, R403 and R406 can be calculated as follows:

For $\alpha > 1$: R403 = $(\alpha - 1) * 54{,}9\ k\Omega$

For $\alpha < 1$: R406 = $(1 - \alpha) * 54{,}9\ k\Omega$

7. Additional Adjustment Points

These test points are not used during the standard calibration procedures.

Slew rate adjustment range too small, rise time to short:

install C401 (22..100 nF)

and / or change R407 (SMD, Standard 1K)

Proportional term too small, servo loop too slow:

increase P402 (potentiometer type Bourns 90°, Standard 50 K)

increase R416 (SMD, Standard 470 Ω)

Proportional term too large:

decrease P402 (10K, 5K, Potentiometer Bourns, 90°, Standard 50 K)

Integral term to small (settling time too long)

install C410 (wired RM 2,5, 22..100nF)

Integral term too large:

decrease P403 (20K, 10K, Standard is 50K)

Servo loop too slow, despite of optimal setting

install P404 (20 K)

adjust to best compromise of rise time and overshoot.

Notch-Filter, range of potentiometer too small:

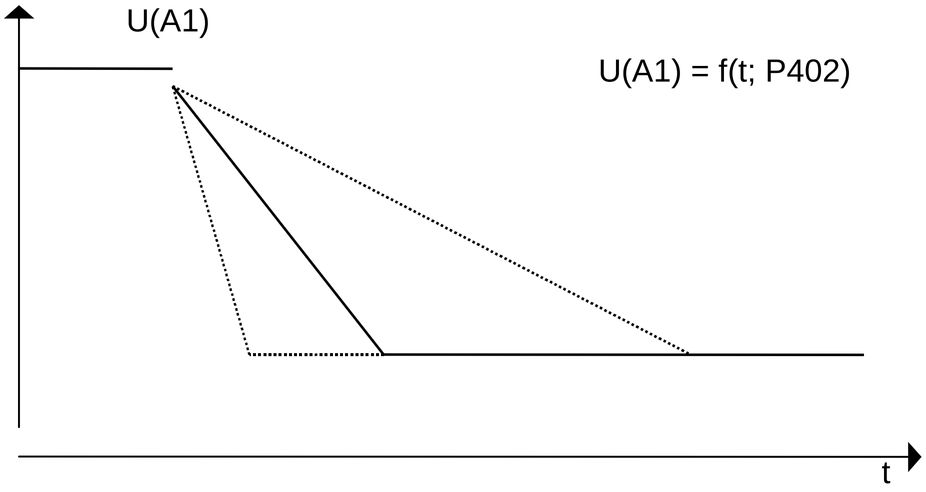
see table 2

8. Additional Test Points

Test point A1, Slew Rate; Servo ON and OFF

set required rise time, watch PZT voltage and Sensor value

Typical curve at positive input step:



After the rise time the input voltage has to be reached.

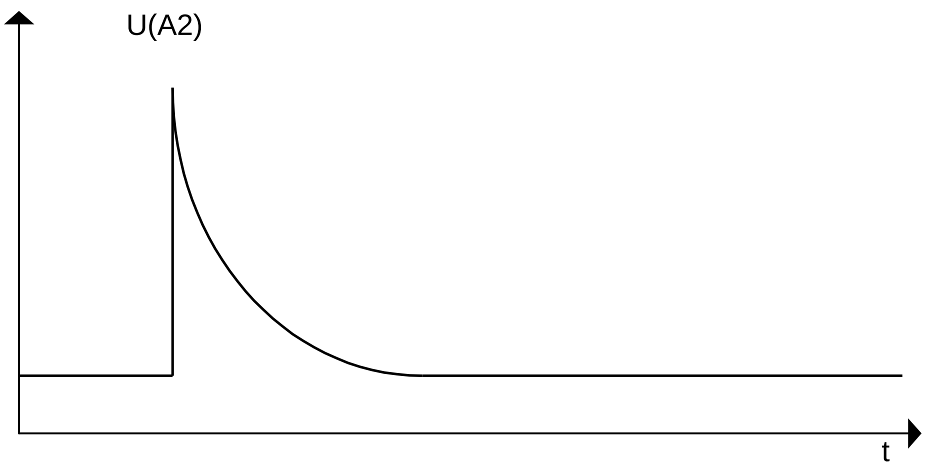
Note: This stage inverts the input signal.

Test point A2, compare point, only servoON

After settling this voltage must be zero.

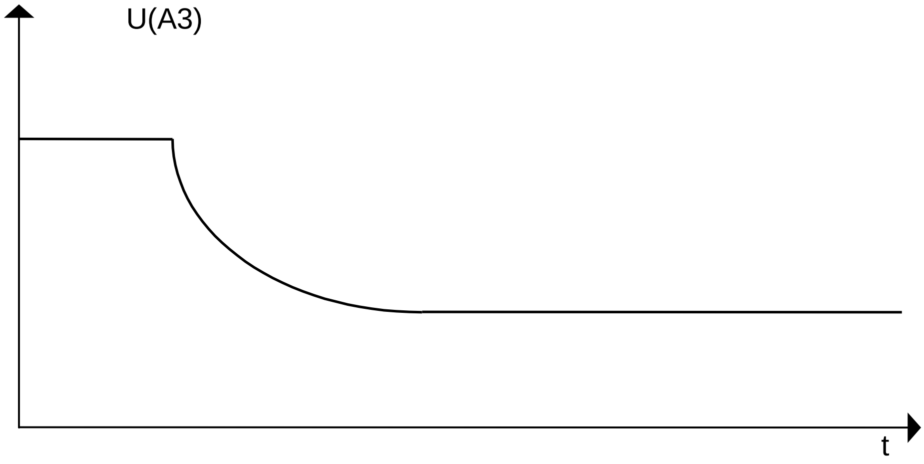
Note: If there is a permanent voltage, there is one place in the servo loop with unwanted limitation. (amplifier, PZT , Sensor or controller)

Typical curve at positive Input signal step.



Test point A3, Integrator, only Servo ON

typical curve at (positive) input step



Test Criterion: Voltage within the limits

max. -9.5V < U(A3) < 12,5V

typ. allowed input range of the amplifier.

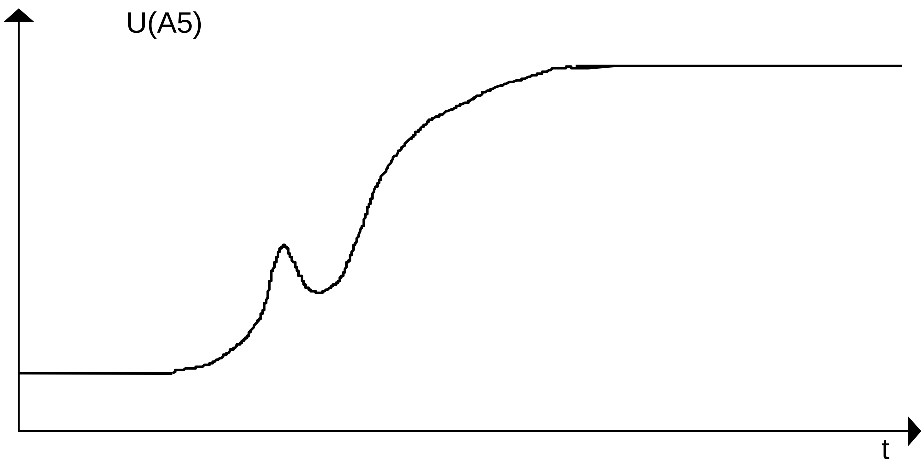
Servo OFF: Voltage equals the input voltage

Test point A4, Controller, only Servo ON

Test Criterion: Sum signal of test point A3 and test point A2 (inverted)

Test point A5, Notch, only Servo ON

Time response at input step depends on setting, Example:



Test Criterion : Final value equals input signal