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Technical paper

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DEVELOPMENT OF AN ELECTRONIC MEASUREMENT SYSTEM FOR TURBOCHARGER WASTEGATE ACTUATOR RESPONSE-TIME TESTING

ABSTRACT: A low-cost electronic measurement system for experimental determination of the response delay of a pneumatic turbocharger wastegate actuator is presented. The test bench separates the excitation and measurement functions: a programmable logic controller generates a repeatable command for a 24 V solenoid valve, while an ESP32-based acquisition unit independently observes the valve-coil voltage and two position sensors. Galvanic isolation is provided by a PC817 optocoupler. A linear potentiometer detects actuator-rod motion and a rotary potentiometer detects wastegate-flap motion. The acquisition algorithm includes edge validation, adaptive motion thresholds, oversampling and automatic session statistics. The achieved time resolution is approximately 0.33 ms. Experimental testing over 501 actuation cycles, of which 429 were retained for analysis, demonstrated repeatable detection of actuator and flap dead times and enabled the influence of pneumatic-line length to be distinguished. The proposed architecture is suitable for laboratory investigation of electropneumatic automotive actuators where the timing relationship between an electrical command and mechanical response is of primary interest.

KEYWORDS: wastegate actuator; turbocharger; ESP32; data acquisition; automotive mechatronics

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RAZVOJ ELEKTRONSKOG MERNOG SISTEMA ZA ISPITIVANJE VREMENA ODZIVA WASTEGATE AKTUATORA TURBOPUNJAČA

REZIME: Predstavljen je jeftin elektronski merni sistem za eksperimentalno određivanje kašnjenja odziva pneumatskog wastegate aktuatora turbopunjača. Na ispitnom stolu razdvojene su funkcije pobude i merenja: programabilni logički kontroler generiše ponovljivu upravljačku komandu za elektroventil napona 24 V, dok akviziciona jedinica zasnovana na ESP32 nezavisno prati napon na kalemu elektroventila i signale dva senzora položaja. Galvanska izolacija obezbeđena je pomoću optokaplera PC817. Linearni potenciometar registruje pomeranje klipnjače aktuatora, dok kružni potenciometar registruje pomeranje wastegate klapne. Algoritam za akviziciju obuhvata potvrdu ivice signala, adaptivne pragove detekcije pomeranja, oversampling i automatsko formiranje statistike merne sesije. Ostvarena vremenska rezolucija iznosi približno 0,33 ms. Eksperimentalna ispitivanja sprovedena tokom 501 ciklusa aktiviranja, od kojih je 429 zadržano za analizu, pokazala su ponovljivu detekciju mrtvog vremena aktuatora i klapne i omogućila izdvajanje uticaja dužine pneumatskog voda. Predložena arhitektura pogodna je za laboratorijska ispitivanja elektropneumatskih aktuatora u motornim vozilima kod kojih je od primarnog značaja vremenski odnos između električne upravljačke komande i mehaničkog odziva.

KLJUČNE REČI: wastegate aktuator; turbopunjač; ESP32; akvizicija podataka; mehatronika motornih vozila

INTRODUCTION

Precise boost-pressure control in turbocharged engines depends not only on the static characteristics of the wastegate actuator but also on the dynamics of the complete command chain (Thomasson et al. 2009). In a pneumatic wastegate system, the delay between the electrical command to the solenoid valve and the beginning of actuator motion includes electrical, pneumatic and mechanical contributions (Galindo et al. 2009; Szente & Vad, 2001). For experimental investigation of such short delays, the excitation source and the measurement system should be functionally separated, while the electrical command should be observed as close as possible to the boundary between the electrical and pneumatic domains.

The aim of this work is therefore to present the electronic and measurement architecture of a dedicated test bench developed for response-time measurements of a pressure-operated wastegate actuator. The mechanical and pneumatic arrangement is described only to the extent required to explain the measurement chain. Particular attention is given to galvanic isolation, acquisition of two displacement signals, robust detection of the excitation edge and the algorithm used to determine the beginning of motion.

TEST-BENCH CONCEPT AND MEASURED QUANTITY

The test bench consists of a pneumatic chain and an independent measurement chain. A Xinje XC3-32T-E programmable logic controller drives a 3/2 solenoid valve (3V210-06). The valve supplies a membrane-and-spring wastegate actuator through a polyurethane hose of 4 mm internal diameter. The actuator rod drives the wastegate flap through a lever mechanism. During the experiment the hose length was varied from 5 to 30 cm in 5 cm increments, while the remaining test conditions were kept unchanged.

The measured quantity is the dead time between the change of voltage at the solenoid-valve coil and the instant at which the corresponding position-sensor signal departs from its steady value by a prescribed threshold:

$$t_M = t_{det} - t_0 \tag{1}$$

Two dead times are obtained simultaneously: one for the actuator rod and one for the wastegate flap. Their difference provides an additional indication of the delay introduced by clearance in the mechanical linkage:

$$\Delta t = t_{M,\mathrm{flap}} - t_{M,\mathrm{rod}} \tag{2}$$

CONTROL AND ELECTRONIC MEASUREMENT SYSTEM

Functional architecture

The control and measurement functions are deliberately separated. The PLC generates the excitation, whereas the microcontroller only observes the excitation and sensor responses. The 24 V coil voltage is routed through an optocoupler to a digital input of the ESP32. At the same time, the ESP32 samples a linear potentiometer attached to the actuator rod and a rotary potentiometer attached to the flap shaft. Measured data are transferred to a computer through a serial USB connection. This architecture prevents the acquisition unit from participating in the control loop and reduces the possibility that its own command latency becomes part of the measured actuator delay.

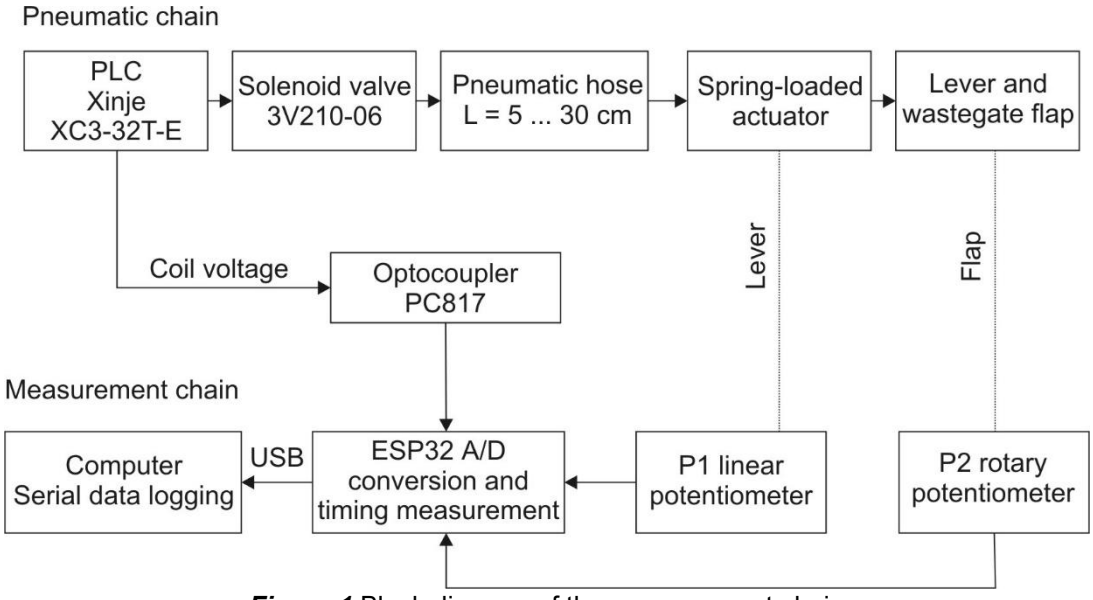


Figure 1 Block diagram of the measurement chain

Solenoid-valve excitation

The Xinje XC3-32T-E PLC generates a periodic excitation: output Y0 is ON for 1 s and OFF for 1 s. Two PLC timers alternately trigger each other, producing a 2 s period (0.5 Hz). The one-second interval between successive state changes is much longer than the measured dead time, allowing the actuator to reach a steady condition before the next transition. This provides repeatable initial conditions for opening and closing measurements.

Galvanic isolation and signal conditioning

The solenoid coil operates at 24 V, whereas the ESP32 uses 3.3 V logic. Direct connection is therefore unsuitable both because of the voltage-level mismatch and because switching an inductive coil can generate transient overvoltage and ground-coupled disturbances. A PC817 optocoupler is used between the control and measurement circuits. On the input side, a 5.6 kΩ series resistor limits the optocoupler LED current. On the output side, the phototransistor interfaces with ESP32 input IO18, with a 4.7 kΩ resistor defining the low state. The resulting logic is non-inverting: an energized solenoid corresponds to a high logic level at the microcontroller input.

During development, incorrect collector/emitter connection prevented reliable switching, and edge chatter was subsequently observed. The hardware connection was corrected and residual edge instability was handled in software by multi-sample validation and a lockout interval.

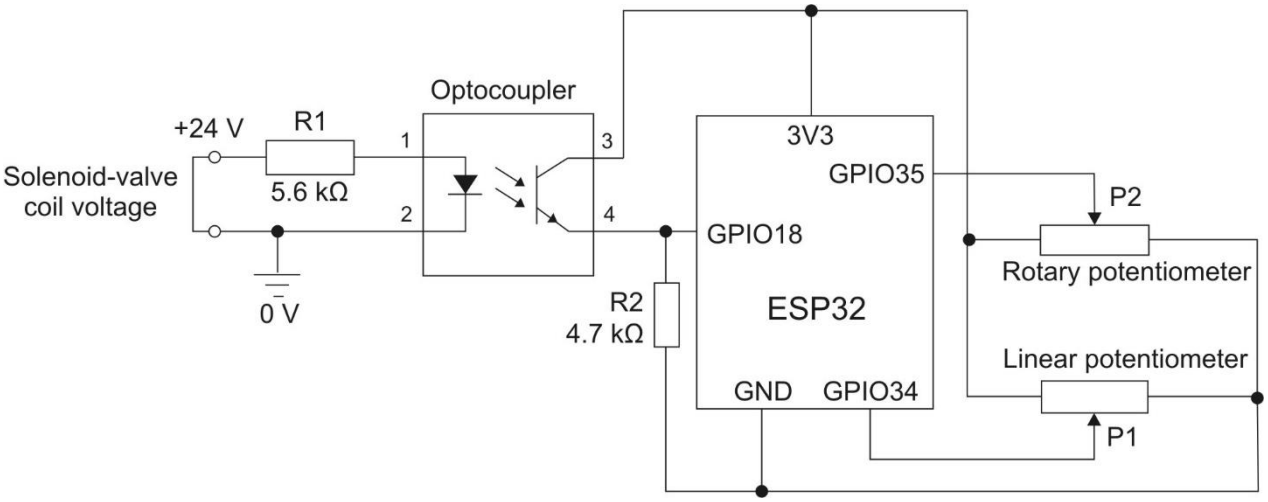


Figure 2 Electrical connection diagram

Position sensing and A/D acquisition

Two inexpensive resistive sensors are used because the measurement objective is the instant of motion onset rather than accurate absolute displacement. A 10 kΩ linear potentiometer with approximately 10 mm working stroke measures actuator-rod displacement, while a rotary potentiometer measures flap rotation over an effective angular range of approximately 15–20°. Both potentiometers are connected as voltage dividers between 3.3 V and ground, and their wipers are connected to ESP32 analog inputs IO34 and IO35. The ESP32 A/D converter is operated at 12-bit resolution. Each analog channel is read four times and averaged to reduce conversion noise.

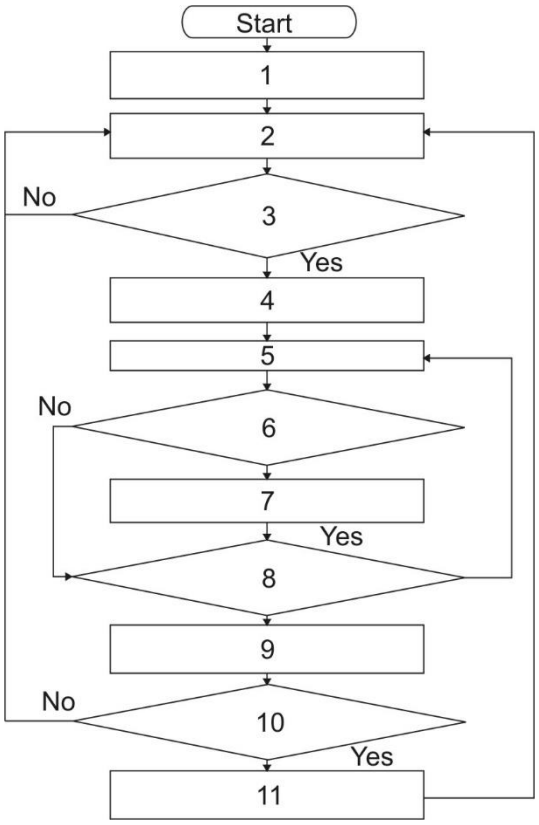
DATA-ACQUISITION ALGORITHM

Detection of the electrical reference instant

The program continuously reads the optocoupler output and both analog channels. A new solenoid state is accepted only after the same new digital level has been detected in eight consecutive reads. Importantly, the time stamp assigned to the transition is the time of the first sample in that sequence, so validation does not intentionally add eight-sample delay to the measured value. After a valid edge, further transitions are ignored for 200 ms. This suppresses residual chatter while remaining well below the approximately one-second interval between genuine transitions.

Adaptive detection of motion onset

The steady-state value of each position channel is continuously estimated from the mean of the latest 48 readings. The motion threshold is set to 4% of the measured signal travel for the corresponding channel. This adaptive approach is required because the linear and rotary potentiometers use substantially different portions of the A/D range. Motion is accepted only when the deviation exceeds the threshold in three consecutive readings; the time of the first of these readings is stored as the onset time. The first cycle of each measurement session is used to establish the signal travel and is excluded from subsequent analysis.



1. Configure A/D converter (12-bit) and serial communication with computer
2. Read signals from optocoupler and both potentiometers
3. Solenoid-valve state change confirmed over 8 readings?
4. Store transition time t_0, baseline values and threshold for each channel
5. Read both potentiometers
6. Channel deviation exceeds threshold in three consecutive readings?
7. Record dead time $t_M = t_{det} - t_0$
8. Both channels detected or 400 ms elapsed?
9. Output cycle data and update measurement-session statistics
10. 10 s elapsed without solenoid-valve state change?
11. Output measurement-session report and return to slow mode

Figure 3 Flow chart of the acquisition algorithm

Sampling rate and data output

Outside an active measurement, the program uses a 1 ms delay between loop iterations. After a valid excitation edge it enters a fast mode without the delay, achieving a time resolution of approximately 0.33 ms, corresponding to about 3 kHz. A measurement window is terminated after both channels have detected motion or after 400 ms. Each cycle is stored as a semicolon-separated record containing session number, cycle number, opening times, opening-time difference, closing times and closing-time difference. The software also calculates the mean, standard deviation, minimum and maximum values for the current session and automatically prints a session report after 10 s without further activity.

EXPERIMENTAL EVALUATION OF THE MEASUREMENT SYSTEM

Six pneumatic-line lengths (5, 10, 15, 20, 25 and 30 cm) were tested at a supply pressure of approximately 1.9–2.0 bar. A total of 501 actuation cycles were recorded and 429 were retained for analysis. The test programme was designed primarily to determine whether the measurement system could resolve physically meaningful changes in dead time and provide repeatable results.

Table 1 Opening dead time, mean value and standard deviation

Hose length [cm]	Rod opening [ms]	Flap opening [ms]	Accepted cycles
5	33.60 ± 1.01	41.15 ± 0.66	40
10	35.04 ± 1.01	42.12 ± 0.56	75
15	36.76 ± 1.20	44.40 ± 1.11	82
20	36.51 ± 1.19	43.25 ± 1.44	85
25	36.87 ± 1.19	43.80 ± 0.53	79
30	37.78 ± 1.20	45.84 ± 0.90	68

The measured opening delay increased with hose length. The fitted slope was 0.137 ms/cm for the actuator rod and 0.147 ms/cm for the flap, corresponding to approximately 1.4 ms additional delay per 10 cm of hose. Closing behaviour was different: the rod dead time remained near 26.9 ms and showed practically no dependence on hose length (reported fitted slope 0.003 ms/cm), while the flap showed only a weak dependence.

The distinction between the two position channels was also repeatable. During opening, the actuator rod preceded flap motion by an average of 7.29 ms and was detected first in all 429 accepted opening cycles. During closing, the average difference was 1.18 ms. The within-session scatter reported for the final data was approximately 0.7–3.3% of the measured value. These results demonstrate that the electronic system has sufficient temporal resolution and repeatability to separate the electrical-to-rod delay from the additional rod-to-flap delay.

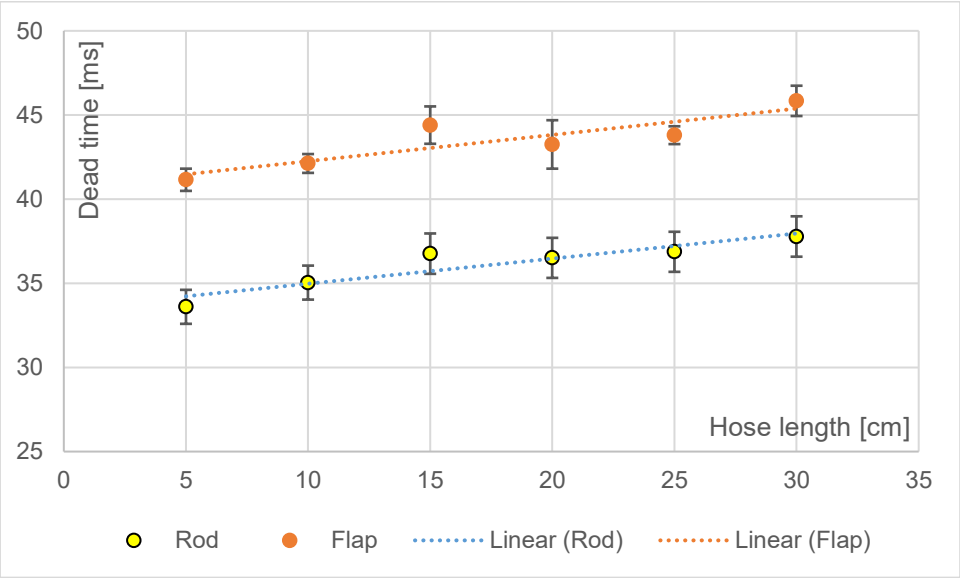


Figure 4 Opening dead time versus hose length

DISCUSSION

The main contribution of the presented test bench is not the use of individual low-cost components, but their organization into a measurement architecture in which excitation and observation are independent. Using the actual solenoid-coil voltage as the timing reference places t0 at the electrical/pneumatic interface and avoids including the controller's command-generation latency in the measured dead time. Galvanic isolation protects the 3.3 V acquisition electronics from the 24 V inductive circuit and prevents a common control-circuit ground from directly contaminating the analog sensor signals.

The software is an integral part of the measurement method. Multi-sample validation of the digital edge, oversampling of the analog inputs, adaptive thresholds and confirmation of motion over three consecutive samples were introduced specifically to suppress false detections. The achieved 0.33 ms loop resolution is small compared with the measured delays of roughly 27–46 ms. According to the thesis analysis, the maximum delay associated with three-sample confirmation is of the order of 1 ms, below approximately 3% of the measured quantity.

The principal limitations are that the wastegate flap was unloaded, tests were performed at room temperature, and pressure inside the actuator chamber was not measured. Consequently, the individual contributions of solenoid dynamics, pneumatic filling and mechanical friction cannot be separated. These limitations should be stated explicitly in a conference paper; they also define natural directions for further development, particularly the addition of a pressure transducer and testing under representative thermal and aerodynamic loading.

CONCLUSIONS

A dedicated electronic measurement system for wastegate-actuator response-time testing was developed and experimentally evaluated. The system combines PLC-based repeatable excitation, optically isolated observation of the 24 V solenoid-coil signal, two independent position sensors and ESP32-based data acquisition. Software filtering and adaptive event detection enabled reliable determination of the onset of rod and flap motion with approximately 0.33 ms time resolution. The system successfully distinguished changes in opening dead time caused by pneumatic-line length and consistently resolved the additional delay between actuator-rod and flap motion. The architecture therefore provides a practical low-cost platform for laboratory investigation of the dynamic response of electropneumatic automotive actuators.

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