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Research Article

Application of Artificial Swarm Intelligence to Enhance Kinematic Response of Piezoelectric Actuator for Precision Control

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Abstract: A hybrid control system is developed to manage the inherent nonlinearities of piezoelectric pneumatic servo valves, such as hysteresis and creep in this paper: A novel swarm-intelligence-based optimization approach. It unites the strong transient response of conventional control with adaptive intelligent algorithm capabilities. The controller's parameters are systematically tuned using Particle Swarm Optimization (PSO) in order to minimize overshoot, settling time and tracking errors. This scheme has been validated through simulations and experiments, greatly achieving oscillation suppression, response time acceleration as well as steady-state error reduction that will serve a solid foundation for high-precision pneumatic automation in industry.

Keywords: *Piezoelectric actuator, Pneumatic servo valve, Swarm intelligence, Hybrid process, Simulation, Dynamic.*

1. Introduction

Pneumatic servo systems utilize compressed air as a clean, safe, and inexpensive medium for energy transmission, making them vital in automated production, robotics, and manufacturing. Compared to other technologies, pneumatics combine the direct-load capabilities of hydraulics without fluid leak hazards, and the cleanliness of electric systems without needing complex mechanical transmissions. Additionally, they reduce explosion hazards in dangerous environments. However, air compressibility limits positioning accuracy, and traditional electromagnetic valves are bulky with slow response times. To overcome these dynamic constraints and achieve accurate high-speed positioning, researchers continuously improve control methods. This paper proposes a hybrid control system, combining a hybrid approach with a swarm-intelligence algorithm to significantly optimize the dynamic response and operational reliability of a piezoelectric pneumatic servo valve.

2. Litterature reviews

Basic Actuators utilized in the Industries

An actuator is one of the devices that converts a specific type of energy including air, electricity or liquid into mechanical work according to industrial functions such as clamping and pumping. These include the most common type, pneumatic actuators where pressure caused by compressed air powers a piston. They are often a choice for fast and accurate movement in manufacture, assembly & robotics together with electrical and hydraulic options.

1.0 Structure and Component of Bimorph Bender Actuator

Ring benders consist of multiple thin piezoceramic layers with internal silver-palladium electrodes linked to external ones. Applying voltage (typically -100 V to $+100\text{ V}$) triggers electromechanical behavior, causing the actuator to deform into either a convex or concave shape.

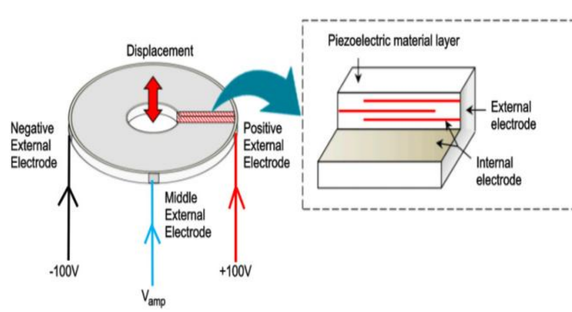

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Figure:1 Ring bender structure and component (Kim *et al*., 2021)

2.0 Structure and Component of Bimorph Bender Actuator

Bimorph (rectangular) benders feature two or three piezoceramic layers sandwiched between electrodes, sometimes with an internal metal alloy layer, designed to maximize the displacement-to-volume ratio. Polarized in opposite directions, the ceramic layers operate inversely (one contracting while the other expands). This opposing movement causes the plate actuator to bend when voltage is applied.

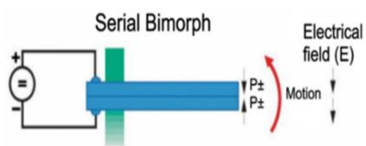

Figure:.2 Structure of bimorph bender actuator (Piezosystem, n.d.)

3.0 Structure and Component of Amplified Piezo Stack Actuator

An **amplified piezo stack actuator** uses an elliptical shell mechanism to convert and amplify axial deformation along its main axis into much larger displacement along its short axis.

This mechanical amplification allows the actuator to achieve substantial deformations of up to $1000\ \mu\text{m}$. However, this high displacement comes at the cost of its actuation force, which is significantly lower than a standard piezo stack.

A key advantage of this design is that the shell's thermal expansion coefficient matches the internal stack. This prevents detrimental heating effects, giving it a performance edge over alternative piezo stack designs

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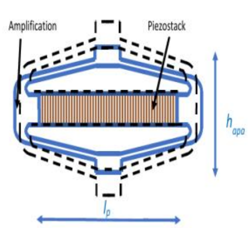

Figure 3: Schematic diagram of amplified piezo stack actuator with elliptical shell (Tamburrano *et al*., 2021)

4.0 Structure and Component of Piezo Stack Actuator

A typical **piezo stack actuator** consists of hundreds of individual piezoelectric layers ($25\text{ to }100\ \mu\text{m}$ thick) stacked together.

Electrical Configuration: The layers are wired in **parallel**, which reduces the voltage level required to generate the necessary electric field. The specific voltage depends directly on each element's thickness.

Mechanical Configuration: The layers are arranged in **series**. This allows the elongation of each individual layer to accumulate, producing a much larger overall displacement than a single element could achieve.

Ultimately, the stack's total displacement depends on this combined structural elongation.

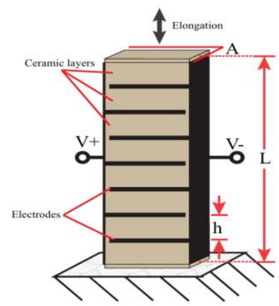

Figure 4: Piezoelectric stack actuator diagram (Zsurzsan *et al*., 2014)

5 Concept of LQR System

Overview of the Linear Quadratic Regulator (LQR)

A traditional optimal control method for dynamically oper ating a system at the lowest possible cost is the Linear Qu adratic Regulator (LQR).
Finding the best control signal to steer a system along an i deal state trajectory while reducing a specified quadratic p erformance index, or cost function, is the main goal of a L QR design.

$$\dot{x} = f(x(t), u(t), t)$$ --------------------------------(1)-

The Cost Function and Weighting Matrices

The LQR cost function penalizes both state errors and control effort. It relies heavily on two user-defined weighting matrices,

$$J = h(x_{tf}, t_f) + \int_{t_0}^{t_f} g(x(t), u(t), t)\,dt$$ _________________(2)

The Error Weighted Matrix, which must be positive semi-definite, penalizes deviations from the desired output vector, allowing prioritization of specific parameters through larger weights. Conversely, the Control Weighted Matrix must be positive definite, penalizing excessive control effort to avoid unrealistic or damaging input energy. The optimal control law applies these calculated gains via direct state feedback.To guarantee an optimal controller exists, the system's state space model must be verified for controllability and observability, meaning the ranks of their respective matrices must equal the system's state matrix rank. This ensures states are fully influenceable and estimable.

While selecting these tuning matrices traditionally relies on trial-and-error, an algebraic approach provides a systematic calculation method. By comparing the actual characteristic equation against a desired equation derived from specific performance metrics like undershoot and settling time, the Riccati equation can be solved directly, enabling the analytical calculation of the matrices rather than guessing.

6. PID Control Method

A Proportional-Integral-Derivative (PID) controller is a standard industrial control loop feedback mechanism. It calculates an error value as the difference between a measured process variable and a desired setpoint, minimizing this error by adjusting a manipulated variable. This three-term control structure provides optimum control dynamics, featuring zero steady-state error, fast response times, and high stability. Incorporating a derivative gain component alongside proportional and integral terms is essential to eliminate overshoot and oscillations in the output response. A primary advantage of the PID controller is its capability to effectively regulate higher-order processes with multiple energy storage elements, making it a robust, versatile choice for diverse industrial automation applications.

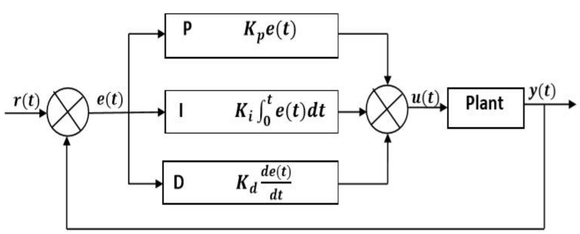

Figure 5: The Schematic Model of a PID Controller Configuration

A Proportional (P) controller functions as an amplifier with adjustable gain, establishing a continuous relationship between the controlled variable and the present error signal. Its primary purpose is to reduce steady-state error. Increasing the proportional gain factor decreases this error but cannot eliminate it entirely, meaning some offset will always remain in the system. The equation for P is

$u(t) = K_p e(t)$ --------------------------------------(3)

where u(t) = controller output, K_p = Proportional gain/sensitivity, and e(t) = actuating error signal

Integral Controller (I): In the integral controller action (also known as Reset Control), the output of the controller changes at a rate proportional to the actuating accumulation of past error signal e(t).

$u(t) = K_i e \int_0^t e(t)$ (t) --------------------------------- (4)

where K_i = Integral gain,

Derivative Controller (D): In a controller with derivative control action, the output of the controller depends on the rate of change of the actuating prediction of future error signal e(t). This type of controller cannot be used alone because when the error is zero or constant, the output of the controller will be zero. The equation for D is written as

$u(t) = K_d \frac{de(t)}{dt}$ ------------------------------------- (5)

where K_d = Derivative gain constant.

7. Trending important Pneumatic Systems review

The main focus of recent research is on using smart materi als,optimal geometries, and sophisticated control algorith ms to overcome the inherent drawbacks of conventional p neumatic systems, such as air compressibility, nonlinear fr iction, and poor response

times.

a. Piezoelectric Actuators and Smart Materials

Piezoelectric components are highly efficient and offer fast dynamic responses across various industries. Research shows piezoelectric stacks and high-speed valves achieve high flow rates and bandwidths, even under extreme temperatures, using mechanisms like rhombus-type amplification and fuzzy-PID control. These actuators successfully reduce the weight and leakage of traditional servo valves. Additionally, piezoelectric bimorphs significantly lower power consumption in medical devices, while flexible sensors combined with soft actuators enable advanced wearable technologies like haptic feedback gloves.

b. Mechanical Design & Optimization

Structural refinements mitigate internal disturbance forces in valve systems. Yang et al. (2021) used an aerostatic bearing to drastically slash static friction. Gui et al. (2022) optimized spool geometry via genetic algorithms and CFD, reducing mass and expanding band dynamic width by 26%. Furthermore, Kang et al. (2020) leveraged high-frequency longitudinal resonance to reduce internal friction and significantly boost tracking precision.

c. Advanced and Intelligent Control Schemes

To cope with the nonlinearities of complex systems, researchers are replacing the conventional controllers with more sophisticated ones. In fuzzy and neural engineering, Shi et al. (2019) linked ANFIS with low-cost valves to achieve minimal steady-state errors.Zhao et al. (2019) combined predictive fuzzy logic with neural networks. Teodoro et al (2018) proposed fuzzy-PD/PI control to solve dead-zone errors. Eze et al. (2021) showed that ANFIS is effective in solving nonlinear positioning. In terms of algorithmic choices, Qi et al. (2019) suggested model-predictive control to prolong hardware lifetime. Fractional order PID was used by Mazare et al. (2019) and Zhang et al. (2021) optimized friction models with differential evolution for high precision medical micro-grabbing. Shaikh et al (2024)

3. The Method

This study optimizes a piezoelectric pneumatic servo valve's dynamic response and positioning precision by countering asymmetric hysteresis, creep, and fluid compressibility. The technical framework is systematically organized into five sequential phases executed entirely within a simulated computer environment.

3.1 Plant Modelling and System Identification

Plant modeling and system identification begins with creating a precise mathematical model of the physical plant, accounting for fluid dynamics, pneumatic compressibility, and mass flow in pneumatic servo valves. It integrates the inverse piezoelectric effect and hysteresis, addressing the electrical-to-mechanical conversion and displacement-force-voltage tracking errors in high-speed piezoelectric systems.

3.2 Conventional Controller Formulations:

Then standard linear control benchmarks are obtained after system modeling by a PID controller tuned with an ITAE performance index. In the meantime, a LQR is designed whose state feedback matrix is derived via controllability and observability checks, balancing between state error minimization and control effort penalties.

3.3 Swarm Intelligent Controller Design:

To address higher-order nonlinearities affecting single-loop performance, an intelligent controller architecture employs a separate PID tracking configuration. The proportional, integral, and derivative gain constants are optimized using Particle Swarm Optimization (PSO), which iterates through particle swarms to identify optimal gains, minimizing settling time and overshoot.

4. Conclusion

This research proposal describes a systematic framework for the improvement of dynamic response of piezoelectric pneumatic servo valves. The conventional systems suffer from problems such as slow response and non-linearity. The study employs high-frequency piezoelectric actuators to enhance the mechanical conversion and control accuracy. It also proposes a multi-loop hybrid control system, which integrates a Linear Quadratic Regulator (LQR) with a Swarm Intelligent-tuned PID controller, to address issues such as integral windup. It achieves a good trade-off between quick responses and stability by the Integral of Time Absolute Error (ITAE) criterion. A cost-effective way to assess the performance improvement in terms of rise time, settling time and overshoot for the realization of reliable and high precision servo valves in industrial applications is through a verification phase in MATLAB/Simulink.

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