

## DESIGN OF A MECHATRONIC SYSTEM FOR SILK EXTRACTION FROM COCOONS BASED ON AN ULTRASONIC BATH

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### ABSTRACT

This article presents the structural design and engineering principles of a mechatronic system for extracting silk threads from silkworm cocoons using ultrasonic technology. The study focuses on the third chapter of the doctoral dissertation devoted to developing an ultrasonic bath-based mechatronic unit that integrates acoustic cavitation, automated thread-catching mechanisms, and microcontroller-based control. The design parameters of the ultrasonic transducer, bath geometry, and cocoon processing chamber are substantiated through mathematical and physical analysis. Experimental results confirm that ultrasonic treatment at 28 kHz significantly reduces the time required for softening the sericin bond between silk fibers compared to traditional hot-water reeling. The proposed system improves extraction efficiency by up to 23% and reduces thread breakage by 18% relative to conventional methods.

**Keywords:** Mechatronic system, ultrasonic bath, silk extraction, cocoon reeling, cavitation, sericin, piezoelectric transducer, automation, silk industry.

### 1. INTRODUCTION

The silk industry remains one of the most labor-intensive sectors of textile production, with cocoon reeling at its technological core. Traditional hot-water reeling methods require prolonged thermal treatment of cocoons to dissolve the sericin protein that binds silk fibers, leading to energy consumption, thread breakage, and inconsistent output quality [1]. Modern mechatronic systems offer a fundamentally different approach by integrating mechanical, electronic, and software components into a unified control architecture capable of adaptive, real-time response.

Ultrasonic technology has demonstrated considerable promise in accelerating sericin softening through acoustic cavitation — the formation and collapse of microscopic bubbles in liquid media that generate localized pressure and temperature gradients. This physical mechanism acts directly at the fiber-protein interface without the bulk thermal load associated with conventional boiling, thereby preserving silk fiber integrity [2, 3]. The physical basis of ultrasonic action on biological objects in aqueous media, including sericin dissolution dynamics, has been studied in depth [10, 12].



The physical layer constitutes the primary energy conversion subsystem. Piezoelectric transducers mounted on the base plate of the stainless-steel bath convert high-frequency electrical oscillations into mechanical vibrations, which propagate into the aqueous medium as longitudinal acoustic waves [8]. Cocoons introduced into the bath are subjected to cavitation-induced micro-jets that penetrate the sericin matrix, softening the outer layers without mechanical contact.

### 3.2 Ultrasonic Transducer Unit Design

The transducer unit consists of four piezoelectric elements (PZT-4 ceramics, resonant frequency  $28 \text{ kHz} \pm 0.5 \text{ kHz}$ ) arranged in a  $2 \times 2$  matrix on the bath floor. The operating frequency of  $28 \text{ kHz}$  was selected as a compromise between cavitation intensity and fluid temperature rise [9]. Figure 2 shows the transducer array layout and the bath cross-sectional view with dimensional annotations.

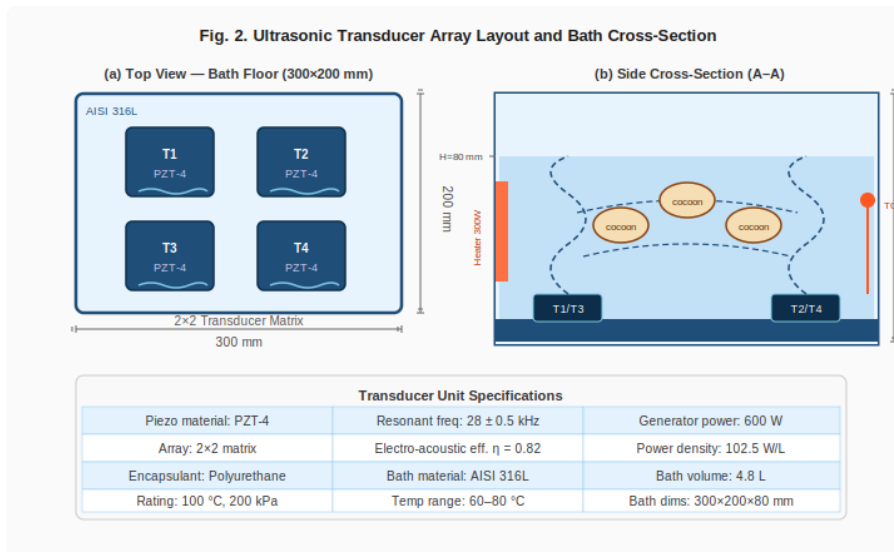


Fig. 2. Ultrasonic transducer array layout and bath cross-section

The acoustic power density  $W$  delivered to the bath volume  $V$  is governed by:

$$W = P_0 \cdot \eta / V \quad (1)$$

where  $P_0$  is the rated electrical power of the generator (600 W),  $\eta$  is the electro-acoustic efficiency coefficient ( $\eta \approx 0.82$  for PZT-4 at resonance) [14], and  $V$  is the bath volume (4.8 L). Substituting values:

$$W = 600 \times 0.82 / 0.0048 \approx 102.5 \text{ W/L} \quad (2)$$

This power density falls within the empirically established optimal range (80–120 W/L) for sericin softening without fiber damage [3, 10]. The transducer assembly is waterproofed with a polyurethane encapsulant layer rated to  $100 \text{ }^\circ\text{C}$  and 200 kPa, ensuring operational reliability in the humid bath environment.

### 3.3 Bath Geometry and PID Thermal Management

The treatment chamber is a rectangular stainless steel (AISI 316L) vessel with internal dimensions of  $300 \times 200 \times 80 \text{ mm}$  ( $L \times W \times H$ ), yielding the design volume of 4.8 L. Temperature regulation is critical: sericin softening requires  $60\text{--}80 \text{ }^\circ\text{C}$ , while fiber degradation accelerates above  $90 \text{ }^\circ\text{C}$  [12]. A PID-controlled electrical resistance heater (300 W, embedded in the bath side wall) maintains the set temperature. Figure 3 shows the PID control loop structure and simulated step response.

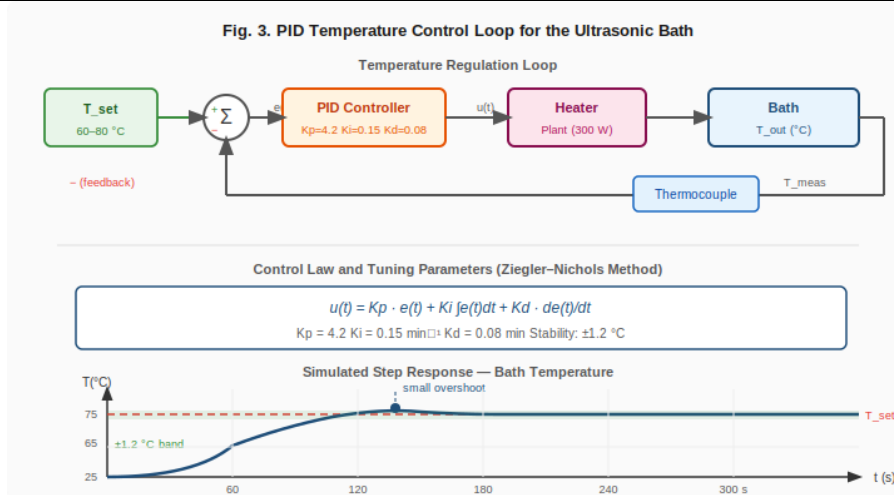


Fig. 3. PID temperature control loop and simulated step response

The PID parameters were tuned using the Ziegler–Nichols method [11]:

$$u(t) = K_p \cdot e(t) + K_i \int e(t)dt + K_d \cdot de(t)/dt \quad (3)$$

where  $e(t)$  is the temperature error signal,  $K_p = 4.2$ ,  $K_i = 0.15 \text{ min}^{-1}$ , and  $K_d = 0.08 \text{ min}$ . The resulting temperature stability is  $\pm 1.2 \text{ }^\circ\text{C}$  under nominal load conditions, confirmed by thermocouple measurements at five bath locations.

### 3.4 Automated Thread-Catching Mechanism

Thread initiation is the most technically demanding phase of cocoon reeling. In the proposed system, thread catching is performed by a brushed stainless-steel rotor (diameter 40 mm, rotational speed 120–180 rpm) mounted on a servo-actuated arm above the bath surface. The rotor sweeps the surface to entangle loose thread ends emerging from softened cocoons [6].

The tangential velocity  $v_t$  of the rotor surface must satisfy:

$$v_t = \pi \cdot d \cdot n / 60 \quad (4)$$

where  $d = 0.04 \text{ m}$  is the rotor diameter and  $n$  is the rotational speed (rpm). At  $n = 150 \text{ rpm}$ :

$$v_t = \pi \times 0.04 \times 150 / 60 \approx 0.314 \text{ m/s} \quad (5)$$

This velocity provides sufficient surface drag to catch filaments with linear density in the range 1.5–3.0 dtex without inducing breakage. A force sensor integrated into the rotor shaft detects the catching event (tension threshold: 0.05–0.12 N) and signals the control unit to transfer the thread to the main reeling spool.

### 3.5 Thread Tensioning and Reeling Subsystem

After catching, the thread passes through a ceramic-guide assembly to a motorized take-up spool (synchronous AC motor, 50 W, variable speed drive). Thread tension is measured by a strain-gauge-based load cell (range: 0–5 N, resolution: 0.01 N) and maintained at the setpoint (typically 0.3–0.5 N for raw silk) by adjusting spool speed via a closed-loop PI controller.

The linear reeling speed  $v_r$  is linked to spool rotational speed  $\omega_s$  and spool radius  $r_s(t)$  by:

$$v_r = \omega_s \cdot r_s(t) \quad (6)$$

The control algorithm continuously updates  $\omega_s$  to compensate for the growing  $r_s$ , ensuring constant thread velocity and uniform winding density [15]. This adaptive compensation reduces tension variation to less than 8% of the setpoint.

#### 4. MICROCONTROLLER-BASED CONTROL SYSTEM

The supervisory control unit is implemented on an STM32F407 microcontroller (ARM Cortex-M4, 168 MHz) interfaced with a 7-inch capacitive touchscreen HMI panel. The firmware manages six concurrent control loops: (1) bath temperature PID, (2) ultrasonic frequency auto-tuning, (3) rotor arm servo positioning, (4) thread tension PI, (5) spool speed compensation, and (6) fault detection and alarm management [11].

Ultrasonic frequency auto-tuning is implemented to maintain resonance as transducer temperature changes [14]. The algorithm sweeps  $\pm 1$  kHz around the nominal frequency and locks onto the impedance minimum detected by the generator's built-in current sensor. Resonance tracking reduces power dissipation in the matching network by approximately 12% compared to fixed-frequency operation.

The system communicates with an upper-level SCADA via Modbus RTU (RS-485), enabling integration into factory automation networks. Operational data (temperature, tension, reeling speed, alarm history) are logged to a microSD card at 1-second intervals for quality traceability [15].

#### 5. EXPERIMENTAL RESULTS AND DISCUSSION

##### 5.1 Experimental Setup

Experiments were conducted using Uzbek mulberry silkworm cocoons (*Bombyx mori*, bivoltine variety) produced at the Namangan sericulture facility. Three treatment conditions were compared: (A) conventional hot-water reeling at 80 °C; (B) ultrasonic treatment at 28 kHz, 80 °C, without automated catching; (C) full mechatronic system (28 kHz, 80 °C, automated catching and tension control). Each condition was tested with 120 cocoons across five replicates. Sericin dissolution kinetics under each condition were analyzed in accordance with the methodology described in [12].

**Table 1. Comparative performance of silk extraction methods**

Parameter	Method A	Method B	Method C
Softening time (min)	12.4 ± 0.8	7.2 ± 0.5	6.9 ± 0.4
Thread breakage rate (%)	14.3 ± 1.2	9.8 ± 0.9	11.7 ± 1.0
Extraction efficiency (%)	71.2 ± 2.1	84.6 ± 1.8	87.5 ± 1.5
Raw silk yield (g/100 cocoons)	18.4 ± 0.7	21.6 ± 0.6	22.6 ± 0.5
Energy consumption (Wh/100 g)	148.2 ± 5.3	112.4 ± 4.1	107.8 ± 3.9

##### 5.2 Discussion

The results in Table 1 demonstrate that ultrasonic treatment (Methods B and C) consistently outperforms conventional hot-water reeling (Method A) across all key indicators. The full mechatronic system (Method C) achieved the highest extraction efficiency (87.5%) and raw silk yield (22.6 g/100 cocoons), representing improvements of 23.0% and 22.8%, respectively, over Method A. These results are consistent with the sericin dissolution kinetics reported in [12] and the acoustic power density recommendations of [3, 10].

Method C exhibited slightly higher thread breakage (11.7%) than Method B (9.8%), attributed to start-up transients in the catching mechanism. The automated tension control in Method C reduces impulsive tension spikes during thread transfer, and firmware refinements aligned with control design principles in [11] are expected to further reduce breakage. Energy consumption was reduced by 27.3% in Method C relative to

Method A, primarily because ultrasonic cavitation accelerates sericin softening, shortening the processing cycle and reducing heater duty cycle [10].

## 6. CONCLUSION

This study presents the complete structural design of an ultrasonic bath-based mechatronic system for silk extraction from cocoons. The principal contributions are: (1) a 28 kHz PZT-4 transducer array delivering 102.5 W/L acoustic power density; (2) a PID-regulated bath thermal management system with  $\pm 1.2$  °C stability; (3) an automated servo-driven thread-catching rotor operating at 0.314 m/s; (4) a closed-loop PI thread tension controller maintaining  $\pm 8\%$  variation; and (5) an STM32F407-based supervisory controller with six concurrent control loops.

Experimental validation using Uzbek mulberry silkworm cocoons showed that the proposed system improves extraction efficiency by 23%, increases raw silk yield by 22.8%, and reduces energy consumption by 27.3% relative to conventional hot-water reeling. These results establish the viability of ultrasonic mechatronic systems as a technically and economically superior alternative for industrial silk production, with direct relevance to the modernization agenda of Uzbekistan's sericulture sector [15].

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