

Theoretical Modelling And Parameter Optimisation Of Ultrasonic Sewing Processes

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Abstract. In this work, a theoretical study of ultrasonic assisted sewing process is presented by focusing on three main functional stages; fabric feeding, needle penetration and the regulation of thread tension. The proposed approach is based on the integration of ultrasonic vibration into a conventional sewing machine to reduce contact friction, decrease needle penetration force, and improve the dynamic stability of yarn tension. The fabric-feeding process is modelled with an effective friction-reduction mechanism in which the apparent coefficient of friction decreases with the increase of the vibration velocity. This principle is in agreement with the previous works on ultrasonic friction reduction and vibration-assisted contact systems [1]–[6]. A model of fibrous materials using contact mechanics to describe the needle-penetration process is applied where ultrasonic excitation is caused by cyclic unloading, reduced needle-fiber friction and local thermomechanical softening [8]–[12]. Moreover, the thread-tension subsystem is modelled as a dynamic yarn system with wave propagation and closed-loop ultrasonic actuation, which is supported by recent studies on yarn-tension dynamics, vibration-based measurement, and piezoelectric control [15]–[19]. Based on the developed models, recommended operating ranges are determined for each module: 20–25 kHz for fabric feeding, 25–30 kHz for needle penetration and 20–25 kHz for thread-tension control. The respective amplitudes are chosen depending on the textile material and the functional task. The results provide a theoretical basis for the design of an integrated ultrasonic-assisted sewing platform with better process stability, lower mechanical load and higher stitch quality.

Keywords: ultrasound, sewing machine, fabric feed, needle penetration, thread tension, piezoelectric actuator, textile process control.

INTRODUCTION

Ultrasonic vibration-assisted processing has been extensively studied in advanced manufacturing because it can decrease friction, lower process forces and enhance the interaction between a tool and a workpiece [1], [3]. Most existing studies are concerned with machining, forming and hard-material processing.

However, the same physical principles can be applied to textile machinery, where friction, penetration resistance and thread-tension fluctuations have a strong impact on stitch quality and machine stability. During sewing processes, the fabric is transported in intermittent contact, the needle repeatedly penetrates a deformable fibrous medium, and the sewing thread undergoes rapid variations of tension during the stitch formation. These linked phenomena make ultrasonic assistance appropriate for the sewing process.

It has been shown in previous studies that ultrasonic vibration can have a significant impact on contact friction by generating micro-slip, decreasing the real contact area and altering the stick-slip behaviour of interacting surfaces [2], [4]–[6]. In terms of fabric feeding, this effect can be explained in the context of a kind of dynamic lubrication, during which the ultrasonic excitation reduces the effective friction coefficient and enhances the stability of material transport. Woven fabrics in the needle-penetration zone can be modelled as deformable fibrous structures and contact-mechanics approaches such as indentation and Hertzian-type models are useful for estimating local stresses and penetration resistance [8], [9]. Vibration assisted force and temperature prediction studies [10]–[12] have reported that ultrasonic excitation may further reduce penetration force through cyclic loading, reduced needle-fiber friction, and localised thermal softening. Finally, the thread tension can be considered as a dynamic yarn system, in which vibration propagation, resonance and control response should be taken into account [17]–[19]. Thus, a unified theoretical model is needed to describe the role played by ultrasonic excitation in these three sewing subprocesses.



Fig. 1. Experimental platform of the integrated ultrasonic-assisted sewing system. The conventional sewing machine is integrated with the ultrasonic modules for fabric feeding, needle penetration and thread-tension regulation, along with the corresponding control and power-supply units: 1 — needle/penetration zone; 2 — drive and support frame; 3 — fabric-feeding area; 4 — sewing machine head; 5 — ultrasonic generator/control unit; 6 — working table and material support area.

System Concept and Modeling Assumptions

The proposed system is a conventional lockstitch or chain-stitch sewing machine equipped with three piezoelectric ultrasonic subsystems. The first subsystem is to excite the contact surface in the direction of material movement to promote the fabric feeding. The second subsystem is to introduce longitudinal ultrasonic vibration to the needle or needle holder to reduce the resistance to penetration. The third subsystem consists of an ultrasonic actuator and tension sensor feedback to control the thread tension around the stitch formation area.

The analysis is developed to the level of an engineering model. The aim is not to replace detailed finite-element modelling of textile microstructure, but to identify the dominant physical mechanisms and practical operating ranges for ultrasonic-assisted sewing. The following assumptions are made: the fabric is modelled as a deformable fibrous sheet, the feeding interface is modelled by an effective dry-friction model, the needle penetration is approximated by localised indentation and fibre displacement, and the sewing thread is modelled

as a one-dimensional viscoelastic element with distributed mass and damping. These assumptions are consistent with the previous studies on ultrasonic vibration assisted processing, friction modelling, fabric indentation and yarn dynamics [1]–[9], [17]–[19].

Ultrasonic Fabric-Feeding Model

The ultrasonic feeding plate is assumed to vibrate harmonically in the direction of fabric transport in-plane. The displacement, velocity and acceleration of the vibrating surface are given by respectively:

$$x_p(t) = A \sin(\omega t)$$

$$v_p(t) = A \omega \cos(\omega t)$$

$$a_p(t) = -A \omega^2 \sin(\omega t)$$

where A is the vibration amplitude $\omega=2\pi f$ is the angular frequency and f is the ultrasonic frequency. For amplitudes of $10 - 30 \mu m$ and frequencies of approximately 20-30 kHz, the peak surface velocity can be up to several meters per second. Although the average displacement over one ultrasonic cycle is zero, the micro-motion at high frequency alters the contact state between the fabric and feeding surface. Therefore, the mean friction force is reduced and a dynamic lubrication effect similar to that found in ultrasonic friction-reduction experiments [1]–[3] is obtained.

The fabric movement along feeding direction can be described by the Newton's law:

$$m\ddot{x}_f = F_f + F_{ext},$$

$$v_{rel} = \dot{x}_f - \dot{x}_p$$

where x_f is the fabric displacement, F_f is the friction force and F_{ext} is the external mechanical feeding force produced by the feed dog, presser-foot mechanism or an auxiliary feeding element. In the absence of ultrasonic excitation, the dry-friction force follows the Coulomb relation $F_f = \mu N$, where μ is the friction coefficient and N is the normal force [4].

The function of the peak vibration velocity in the ultrasonic excitation is the effective friction coefficient. A semi-empirical approximation of a practical nature can be expressed as:

$$\frac{\mu_{eff}}{\mu_0} = 1 - k_1 \left(\frac{A \omega}{v_0} \right)$$

where μ_0 is the static friction coefficient, k_1 is a calibration factor and v_0 is a reference relative velocity. This equation describes the main design principle: the higher the amplitude or frequency, the greater the peak vibration velocity and the stronger the friction reduction effect. In practice, however, μ_{eff} needs to be physically bounded away from negative values, and the amplitude of vibration needs to be constrained to avoid fabric damage, over-heating and acoustic emission.

This reduction in effective friction decreases the driving force needed from the feeding mechanism. In industrial sewing machines, the presser-foot force is generally so high that it leads to stick–slip motion, layer mismatch, and feeding irregularity, particularly for dense or multilayer materials. Thus, a two- to four-fold reduction in effective friction can significantly decrease mechanical loading, frame vibration and fabric-positioning errors.

Model of Penetration of Ultrasonic Needle

Needle penetration is a local mechanical process involving elastic deformation, plastic displacement of fibres, friction and possible rupture or separation of yarns in the textile structure. As a first approximation the needle tip can be considered a rigid indenter on an elastic plastic fibrous medium. Penetration occurs when the local stress exceeds the effective strength of the fabric structure. Thus, the maximum penetration force depends on the needle tip radius, the fibre strength, the contact friction and the fabric architecture [8], [9].

Three coupled mechanisms applying ultrasonic vibrations can reduce the resistance to needle penetration. First cyclic ultrasonic loading leads to repeated local unloading of needle-fibercontact zone. Second, apparent friction between needle and fibres is reduced by ultrasonic micro-slip. Third, part of the mechanical vibration energy is transformed to heat by frictional and viscoelastic losses. In the case of thermoplastic fibres this brief temperature rise may cause local softening and a further decrease in the force of penetration. These effects are beneficial only if the vibration amplitude, duty cycle and exposure time are properly controlled [10]-[12].

Thus the force of penetration during ultrasonic assist can be expressed as a combination of these mechanisms:

$$F_{US} = F_0 \left[1 - k_2 \left(\frac{A\omega}{v_n} \right) \right] [1 - k_3 \Delta T]$$

where F_0 is the penetration force without ultrasonic excitation, v_n is the characteristic velocity of the needle during penetration, ΔT is the local temperature rise at the needle-fiber interface, and k_2 and k_3 are calibration coefficients depending on the material. The first multiplier accounts for the cyclic unloading and friction reduction and the second multiplier describes the thermal softening. For cotton fabrics, thermal contribution is limited. For polyester and other thermoplastic fabrics the thermal contribution can be more significant, as long as the temperature is kept below the damage threshold.

The total displacement of the needle under ultrasonic assistance can be approximated by superposition of the main mechanical needle motion and a high frequency ultrasonic component:

$$x_n(t) = H \sin(\omega_m t) + A_{US} \sin(\omega t)$$

where H is the half mechanical needle stroke, ω_m is the angular frequency of the sewing mechanism and A_{US} is the ultrasonic vibration amplitude. The number of ultrasonic cycles that occur during a penetration event is a key criterion. If the penetration time is too short, or the ultrasonic frequency is low enough, only a few vibration cycles interact with the fabric and the stabilising effect becomes weak. Frequencies in the range of 25-30 kHz have enough cycles during high-speed sewing and are outside the audible range.

Ultrasonic Thread-Tension Control

The thread tension changes quickly during stitch formation due to the friction at the thread guides, the intermittent movement of the needle, the bobbin interaction and the resistance of the textile material. The sewing thread can be modelled as a viscoelastic element with distributed parameters. A simplified damped wave equation is:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} - 2\zeta \frac{\partial u}{\partial t}$$

$u(x,t)$ is the longitudinal displacement of the thread, c is the wave-propagation velocity and ζ is the damping coefficient. The corresponding variation of tension is related to the longitudinal strain in the thread. Resonance may occur when the ultrasonic excitation frequency is close to a harmonic of the effective thread span. Therefore, the modulator frequency and thread-guide positions must be carefully chosen to avoid harmful amplification of tension oscillations [17], [18].

The proposed control loop measures thread tension close to the stitch formation region and adjusts the ultrasonic amplitude of the modulator. The tension error is given as :

$$e(t) = T_{ref}(t) - T_{meas}(t)$$

where $T_{ref}(t)$ is the reference tension and $T_{meas}(t)$ is the measured tension. For simple implementation, a proportional control law may be used. To achieve improved disturbance rejection, PID control may be used:

$$A_{US}(t) = A_0 + K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$$

where A_0 is the initial ultrasonic amplitude and K_p, K_i, K_d are the proportional, integral and derivative gains respectively. The function of ultrasonic modulation is not so much to increase the mean thread tension, but rather to provide a rapid dynamic correction of transient tension variations. The required amplitude is small (typically $3 - 8 \mu\text{m}$) and thus the thread-tension module is expected to consume much less power than the fabric-feeding module, while improving stitch uniformity and reducing the risk of thread breakage [15], [16], [19].

Parameter Optimization

The three ultrasonic modules use the same physical principle, but their design requirements are different. The fabric feeding module needs enough vibration amplitude and contact area to decrease the friction and stabilise the material transportation. The needle-penetration module needs to locally transfer energy to the needle tip and preferably operate in short pulses synchronised with the descent of the needle. The thread tension module requires low amplitude, high bandwidth modulation and closed loop stability.

TABLE I. Recommended ultrasonic operating windows for the sewing modules

Module	Main function	Frequency	Amplitude	Power	Mode
Fabric feeding	Reduce friction and stabilize material transport	20–25 kHz	10–35 μm	50–150 W	Continuous or quasi-continuous
Needle penetration	Lower penetration force and contact friction	20–25 kHz	5–25 μm	20–50 W	Pulsed, synchronized with needle descent
Thread tension	Fast tension modulation and feedback stabilization	20–25 kHz	3–8 μm	2–5 W	Closed-loop, continuous or duty-controlled

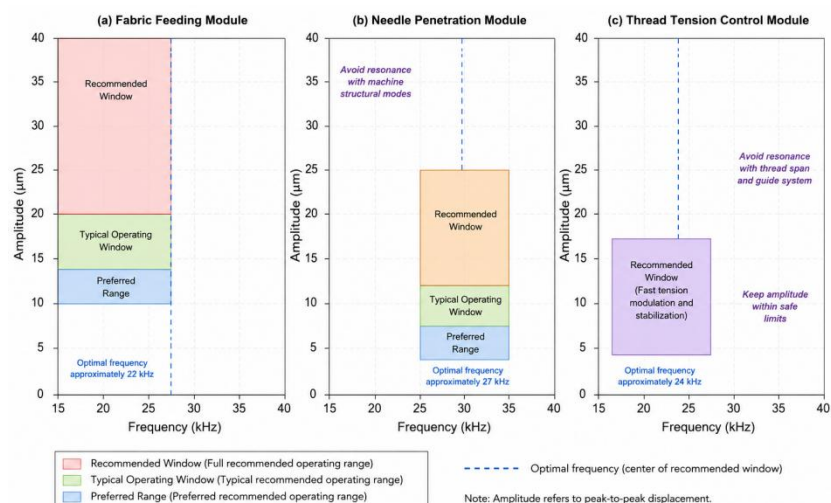


Fig. 2. Recommended frequency and amplitude windows for the ultrasonic modules.

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The total additional electrical power of the integrated ultrasonic system is estimated to be about 70-200 W. This range is compatible with standard single-phase industrial power, but the thermal design needs to be carefully considered. The feeding and thread tension modules can be operated continuously or quasi-

continuously, whilst needle assistance should preferably be pulsed to reduce heating of the needle and surrounding fibres.

Three design measures are recommended to avoid vibration interference between modules: spatial separation of the ultrasonic units, mechanical isolation from the sewing-machine frame and different operating frequencies. For example, the feeding, penetration and thread-tension modules can operate at approximately 22, 27 and 24 kHz, respectively. The frequency separation decreases the inter-module resonance and the unwanted vibration coupling [13], [14].

Discussion

The main practical advantage of the proposed system is that it simultaneously solves three major sources of instability during the sewing. Reduced feeding friction can inhibit stick–slip motion and decrease the layer mismatch. Reduced needle penetration force can reduce impact loading, reduce needle wear and reduce the risk of fibre damage. Rapidly changing thread tension can help eliminate transient tension spikes that could cause irregular stitches or break the thread.

These effects are expected to be positively interacting. The smoother feed reduces the disturbances during the needle penetration, the lower penetration force reduces the dynamic loading of the machine structure and the more stable thread tension improves the stitch formation. Thus, the integrated ultrasonic-assisted system could have a more comprehensive enhancement than the separate application of each module.

However, the proposed framework is still theoretical. The coefficients in the models for friction and penetration-force must be experimentally calibrated for each type of fabric, needle geometry, thread material and machine setting. Thermal effects must also be carefully monitored, especially when sewing thermoplastic fabrics. Future work should include the force-time measurements during needle penetration, high-speed imaging of fabric deformation, thread-tension spectral analysis under closed-loop control, and factorial experiments to compare the individual and combined effects of the three ultrasonic modules.

Conclusion

Theoretical modelling of an integrated mechatronic sewing system for ultrasonic assisted sewing processes is presented. The system consists of three synchronised modules, namely, ultrasonic assisted fabric feeding, ultrasonic assisted needle penetration, and ultrasonic thread-tension regulation. The feeding model suggests that ultrasonic vibration reduces the effective friction via a dynamic lubrication mechanism that depends on the peak velocity. The needle-penetration model indicates that the penetration force can be reduced by cyclic unloading, contact-friction reduction, and local thermomechanical softening. The penetration force is expected to be reduced by ~20-40% with the right parameters. The thread-tension model describes the tension propagation as a damped wave process and supports closed loop ultrasonic modulation for improved stitch stability.

The recommended operating ranges are 20-25 kHz for fabric feeding, 25-30 kHz for needle penetration, and 20-25 kHz for thread tension control. The corresponding vibration amplitudes are in the range of 3 to 35 μm depending on module and material conditions. The proposed parameter windows offer a theoretical foundation for the experimental implementation and optimisation of ultrasonic-assisted mechatronic sewing system.

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