SELECTION OF OPTIMIZED CUTTING REGIMES FOR VIBRATION REDUCTION IN THE TURNING OF GUN BARRELS

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Abstract

This study focuses on the reduction of self-excited vibrations (regenerative chatter) during the turning of gun barrels by selecting optimized cutting regimes. Owing to the high length-to-diameter ratio of barrel blanks (L/D ≈ 26), the machining system exhibits low stiffness, which significantly increases vibration intensity, leading to poor surface quality, accelerated tool wear, and reduced productivity. To address this, a series of experimental trials were carried out on AISI 4340 steel specimens with a length of 800 mm and a diameter of 30 mm under different cutting conditions. Modal analysis through impact testing revealed a fundamental natural frequency of 720 Hz and a damping ratio of 0.032.

A total of 32 experiments were performed with spindle speeds between 400 and 1600 rpm, feed rates from 0.05 to 0.20 mm/rev, and depths of cut ranging from 0.2 to 0.8 mm. The results demonstrated that stability-lobe-based parameter selection reduced vibration amplitude by up to 40% and surface roughness (Ra) by about 25%. Passive tuned mass dampers (TMD) integrated into the toolholder achieved an average reduction of 30–35% in vibration intensity, while ultrasonic vibration-assisted turning (UVAT) at 20 kHz frequency and 15 µm amplitude lowered cutting forces by 20–25% and improved surface roughness by 18–22%. A multi-objective optimization using a genetic algorithm determined the most favorable cutting regime as spindle speed 1180 rpm, feed rate 0.08 mm/rev, and depth of cut 0.40 mm, achieving Ra ≈ 0.65 µm, vibration RMS ≈ 0.20 g, and an estimated 25% increase in tool life.

The findings confirm that vibration suppression in barrel turning requires an integrated approach combining dynamic identification, stability lobe analysis, and damping technologies. The optimized regimes proposed in this study provide practical and effective solutions for precision gun barrel manufacturing.

Keywords: Vibration, suppression, chatter, gun barrel , tool life

Introduction. The machining of gun barrels represents one of the most demanding processes in precision engineering and defense manufacturing, requiring exceptional dimensional accuracy, surface integrity, and process stability [1]. The functional performance and ballistic reliability of firearms are strongly dependent on the precision of the machining operations carried out during barrel production [2]. In practice, the inner and outer surfaces of barrels are expected to meet stringent requirements, with average surface roughness values (Ra) often specified below 0.8 µm, and geometric tolerances such as cylindricity and concentricity restricted to within 10–15 µm. Meeting these requirements is particularly challenging due to the geometry of barrel blanks, which typically have lengths in the range of 600–900 mm and diameters of only 20–40 mm, leading to length-to-diameter ratios (L/D) that frequently exceed 20–30. Such high slenderness ratios result in low structural stiffness, rendering the system prone to excessive vibration during turning operations [3].

The dominant form of vibration encountered in barrel turning is regenerative chatter, a self-excited vibration mechanism that arises from the interaction between the tool and the wavy surface left by previous tool passes [4]. This phenomenon not only deteriorates surface quality but also accelerates tool wear, reduces tool life, and limits the achievable material removal rate [5]. Prior studies have shown that chatter can cause up to 30–40% reduction in process efficiency if left uncontrolled.

Several researchers have attempted to address the problem of chatter in turning operations. Budak (1994) developed analytical stability lobe theory, demonstrating that careful selection of spindle speeds can expand the stable machining zones and allow larger depths of cut without chatter [6]. Altintas and Weck (2004) further refined this concept by integrating adaptive control methods, achieving higher prediction accuracy [7]. Tlusty (2000) highlighted that even small changes in feed rate or depth of cut can lead to significant improvements in chatter stability, though his approach remained primarily empirical [8]. More recently, Kang et al. (2023) demonstrated that ultrasonic vibration-assisted turning (UVAT) at a frequency of 20 kHz and amplitude of 15 µm can reduce cutting forces by 22% and tool wear by 18% [9], while Sørby (2012) showed that passive tuned mass dampers (TMDs) integrated into boring bars can suppress vibration amplitudes by 30–40% [10].

Despite these advances, the existing body of literature exhibits certain limitations [11]. Theoretical models often assume constant system stiffness and damping, which do not adequately represent real industrial environments where clamping conditions, tool wear, and material inhomogeneity continuously alter the system dynamics [12]. Adaptive control approaches, while promising, require expensive sensor networks and complex implementation. UVAT provides significant benefits but involves high equipment costs and technological complexity, restricting its widespread application. Passive dampers, although simple and cost-effective, are typically effective only within narrow frequency ranges [13].

The present study seeks to address these gaps by combining theoretical stability lobe analysis with real experimental validation. AISI 4340 steel blanks with L/D ≈ 26 were subjected to turning trials across a wide range of cutting conditions, with vibration, surface quality, cutting forces, and tool wear carefully measured. Both passive damping (TMD) and UVAT were tested alongside conventional regimes, and the data were processed using a genetic algorithm for multi-objective optimization. The aim of this work is to determine cutting regimes that minimize vibration and surface roughness while extending tool life, thereby providing a practical and reliable methodology for precision gun barrel manufacturing.

Literature Review. The challenge of suppressing chatter and vibrations in turning operations has been extensively studied, and several methods have been proposed in the literature to improve process stability and surface integrity. However, each approach has its strengths and limitations, leaving space for further development.

Budak (1994) introduced analytical stability lobe theory, which has become one of the most widely applied methods for chatter prediction in machining [14]. The strength of this approach lies in its ability to identify chatter-free spindle speed zones and expand the usable depth of cut without instability. Nevertheless, the model assumes constant stiffness and damping, which does not fully represent the dynamic variability of machine–tool–workpiece systems under industrial conditions.

Altintas and Weck (2004) developed adaptive control methods that integrate stability models with sensor-based feedback systems [15]. This approach offers high accuracy and the ability to adjust machining conditions in real time. Its limitation, however, lies in the complexity and high cost of implementation, which restricts its application in conventional industrial setups.

Tlusty (2000) highlighted the influence of basic cutting parameters on chatter suppression, showing that changes in spindle speed, feed rate, and depth of cut can significantly improve stability. While practical and straightforward, this trial-and-error method lacks predictive capability and generalizability across different workpiece geometries and materials [16].

Kang et al. (2023) explored ultrasonic vibration-assisted turning (UVAT) as a modern chatter suppression technique [17]. Their experiments demonstrated that applying 20 kHz vibrations with an amplitude of 15 µm reduced cutting forces by approximately 22% and tool wear by 18%. The major advantage of UVAT lies in its ability to alter the cutting mechanism at the tool–chip interface, improving machinability of hard-to-cut materials. However, the requirement for additional ultrasonic equipment makes industrial adoption challenging due to cost and system complexity.

Sørby (2012) investigated the application of tuned mass dampers (TMDs) in boring operations [18]. These passive devices, when integrated into toolholders, were shown to reduce vibration amplitudes by 30–40%. The main strength of TMDs is their simplicity, low cost, and effectiveness for long slender tools such as boring bars. The limitation, however, is that their efficiency is restricted to a narrow frequency range, and their performance decreases when cutting conditions deviate from the design point.

Summary and contribution of this work: The reviewed literature confirms that while individual methods provide meaningful improvements, none of them alone offer a universal solution for chatter suppression in gun barrel turning. Theoretical models lack robustness in dynamic industrial environments, adaptive control is expensive, passive dampers are frequency-dependent, and UVAT requires specialized equipment [19]. This study seeks to overcome these shortcomings by integrating stability lobe analysis with experimental validation, while simultaneously testing passive damping and ultrasonic assistance. Furthermore, by applying a multi-objective genetic algorithm, this research proposes cutting regimes that balance vibration suppression, surface quality, and tool life, thus filling the gap between theory and practical application in precision barrel manufacturing.

Methodology. The methodology of this research combined theoretical modeling with experimental validation in order to determine optimized cutting regimes for vibration suppression in gun barrel turning. The study began with the dynamic identification of the machine–tool–workpiece system, followed by systematic cutting trials and multi-objective optimization.

The regenerative chatter mechanism was modeled by the classical delay-differential equation [20]:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F_c(t) + K \cdot x(t-\tau)$$

where mmm is the equivalent mass, c the damping coefficient, k the stiffness, $F_c(t)$ the cutting force, K the regeneration constant, and τ the time delay corresponding to one spindle revolution. The critical depth of cut was estimated through the frequency response function (FRF):

$$a_{p,crit} = \frac{-1}{2K} \cdot \Re\left[\frac{1}{G(j\omega)}\right]$$

where $G(j\omega)$ represents the frequency response of the system. Stability lobes were constructed from this formulation to identify chatter-free machining zones.

The experimental trials were carried out on AISI 4340 steel blanks with dimensions of 800 mm in length, 30 mm in outer diameter, and 8 mm in inner diameter, yielding a slenderness ratio of approximately L/D = 26. TiAlN-coated carbide inserts (ISO CNMG 120408) were used as cutting tools, mounted on a CNC lathe with a maximum spindle speed of 3000 rpm and a power capacity of 11 kW.

A full factorial design was adopted with spindle speeds of 400, 800, 1200, and 1600 rpm; feed rates of 0.05, 0.10, 0.15, and 0.20 mm/rev; and depths of cut of 0.2, 0.4, 0.6, and 0.8 mm. This resulted in a total of 32 cutting trials. Each trial was conducted under steady-state conditions for 60 seconds.

Vibrations were measured using ICP accelerometers with a 0–5 kHz bandwidth, and RMS acceleration together with FFT spectra were recorded. Cutting forces were captured using a piezoelectric dynamometer, while surface roughness was measured with a profilometer of ±0.01 µm accuracy. Tool wear was monitored with an optical microscope by observing flank wear (VB). Under baseline conditions of n = 800 rpm, f = 0.10 mm/rev, and ap = 0.6 mm, vibration RMS was measured at 0.34 g and surface roughness at 1.05 µm.

Two vibration suppression technologies were also tested alongside conventional machining. Passive tuned mass dampers (TMD) integrated into the boring bar achieved vibration reductions of 30–35%. Ultrasonic vibration-assisted turning (UVAT) at 20 kHz frequency and 15 µm amplitude lowered cutting forces by 20–25% and improved surface roughness by 18–22%.

The experimental data were processed using a genetic algorithm (GA) to achieve multi-objective optimization, where the goals were to minimize surface roughness (Ra), minimize vibration intensity, and maximize material removal rate (MRR). The optimization function was expressed as:

Min J= w_1·Ra/〖Ra〗_ref +w_2·VB/〖VB〗_ref -w_3·MRR/〖MRR〗_ref

where w_1, w_2, w_3 are weighting coefficients. The GA determined the optimal cutting regime as spindle speed 1180 rpm, feed rate 0.08 mm/rev, and depth of cut 0.40 mm, yielding Ra ≈ 0.65 µm, vibration RMS ≈ 0.20 g, and approximately 25% longer tool life.

A schematic stability lobe diagram was also constructed to illustrate the chatter-free regions, confirming the theoretical predictions with the experimental results.

Results and Discussion. The experimental investigations confirmed that vibration suppression in gun barrel turning can be significantly enhanced by selecting appropriate cutting regimes based on stability analysis and damping technologies. The results are presented here in terms of vibration intensity, surface roughness, cutting forces, and tool life, followed by a critical discussion of their implications.

Under baseline conditions (spindle speed = 800 rpm, feed rate = 0.10 mm/rev, depth of cut = 0.6 mm), the measured RMS vibration amplitude was 0.34 g and the average surface roughness was 1.05 µm. FFT analysis indicated a dominant resonance peak near 720 Hz, corresponding to the system’s fundamental natural frequency. These values exceeded the tolerance limits for precision barrel machining, where Ra ≤ 0.8 µm is typically required.

When optimized stability-lobe-based cutting regimes were applied (spindle speed = 1200 rpm, feed rate = 0.10 mm/rev, depth of cut = 0.4 mm), the RMS vibration decreased to 0.19 g (a 44% reduction) and surface roughness improved to 0.62 µm. With the addition of ultrasonic vibration-assisted turning (UVAT) at 20 kHz and 15 µm amplitude, vibration intensity further declined to 0.16 g, and surface roughness reached 0.55 µm, corresponding to a 48% overall improvement compared with the baseline.

Cutting force measurements demonstrated similar trends. In baseline trials, the average thrust force (Fz) was 240 N, while optimized parameters reduced this to 185 N. UVAT-assisted trials showed the lowest forces at 170 N, indicating a 20–25% reduction relative to baseline values. Lower cutting forces also correlated with improved tool life, as flank wear (VB) measurements revealed a tool life increase of approximately 25% in optimized regimes compared to conventional cutting.

To better illustrate the influence of optimized cutting parameters and advanced vibration suppression techniques, the results of the baseline condition, the optimized stability-lobe-based condition, and the UVAT-assisted condition are summarized in Table 1. The table compares vibration intensity, surface roughness, cutting forces, and tool life across these three representative regimes.

Table 1.

Comparative results of baseline, optimized, and UVAT-assisted regimes

Cutting regime	RMS vibration (g)	Ra (µm)	Fz (N)	Tool life
Baseline (800 rpm, 0.10 mm/rev, 0.6 mm)	0.34	1.05	240	Reference
Optimized (1200 rpm, 0.10 mm/rev, 0.4 mm, TMD)	0.19	0.62	185	+20%
Optimized + UVAT (1200 rpm, 0.08 mm/rev, 0.4 mm)	0.16	0.55	170	+25%

The data clearly highlight the effectiveness of optimized regimes over conventional cutting. Moving from the baseline to the optimized regime with TMD integration reduced vibration intensity by almost half and improved surface roughness to values within acceptable tolerances for barrel manufacturing. The addition of ultrasonic vibration assistance further enhanced performance, delivering the lowest vibration levels, finest surface finish, and longest tool life. These improvements not only confirm the theoretical predictions of stability lobe analysis but also validate the practical value of integrating damping technologies into the machining of long, slender components such as gun barrels.

These findings reinforce earlier studies by Budak (1994) and Kang et al. (2023), while extending them through a combined approach that integrates theoretical modeling, experimental validation, and multi-objective optimization. Unlike studies that focused solely on either stability modeling or a single damping technique, the present research demonstrates that a hybrid methodology yields more robust and practically applicable solutions for precision barrel machining.

Conclusion

This study has demonstrated that vibration suppression in the turning of gun barrels requires a systematic approach that integrates theoretical modeling, experimental validation, and the application of advanced damping technologies. The baseline trials confirmed that due to the high length-to-diameter ratio of barrel blanks (L/D ≈ 26), the machining system is highly prone to regenerative chatter, resulting in excessive vibration amplitudes (0.34 g) and unsatisfactory surface roughness values (Ra = 1.05 µm).

By applying stability lobe analysis and selecting spindle speeds within chatter-free regions, vibration intensity was reduced by approximately 44% and surface roughness improved by 41%. The use of tuned mass dampers (TMDs) provided additional benefits, particularly in long, slender workpieces, reducing vibration amplitudes by 30–35% in practice. Ultrasonic vibration-assisted turning (UVAT) proved to be the most effective technique, lowering cutting forces by 20–25%, reducing surface roughness to 0.55 µm, and extending tool life by nearly 25%.

The integration of experimental data into a genetic algorithm framework enabled multi-objective optimization of the cutting parameters. The optimal regime was identified as spindle speed 1180 rpm, feed rate 0.08 mm/rev, and depth of cut 0.40 mm, which achieved a balance between surface quality, vibration suppression, and productivity.

The findings confirm that no single method provides a universal solution for chatter suppression in barrel machining. Instead, a hybrid methodology—combining stability lobe analysis, passive damping, ultrasonic assistance, and optimization algorithms—offers the most reliable and practical approach. The outcomes of this study provide valuable guidelines for precision gun barrel manufacturing, where surface integrity and dimensional accuracy are critical to ballistic performance.

Future research should focus on the integration of adaptive real-time control strategies and artificial intelligence methods to further improve chatter suppression, as well as the development of cost-effective ultrasonic and damping systems to facilitate wider industrial adoption.

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