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Experimental Study of Sand-Filled Damping for Chatter Suppression in Unsupported Turning of SCH40 Steel Pipes

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ABSTRACT

Chatter during unsupported turning of thin-walled pipes degrades dimensional accuracy, surface quality, and machining stability because of the low bending rigidity of tubular workpieces. This study experimentally investigated the effectiveness of sand-filled damping for suppressing chatter during unsupported turning of seamless SCH40 steel pipes. Turning experiments were conducted on an Emco Maximat V13 lathe using a high-speed steel (HSS) tool under dry cutting conditions. Hollow and sand-filled pipe configurations were evaluated using incremental depth-of-cut settings of 0.25 mm. Vibration responses were measured using a triaxial accelerometer and analyzed in the time and frequency domains through Fast Fourier Transform (FFT). The hollow pipe exhibited severe chatter at an actual depth of cut of 0.95 mm with a vibration amplitude of 58.94 m/s² at 241.02 Hz. In contrast, the sand-filled pipe maintained vibration amplitudes below 7.00 m/s² up to 3.02 mm and became unstable only at 3.53 mm with an amplitude of 28.44 m/s². Sand filling increased the critical depth of cut by more than three times while maintaining surface roughness below 1.07 μm over most cutting conditions. These findings demonstrate that sand-filled damping provides a simple and low-cost approach for improving machining stability in unsupported tubular turning.

1. INTRODUCTION

Thin-walled steel pipe turning without tailstock support remains an unresolved dynamic issue in precision manufacturing, particularly when the length-to-diameter ratio of the workpiece increases and the structural stiffness of the machining system decreases substantially. Under such conditions, radial and tangential cutting forces generate elastic deflections that can readily evolve into regenerative vibrations (regenerative chatter), leading to a marked reduction in cutting stability, even at relatively low depths of cut. This phenomenon becomes more critical during the turning of seamless SCH40 pipes because the tubular structure possesses low bending rigidity and high sensitivity to variations in the clamping conditions and tool overhang. In oil and gas manufacturing applications, piping systems, pressure vessels, and large-diameter tubular components are frequently machined without tailstock support owing to geometric constraints and limited machining accessibility. Consequently, the dynamic stability of the machining system depends predominantly on the chuck stiffness and inherent damping characteristics of the workpiece material [1, 2].

Chatter in turning operations is not merely a random vibration caused by ordinary mechanical excitation but rather a self-excited instability that develops through repetitive interactions among chip thickness variation, elastic deformation of the machining system, and dynamic response of the tool-workpiece interface. When the cutting excitation frequency approaches the natural frequency of the system, the vibration amplitude increases progressively and modulates the chip thickness during the subsequent cutting pass. This condition leads to higher dynamic cutting forces, surface irregularities, accelerated tool wear, and even spindle damage under severe operating conditions [3]. Urbikain et al. [4] reported that chatter in tubular turning systems commonly occurs within a frequency range of 150-800 Hz, depending on the combination of spindle speed, tool overhang length, and clamping stiffness. Meanwhile, Mehdi et al. [5] observed that the radial vibration amplitude in thin-walled tubular turning can increase by more than twofold when the wall thickness decreases from 6.00 to 3.00 mm owing to the reduction in the local structural stiffness of the workpiece.

The practical consequences of chatter are substantial because it directly affects the geometric quality and surface integrity of the turned components. Litak and Rusinek [6] demonstrated that an increase in chatter frequency correlates with a rise in surface roughness exceeding 40% compared with that under stable cutting conditions. In contrast, de Aguiar et al. [7] reported that high vibration acceleration increases the local cutting temperature and accelerates the flank wear of carbide cutting tools during stainless steel turning operations. In the turning of seamless SCH40 pipes, the problem becomes more complex because the elastic deformation of the tubular wall not only affects the dynamic stability but also reduces the dimensional accuracy of the outer diameter and wall thickness after machining.

Various approaches have been developed to suppress chatter in turning operations, ranging from the optimization of cutting parameters to the application of active damping systems based on piezoelectric actuators. However, the implementation of active control in large-scale industrial machining still encounters limitations related to cost, control integration complexity, and sensitivity to variations in operating conditions. Consequently, passive damping methods are generally regarded as more practical for conventional industrial applications, particularly in manual and semi-automatic lathes. Several studies have investigated particle damping, magnetic damping, and axial force modulation to improve the damping ratio of machining systems [8, 9]. However, most of these studies focused on boring bars, tool holders, or spindle structures rather than the internal cavity of tubular workpieces.

The use of granular media as a passive damping mechanism has attracted increasing attention because its energy dissipation mechanism is relatively simple and effective. When vibration occurs, granular particles undergo repeated collisions and internal friction, which convert mechanical energy into thermal energy. The effectiveness of this mechanism is influenced by the particle size, filler mass, cavity volume ratio, and characteristics of the dynamic excitation. Luo et al. [10] demonstrated that particle damping in industrial tubular structures could reduce the vibration amplitude by approximately 35% under specific excitation intensities. Ramu et al. [8] also reported that the application of particle damping in boring bars reduced the surface roughness by 22-30% compared with undamped configurations. However, most of these studies employed metallic media or synthetic particles with relatively high costs and experimental configurations that differed substantially from unsupported pipe turning conditions without tailstock support.

Sand possesses several attractive characteristics as a damping medium because it is inexpensive, readily available, and capable of dissipating energy via interparticle frictional sliding mechanisms. Nevertheless, studies on sand filling inside the internal cavity of steel pipes during turning operations remain limited. Previous investigations have predominantly focused on the influence of boundary conditions, tool overhang, and optimization of cutting parameters using stability lobe diagram approaches [11, 12]. Even when passive damping mechanisms were discussed, the research emphasis was generally directed toward tool holders or external machine structures rather than the direct integration of granular media into the tubular workpiece itself. These conditions indicate that the application of sand-filled damping in seamless steel pipe turning still lacks a sufficiently strong experimental foundation, particularly for machining configurations without a tailstock support.

Another limitation of previous studies is the widespread use of linear models to represent chatter dynamics. Most existing models are still unable to adequately capture the nonlinear effects associated with chip thickness variation, cutting temperature, and local stiffness changes occurring during material removal. In addition, the interaction between the chip serration frequency and modal response of tubular pipes has rarely been investigated experimentally. Several finite element studies have demonstrated changes in the natural frequency as the wall thickness of the workpiece decreases; however, experimental validation under actual cutting conditions remains limited [13, 14].

A considerable number of chatter turning studies have been conducted using solid shafts or short tubes supported by steady rests or tailstocks. In practical large-diameter piping applications, however, the use of tailstock support is often impractical because of limited cutting tool accessibility or the need to machine the internal sections of the component. Consequently, previous findings do not fully represent the actual conditions encountered in seamless pipe turning with long unsupported overhangs. In other words, experimental studies are needed to evaluate the effectiveness of sand-filled damping in SCH40 pipe turning without tailstock support by directly measuring the vibration amplitude and machined surface quality.

In addition to the limitations associated with experimental configurations, most previous studies have evaluated chatter primarily based on surface roughness or a single frequency spectrum. However, these approaches are insufficient to comprehensively describe the dynamic behavior of tubular machining systems. Simultaneous analyses involving vibration amplitude, dominant frequency, cutting stability variation, and machined surface characteristics remain relatively uncommon in studies concerning granular-material-based passive damping. Consequently, the mechanism of chatter reduction arising from granular particle interactions inside tubular cavities has not yet been fully understood.

Based on these issues, the present study aims to analyze the effect of sand-filled damping on chatter suppression during the turning of seamless SCH40 steel pipes without a tailstock support. This study focuses on evaluating changes in vibration amplitude, dynamic frequency characteristics, and machined surface quality resulting from variations in the sand-filled conditions inside the pipe cavity. In addition, this study is expected to provide experimental contributions toward the development of low-cost passive damping methods for pipe turning applications in manufacturing and oil-and-gas industries, particularly under unsupported machining conditions with high chatter susceptibility.

2. MATERIALS AND METHODS

2.1 Experimental design

This study employed an experimental approach to investigate the effectiveness of sand-filled damping in suppressing chatter during the turning of seamless SCH40 steel pipes without a tailstock support. The experiment was designed under controlled machining conditions in which the cutting parameters, tool geometry, spindle rotation, and environmental conditions were maintained constant throughout all tests. The primary objective was to isolate the influence of internal granular damping on the dynamic response of a tubular workpiece during machining.

Two machining configurations were evaluated: (1) hollow pipe turning without an internal filler and (2) turning with sand-filled internal damping. The hollow configuration was considered the reference condition, whereas the sand-filled configuration represented the passive damping treatment. The comparison between these two conditions enabled a direct evaluation of the vibration attenuation and chatter suppression capability resulting from the presence of granular material inside the pipe cavity.

The dynamic behavior of the machining system was assessed using the vibration amplitude and dominant chatter frequency measured during the turning process. Because chatter in thin-walled tubular structures is highly sensitive to stiffness reduction and boundary compliance, the experimental configuration intentionally employed an unsupported overhang condition without tailstock assistance to reproduce unstable cutting conditions commonly encountered in tubular machining applications [15, 16].

2.2 Machine tool and workpiece preparation

The experiments were conducted using an Emco Maximat V13 conventional lathe, as illustrated in Figure 1. The machine was selected because its spindle configuration allowed unsupported turning under controlled laboratory conditions while maintaining a stable rotational motion during vibration measurements.

Figure 1. Emco Maximat V13 lathe used in the turning experiments

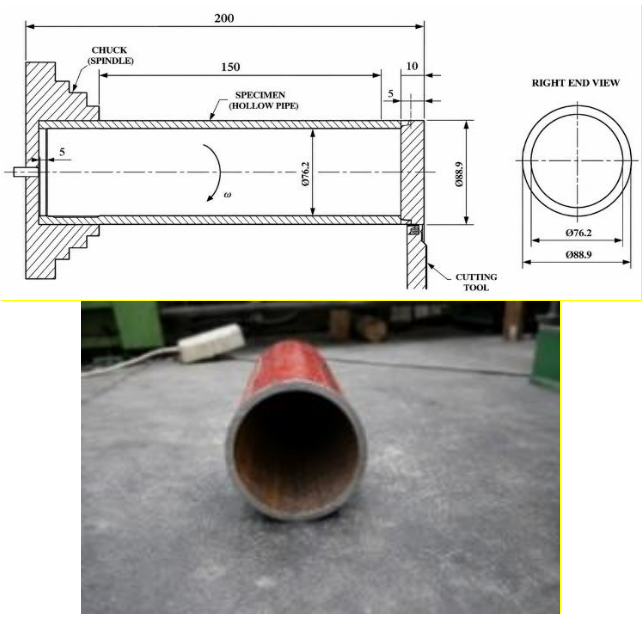

Figure 2. Dimensions of the SCH40 steel pipe and external clamping arrangement

The workpiece material consisted of a seamless SCH40 steel pipe with a nominal diameter of 3 inches, outer diameter of 88.90 mm, and inner diameter of 76.20 mm. The total workpiece length was 200 mm, whereas the unsupported cutting section extended approximately 150 mm from the chuck interface. External clamping via a three-jaw chuck was used without tailstock support to increase unsupported overhang and chatter susceptibility. The dimensional configuration of the workpiece is shown in Figure 2.

The tubular geometry was intentionally selected because thin-walled cylindrical structures generally exhibit lower dynamic rigidity and stronger modal coupling than do solid shafts. During material removal, the reduction in local wall stiffness alters the dynamic characteristics of the workpiece and promotes vibration amplification near the dominant natural frequency.

2.3 Cutting tool and machining parameters

The cutting operation was performed using a high-speed steel (HSS) cutting tool with a principal cutting edge angle (entering angle), denoted as K_r, of 45°. A tool overhang length of 25 mm was maintained throughout the experiments to ensure consistent tool holder flexibility during machining. The machining parameters were selected based on preliminary trials conducted under stable cutting conditions without inducing tool instability. The cutting conditions are summarized in Table 1.

Table 1. Machining parameters used during the experiments

Parameter	Value
Workpiece material	Seamless SCH40 steel pipe
Outer diameter	88.90 mm
Inner diameter	76.20 mm
Cutting tool	High-speed steel (HSS)
Principal cutting edge angle (K_r)	45°
Spindle speed	320 rpm
Feed rate	0.09 mm/rev
Initial depth of cut (mm)	0.25 mm
Spindle rotation	Clockwise (CW)
Chuck type	Three-jaw universal
Machine tool	Emco Maximat V13

In this experiment, a spindle speed of 320 rpm was selected because preliminary observations indicated that unstable vibrations could be readily initiated within this operating range under unsupported tubular conditions. Likewise, the depth of cut for both hollow pipes and sand-filled pipes was initially set at 0.25 mm and then increased incrementally until the vibration limit was reached. This approach was intended to generate measurable dynamic excitation while avoiding severe instability or excessive plastic deformation of the pipe wall.

2.4 Sand-filled damping configuration

Damping treatment was implemented by introducing granular sand into the internal cavity of the seamless steel pipe prior to machining, where the granular medium was intended to function as a passive damping system under vibration excitation. Two experimental configurations were evaluated: a hollow pipe with an empty cavity and a sand-filled pipe in which the cavity was uniformly filled with dry construction sand (Figure 3).

The filler material consisted of medium-grade construction sand with an average particle size of approximately 0.35 mm, a bulk density of 1,500 kg/m³, a moisture content of 0.5913%, and a porosity of approximately 40%, corresponding to a packing fraction of about 0.60. These values were estimated based on the gravimetric-volumetric method using the measured bulk density of the sand (1,500 kg/m³) and the standard true particle density of silica sand (approximately 2,500 kg/m³), where the packing fraction was calculated as the ratio of bulk density to particle density ($\phi = \rho_{bulk}/\rho_{particle}$), and porosity was derived as $n = 1 - \phi$. The pipe cavity (76.20 mm inner diameter and 200 mm length) provided an available volume of approximately 9.12×10^{-4} m³; thus, complete filling required approximately 1.37 kg of sand, corresponding to a fill ratio of 100%, whereas the 150 mm effective unsupported section corresponded to approximately 1.03 kg and a fill ratio of 75%. Prior to testing, the sand was lightly compacted to minimize excessive particle migration during spindle rotation while preserving sufficient inter-particle mobility and frictional interaction.

Figure 3. SCH40 pipe configurations prior to machining

2.5 Vibration measurement

Dynamic vibration during the turning process was measured using a triaxial piezoelectric accelerometer of the Bruel & Kjaer Type 4321 mounted in close proximity to the cutting zone, as shown in Figure 4, to capture the radial vibration generated directly from the tool-workpiece interaction under unsupported machining conditions. The accelerometer possessed a sensitivity of 50 mV/g at 160 Hz, a measurable frequency range of 1–5000 Hz, a maximum acceleration capacity of ±100 g, and shock resistance up to ±1000 g, enabling stable measurements under fluctuating cutting loads and intermittent chatter excitation.

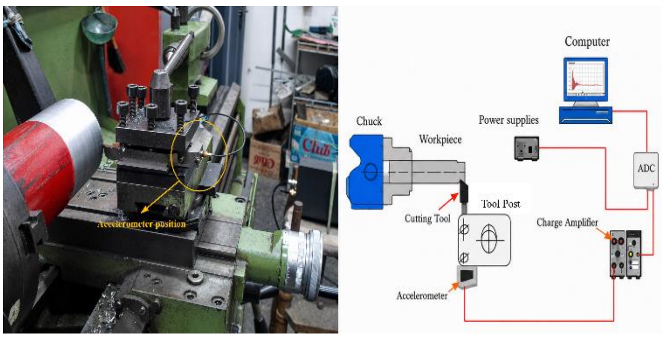

Figure 4. Schematic of accelerometer location in the experimental setup

The acquired signal was transmitted through a charge amplifier to a Pico-based data acquisition system equipped with 16-bit resolution and dual BNC input channels operating within a voltage range of ±50 mV to ±20 V with overload protection of ±100 V. The acquisition unit supported maximum sampling rates of 333 kS/s for single-channel operation and 166 kS/s for dual-channel operation, allowing high-frequency vibration components associated with regenerative chatter to be captured without significant signal distortions. The vibration signal was subsequently converted through an analog-to-digital interface and recorded continuously using a computer-based monitoring system, thereby enabling real-time observation of the amplitude evolution and dominant chatter frequencies under different damping configurations.

2.6 Experimental procedure

Prior to machining, the workpiece surface was cleaned to remove residual contaminants and oxide layers that could affect clamping stability. For the sand-filled condition, dry sand was introduced into the pipe cavity and uniformly distributed along the effective machining section. The pipe was then mounted using external clamping via a three-jaw chuck without tailstock support.

After alignment and spindle calibration, the cutting operation was initiated under constant machining parameters. Vibration signals were recorded continuously from the initial tool engagement until completion of the cutting pass (Figure 4). The experiments were conducted using incremental depth-of-cut settings of 0.25 mm. The setting depth of cut (a_s) represents the nominal machine cross-feed, whereas the actual depth of cut (a_p) is derived from post-machining outer diameter measurements. Due to radial elastic deflection of the unsupported thin-walled pipe under cutting forces, as well as local geometric variations (e.g., ovality or chatter marks), a_p may deviate from as (being either smaller or larger). Therefore, a_p is used throughout the results to accurately reflect the true material removal thickness. The hollow pipe was tested under four cutting conditions (0.25–1.00 mm), whereas the sand-filled pipe was evaluated under thirteen cutting conditions (0.25–3.25 mm) until vibration instability occurred. For each cutting condition, vibration signals were continuously acquired, and the reported values represent the measured peak vibration amplitudes.

After each turning test, surface roughness measurements were performed using a portable surface roughness tester (LANDTEK SRT6200S). The instrument employs an inductive pickup with a 10 µm radius diamond stylus, a stylus angle of 90°, and a measuring force of 16 mN. Surface roughness parameter R_a was measured using a Gaussian digital filter. A cutoff length (λ_c) of 0.8 mm was applied for all measurements, while the evaluation length was set to five cutoff lengths, corresponding to a total evaluation length of 4.00 mm. Measurements were conducted at three different locations along the machined surface under identical conditions, and the reported R_a values represent the arithmetic mean of the three measurements. The instrument provides a resolution of 0.001 µm for readings below 10 µm with an accuracy of ±10%. Among the available roughness parameters (R_a, R_q, R_z, and R_t), R_a was selected as the primary indicator of surface quality because it is the most widely accepted parameter for machined surfaces.

2.7 Signal processing and dynamic analysis

The acceleration signals generated during turning were acquired using a piezoelectric accelerometer connected to a Pico-based data acquisition system. The measured signals were processed in both the time and frequency domains to characterize the dynamic response of the machining system.

Time-domain analysis was employed to evaluate the instantaneous vibration response during cutting, while frequency-domain analysis based on Fast Fourier Transform

(FFT) was used to identify dominant vibration frequencies associated with regenerative chatter. The sampling frequency was estimated to be approximately 1.28–1.30 kHz based on the maximum observable spectral frequency of 650 Hz. Spectral analysis was performed using a Hanning window to minimize spectral leakage. Assuming a 1 s acquisition duration, the FFT length was approximately 1280 samples, providing a frequency resolution of about 1 Hz. Prior to FFT analysis, the signal mean was removed to eliminate the DC component. No additional digital filtering was applied unless specified by the acquisition software. At a spindle speed of 320 rpm (5.33 Hz), the dominant spectral component at 190–200 Hz corresponds to approximately the 36th–37th rotational order. For each cutting condition, the dominant chatter frequency was defined as the frequency corresponding to the highest spectral peak within the measured frequency range.

The vibration reduction ratio used to quantify the damping effectiveness of the sand-filled pipe was calculated as

$$\eta = \frac{A_0 - A_s}{A_0} \times 100\% \quad (1)$$

where, A_0 represents the vibration amplitude under the hollow pipe condition and A_s denotes the vibration amplitude under the sand-filled condition.

A cutting condition was classified as chatter when at least two of the following criteria were simultaneously observed: (i) a sudden increase in vibration amplitude, (ii) the appearance of dominant high-amplitude FFT peaks, and (iii) visible chatter marks on the machined surface. The critical actual depth of cut was defined as the first cutting condition satisfying these criteria consistently in repeated trials.

The dominant vibration frequency (f_d) was determined from the FFT spectrum as

$$f_d = \underset{f}{arg\,max}\{|X(f)|\} \quad (2)$$

where, $X(f)$ denotes the amplitude spectrum of the acceleration signal and f_d represents the frequency associated with the maximum spectral amplitude.

3. RESULTS AND DISCUSSION

3.1 Effect of actual depth of cut on vibration response

The vibration response of the unsupported seamless SCH40 steel pipe exhibited markedly different trends between the hollow and sand-filled configurations as the actual depth of cut increased (Tables 2 and 3). Under the hollow condition, vibration amplitude increased progressively from 1.39 m/s² at an actual depth of cut of 0.28 mm to 5.66 m/s² at 0.68 mm. However, a sharp increase to 58.94 m/s² occurred when the actual depth reached 0.95 mm, accompanied by a dominant frequency of 241.02 Hz. The abrupt increase in vibration amplitude indicates a transition from stable to unstable cutting conditions. Similar instability transitions have been reported in thin-walled turning systems, where decreasing structural rigidity increases susceptibility to chatter excitation [15]. In contrast, the sand-filled pipe maintained relatively low vibration amplitudes over a substantially wider cutting range. Between actual depths of cut of 0.25 and 3.27 mm, vibration amplitudes remained within 2.31–6.87 m/s² despite increasing cutting load. A pronounced increase in vibration was observed only at an actual depth of cut of 3.53 mm, where the amplitude reached 28.44 m/s² with a dominant frequency of 246.02 Hz. These results suggest that internal sand filling increased the dynamic stability limit of the unsupported tubular structure [16, 17].

Table 2. Measured vibration response for hollow pipe without sand-filling

Depth of Cut (mm)		f_d (Hz)	A_o (m/s²)	R_a (μm)
a_s	a_p			
0.25	0.20	234.01	1.39	0.72
0.50	0.44	237.01	1.85	0.75
0.75	0.68	222.01	5.66	0.99
1.00	0.95	241.02	58.94	4.36

Note: a_s = setting depth of cut, a_p = the actual depth of cut, f_d = vibration frequency, A_o = amplitude under the hollow pipe condition and R_a = arithmetic average roughness.

Table 3. Measured vibration response for sand-filled pipe

Depth of Cut (mm)		f_d (Hz)	A_s (m/s²)	R_a (μm)
a_s	a_p			
0.25	0.25	254.02	2.31	0.78
0.50	0.49	290.02	2.98	0.82
0.75	0.74	261.02	2.78	0.81
1.00	0.96	146.02	2.96	0.82
1.25	1.22	251.02	3.62	0.86
1.50	1.43	264.02	3.80	0.87
1.75	1.98	257.02	4.72	0.93
2.00	2.23	250.02	5.20	0.96
2.25	2.49	245.02	5.32	0.97
2.50	2.71	240.02	5.77	1.00
2.75	3.02	266.02	6.69	1.06
3.00	3.27	286.02	6.87	1.07
3.25	3.53	246.02	28.44	2.21

Note: a_s = setting depth of cut, a_p = the actual depth of cut, f_d = vibration frequency, A_s = amplitude under the sand-filled condition and R_a = arithmetic average roughness.

The improvement in machining stability is evident from the shift in critical depth of cut. The hollow pipe became unstable at approximately 0.95 mm, whereas the sand-filled pipe maintained stable cutting up to 3.53 mm, corresponding to an increase in the stable machining region by more than three times under identical spindle speed and feed conditions. Furthermore, the vibration reduction ratio calculated using Eq. (1) reached 51.75% under severe cutting conditions (Table 4). The substantial decrease in vibration amplitude confirms the effectiveness of granular damping during unsupported turning [18, 19].

Table 4. Comparison of dynamic response between hollow and sand-filled configurations

Parameter	Hollow Pipe	Sand-Filled Pipe
Critical actual depth of cut (mm)	0.95	3.53
Maximum vibration amplitude (m/s²)	58.94	28.44
Dominant frequency (Hz)	241.02	246.02

The observed stabilization is likely associated with multiple damping mechanisms acting simultaneously inside the pipe cavity. Although particle motion was not measured directly in the present study, previous studies on granular damping have suggested that sand particles may undergo repeated collisions and frictional sliding under vibration, potentially converting part of the mechanical energy into heat. In addition, the granular medium may alter the effective mass distribution and dynamic characteristics of the tubular workpiece. Therefore, the improved stability observed in the sand-filled configuration should be interpreted as being consistent with these mechanisms rather than as direct experimental confirmation of their occurrence. Similar interpretations have been reported in particle-damped machining systems and flexible structures [8, 20-22].

3.2 Frequency evolution and Fast Fourier Transform characteristics

The dominant vibration frequencies exhibited distinct distributions between the hollow and sand-filled configurations. The hollow pipe showed frequencies concentrated within a relatively narrow range of 222.01–241.02 Hz, whereas the sand-filled pipe displayed a broader distribution extending from 240.02 to 290.02 Hz, together with an isolated response at 146.02 Hz. The absence of a monotonic relationship between depth of cut and dominant frequency suggests that the machining system behaved as a multi-degree-of-freedom structure in which several structural modes participated in the vibration response [23-25].

An important observation emerges when these frequencies are compared with the spindle rotational frequency. At a spindle speed of 320 rpm, the rotational frequency can be expressed as

$$f_r = \frac{n}{60} = \frac{320}{60} = 5.33 \text{ Hz} \quad (3)$$

where, n denotes spindle speed in rpm. The measured dominant frequencies were substantially higher than the spindle frequency and cannot be directly attributed to spindle harmonics. Instead, these spectral peaks are more likely associated with structural modes excited by regenerative cutting forces. Similar chatter frequencies have frequently been reported in thin-walled and slender turning systems operating under flexible boundary conditions [4, 26].

The FFT spectrum of the hollow pipe (Figure 5) revealed a narrow and highly concentrated peak near 240.02 Hz. At an actual depth of cut of 0.95 mm, vibration amplitude reached 58.94 m/s² at 241.02 Hz, indicating strong energy localization within a dominant mode. Such spectral concentration is commonly associated with unstable vibration growth and resonance persistence during machining [27].

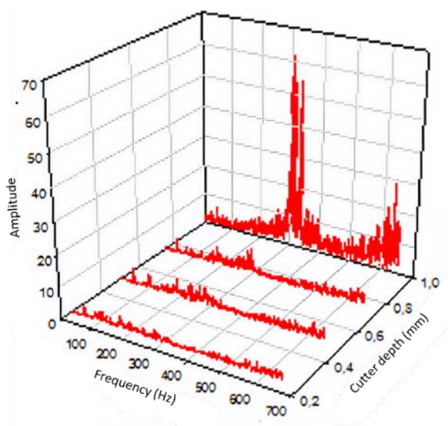

Figure 5. Vibration amplitude spectrum of the hollow pipe without sand filling

By contrast, the FFT spectra of the sand-filled configuration (Figure 6) exhibited broader frequency bands with lower peak intensity. The broader spectral distribution suggests that vibrational energy was distributed across multiple frequency components rather than concentrated within a single resonance band. Similar spectral broadening has been observed in particle-damped machining systems, where granular media increase damping ratio and suppress vibration growth [8, 28].

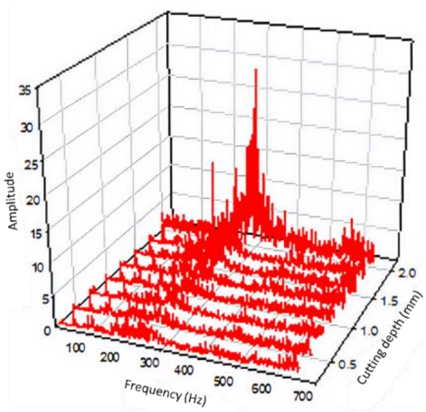

Figure 6. Vibration amplitude spectrum of the sand-filled pipe

A notable exception occurred at an actual depth of cut of 0.96 mm, where the dominant frequency shifted to 146.02 Hz while vibration amplitude remained relatively low at 2.96 m/s². This behavior may indicate temporary mode switching or changes in modal participation induced by the granular medium. However, further modal analysis would be required to confirm the underlying mechanism.

3.3 Surface integrity and surface roughness

Surface quality provides an independent indicator of machining stability because regenerative vibration directly influences the morphology of the generated surface. Figure 7 presents the representative machined surface of the unsupported seamless SCH40 steel pipe after turning. The surface exhibits circumferential tool marks and localized waviness distributed along the cutting direction. Such features are characteristic of intermittent variations in tool–workpiece interaction and are frequently observed in machining processes involving flexible structures.

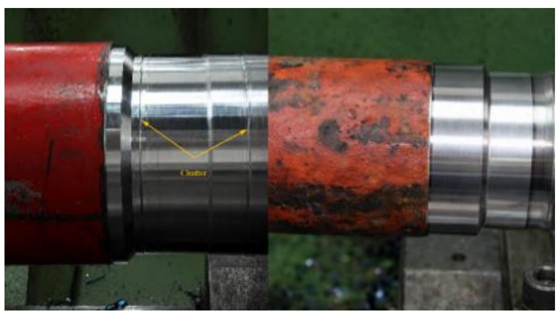

Figure 7. Surface roughness and chatter on the SCH40 pipe surface

The periodic nature of the observed surface marks suggests the presence of regenerative effects during cutting. In turning operations, waviness generated during one spindle revolution may be re-cut during subsequent revolutions, producing successive surface undulations commonly referred to as chatter marks. The formation of these marks becomes increasingly pronounced when the dynamic stiffness of the workpiece is insufficient to suppress self-excited oscillations. Unsupported tubular workpieces are particularly susceptible to this phenomenon because their cantilever-like boundary condition reduces bending rigidity near the free end.

The measured surface roughness exhibited different trends between the hollow and sand-filled configurations (Table 2 and Table 3). For the hollow pipe, roughness increased from 0.72 µm at an actual depth of cut of 0.28 mm to 0.99 µm at 0.68 mm, followed by a sharp increase to 4.36 µm at 0.95 mm. The abrupt deterioration in surface quality indicates a transition from stable cutting to chatter-dominated machining. Surface roughness values exceeding 4.00 µm are generally associated with significant dynamic disturbances and unstable chip formation in turning operations.

A markedly different response was observed in the sand-filled pipe. The estimated roughness remained within a relatively narrow range of 0.78–1.07 µm over a wide interval of actual depth of cut from 0.25 mm to 3.27 mm. A pronounced increase occurred only at 3.53 mm, where the roughness reached 2.21 µm. Although surface quality deteriorated under the highest cutting condition, the resulting roughness remained substantially lower than that observed in the hollow configuration during severe instability. These results suggest that internal granular filling delayed the degradation of surface integrity under unsupported machining conditions.

The improved surface quality of the sand-filled pipe may be attributed to the suppression of regenerative surface waviness during cutting. Reduced dynamic displacement limits fluctuations in instantaneous chip thickness and promotes more uniform material removal. Previous studies on thin-walled machining have reported that surface roughness is strongly coupled with structural vibration because tool deflection directly affects the generated surface profile. Consequently, the lower roughness observed in the sand-filled configuration appears consistent with the enhanced dynamic stability introduced by the granular medium [27, 17].

From a practical perspective, maintaining surface roughness below approximately 1.00 µm across a broad range of cutting depths is advantageous for applications requiring dimensional consistency and improved surface finish. The present findings indicate that sand-filled damping not only modified the dynamic response of the workpiece but also extended the operating window in which acceptable surface quality could be maintained during unsupported turning of SCH40 steel pipes.

3.4 Implications for unsupported pipe turning

These findings have several implications for unsupported pipe turning operations in industrial manufacturing. First, the results demonstrate that internal granular damping can significantly extend the stable machining range without requiring expensive active control systems or structural modifications of the machine tool. This aspect may be particularly relevant for small- and medium-scale workshops, where sophisticated chatter suppression technologies remain economically impractical.

Second, this study challenges the common assumption that chatter suppression in turning must primarily focus on tool holder dynamics. In the present configuration, the dominant instability originated from the flexible tubular workpiece. By directly modifying the internal damping characteristics of the workpiece, this study achieved substantial vibration reduction even though the cutting tool geometry and spindle conditions remained unchanged.

From a theoretical perspective, the findings reinforce the importance of considering the coupled structural dynamics between the cutting tool and hollow workpiece during chatter analysis. Many predictive chatter models still assume simplified linear stiffness conditions and often neglect the internal damping mechanisms associated with granular interactions. The present results suggest that nonlinear damping effects may play a more influential role in tubular machining stability than previously assumed in the literature.

3.5 Limitations and future work

Despite these contributions, this study has several limitations. The study employed a single spindle speed and one feed rate condition, which limits the broader generalization of the process stability boundaries. In addition, the particle size distribution, density, and moisture content of the sand were not varied systematically. These factors may influence the frictional interaction and energy dissipation efficiency inside the pipe cavity. The accelerometer measurements were also concentrated near the cutting zone, indicating that the full modal behavior of the tubular structure could not be completely reconstructed.

Future research should investigate the interaction between granular material properties and machining parameters through a broader stability map analysis involving spindle speed variation, feed rate adjustment, and multiple tool–workpiece overhang configurations. The integration of experimental modal analysis with finite element modeling may provide deeper insights into the nonlinear coupling between granular damping mechanisms and regenerative chatter evolution in tubular turning systems. Further studies should evaluate alternative filler media, including metallic particles, ceramic granules, and hybrid visco-granular materials, to determine their damping effectiveness under severe cutting conditions, various tubular dimensions, and different machining configurations.

4. CONCLUSIONS

This study investigated the effectiveness of sand-filled damping for suppressing chatter during the turning of seamless SCH40 steel pipes without tailstock support. Under the present machining conditions of 320 rpm spindle speed, 0.09 mm/rev feed rate, HSS tooling, and dry cutting, sand-filled damping delayed the onset of chatter from approximately 0.95 mm to 3.53 mm actual depth of cut. The instability was consistently associated with dominant vibration frequencies in the range of approximately 222.01–240.02 Hz, suggesting strong coupling between cutting excitation and the structural mode of the tubular workpiece.

The introduction of sand-filled damping substantially modified the dynamic behavior of the machining system. Compared with the hollow pipe condition, the sand-filled configuration maintained relatively stable vibration amplitudes over a significantly wider cutting range. Severe chatter did not emerge until the actual cutting depth reached approximately 3.53 mm, where the vibration amplitude increased to 28.44 m/s². This result indicates that the granular medium effectively delayed the onset of regenerative instability and expanded the stable machining region by more than three times relative to the unsupported hollow configuration.

The reduction in chatter severity may be associated with nonlinear granular damping mechanisms inside the pipe cavity. Based on established particle-damping theory, frictional sliding, particle collisions, and momentum redistribution among sand particles may contribute to vibrational energy dissipation during cutting. In addition to energy dissipation, the presence of sand appears to have modified the dynamic response of the tubular structure, as suggested by the broader frequency distribution and reduced resonance concentration observed in the FFT spectra. The results suggest that the damping mechanism not only attenuated vibration amplitude but may also have modified the dynamic interaction between the cutting process and the flexible pipe structure. From a machining perspective, the findings demonstrate that passive granular damping can provide meaningful stability improvement for unsupported tubular turning operations without requiring active control systems or structural modification of the machine tool. The approach offers practical relevance for conventional manufacturing environments, particularly in pipe machining applications where tailstock support cannot be applied because of geometric or accessibility constraints.

This study is still limited to a single machining configuration and a single type of granular material. The effects of variations in spindle speed, particle size distribution, packing ratio, and moisture content have not been systematically evaluated. These parameters can significantly affect damping efficiency and stability behavior. Therefore, future research could combine modal characterization, stability lobe analysis, and nonlinear numerical modeling to clarify the interactions between granular dynamics and regenerative chatter mechanisms in flexible tubular machining systems.

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NOMENCLATURE

a	depth of cut, mm
a_p	actual depth of cut, mm
a_s	setting depth of cut, mm
A	amplitude, $m \cdot s^{-2}$
A_o	amplitude under the hollow pipe condition, $m \cdot s^{-2}$
A_s	amplitude under the sand-filled condition, $m \cdot s^{-2}$
f_d	dominant vibration frequency, Hz
f_r	rotational frequency, Hz
n	spindle speed, rpm
R_a	arithmetic average roughness, μm
R_q	root mean square roughness, μm
R_z	average maximum height, μm
R_t	total height of profile, μm

Greek symbols

η	quantify chatter suppression performance, %