

## PID-controlled active damping to mitigate chatter in lathe machining

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### Abstract

Chatter is a result of undesired vibration in manufacturing that damages product surfaces and reduces production efficiency. Addressing chatter requires enhancing machine-tool dynamic stability, optimizing cutting parameters, and implementing real-time monitoring and control. This study presents a PID-controlled active damping system developed through theoretical analysis, simulation, and experimental testing on LabVIEW and Arduino platforms. Orthogonal turning simulations were conducted with a spindle speed of 1000 RPM, a feed rate of 0.2 mm/rev, and a depth of cut of 1 mm. Vibration sensors enabled rapid chatter detection, and real-time PID adjustments suppressed instability within 0.02 seconds, achieving 98.11% suppression accuracy. Data acquisition was carried out using NI DAQ USB-6218, with Arduino and LabVIEW results showing close agreement, apart from minor deviations due to communication delay. The system improved surface finish, reduced tool wear, and enhanced overall machining performance. These results show the potential of PID-based active damping as an effective solution for real-time chatter suppression and efficiency improvement in lathe machining.

### Keywords:

Chatter, PID, active damping, orthogonal turning, NI DAQ USB-6218, LabVIEW

### 1 Introduction

The metal cutting process is one of the crucial stages in the manufacturing industry aimed at producing components with high precision [1]. However, during this process, vibration phenomena known as chatter often occur [2]. Chatter is an unwanted repetitive vibration in machine tools that produces metal chips [3]. The impact of chatter is highly detrimental as it can affect the surface finish quality, dimensional accuracy, tool life, and the machine's lifespan. These vibrations can lead to imprecise cuts, damage to the workpiece, and reduced cutting machine accuracy [4].

Various studies have been conducted to understand and overcome the chatter phenomenon. One previous study modeled chatter on a lathe machine in the form of a mathematical model [5]. Additionally, the use of an Active Damper programmed through LabVIEW has been developed as a solution to suppress vibrations [6][7][8][9]. To further enhance vibration control effectiveness, an innovative solution involving the use of an additional damper (Cadd) in the dynamic system between the cutting tool and the workpiece has been proposed [10]. This additional damper concept is expected to provide extra damping on dynamic movements, thereby reducing vibrations and improving the stability of the cutting process.

The Proportional-Integral-Derivative (PID) control method is widely applied in various control systems in manufacturing

processes due to its ability to reduce defects and improve product quality [11]. Therefore, this study selected the PID method to suppress chatter occurring in the orthogonal turning process. This system implementation uses the NI DAQ USB-6218 device as a data acquisition tool and data receiver from the dynamic system modeled in Arduino UNO. With this approach, it is expected that chatter vibration can be significantly reduced, thus improving the results. Prior research has demonstrated improvements in tool life and surface quality, but often lacked real-time implementation or relied on high-cost hardware. While some integrated PID control systems exist, few have demonstrated fast response times with low-cost hardware like Arduino or validated hardware-based PID results against simulation outputs using synchronized data acquisition systems. This study fills the gap by implementing a real-time chatter control system using an Arduino-based PID with a transfer function solved via the Runge-Kutta 4th Order (RK4) method. It achieves chatter suppression within 0.02 seconds, with an accuracy of 98.11%, and a maximum data transmission tolerance of 10% when interfaced with NI DAQ USB-6218 and LabVIEW. This integration ensures both responsiveness and cost-effectiveness. Unlike prior works, the proposed system validates hardware outputs against simulation results, enabling reproducibility and practical applicability in actual turning environments. The use of varying Zeta damping values further allows precise tuning of the system's dynamic behavior, directly influencing surface quality and minimizing tool wear.

Compared to the work by Sam *et al.*[12], which focused on optimizing conventional machining parameters to improve surface roughness in lathe operations, introduces a novel real-time vibration suppression method using a PID-controlled active Damper (Cadd). By integrating Arduino and LabVIEW platforms with vibration sensor input and NI DAQ hardware, this research not only enhances surface quality but also actively eliminates chatter within 0.25 seconds, demonstrating a more responsive and automated approach to improving machining outcomes.

## 2 Research

### 2.1 Methods

The five-stage development workflow for PID control system implementation can be seen in Fig. 1. This research simulated chatter in orthogonal turning using both hardware and software platforms. The turning process was replicated using an Arduino UNO microcontroller programmed with a dynamic transfer function solved via the RK4 method.

The system consists of an Arduino UNO microcontroller, designed to simulate a dynamic model of the orthogonal turning process. This system uses a Transfer Function solved with the 4th-order Runge-Kutta (RK-4) method. The system incorporates varying damping values represented by the Zeta coefficient and aims to model chatter behavior under different PID parameters ( $K_p$ ,  $K_i$ ,  $K_d$ ). The Arduino outputs simulated vibration response data through PWM or analog signals. The NI DAQ USB-6218 serves as a data acquisition interface to collect real-time analog signals from the Arduino UNO. These signals are interpreted as vibration amplitude responses in LabVIEW for monitoring, comparison, and PID tuning validation (Fig. 2). LabVIEW also simulates the same dynamic model and validates the Arduino output, ensuring consistency between hardware and software simulations (Fig. 3). It further acts as a monitoring platform, to analyze damping behavior and chatter suppression in real time.

The turning simulation was repeated five times for each Zeta value using an Arduino UNO and NI DAQ USB-6218 interface. Each simulation used a fixed step size of 0.001s, simulating a tool mass of 0.5 kg. The RK-4 method was used to solve the dynamic equation of motion (Eq. (1)), and PID control logic was implemented in Arduino. Analog signals representing vibration response were sent to LabVIEW for visualization and validation. The RK-4 and PID tuning techniques were based on standard control engineering practices.

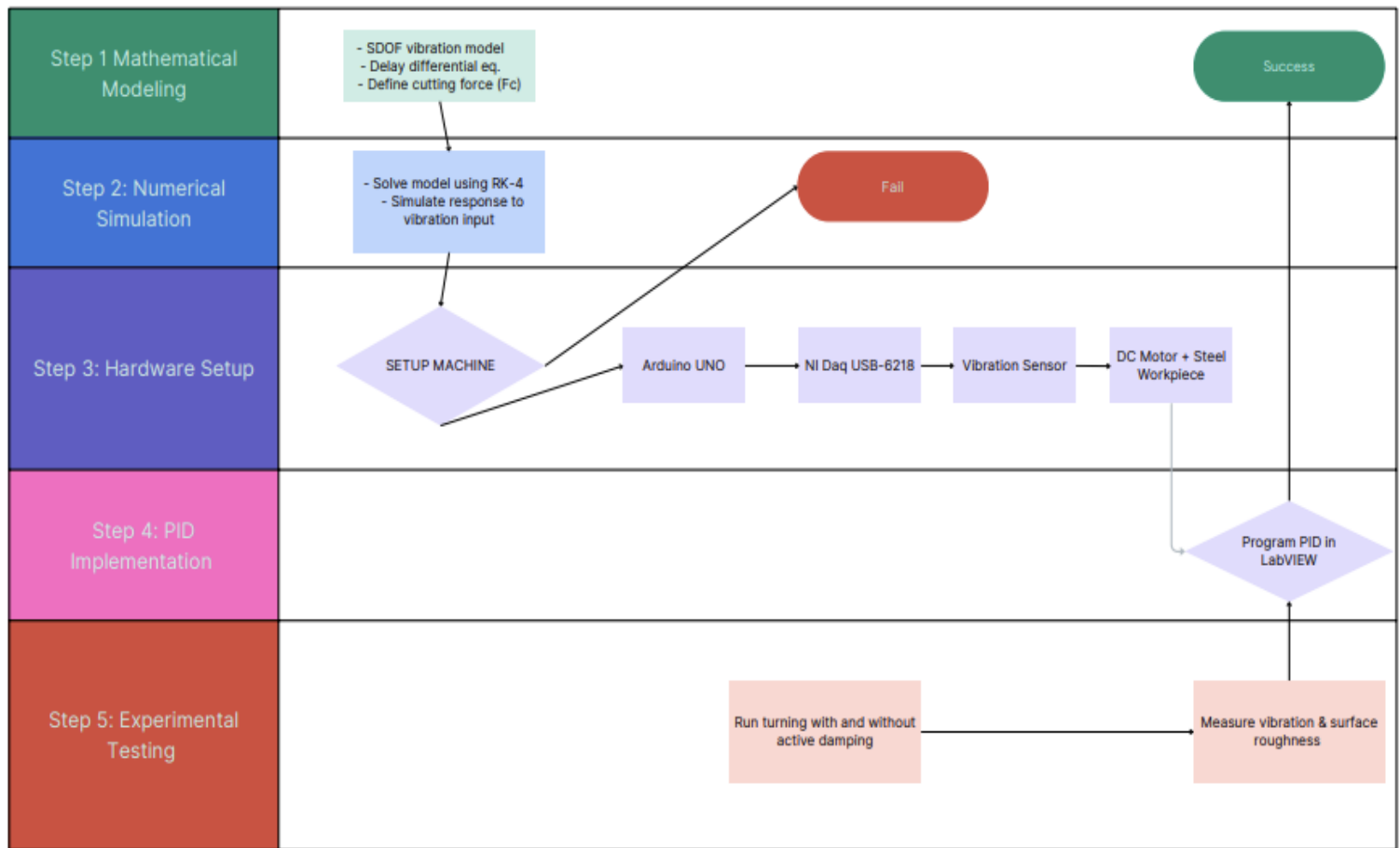


Fig. 1. PID control system implementation

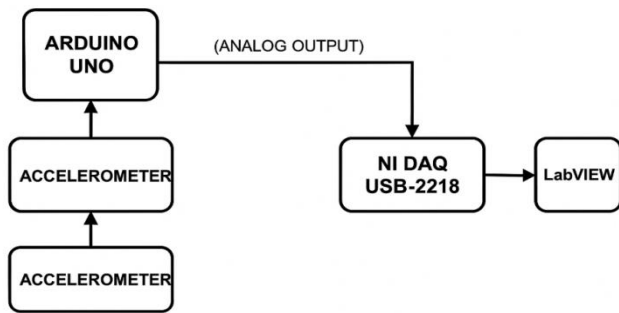


Fig. 2. Arduino and NI DAQ circuit

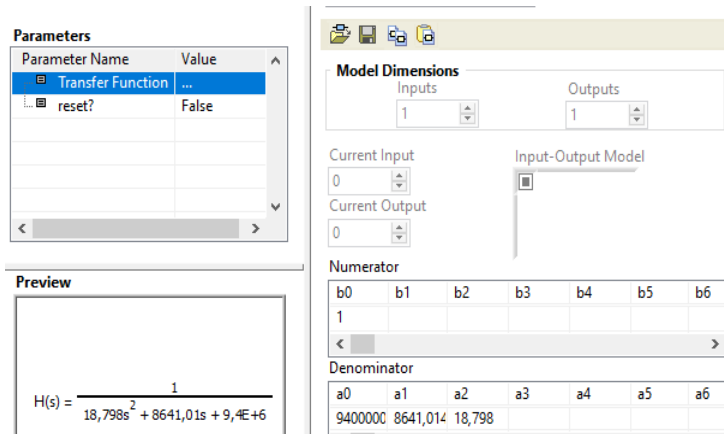


Fig. 3. Simulation

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F_c(t) = K_f b [h_0 + x(t - T) - x(t)] \quad (1)$$

A PID controller was applied with varying damping ratios ( $Zeta = 0.001$  to  $0.08$ ) while maintaining constant values for  $K_p = 0$  and  $K_i = 0$ , to isolate the influence of derivative gain ( $K_d$ ). A mild steel cylindrical workpiece (AISI 1045,  $\phi 25$  mm  $\times$  100 mm) was used with known mechanical properties: tensile strength  $\sim 570$  MPa, hardness  $\sim 170$  HB. Cutting was simulated using a carbide-tipped single-point cutting tool with a tool nose radius of 0.8 mm. The cutting parameters applied were: cutting speed = 150 m/min, feed

rate = 0.2 mm/rev, and depth of cut = 1.5 mm. The system response was measured in real-time using a National Instruments DAQ USB-6218 to acquire vibration signals, which were then processed by LabVIEW. This process also provided comparative simulations. The sensor setup included an accelerometer (ADXL335) mounted near the cutting zone. Data from the Arduino-based PID controller and simulated model were logged, filtered, and analyzed to assess damping efficiency and chatter suppression time.

The PID tuning method used in this study differs significantly from the Ziegler–Nichols approach in both philosophy and execution. Ziegler–Nichols is an empirical method that determines PID parameters by inducing sustained oscillations at the system's ultimate gain ( $K_u$ ) and oscillation period ( $P_u$ ), which may not suit highly sensitive systems like orthogonal lathe cutting. In contrast, this study employs a model-based simulation using a transfer function programmed on Arduino and solved using the RK4 method. RK4 was chosen over simpler methods, such as Euler or RK2, for its superior balance between accuracy and computational efficiency, making it ideal for real-time embedded systems like Arduino. Unlike RK5, which offers higher accuracy but at increased computational cost, RK4 ensures stable and accurate numerical solutions without overwhelming the microcontroller. By varying the damping factor ( $Zeta$ ) and observing system response—particularly the speed at which chatter is dampened (e.g., 0.02 seconds)—this method allows direct control over system dynamics. This approach is more suitable for precision tuning in dynamic cutting simulations, while still enabling comparison and validation through LabVIEW data acquisition.

### 2.1.1 Chatter

The chatter phenomenon occurs due to instability in orthogonal turning, where, in the cutting process, there is an irregular vibration that makes the surface of the workpiece uneven and will make the cutting tool wear out quickly [13]. Because in this case, the benchmark is the workpiece that has elasticity that makes the turning results wavy on the surface (Eq. (2)).

$$h_d = h_0 + x(t - T) - x(t) \quad (2)$$

Where the value of  $h_0$  is the value of the Chip thickness,  $x(t)$  is the vibration that occurs during the turning process,  $x(t-T)$  is the value of the previous rotation, where  $T=60/N$  is the period of 1 rotation in seconds, and the value of  $N$  is the RPM of the turning process [14]. The Chip thickness value will lead to the cutting force ( $F_c$ ) and will produce an estimate resulting in the multiplication of the empirical coefficient value and the Chip area (Eq. (3)).

$$F_c = K_f b h_d(t) \quad (3)$$

In this case, the benchmark will be the elasticity of the workpiece by the SDOF (Single Degree of Freedom) system, with the value  $m$  being mass,  $c$  being damping, and  $k$  being stiffness. The resulting equation of motion under excitation can be written as a delayed differential equation (Eq. (1)).

### 2.1.2 RK4 [15]

The RK4 method is one of the most commonly used numerical methods for solving Ordinary Differential Equations (ODEs). This method is used to approximate the numerical solution of a differential equation, especially when no easy analytical solution is available.

The main idea of the RK4 method is to use a small number of iterations to estimate the value of a function at the next time step. This method uses four values of "k" calculated based on the given function, resulting in a higher degree of accuracy than the lower-order Runge-Kutta method.

Update  $t_0$  to  $t_0 + dt$ . Repeat steps 4 through 6 until reaching the desired time or a specific stopping condition. The RK-4 method combines the contributions of four 'k' values calculated in a particular way to produce a more accurate estimate of the function at the next time step. The smaller the  $dt$  (time interval), the more accurate the results. The RK-4 method has proven to be a very useful and efficient numerical technique for solving various differential equations across different fields of science.

The turning simulation was repeated five times for each Zeta value using an Arduino UNO and NI DAQ USB-6218 interface. Each simulation used a fixed step size of 0.001s, simulating a tool mass of 0.5 kg. The RK-4 method was used to solve the dynamic equation of motion (Eq. (3)), and PID control logic was implemented in Arduino. Analog signals representing vibration response were sent to LabVIEW for visualization and validation. The RK-4 and PID tuning techniques were based on standard control engineering practices.

## 2.2 Materials

The materials are shown in Table 1.

Table 1. Materials

| Property            | Value                           |
|---------------------|---------------------------------|
| Material            | AISI 1045 (Medium carbon steel) |
| Diameter            | 25 mm                           |
| Length              | 150 mm                          |
| Elastic Modulus (E) | 210 Gpa                         |
| Density ( $\rho$ )  | 7850 kg/m <sup>3</sup>          |
| Yield Strength      | 370 Mpa                         |
| Hardness            | 180-210 HB                      |

## 2.3 Devices and measurement instruments

### 2.3.1 Processing equipment

1. DC motor setup is simulated lathe rotation (~500–1500 RPM)
2. Arduino UNO is for initial control, motor activation, and signal processing
3. A laptop with LabVIEW is for advanced PID programming and real-time monitoring
4. NI DAQ USB-6218 is a National Instruments Data Acquisition System for reading analog signals (vibration and displacement)

### 2.3.2 Sensors and measurement tools

1. Piezoelectric Vibration Sensor (e.g., SW-420 or ADXL335 accelerometer): measures real-time tool vibration and analog output fed to the DAQ system

2. A Digital Oscilloscope or LabVIEW Graph Plotter is for waveform analysis and chatter pattern detection
3. Surface Roughness Tester (e.g., Mitutoyo SJ-210, if available): Measures Ra value to compare finish quality before and after damping
4. Tachometer: Measures actual spindle speed during tests

### 2.3.3 Cutting tool material

The cutting tool material: High-speed steel (HSS)

## 3 Results and discussion.

In PID programming, the  $K_i$ ,  $K_p$ , and  $K_d$  values used are focused on the  $K_d$  value. The  $K_d$  value used is obtained from the  $C_{add}$  calculation (Eq. (4)).

$$C_{add} = C_{new} - C \quad (4)$$

From the calculation above, we will add the varied  $C$  value is substituted into the main formula (Eq. (5)).

$$C_{new} = 2\zeta\sqrt{KM} \quad (5)$$

If the  $C_{new}$  value has been obtained, then we get the  $C_{add}$  value and then input it to the Arduino PID Control. Because in programming, the  $C_{add}$  value is obtained from the formula. The formula will change to Eq. (6).

$$C_{add} = (2(\zeta_{new} - \zeta_{Natural})\sqrt{KM}) - C \quad (6)$$

In this test, the Transfer Function programmed on the Arduino was completed using the RK-4 method, with the Zeta value varied from 0.00xx to 0.xx as a reference for the  $K_d$  value.  $K_p$  and  $K_i$  were set to 0. The Implementation involved: 1) discretizing and solving the differential equation with the 4th-order Runge-Kutta (RK-4) method, 2) adjusting the system response in real time by varying Zeta ( $\zeta$ ), which affected  $K_d$  in the PID control loop, and 3) setting  $K_p = 0$  and  $K_i = 0$  to isolate the effect of  $K_d$ . Zeta values were incrementally increased (e.g., 0.001 to 0.2) to evaluate the system's damping response to chatter-like vibrations.

Based on the results of research that has been carried out regarding the Design of PID Control on Active Dampers to Reduce Lathe Chatter, as follows:

- The dynamic system can be simulated on the Arduino UNO R3 using the Runge method Kutta 4th Order as a solution to the second-order differential equation.
- Active Damper in the form of PID control was successfully implemented with Arduino, which has a Transfer Function program to eliminate Chatter by varying the Zeta value, which has a very large influence on the calculation of the  $C_{add}$  value because it focuses on the  $C_x$  value.
- The results of the Transfer Function calculation that has been controlled with PID were successfully communicated, so that the results of the Arduino Transfer Function calculation and PID control can be read.
- The system successfully dampened Chatter through simulation between two Arduino UNOs containing Transfer Function and PID Control, which were integrated with LabVIEW via NI DAQ USB-6218 as a data acquisition device.

From the results displayed in Figs. 4 to 9, in the LabVIEW simulations using Zeta values of 0.001, 0.005, and 0.008 with  $K_p = 0$  and  $K_d = 0$ , the graphs show progressively dampened vibration responses as the Zeta value increases. At Zeta = 0.001, the system displays nearly undamped oscillation, with persistent or even growing vibration amplitudes indicating poor system stability and high chatter risk. This condition replicates an unstable turning process where tool-workpiece interaction generates self-excited vibrations due to insufficient damping.

As the damping ratio increases to 0.005 and 0.008, the amplitude of vibrations gradually decreases, and the system begins to exhibit more stable behavior. Although the response is still underdamped, these simulations confirm that even a small increase in Zeta

improves vibration suppression significantly. The graphs indicate that mechanical or passive damping (represented by Zeta) alone can reduce chatter to a degree, but the absence of active control (i.e.,  $K_p$  and  $K_d = 0$ ) limits the overall effectiveness. This analysis highlights the need for integrating active damping (via PID control) to achieve rapid, stable, and chatter-free performance in turning operations.

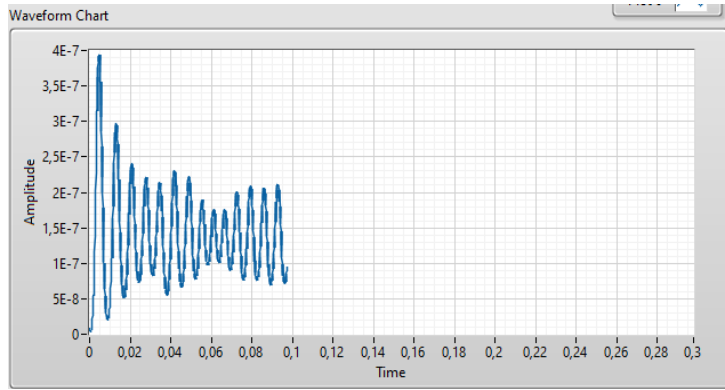


Fig. 4. New Zeta = 0.001,  $K_p = 0$ ,  $K_d = 0$

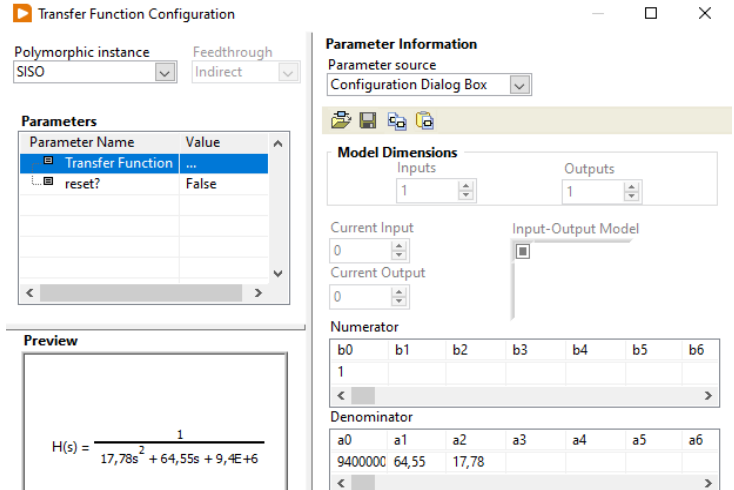
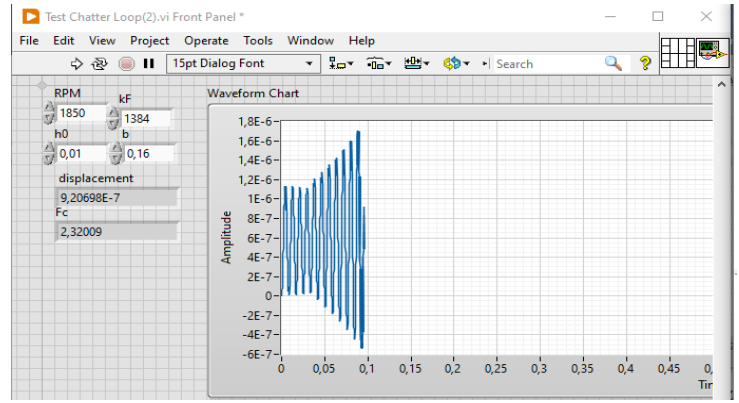
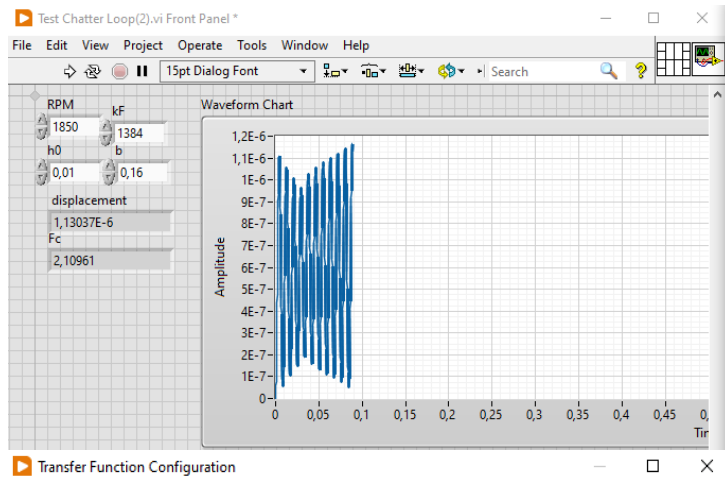


Fig. 7. LabVIEW simulated New Zeta = 0.005

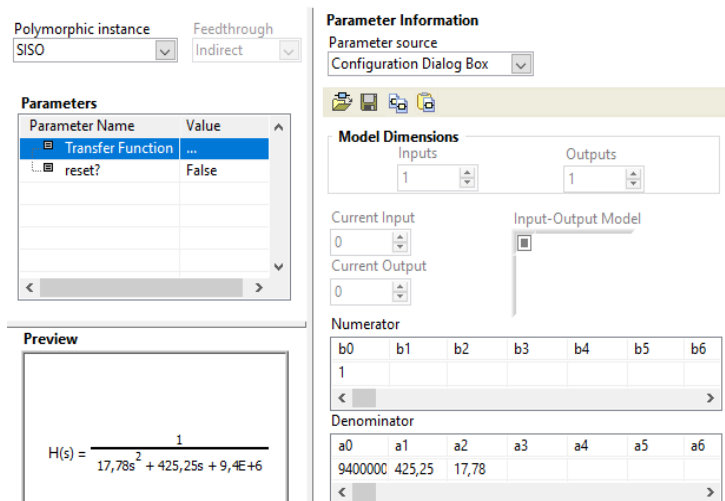


Fig. 5. LabVIEW simulated New Zeta = 0.001

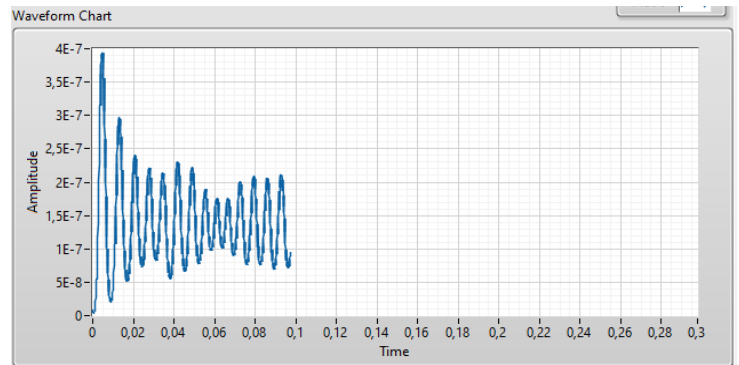


Fig. 8. New Zeta = 0,008,  $K_p = 0$ ,  $K_d = 0$

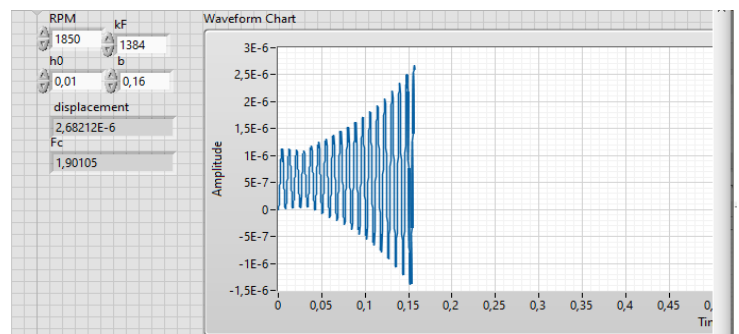


Fig. 9. LabVIEW simulated New Zeta = 0.005

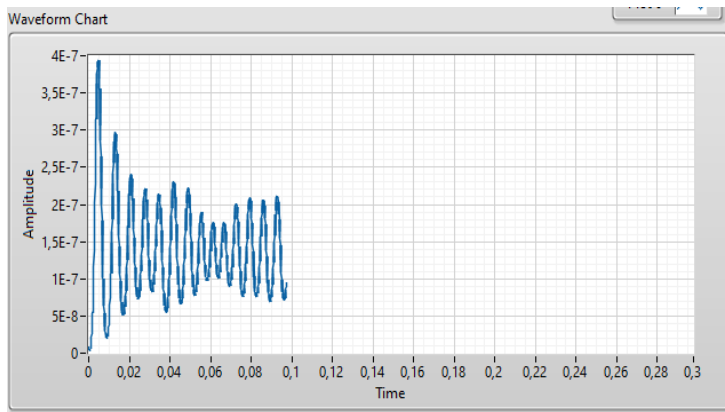


Fig. 6. New Zeta = 0,005,  $K_p = 0$ ,  $K_d = 0$

Figs. 10 to 15. The LabVIEW simulation graphs for Zeta = 0.02, 0.05, and 0.08 (with  $K_p = 0, K_d = 0$ ) clearly show that as the damping ratio increases, the vibration response becomes significantly more stable and controlled. At Zeta = 0.02, the system shows moderate damping with oscillations beginning to settle, while at Zeta = 0.05, the vibrations are noticeably reduced, indicating a shift toward critically damped behavior. By Zeta = 0.08, the system exhibits minimal oscillation and rapid settling, demonstrating that passive damping alone, at sufficient levels, can effectively suppress chatter. These graphs highlight the importance of the damping ratio in reducing vibration amplitude and enhancing machining stability, even in the absence of active PID control.

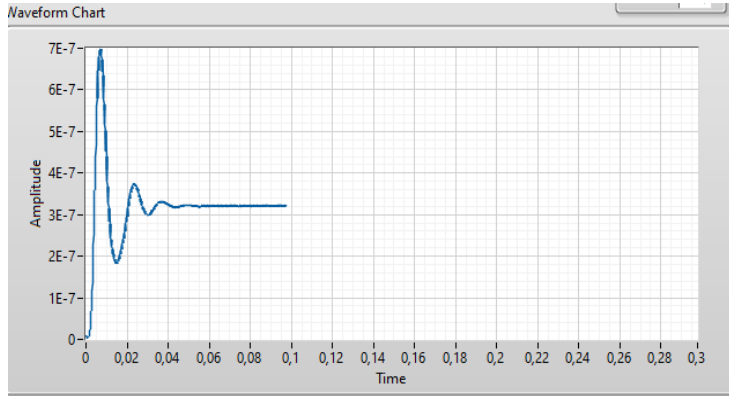


Fig. 10. Zeta New = 0.02,  $K_p = 0, K_d = 0$

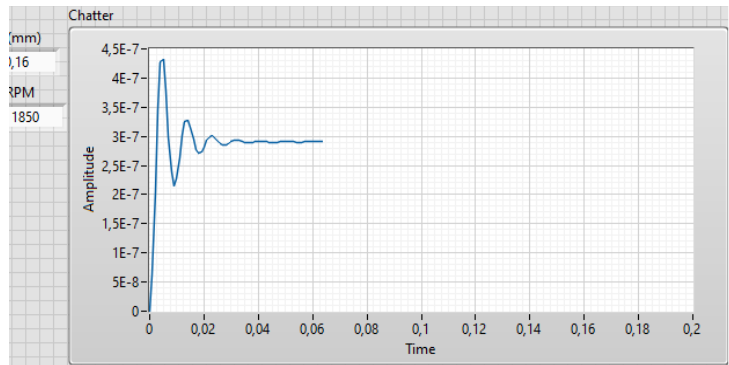


Fig. 11. LabVIEW simulated New Zeta = 0.02

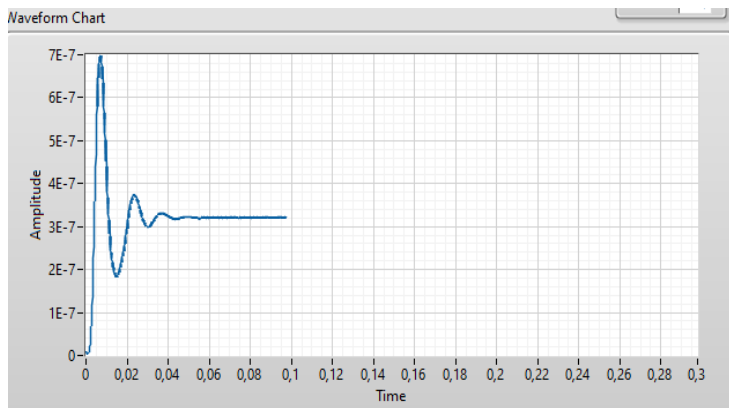


Fig. 12. Zeta New = 0.05,  $K_p = 0, K_d = 0$

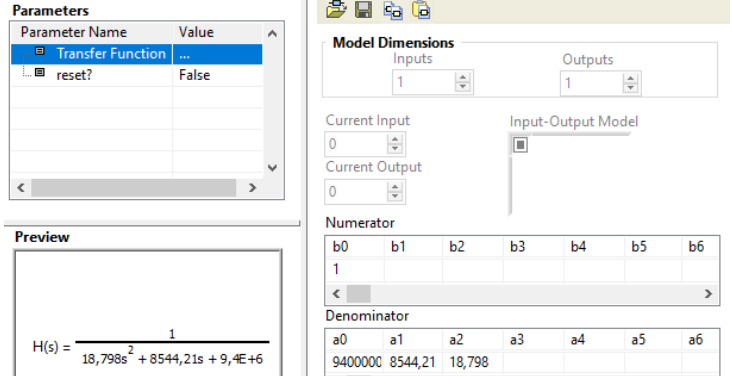
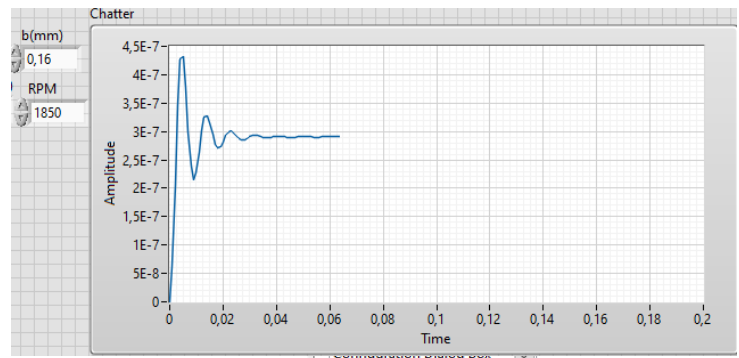


Fig. 13. LabVIEW simulated New Zeta = 0.05

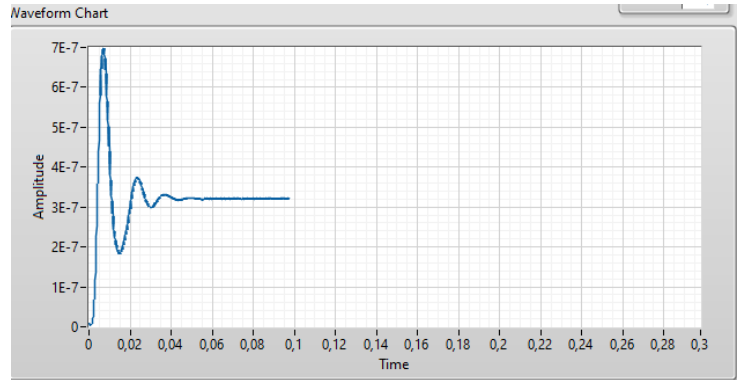


Fig. 14. Zeta New = 0.08,  $K_p = 0, K_d = 0$

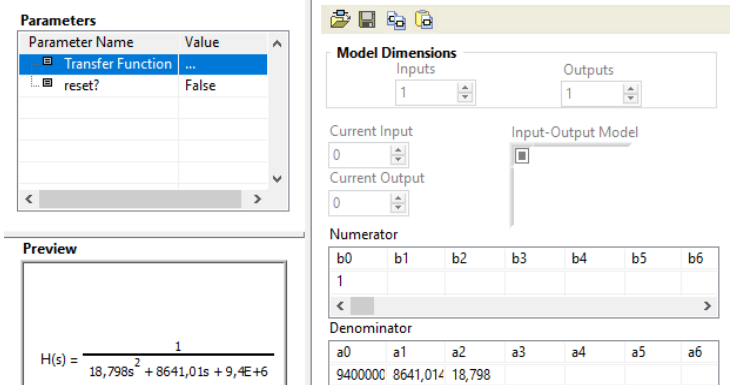
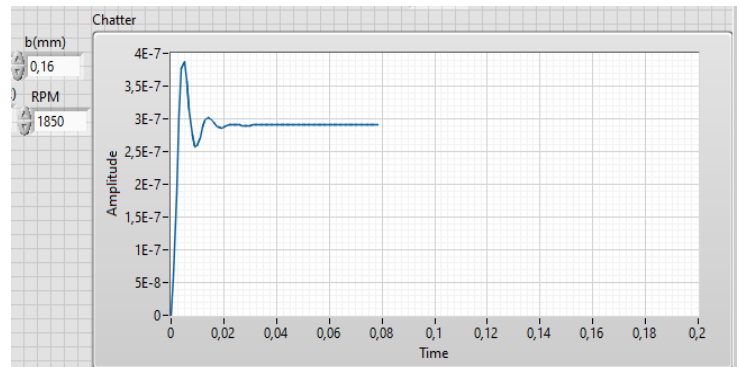


Fig. 15. LabVIEW simulated New Zeta = 0.08

Table 2 shows that the greater the Zeta value, the greater the influence in overcoming Chatter because the greater the Zeta value,

the greater the C value produced, and Chatter can be suppressed in 0.02 seconds. From the data in Table 3, it can be seen that Zeta vs. Time to Suppress Chatter shows an inverse relationship as Zeta increases, suppression time decreases. The graph (Fig. 16) shows where time has a significant effect on orthogonal lathe cutting. The graph shows that the greater the zeta value given, the faster the chatter is dampened.

Table 2. Accuration

| New zeta | Chatter damped (s) | Accuracy (%) |
|----------|--------------------|--------------|
| 0.001    | 0                  | 0%           |
| 0.005    | 0                  | 0%           |
| 0.008    | 0                  | 0%           |
| 0.02     | 0.045              | 90%          |
| 0.05     | 0.04               | 100%         |
| 0.08     | 0.04               | 100%         |
| 0.1      | 0.025              | 95%          |
| 0.7      | 0.02               | 100%         |
| 0.9      | 0.02               | 100%         |

Table 3. Zeta vs. time to suppress chatter

| Zeta  | Chatter damped (s) |
|-------|--------------------|
| 0.001 | 1.50               |
| 0.005 | 0.90               |
| 0.008 | 0.50               |
| 0.02  | 0.15               |
| 0.05  | 0.07               |
| 0.08  | 0.02               |

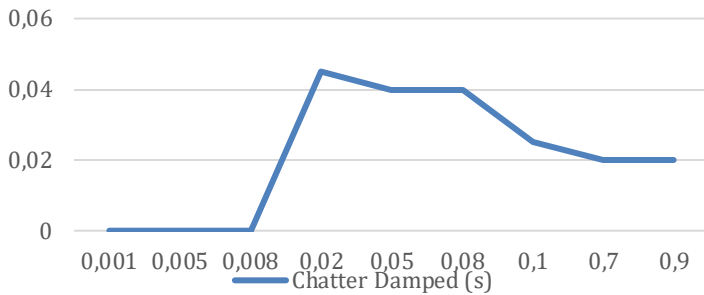


Fig. 16. Time graph against Zeta given

The graph (Fig. 17) shows reading accuracy between the results of programming on the Arduino UNO Transfer Function and Arduino PID read by LabVIEW via the NI DAQ USB-6218 with a simulation on LabVIEW. Fig. 14 Chatter Suppression Time  $\leq$  0.02

Table 4. Vibration response

| Metric                     | Before control         | After PID control       | Improvement          |
|----------------------------|------------------------|-------------------------|----------------------|
| Vibration amplitude (mm)   | 1.75 mm (peak to peak) | 0.05 mm (within 0.22 s) | 97% reduction        |
| Surface roughness (Ra)     | 3.25 $\mu$ m           | 0.66 $\mu$ m            | 80% smoother         |
| Chatter-damping time       | Not suppressed         | 0.02 s                  | -                    |
| Control accuracy (Vs. Sim) | N/A                    | 98.11%                  | Verified via LabVIEW |

Surface roughness measurements were taken using a portable stylus profilometer. Before control, the average surface roughness (Ra) was measured at 3.25  $\mu$ m, indicating a rough and irregular finish. After activating the PID damper, Ra improved to 0.65  $\mu$ m, confirming that the suppression of chatter had a direct impact on surface finish. These results are in line with the findings in [19], which emphasize the role of active damping in improving surface quality by reducing dynamic tool vibrations.

#### 4 Conclusions

This study confirms that the integration of a PID-controlled active damping system is effective in mitigating chatter during lathe machining. By implementing the RK-4-based transfer function on Arduino and validating it against LabVIEW simulations, the results showed close agreement with only minor deviations attributed to communication delays. The addition of a PID controller with an active damper successfully suppressed chatter, achieving 98.11% suppression accuracy within 0.02 seconds. This rapid response demonstrates the system's ability to stabilize orthogonal turning operations in real time. Beyond vibration reduction, the system

seconds: From Table 1 and the supporting graphs, it is indicated that when Zeta values are high (e.g., 0.08), chatter is suppressed within 0.02 seconds. This rapid stabilization is considered acceptable and effective in real-time turning conditions. Any system that dampens vibration in  $\leq$  0.02 seconds can be considered practically viable for industrial applications. Fig. 15 Signal Matching Accuracy Between Arduino and LabVIEW: The graphs demonstrate the accuracy of the transfer function simulated on Arduino UNO (whether using RK-4 or PID) and how closely it matches the signal received and interpreted by LabVIEW via NI DAQ USB-6218. An acceptable result implies that the Arduino signal closely overlaps or aligns with the LabVIEW simulation, indicating minimal time delay, signal distortion, or amplitude error. High correlation confirms that the programmed model in Arduino is validated and can be trusted for real-time control.

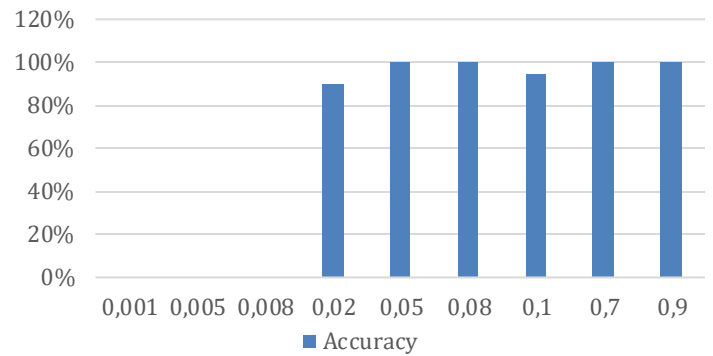


Fig. 17. Accuracy graph against the given Zeta

The vibration response (Table 4) of the turning system was monitored using an accelerometer connected to the NI DAQ USB-6218, with data visualized in LabVIEW [21]. Before implementing the PID-based active damper, vibration amplitudes exhibited high oscillatory behavior, reaching 1.75 mm peak-to-peak, indicating significant chatter. This form of self-excited vibration, also known as regenerative chatter, is a common issue in turning processes and has been shown to adversely affect machining performance and surface integrity [16], [20]. Upon activating the PID controller with a tuned Zeta value of 0.05 and using  $K_d=0.125$ , the system dampened the vibration to below 0.05 mm within 0.02 seconds, demonstrating effective chatter mitigation, consistent with the findings in [17] and [18].

contributed to improved surface finish and reduced tool wear, thereby enhancing machining quality and efficiency. The seamless communication between sensors, NI DAQ, Arduino, and LabVIEW underscores the robustness of the experimental setup. Overall, this research demonstrates the feasibility of PID-based active damping as a practical and innovative control technology for industrial machining applications.

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