



Hardware-in-the-loop simulator for emulation and active control of chatter

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ABSTRACT

Machine tool cutting performance is limited by the onset of regenerative chatter vibrations. Chatter damages the machine tool system and must be avoided. Efficacy of models guiding circumvention of chatter in actual industrial contexts remains restricted due to cutting process nonlinearities and due to uncertainties in dynamics of machine tools. To verify chatter models in the presence of nonlinearities and uncertainties and to explore active control of chatter, a mechatronic hardware-in-the-loop (HiL) simulator is presented in this paper. Hardware layer of the simulator has a flexure approximating a flexible work-piece and two actuators to emulate cutting forces and apply active damping forces. Software layer involves control architecture that is to be emulated on the hardware layer. Since HiL simulators offer a non-destructive, repeatable, and safe platform for emulations and active control of chatter, and because this paper presents the design of a validated simulator with all accompanying source files along with build and operating instructions, the research community can build such simulators to investigate other complex chatter phenomena and can also use it as a pedagogical tool. Learnings from building and using such simulators can also be leveraged to characterize and solve problems across other engineering domains.

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Specification table

Hardware name	Hardware-in-the-loop simulator for emulation and active control of chatter
Subject area	<ul style="list-style-type: none"> • Engineering and material science • Educational tools and open source alternatives to existing infrastructure • Mechanical engineering and materials science
Hardware type	No commercial analog is available
Closest commercial analog	CC BY 3.0
Open source license	~ US \$ 41,658
Cost of hardware	https://doi.org/10.17605/OSF.IO/8N47G
Source file repository	

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Hardware in context

Chatter vibrations that occur during cutting deteriorate the part's surface finish, reduce tool life, and may eventually destroy elements of the machine tool system [1]. Because of chatter's destructive potential and because of its limiting productivity improvements, modelling to guide its suppression has been of great interest to the machine tool user and research community. Of the different types of chatter, the self-excited regenerative type is the most problematic [2]. In it, the vibrating tool traces its motion on the surface of the workpiece, and because in succeeding revolutions, the tool encounters the same surface, the resulting vibrations are of even greater amplitudes that are destructive for the process, the part, and the machine. However, since chatter can destroy the part and damage the tool/machine, cutting is usually performed well-below the theoretically identified stability limits [1]. Operating conservatively results in a potential loss in productivity.

Different methodologies have hence been proposed to improve machine tool productivity, such as improvements in the cutting tool materials and tool geometries, structural modification at the design stage by topology optimization, and increasing dynamic stiffness of the machine tool by passive damping and/or active damping techniques [1]. Of these different chatter mitigation techniques, the active damping technique is one of the promising solutions to improve machine tool productivity, even when there are nonlinearities in the machines/cutting processes and/or uncertainties due to the machine tool dynamics. Active control requires a sensor and a control law applying a compensatory force to damp chatter using an actuator. Active control is hence easier to implement on machines already in use.

However, conducting experiments on machines to examine stability behaviour in the presence of cutting process nonlinearities and/or testing various active vibration control strategies to meet targeted productivity is problematic due to chatter's destructive potential. In this context, a mechatronic hardware-in-the-loop (HiL) simulator is developed to emulate regenerative chatter in a controlled manner and to plan strategies to mitigate it. HiL simulators for emulating cutting process stability usually comprises a flexure approximating a flexible workpiece and two actuators, of which one imitates real-time regenerative cutting forces estimated in the software layer and another applies the active damping force.

HiL simulators have been shown to be useful to investigate chatter [3–13], and to actively control it [3–5,9–13]. Ganguli et al. [3,4] and Mancisidor et al. [5] used a cantilever beam approximating a flexible workpiece and actuators for cutting force emulation. However, such setups have less space for mounting and testing actuators that are generally used for controlling vibrations in typical CNC milling machines or portal milling machines. Matsubara et al. [6] and Stepan et al. [7,8] used a realistic machine with an actual spindle unit and a dummy tool/workpiece to emulate chatter vibrations while incorporating speed-dependent dynamics. They, however, did not investigate any active damping strategies. Though the setups used in [6–8] are real machines with an actual spindle unit, they are costly. Mancisidor et al. [9,10] and Sahu et al. [11–13] have used a simpler flexure that approximates a linear flexible single degree of freedom workpiece. The flexure used in [9–13] provided sufficient space to mount two actuators, one of which imitated cutting forces and the other served as an active damper. The simple design facilitated emulations to study the influence of different nonlinear force characteristics on chatter without having to worry about potential nonlinearities in the structure influencing stability. The simple design also facilitated investigations for gain tuning for active vibration control in the presence of cutting process nonlinearities resulting in bistabilities [11–13]. This paper hence prefers to report on emulations on a HiL simulator with a simple hardware design.

Though there exist HiL simulators for emulations and active control of chatter, there exist no reports on how to systematically design, build, characterize, and operate one. This paper aims to remedy that by presenting detailed designs, build descriptions, and operating instructions for a HiL simulator to emulate chatter and for it to be useful for testing of active control strategies to mitigate chatter. It is not the aim of emulations on the HiL simulator to be compared with the real cutting processes, but instead to guide cutting parameter selection and detection and suppression of chatter during real cutting. The remainder of the paper discusses the workings of the HiL simulator followed by presenting its design, build and operating instructions. That is followed by discussions on validating the simulator.

Hardware description

The HiL simulator has two layers: a hardware layer and a software layer. Fig. 1 shows the interaction of these two layers. The hardware layer consists of a flexure that approximates a flexible workpiece, two shakers (actuators) with its power amplifiers, a Compact RIO controller with analog input and analog output modules, two force sensors measuring emulated cutting force and active damping force, an accelerometer to measure the response of the flexure and a computer that connects the hardware and software layer via a LAN connection. The software layer runs on LabVIEW. It includes data acquisition, filtering, regenerative cutting force, active damping force calculations, real-time plotting of time-series and frequency data, and data logging for further post-processing.

The HiL simulator has sensors, actuators, and involves computation and digital filtering, and characteristics of each influence the closed-loop stability of the system. Hence, the key components of the HiL simulator are separately characterized to identify their phase-frequency behavior. Details can be found in [11]. The HiL simulator for chatter was found to have a phase lag that corresponds to a total delay of ~ 0.8 ms [12]. Since delays in the simulator will result in emulations differing from theoretical predictions, a suitable phase lead compensator was designed and implemented within the software layer. Since the active damping loop also involves the use of a different sensor and actuator than the regenerative loop, their behaviour

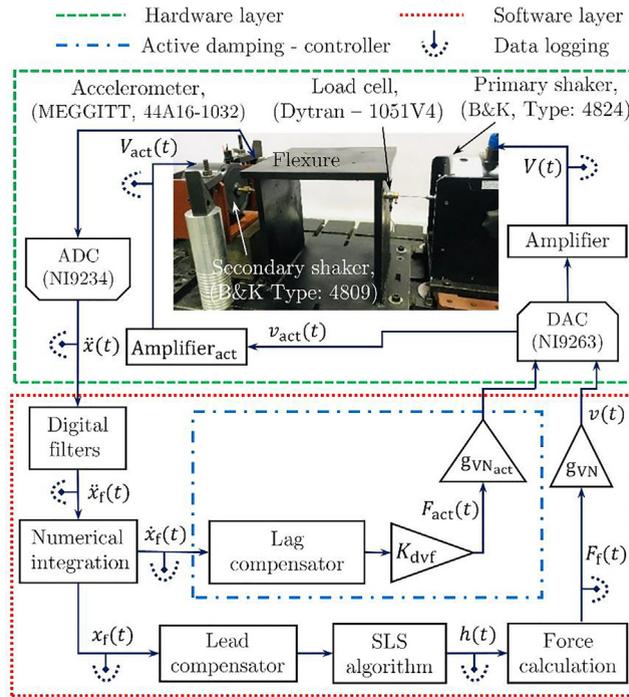


Fig. 2. Block diagram of the hardware-software layer interactions in the HiL simulator.

- investigate new advanced robust control strategies, and to
- generate data sets to train the AI-ML-based data-driven models that could help detect and avoid chatter during real cutting in Industry settings.

Design files

An exploded view of a CAD assembly of the flexure coupled with the primary and the secondary shaker is shown in Fig. 3. Part numbers shown in Fig. 3 are also used in a making design file summary (Section 3.1) and a bill of materials summary (Section 4).

Design files summary

Design file name	File type	Open source license	Location of the file
Part #1	.SLDTPRT, CAD file	CC	https://doi.org/10.17605/OSF.IO/8N47G
Part #2	.SLDTPRT, CAD file	CC	https://doi.org/10.17605/OSF.IO/8N47G
Part #3	.SLDTPRT, CAD file	CC	https://doi.org/10.17605/OSF.IO/8N47G
Part #4	.SLDTPRT, CAD file	CC	https://doi.org/10.17605/OSF.IO/8N47G
Flexure shaker assembly	.rar, (CAD files)	CC	https://doi.org/10.17605/OSF.IO/8N47G
Engineering drawings of Parts #1-#4	.rar, (PDF files)	CC	https://doi.org/10.17605/OSF.IO/8N47G
Control program	.rar, (LabVIEW files)	CC	https://doi.org/10.17605/OSF.IO/8N47G

- Part #1** is the flexure that represents a flexible workpiece and is akin to a single degree of freedom system.
- Part #2** is the base that secures the primary shaker with the rigid table.
- Part #3** is the base that secures the secondary shaker with the rigid table.
- Part #4** is the coupler that connects the stinger and force sensor, which connects the primary shaker and secondary shaker with the flexure.

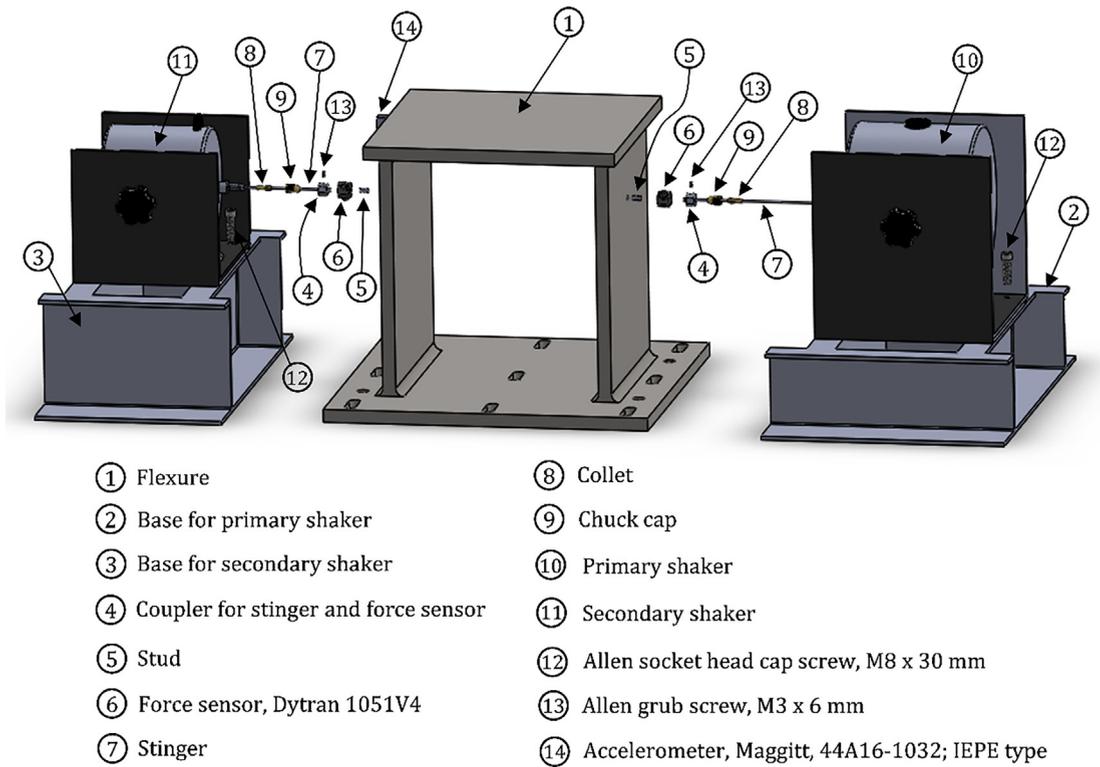


Fig. 3. Exploded view of a CAD assembly of the flexure coupled with the primary and secondary shaker.

Flexure shaker assembly is a SolidWorks CAD assembly file that includes all the components shown in Fig. 3.

Engineering drawings of Part #1-#4 include the design and dimensions of the flexure, the base for primary and secondary shaker, and the coupler for stinger and force sensor. These are used to manufacturing them.

Control program is a LabVIEW project file, and it is the only element of the software layer. Control programs involve data acquisition, filtering, data plotting, numerical integration, calculation of regenerative cutting forces, active damping forces, and data logging. File nomenclature of the LabVIEW project files is as in Fig. 1.

Bill of materials

Bill of materials summary

Designator	Component	Number	Cost per unit -currency (US \$)	Total cost – currency (US \$)	Source of materials	Material type
Part #1	Flexure	1	36.6	36.6	Source and product specifications of the parts mentioned in this table are uploaded in the OSF repository: https://doi.org/10.17605/OSF.IO/8N47G	Mild steel
Part #2	Base for primary shaker	1	14	14		Mild steel
Part #3	Base for secondary shaker	1	14	14		Mild steel
Part #4	Coupler for stinger and force sensor	2	2	4		Brass
Part #5	Stud	2	1.5	3		Brass
Part #6	Force sensor, Dytran 1051V4, IEPE Type	2	655	1310		Electronic
Part #7	Stinger	2	–	–		Stainless steel
Part #8	Collet	2	–	–		Stainless steel

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(continued)

Designator	Component	Number	Cost per unit -currency (US \$)	Total cost – currency (US \$)	Source of materials	Material type
Part #9	Chuck cap	2	–	–		Stainless steel
Part #10	Primary shaker, Type 4824	1	~16170	~16170		Electrical and Electronics
	Amplifier, Type 2732	1				Electrical and Electronics
Part #11	Secondary shaker, Type 4809	1	~13475	~13475		Electrical and Electronic
	Amplifier, Type 2718	1				Electrical and Electronics
Part #12	Allen socket head cap screw, M8x30mm	8	0.2	1.6		Hardened carbon steel
Part #13	Allen grub screw, M3x6mm	2	1	2		Hardened carbon steel
Part #14	Accelerometer, Maggitt, 44A16- 1032; IEPE type	1	~2120	~2120		Electronic
Stepped Strap Clamp	TSSC-12-100	8	4.6	37.2		Hardened carbon steel
Step block	THSB-5	8	6.7	54.0		Hardened carbon steel
Clamping stud	M12 × 75 mm	8	0.61	4.9		Hardened carbon steel
Allen socket Head cap screw	M12 × 40 mm	4	0.5	2		Hardened carbon steel
Flange Nut	M12	8	0.78	6.2		Hardened carbon steel
Nut	M12	8	0.2	1.6		
T-nut	TTN-18-12	12	0.56	6.7		Hardened carbon steel
Analog Input Module	NI9234	1	2673	2673		Electronic
Analog Output Module	NI9263	1	625	625		Electronic
Compact RIO	Controller	NI cRIO 9040	1	4032		4032
Electronic Industrial Power Supply	NI PS-15	1	384	384		Electrical and Electronic
LAN Cable	–	1	1	1		Electronic
Computer	–	1	678	678		Electronic
BNC Cable (one end is open)	–	2	1	2	Electronic	
Total cost (in US \$)				~41657.8		

Build instructions

Parts #1–#4 were manufactured in-house, and the rest of the components mentioned in the bill of materials summary were bought. Additional tools required to assemble the HiL simulator are:

- Metric Allen key set
- 2 mm cross screwdriver
- M12 Spanner

The preparation of hardware components, assembly of hardware components, wiring of electronics components, and control programs for the HiL simulator are discussed subsequently.

Preparation of hardware components

Part #1 – Flexure: The flexure is designed to have a single resonance frequency over the range of 30 Hz – 300 Hz. The flexure is designed such that different actuators can be mounted easily for testing active damping strategies. For fabrication of the flexure, 16 mm thick mild steel plates were cut in required dimensions using an abrasive water jet machining process and then welded using an arc welding process. For mounting force sensors, drilling and tapping with $\frac{1}{4}$ 28 UNF was done on two vertical flexure plates.

Part #2 and Part #3 – Base for primary and secondary shaker: Dimensions for part #2 and Part #3 were determined based on the force sensor mounting height and the height of the primary and secondary shaker (when its axis is parallel to the ground), respectively. For fabrication of Part #2 and Part #3, 5 mm thick mild steel plates were cut in required dimensions using an abrasive water jet machining process and then welded using an arc welding process.

Part #4 – Coupler for stinger and force sensor: Part dimensions were decided based on dimensions of the stinger and force sensor. For fabrication of Part #4, turning, milling, drilling, and tapping operations were performed.

Remaining parts: Besides Parts #1–#4, the rest of the parts mentioned in Section 4.1 were purchased.

Assembly of hardware components

Assembly sequence and procedures for components shown in Fig. 3 is as follows:

- Secure Part #1 onto the rigid table using T-nuts and M12x40 mm bolts.
- Secure Part #10 onto Part #2 and Part #11 onto Part #3 using Part #12 and nuts.
- Secure Part #4 and Part #5 onto Part #6. Secure the coupled Parts #4–#6 onto two vertical plates of Part #1 as shown in Fig. 3.
- By adjusting Part #2 and Part #10, align the axis of Parts #4–#6 with the axis of the primary shaker. Similarly, by adjusting Part #3 and Part #11, align the axis of Parts #4–#6 with the axis of the secondary shaker.
- Secure Part #2 and Part #10 and Part #3 and Part #11 onto the rigid table using stepped strap clamps, step blocks, clamping studs, T-nuts, and flange nuts.
- Connect Part #10 with Part #4 via Part #7 and tighten the primary shaker's end with Part #8-Part #9 and coupler's end with a grub screw (Part #13). Similarly, connect Part #11 with Part #4 via Part #7, and tighten the secondary shaker's end with Part #8-Part #9 and coupler's end with a grub screw (Part #13).

Wiring of electronic components

Connections of electronic components follow the schematic in Fig. 1 with the following procedures:

- Connect the main 230 V AC power supply to amplifiers of primary and secondary shakers, NI PS-16, and to a computer that has LabVIEW installed on it.
- Connect the Type 2732 power amplifier to the primary shaker (B&K Type 4824) and the Type 2718 power amplifier to the secondary shaker (B&K Type 4809).
- Connect the 24 V DC output of NI PS-16 to NI cRIO 9040.
- Establish a LAN connection between the Computer and NI cRIO 9040. Connect NI 9263 and NI 9234 to module 1 and module 2 of the NI cRIO 9040.
- To monitor the cutting forces, active damping forces, acceleration response, and voltage given to the primary shaker, connections have been made using their respective BNC cables. See Fig. 1.

Once all wiring is done, the next step is to run the LabVIEW control programs to perform the HiL experiments. A brief description of control programs is discussed in Section 5.4.

Control programs

The control programs for the HiL simulator have been written in LabVIEW. The prerequisite modules that need to be installed within LabVIEW are Data acquisition, FPGA, and Control and Simulation modules.

- The LabVIEW codes used to execute the HiL simulator are listed in Section 3.1.
- The LabVIEW code has a project file (Project.lvproj) which includes four subfiles. Subfiles are FPGA.vi, RT.vi, var.lvlib and Logging.vi., as also depicted in Fig. 1.
- These codes were written separately to save computational time in a single loop iteration.
- In the FPGA.vi, data acquisition (analog input from NI 9234) and filtering has been implemented. The voltage signals corresponding to calculated cutting force and active damping force are also taken as outputs from the analog output device (NI 9263) through an FPGA.vi, see Fig. 1.
- RT.vi reads the signal from FPGA.vi wherein calculation of regenerative cutting force, surface location storage (SLS) algorithm involving multiple regenerative effects, chatter detection system, delay compensation, active damping force calculations, and real-time plotting of time series and frequency spectrum are done. Subsequently, calculated cutting force and active damping force are converted into voltage and written on the FPGA.vi for analog voltage output.
- The experimental data points (spindle speed, depth of cut, chip thickness, chatter frequency, and chatter amplitude) and time series data corresponding to the critical stability limits are stored in a variable called var.lvlib.
- Logging.vi reads var.lvlib and writes a .txt file. The computational power for data logging is given to the host computer.
- A graphical user interface (front panel of RT.vi) shown in Fig. 4 is used to perform the HiL experiments.

Safety instructions

- During wiring connection, ensure that no AC/DC power is given to any of the electronic components of the HiL simulator.
- Before performing any experiments, ensure that electronic components are connected correctly.

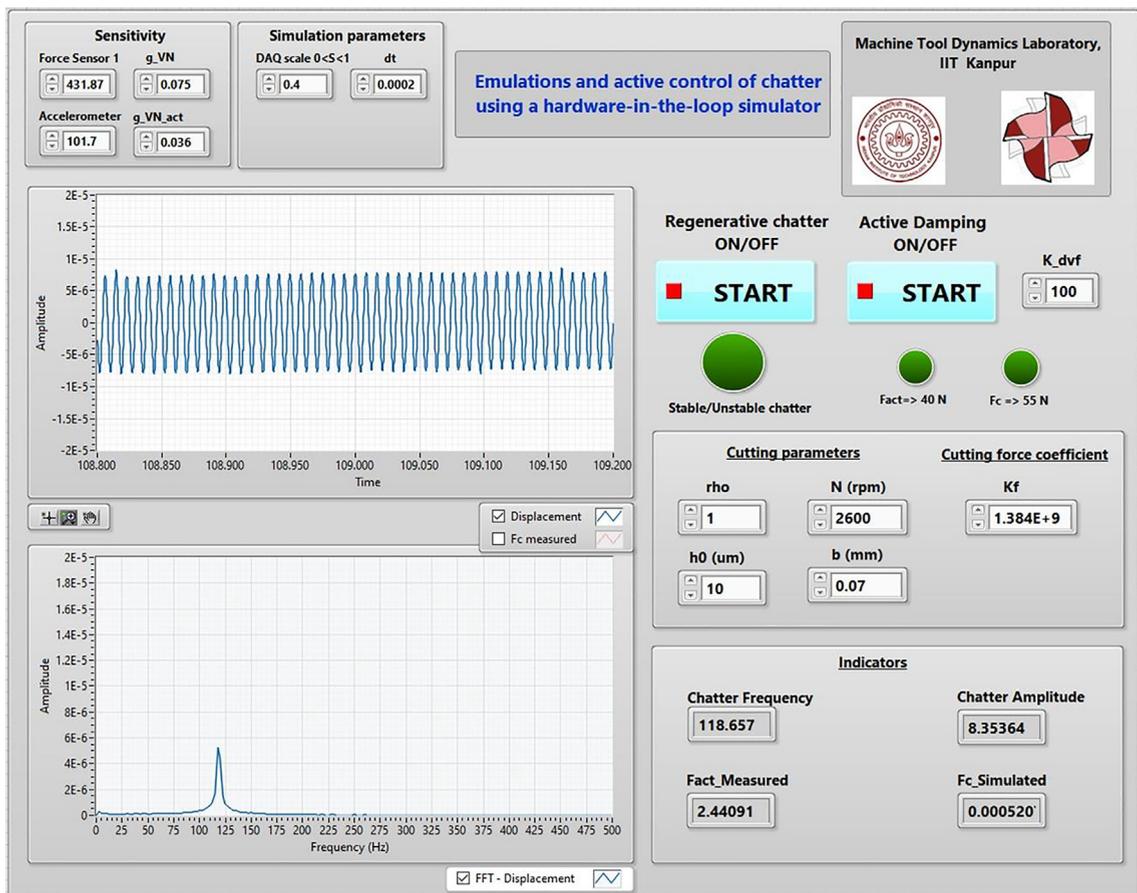


Fig. 4. A graphical user interface (GUI) to perform chatter and active damping experiments in the HiL simulator.

- Before performing any chatter experiments, ensure that the GUI displays a response corresponding to a random perturbation.
- In the GUI, carefully check the entered numerical values of cutting parameters and cutting force coefficient.
- Select the cutting force coefficient such that the minimum stability limit of the cutting process can be obtained using the HiL simulator without reaching the shaker's force and/or current limit.
- For active damping experiments, ensure that the entered control gain is stable from a control perspective.

Operation instructions

Two sets of experiments can be performed on the HiL simulator under consideration. One is chatter experiments, and another is chatter experiments with active damping. In the present case, a cutting force coefficient corresponding to the linear force model is selected ($K_f = 1384\text{N/mm}^2$). In this work, the experiments are conducted for a fixed value of chip thickness ($h_0 = 20\mu\text{m}$) and cutting ratio ($\rho = 1$). A video on how to perform chatter experiments on the HiL simulator is uploaded in the same repository as that which has the software files (see Section 3.1 for link). The operation instructions for the chatter experiments using the HiL simulator are now described as follows:

- First, run the GUI shown in Fig. 4 without switching 'On' the "Regenerative chatter ON/OFF". Then run the front panel of Logging.vi for logging the required experimental data points.
- Switch 'On' the "Regenerative chatter ON/OFF" for a particular combination of spindle speed (N) and depth of cut (b). If displacement response corresponding to initial perturbation starts to decay with time, the cutting process is said to be stable. The cutting process is said to be unstable (chatter) if the response starts to increase with time and eventually saturates at finite amplitude due to the tool out of cut condition. For the case of chatter vibration, "Stable/Unstable chatter" Boolean indicator shown in Fig. 4 starts to blink; for this case, spindle speed, depth of cut, chatter frequency, and chatter amplitude are recorded. In this technique, chatter experiments are repeated for the spindle speed under consideration.
- Representative stable and unstable responses are presented in Fig. 5.
- For chatter experiments with active damping case, switch 'On' the "Active Damping ON/OFF" with the desired value of control gain (K_{dvf}) and repeat the experiments over the spindle speed range of interest. In active damping experiments, a control gain of $K_{dvf} = 400\text{Ns/m}$ is used.

Validation and characterization

The HiL simulator is validated for an orthogonal turning process with and without the use of active damping. Emulated stability behaviour on the HiL simulator is overlaid with the theoretically predicted stability behaviour as shown in Fig. 6. To construct theoretical stability chart shown in Fig. 6, a mathematical model presented in [11,12] is used. Cutting with parameters that lie above the boundaries shown in Fig. 6 results in chatter vibrations.

As is evident from Fig. 6, the emulated stability points for both Control 'Off' and 'On' case are in good agreement with the model predictions. It is also evident that the minimum stability limit increases significantly with active damping, which is equivalent to $\sim 700\%$ improvement in productivity.

In conclusion, since HiL simulators offer a non-destructive, repeatable, and safe platform for emulations and active control of chatter, and because this paper presents the design of such a simulator with all accompanying source files along with build and operating instructions, the research community can build such simulators to investigate other complex chatter phenomena and can also use it as a pedagogical tool. The community may also choose to modify the experimental test rig to include potential nonlinearities on account of the mechanical structure (such as due to contacts and damping). That may further improve the relevance of the test rig for it to become more representative of real machine tool systems. Furthermore, since the simulator has already been shown capable of emulating highly interrupted turning processes, it may also be used to emulate interrupted milling processes with suitable hardware/software modifications as necessary.

Learnings from building and using such simulators can also be leveraged to characterize and solve problems across other engineering domains.

CRedit authorship contribution statement

Govind N. Sahu: Methodology, Software, Data curation, Writing – original draft, Visualization, Investigation, Software, Validation. **Mohit Law:** Conceptualization, Visualization, Investigation, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

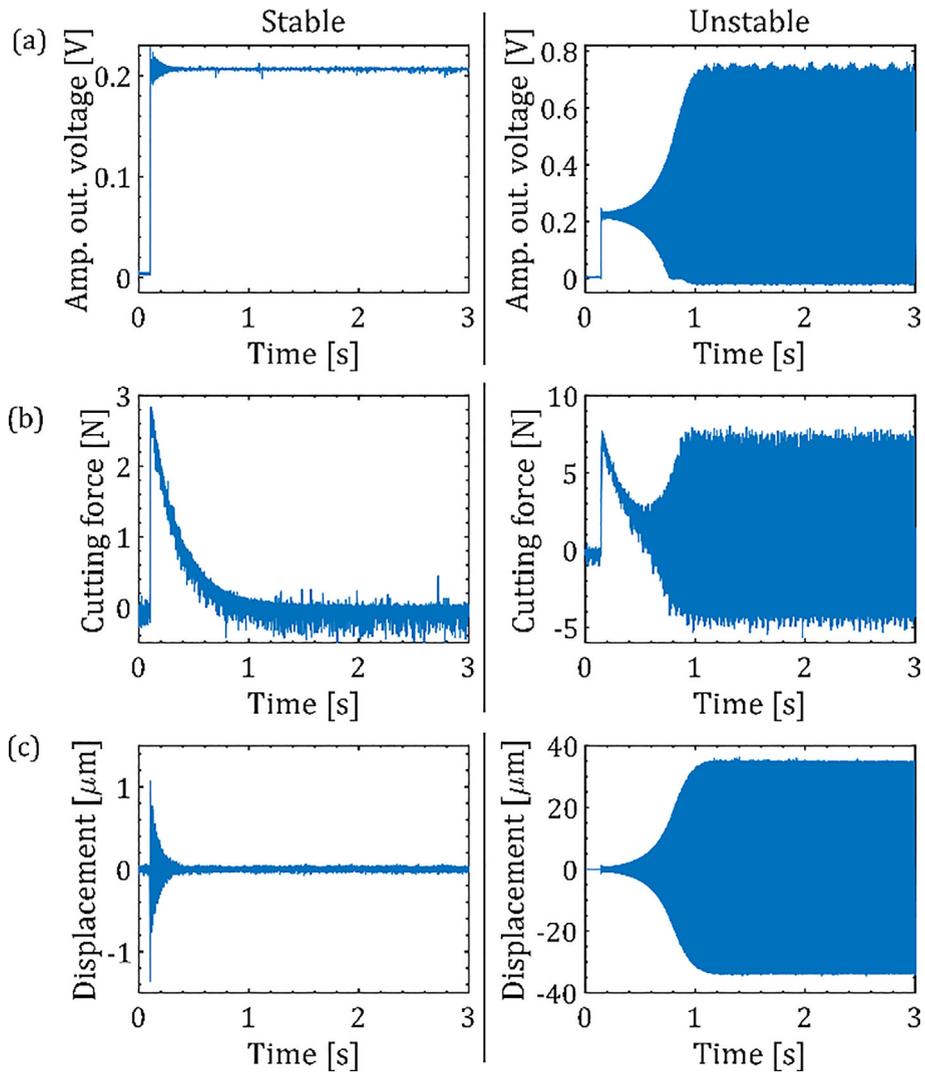


Fig. 5. Representative experimental cases with linear force model, $h_0 = 20\mu\text{ m}$, displaying stable ($b = 0.1\text{ mm}$, $N = 3000\text{ rpm}$) and unstable behavior ($b = 0.1\text{ mm}$, $N = 2600\text{ rpm}$). (a) Voltage output from the amplifier, (b) Measured forces, (c) Measured displacements.

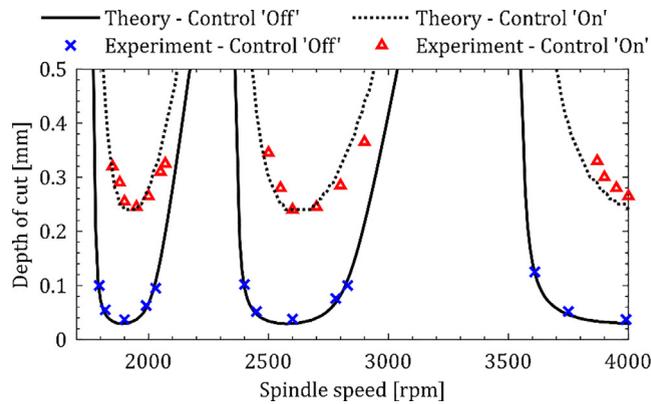


Fig. 6. Theoretical and emulated experimental stability chart with and without active control of vibrations.

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Human and animal rights

Not relevant.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ohx.2022.e00273>.

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