Investigating nonlinear finite amplitude chatter instabilities using a hardware-in-the-loop simulator

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Abstract

This paper presents investigations on nonlinear finite amplitude instabilities (FAI) in turning using a hardware-in-the-loop (HiL) simulator. The HiL simulator, being non-destructive and repeatable, facilitates investigations of nonlinearities prevalent in real cutting processes, which are otherwise difficult to study due to the vagaries of changing machine tool dynamics. We investigate two nonlinearities in this paper – one due to nonlinear cutting force characteristics, and another due to the tool moving out of the cut in the case of large amplitude unstable vibrations. We propose a new time domain surface location storage algorithm to efficiently emulate nonlinearities in the HiL simulator. Regions of FAI are found by performing experiments on the HiL simulator by varying the depth of cut for fixed speeds and static chip thicknesses. Experiments on the HiL simulator provide insights into regenerative cutting process dynamics, thereby facilitating the study of more complex phenomena like in intermittent turning and milling.

Key Words: Hardware-in-the-Loop, Regenerative chatter, Nonlinear dynamics

1. Introduction

Chatter in metal cutting, arising from regenerative type self-excited vibrations, proves to be a major limitation in improving the part surface quality and machine tool productivity. Regenerative chatter occurs due to the interaction of the dynamics of the machine tool with that of the cutting process. These closed loop interactions can lead to large amplitude unstable vibrations, and hence there has been a sustained interest in modelling chatter to avoid it. Seminal models for chatter were developed based on a linear stability analysis of the closed-loop interactions [1]. Linear theories predict the boundaries of stability mapped on a cutting parameter space of depth of cut and spindle speed. These boundaries have proved useful to guide the selection of parameters that result in stable cutting. For parameters selected above these boundaries, the linear theories predict the vibration amplitudes to grow indefinitely. However, experiments have shown that vibrations settle to a finite amplitude after an initial surge. Additionally, the experiments in [2-4] highlight a region of finite amplitude instability (FAI) wherein the cutting process is stable for small disturbances but becomes unstable when large disturbances arise. These finite amplitude instabilities cannot be explained by the linear stability models.

Tobias [4] attributed the phenomenon of finite amplitude instabilities to two nonlinearities present in the cutting process – one due to the nonlinear characteristics of the cutting process, and a second one due to the loss of contact between the tool and workpiece when vibration amplitudes breached a certain threshold. The loss of the contact of the cutting tool from the workpiece is governed by the cutting process itself and is known as self-interrupted cutting. Unlike the linear stability analysis in which the dynamics are governed by the vibrations in the current revolution and vibrations one revolution before, i.e. single regeneration, the dynamics of the self-interrupted cutting can be affected by vibrations from multiple prior revolutions, i.e. multiple regenerations. The multiple regenerative effects can be incorporated into analytical models as presented in [5-6].

The challenge associated with investigating nonlinear finite amplitude instabilities based on exhaustive real cutting experiments, as was done in [2-4], is that the uncertainties in the machine tool system lead to a considerable degree of non-repeatability in results. Furthermore, the cumbersome theoretical models reported in [5-6] attempt to study the global dynamics of self-interrupted cutting without acknowledging the limitations in the experiments. In the context of doing experiments that are repeatable, cost-effective and safe, this paper presents a new approach based on a mechatronic hardware-in-the-loop (HiL) simulator to investigate finite amplitude instabilities due to the nonlinear cutting process characteristics.

The HiL simulator is a hybrid system of hardware and software components substituting the actual cutting tool-workpiece interaction through an actuator exciting a flexure by an emulated real time cutting force. HiL simulators have been shown to be useful to investigate chatter [7-10], albeit mostly using only linear stability models. This paper incorporates nonlinear characteristics in our previously validated linear HiL simulator for chatter [10] – as discussed in Section 2. The nonlinear cutting force model is characterized by a power law, and the multiple regenerative effects due to self-interruption are incorporated using a new and computationally efficient time-domain algorithm, called the 'Surface Location Storage Algorithm'. Experiments on finite amplitude instabilities using the HiL simulator are discussed in Section 3, followed by the main conclusions in Section 4.

2. Hardware-in-the-loop simulator

The HiL simulator is a hybrid system consisting of a hardware (H/W) and a software (S/W) layer. The hardware layer includes a flexure representing a flexible machine or workpiece on which an emulated cutting force is applied using an actuator, and the response transducer measures the response of the flexure as shown in Fig. 1. The flexure has a single dominant mode at $112.6\ Hz$, with a damping ratio of $\zeta = 1.6\ \%$, and a stiffness of $k = 9.4 \times 10^6\ N/m$. A hardware-based integrator is used to obtain the displacement signal from the accelerometer. This measured signal is transferred to the software layer through an analog to digital converter (ADC). This information is then used in the 'Surface Location Storage Algorithm' (SLS) algorithm to compute the regenerative cutting force as dictated by the theory of orthogonal cutting process. The computed force is then sent through the amplifier to the electrodynamic shaker through a digital to analog converter (DAC).

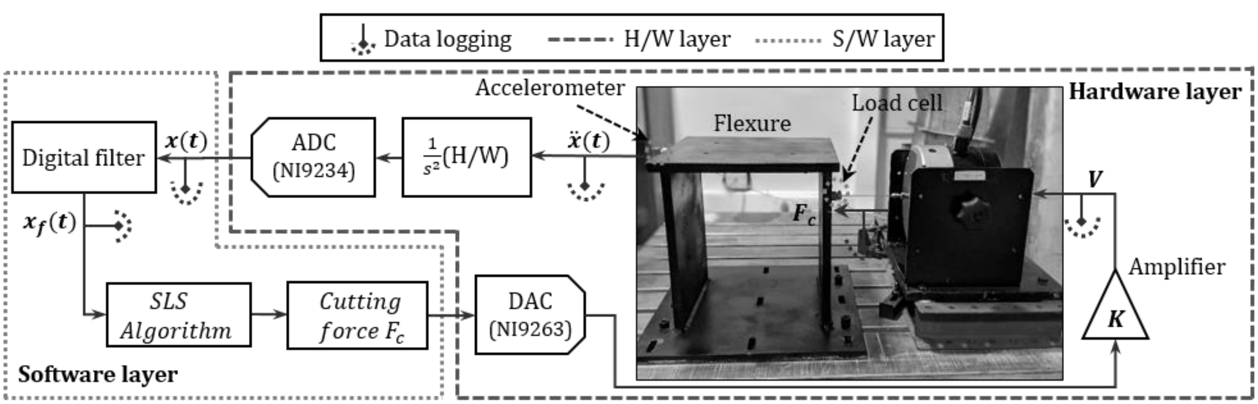

Figure 1: Hardware and software layers of the HiL simulator for investigating chatter

National Instruments (NI) LabVIEW is used to develop the software layer, which consists of three main layers: a Field Programmable Gate Array (FPGA) layer, a Real-Time (RT) environment, and, a Host. The FPGA code contains the analog input/output and Butterworth high and low pass digital filters. Signals are sampled at $8.2\ kHz$. Filtered signals are sent to the RT code. The RT computation is performed on a NI cRIO-9036 module where variables are accessed using the *FPGA reference* and are used to compute the force signal using the SLS algorithm as discussed in the subsequent section. The Host code uses the host computer to log the data. For additional details on the elements of the HiL simulator, the reader is directed to [10].

2.1 Surface Location Storage Algorithm

When the vibration of the tool is large enough, the tool loses contact with the workpiece. The resulting dynamic chip thickness, $h(t)$ will thus not only depend on the current tool vibration but also on all the previous vibrations of the tool. Therefore, it is necessary to use the data of earlier revolutions to calculate the actual $h(t)$ at any instant. This can be done by storing vibration data from earlier revolutions, as was done in [9]. However, storing a large amount of data taxes the computational speed. To overcome this, we propose a new surface location storage (SLS) algorithm that stores data of only the surface resulting from all the previous vibrations of tool along with the relative revolution number, thereby lowering the computational cost. This method can account for multiple regenerative effects and overcomes the limitation of using a transport delay block within LabVIEW that can account for only a single regeneration [10]. An overview of the proposed algorithm is shown in Fig. 2.

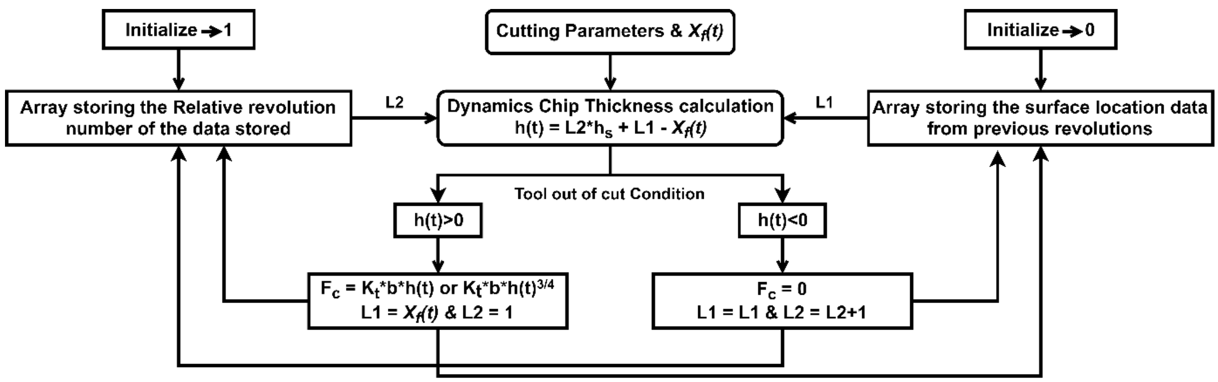

Figure 2: Surface location storage (SLS) algorithm

The length of the arrays storing the relative revolution number and the surface location data is governed by the number of samples per revolution, and are initialized to 1 and 0 respectively for the first revolution. Using the data from these arrays for a particular sample, the dynamic chip thickness $h(t)$ is calculated, as shown in Fig. 2. For this specific sample if the surface is being cut by the tool, i.e., if $h(t) > 0$, then the surface location data will be modified with the current response and relative revolution number for the next revolution will become 1. However, if the surface is not cut by the tool, i.e., if $h(t) < 0$, then the surface location data will remain unchanged, but the relative revolution number will be increased by 1. The proposed algorithm includes all the regenerations and can accommodate a linear as well as nonlinear power law cutting force model as necessary, making it versatile enough to investigate finite amplitude instabilities as desired.

2.2 Experimental characterization of chatter with the HiL Simulator

Experiments on the HiL simulator are conducted by sequentially increasing the simulated depth of cut at a specified spindle speed until the response starts to grow with time and the observed oscillation frequency (chatter frequency) for that case is recorded. Experimental results are overlaid on results obtained using a linear force model [1, 10], as shown in Fig. 3. As is evident, results diverge significantly from the theoretical prediction due to delay in the mechatronic system as discussed in [8-10]. Hence, for effective utilization of the HiL simulator, it is necessary to identify the total delay in the system and to compensate for this delay. Separate experiments were conducted for the identification of delays caused by the H/W and the S/W layer(s). The total delay was estimated using the '*fixed frequency phase information*' [10] and was found to be 2.1 ms. Results with this delay introduced into the theoretical model compare well with the experimental results, as also shown in Fig. 3. Fig. 3 also shows results with a well-designed compensation filter implemented on the HiL simulator, and, as is evident, the experimental results on the HiL simulator with a compensation filter also match up well with the theoretical predictions without delay. The interested reader is directed to [10] for additional details on the design of the compensation filter.

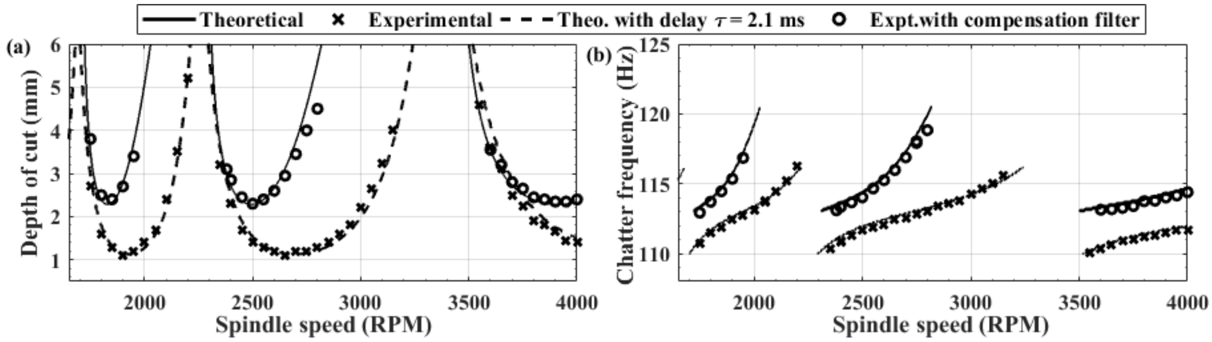

Figure 3: Theoretical and experimental (a) stability lobe diagram, (b) chatter frequencies

Having validated the HiL simulator for a linear stability model, the next section discusses results with nonlinearities introduced in the model to investigate finite amplitude machine tool instabilities – which is the main focus of this paper.

3. Results with finite amplitude instabilities

To demonstrate finite amplitude instabilities, experiments were conducted by assuming a nonlinear power law force model, i.e. with $F_c = K_{t-nl} \cdot b \cdot [h(t)]^{0.75}$, and by also allowing for multiple regenerations to take place. The resulting time domain response for this case is contrasted in Fig. 4 with the case of assuming a linear force model, i.e. $F_c = K_t \cdot b \cdot h(t)$, and by not allowing self-interruptions to take place, i.e. for the case of only a single regeneration being allowed in the model. Results in Fig. 4 are for the representative depth of cut of $b = 0.29$ mm for the nonlinear case, and for $b = 2.5$ mm for the linear case. The coefficients, K_t and K_{t-nl}, are taken to be 138.4 N/mm^2 and 138.4 $N/mm^{1.75}$ for the linear and nonlinear force models respectively. The speed 2500 RPM is kept the same for both force models, as is the static chip thickness, $h_s = 0.05$ mm.

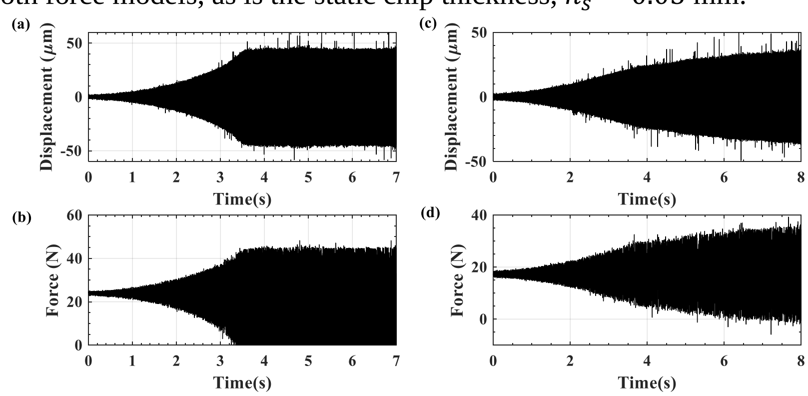

Figure 4: Measured time domain response of the flexure: (a-b) nonlinear force model with multiple regenerations, (c-d) linear force model with single regeneration

As is evident from Fig. 4(a-b), for the case with nonlinearities in the model, for large amplitude vibrations, since the tool leaves the cut, the amplitude of chatter saturates, and the corresponding force at those time instants drops to zero. Whereas, as in evident from Fig. 4(c-d), for the case of the linear force model, the amplitude of vibrations along with the force levels grow indefinitely, being bounded only by the force being supplied by the actuator. We emphasize here that since the force models are different, the amplitudes of chatter, and forces are also different for the linear and the nonlinear models. Vibrations and forces cannot possibly grow unbounded since the tool will eventually leave the cut for large amplitude vibrations, and this can be nicely investigated on the HiL simulator, as has been shown above. To further understand finite amplitude instabilities, we investigate what happens when the cutting force model is linear, but self-interruption can take place, and when the force model is nonlinear and multiple regeneration can take place, as is discussed next.

3.1 Self-interrupted finite amplitude instabilities with a linear cutting force model

Assuming a linear cutting force model ($F_c = K_t \cdot b \cdot h(t)$), as is typically done in many models for chatter, but allowing for self-interruptions ($F_c = 0 \; if \; h(t) \leq 0$)), i.e., for finite amplitude of chatter vibration to take place, we perform experiments on the HiL simulator for a fixed static chip thickness of $h_s = 0.05$ mm, and for a fixed spindle speed of 2500 RPM. For these parameters, we first perform experiments by increasing the depth of cut in steps of 0.1 mm, starting at a value below the stability boundary (see Fig. 3), and continuing experiments for a depth of cut above the stability boundary, and record the amplitude at which the chatter amplitude saturates on account of finite amplitude instabilities. We also perform experiments by starting at a depth of cut above the stability boundary, and then systematically decrease the depth of cut until we reach below the boundary, and again record the finite amplitude of the chatter vibrations. Results for these investigations are shown in Fig. 5. As is evident from the results, there is no sudden jump and/or drop in the amplitude of chatter vibrations for both cases of increasing and/or decreasing the depth of cut. These findings confirm that sudden jumps and/or drops can only take place when the force model is also nonlinear, as is discussed next.

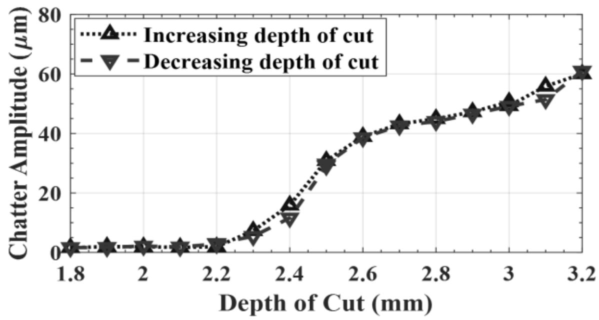

Figure 5: Finite amplitude instabilities with self-interruptions and a linear force model

3.2 Self-interrupted finite amplitude instabilities with a nonlinear cutting force model

Assuming a nonlinear cutting force model ($F_c = K_t \cdot b \cdot [h(t)]^{0.75}$) and also allowing for self-interruptions ($F_c = 0 \; if \; h(t) \leq 0$), we again perfromed experiments on the HiL simulator for a fixed static chip thickness of $h_s = 0.05$ mm, and for a fixed spindle speed of 2500 RPM. As discussed in Section 3.1, experiments were again performed by separately increasing and decreasing the depths of cut in steps of 0.01 mm, starting on either side of the stability boundary. Since the nonlinear force model results in different stability behaviour as compared to the linear case, the stability limits (depths of cut) are different, and are lower in the case of the nonlinear force model. Results with these experiments are shown in Fig. 6.

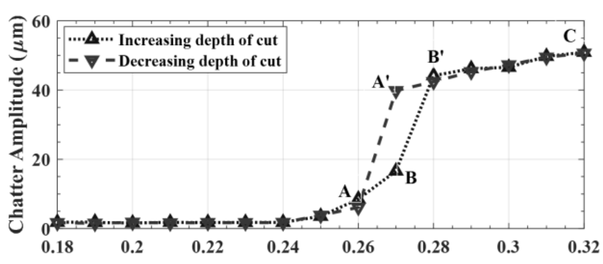

Figure 6: Finite amplitude instabilities with self-interruptions and a nonlinear force model

As is evident, and unlike the case with the linear force model, with the nonlinear force model there appear significant jumps/drops in the finite amplitude of chatter vibrations while increasing/decreasing the depths of cut. While increasing the depth of cut, the amplitude of chatter remains negligible till point A – a marginally stable point. From A to B the amplitude of chatter vibrations grows slowly. This region is a conditionally stable zone, and a large perturbance to the process, e.g. the cutting operation of a shaft with a key slot, will make the process unstable – making the amplitude to suddenly jump to a value on the segment $A'B'$. A further increase in the depth of cut causes a relatively slow increase in the chatter amplitude along the line $B'C$. For the case of decreasing depth of cut, chatter amplitude decreases slowly along CA', and after A', a sudden drop in amplitude of chatter vibrations is observed, after which the amplitude tends to zero. This peculiar finite amplitude instability behavior with jumps and drops has also been experimentally observed and reported in [2, 4], and the HiL simulator makes possible such nuanced investigations in controlled laboratory settings to help understand the intricacies in chatter.

4. Conclusions

Nonlinear finite amplitude instabilities that are prevalent in real cutting processes were investigated in this paper using a validated hardware-in-the-loop simulator. Nonlinearities discussed include cutting force nonlinearities and nonlinearities due to self-interruptions. The HiL simulator emulates these nonlinearities for an orthogonal cutting process. A novel time-domain surface location storage algorithm was used to effectively incorporate both the nonlinearities in the HiL domain. Experimental results with linear and nonlinear cutting force characteristics including the tool out of cut nonlinearity demonstrate that a conditionally stable zone exists only in the case of nonlinear cutting force characteristics, in which case sudden jumps and drops were observed in chatter vibration amplitudes when the depth of cut was increased and/or decreased. Successful investigations of self-interruptions in cutting along with nonlinear force models on the HiL simulator pave the way for the planned study of the dynamics of parametrically interrupted cutting such as in highly interrupted turning and milling processes.

5. Acknowledgements

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6. References

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