Input Shaping versus Ulendo VC

This document provides a comparison of two software solutions that compensate for vibration in extrusion-based 3D printers: input shaping and Ulendo VC (vibration compensation). Input shaping has become a popular approach to compensating for vibration when a 3D printer is operated at high speeds, but this solution may not be adequate for users who require reliably high precision parts.

Alternatively, when installed on the controller of the 3D printer, Ulendo VC compensates for the vibration of the machine enabling higher speeds *without sacrificing quality*. The primary underlying vibration compensation algorithm is FBS (filtered B-splines), a software innovation patented in 2020. Subsequent to the patent, the company has expanded its solution to include other advanced algorithms to complement the original algorithm.

What is Input Shaping?

Input shaping (also known as command shaping) is a clever vibration compensation technique that was put forward by OJM Smith in the late 1950s[1,2]. In its most basic form, a command to a vibration-prone machine is split into two portions delayed by half the period of vibration such that the vibration produced by the second portion cancels that introduced by the first portion via destructive interference. This concept is often demonstrated using Figure 1. The first portion of the command applies an impulse (e.g., a quick impact) A_1 at time t_1 generating the vibration shown by the dashed blue line. Then the second portion of the command applies another impulse A_2 at time t_2, which is separated from t_1 by half the period T of vibration, leading to the vibration shown by the dotted red line. The vibration from A_2 cancels out that from A_1 resulting in zero vibration after t_2 as shown by the solid black line.

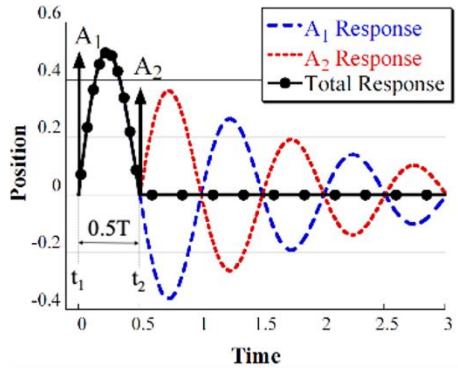

Figure 1: Input shaping uses destructive interference between the vibration responses created by two or more to cancel out vibration. (Adapted from Singhose 2009[2]).

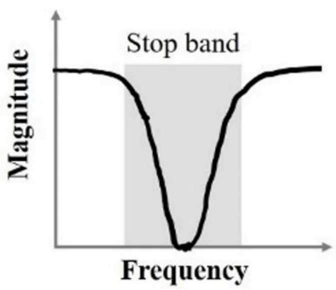

Figure 2: Input shaping is a form of band-stop filter applied around the resonance frequency of a vibrating machine.

Input shaping belongs to a larger class of band-stop filtering, because it has the net effect of creating a band-stop filter around the resonance frequency of the machine to prevent motion commands from causing the machine to vibrate. Various types of input shapers often differ from each other based on the range of frequencies they can effectively stop (i.e., their stop band). The wider the stop band, the more robust the input shaper is.

What is Ulendo's vibration compensation algorithm?

Ulendo's underlying algorithm, FBS (filtered B -splines), is a more recent vibration compensation approach put forward in 2015 by Duan, Ramani and Okwudire[3,4]. It prevents a machine from vibrating by sending the machine a command that is an inverted form of the way it naturally wants to vibrate. A very simplified way of describing what Ulendo VC does is depicted in Figure 3. Suppose we want a vibrating machine to travel straight. However, due to vibration it veers upward. Ulendo VC commands the machine to veer downward. In trying to follow the downward command, it

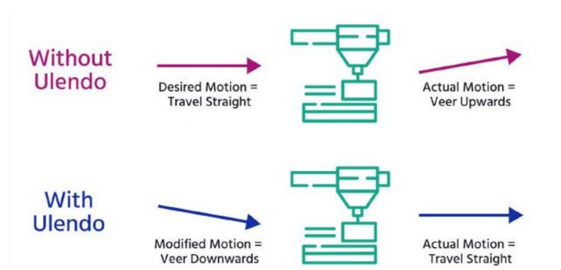

Figure 3: The FBS algorithm compensates vibration by commanding the machine to travel in a direction that is opposite to how it would have traveled without FBS. It essentially tricks the machine to move vibration free.

ends up traveling straight – which is exactly what we wanted in the first place. In other words, Ulendo VC tricks the machine into moving in the way it would have if it were a perfectly rigid machine with no vibration. Ulendo's core FBS algorithm falls into a broader class of so-called model inversion tracking controllers.

Input shaping uses **delayed commands** while

Ulendo uses **inverted commands**.

This distinction makes a world of difference in their respective performances.

How does the performance of input shaping differ from that of the Ulendo VC?

The delays introduced by input shaping cause it to round sharp corners and smooth out intricate features in the process of eliminating vibration. The severity of this undesirable corner rounding or smoothing increases with the speed of the motion. Therefore, to use input shaping without excessive corner rounding or smoothing, the motion speed of the machine needs to be kept relatively low. In other words, input shaping replaces vibration-induced defects, which intensify with speed, but introduce other quality defects which also intensify with speed.

Unlike input shaping, Ulendo VC eliminates vibration-induced defects without introducing corner rounding or smoothing, allowing the machine to travel much faster without quality defects compared to input shaping.

To demonstrate these differences, consider the 20 mm XYZ calibration cube printed by a 3D printer under two scenarios.

Low Speed Scenario

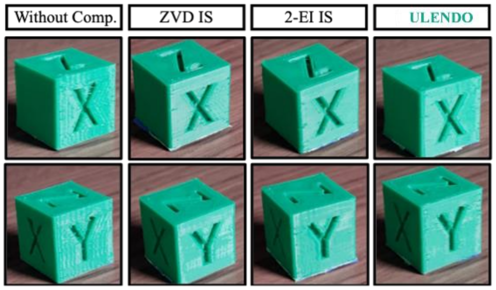

Figure 4: Comparison of input shaping (IS) and Ulendo on the XYZ calibration cube at 60 mm/s feedrate and 3,000 mm/s^2 acceleration. ZVD input shaping reduces ringing but introduces some corner rounding. 2-EI input shaping eliminates ringing at the expense of increased corner rounding. Ulendo eliminates ringing without introducing corner rounding. One may consider the degree of corner rounding introduced by input shaping acceptable at low speeds and accelerations.

The printer is commanded to travel at 60 mm/s feed rate and 3,000 mm/s^2 acceleration, which are fairly standard for the printer. Without vibration compensation, the printer exhibits some ringing on the X and Y faces of the cube. A basic input shaper (the ZVD shaper) is able to remove the ringing on the X face and reduce the ringing on the Y face. The Two-Hump EI (2-EI) shaper, which has a larger stop band than ZVD, is able to eliminate the ringing on both faces but it introduces a decent amount of corner rounding in the process. Ulendo is able to eliminate the ringing on both faces without introducing corner rounding. The degree of corner rounding introduced by input shaping in this low-speed scenario may be considered acceptable for many 3D printer users.

High Speed Scenario

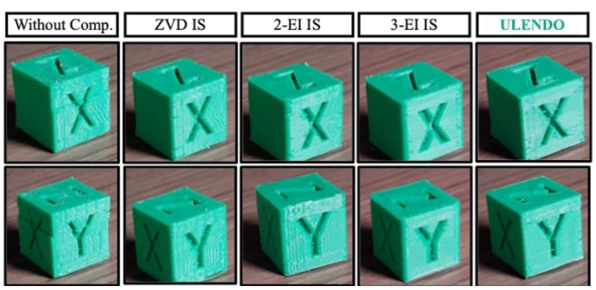

Figure 5: Comparison of input shaping (IS) and Ulendo on the XYZ calibration cube at 120 mm/s feedrate and 10,000 mm/s^2 acceleration. ZVD and 2-EI input shaping reduce ringing, at the expense of corner rounding, but are unable to eliminate it. 3- EI input shaping significantly reduces it while introducing extreme corner rounding. Ulendo significantly reduces ringing without introducing corner rounding.

The printer is commanded to travel at 120 mm/s feed rate and 10,000 mm/s^2 acceleration. Without vibration compensation, the printer exhibits severe ringing on the X and Y faces of the cube and some layer shifting. The ZVD shaper significantly reduces the layer shifting but is unable remove the ringing on both faces, though it reduces them to some extent. The 2-EI shaper is able to eliminate the ringing on the X face but only reduces it on the Y face. To completely eliminate ringing on both faces, a shaper with a larger stop band, the three-hump EI (3-EI) shaper, is needed. Each shaper introduces corner rounding and smoothing which increases with its effectiveness in eliminating vibration. Again, Ulendo is able to significantly reduce layer shifting and ringing in this high speed case without introducing corner rounding and smoothing.

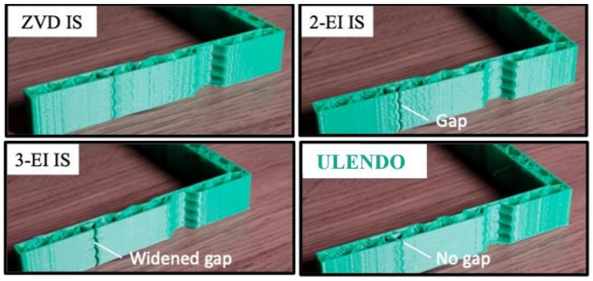

Figure 6: Comparison of input shaping (IS) and Ulendo on a portion of the ringing tower at 120 mm/s feedrate and 10,000 mm/s² acceleration. ZVD and 2-EI input shaping reduce ringing at the expense of corner rounding but are unable to eliminate it. 3-EI input shaping eliminates it while introducing extreme corner rounding (widened gap). Ulendo significantly reduces ringing without introducing corner rounding.

The high-speed scenario is repeated on a portion of the ringing tower, which is commonly used to test input shapers on 3D printers. As seen from Figure 6, the ZVD shaper leaves a lot of ringing uncompensated. The 2-EI shaper further reduces ringing but increases corner rounding, as easily seen from the gap. The 3-EI shaper significantly reduces ringing but leaves a very wide gap due to excessive corner rounding. Again, Ulendo is able to significantly reduce ringing without introducing a gap due to corner rounding.

In a nutshell, input shaping forces one to choose between ringing and corner rounding while Ulendo does not.
Thus, compared to input shaping,
Ulendo enables much higher speed printing without loss of quality.

Ulendo's VC software solution is specifically designed to enable 3D printer manufacturers to double the speed of their newly manufactured extrusion-based printers. It can also be used to double the throughput of extrusion-based printers being used by large scale 3D printing service bureaus and additive contract manufacturers.

The Future

As a company, Ulendo continues to innovate in this space. We are currently working on new machine learning algorithms that can leverage accelerometers attached to a 3D printer to learn its vibration behavior and update the parameters of Ulendo as the machine ages. We are also working on algorithms to automatically detect part failures during 3D printing and to compensate for distortion and residual stress in parts made by laser powder bed fusion.

We believe that additive manufacturing is the most promising manufacturing technology of the 21st century, and we are committed to realizing the full extent of that promise.

Visit our www.ulendo.io or email us at info@ulendo.io.

References

1. Smith, O. J. M. (1958). Feedback control systems. McGraw-Hill.
2. Singhose, W. (2009). Command shaping for flexible systems: A review of the first 50 years. International journal of precision engineering and manufacturing, 10(4), 153-168.
3. Duan, M., Ramani, K. S., & Okwudire, C. E. (2015, October). Tracking control of non-minimum phase systems using filtered basis functions: a NURBS-based approach. In Dynamic Systems and Control Conference (Vol. 57243, p. V001T03A006). American Society of Mechanical Engineers.
4. Duan, M., Yoon, D., & Okwudire, C. E. (2018). A limited-preview filtered B-spline approach to tracking control– With application to vibration-induced error compensation of a 3D printer. Mechatronics, 56, 287-296.