SOFT STEPPING AND DISTURBANCE COMPENSATION THROUGH ROTARY ACCELERATION SIGNAL PROCESSING

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ABSTRACT

Stepper Motors are extremely popular in space mechanisms due to their simple control electronics, and high torque margin capacity. However, a limitation to the application of stepper motors is their susceptibility to lose torque capacity at resonant disturbances when driving high load inertia. This paper will discuss the reasons for the performance degradation and the means to compensate with Rotary Acceleration signal feedback, and a technique referred to herein as "*Soft Stepping*".

1. INTRODUCTION

We will discuss the problems associated with driving high load inertia and/or high compliance systems with stepper motors. With the problematic background established, we will introduce a concept of signal processing a Rotary Acceleration signal of the stepper motor in order to help compensate resonant operational stepping rates, assuring in higher torque margins and more stable operational performance. To demonstrate the concept, we will test a sample stepper motor actuator driving a high inertial load. This sample system will be driven conventionally in our test set-up with the three states of motion monitored. Once the test system is characterized, the Soft Stepping circuit will be incorporated, and the diagnostic test information will be compared to the original test results. After the comparative results are detailed, we will discuss other potential applications for the Soft Stepping technique.

2. DEFINING THE PROBLEM

A stepper motor's performance is dramatically affected by the introduction of load inertia. While a stepper motor's inertia factored response rate may be easily calculated with the introduction of load inertia [1], it is more difficult to analyze the stepping oscillatory response; where the overshoot and undershoot positions occur. High load inertia and/or high compliance stepping resonant points can occur when the stepper motor significantly overshoots or undershoots the stable step position. When the motor is operated at these over/undershoot points, a dramatic alteration in motor performance can occur, that may result in reduced performance or missed steps.

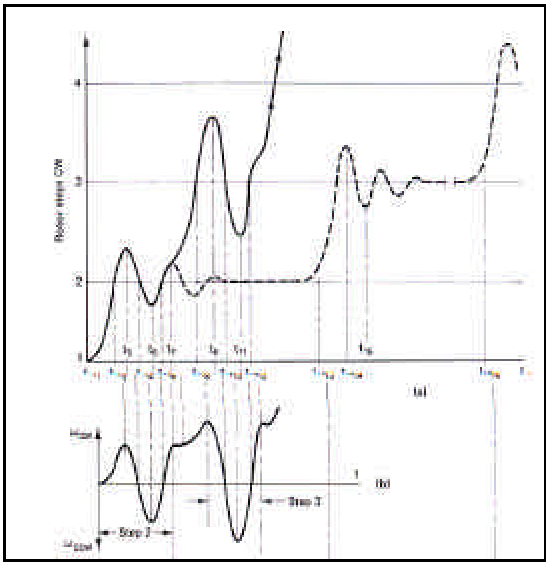

Figure 1

Figure 1 shows a classical under-damped response of a stepper motor driving high load inertia. Position versus time (a) and velocity versus time (b) are shown to demonstrate the consequences of stepping at an overshoot point; when velocity and angular momentum are at a maximum [2]. The motor pulse rate versus torque experiences a loss in torque at this resonant pulse rate. See Figure 2. In some instances the problem can be remedied by simply slowing down the pulse rate. However, this is not always possible due to specified velocity requirements of the system. Additionally, simply changing the operational pulse rate is a potentially dangerous solution, because you may only be *conditionally stable* at a particular operating condition that may change with voltage or temperature variation. Changing the gear ratio is not always practical either because lower gear ratios result in higher reflected inertia, or higher gear ratios may require too high a pulse rate. Increasing the power input to get back torque margin is also a problem, because higher generated torques result in more overshoot.

The speed-torque performance shown here demonstrates the torque loss at the resonant frequency. Torque loss resonances may be primarily attributed to the oscillatory response of the stepper motor, but similar occurrences could be attributed to system Eigen Frequencies. In either event, the concept and implementation of Soft Stepping would be applicable.

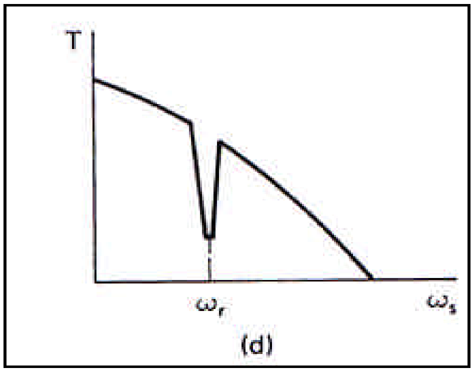

Figure 2

3. SOFT STEPPING DEMONSTRATION CIRCUIT

The circuit shown in Figure 3 is the circuit used for Soft Step demonstration. The stepper motor driver is a conventional bipolar two-phase stepper controller. The acceleration signal from the Rotary Accelerometer (RA) is filtered (a) and multiplied (b) before it is sent into the summing junction (c). The filtering is required because you will see the Eigen Frequency from the load disturbance on the acceleration signal [3]. The unity gain follower (d), after the summing junction, is a power operational amplifier; the output of which supplies the voltage supply to the stepper driver, and hence the motor. For this demonstration, we have elected to accomplish the Soft Stepping through voltage regulation; however, the same result may be accomplished through current regulation of the motor through pulse width modulation.

We have included a Resolver (RX) on the motor, used only for informational purposes of this demonstration. The output of the Resolver is converted to a DC analog signal and monitored. The DC position output is also differentiated (e) and filtered (f) to provide a motor velocity signal. We can now view motor position, velocity and acceleration in real-time, under all conditions. This will provide interesting information as we see the dynamic behavior of the stepper motor.

Important Note: Direction of Rotation (DOR) logic was *not* included in our demonstration circuit, but needs to be added for bi-directional operation. Since the RA is phase sensitive, you must include a logic circuit that triggers the proper attenuation for the proper DOR. *Otherwise, the power attenuation will be offset to the overshoot, rather than at the peak acceleration, for one DOR.* Interested persons can contact the authors to obtain an example of the DOR logic circuit.

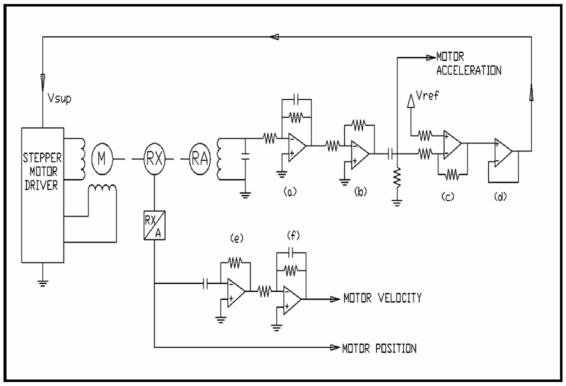

Figure 3

3.1 What the Circuit Accomplishes

At the start of a pulse, as the acceleration signal comes out of op-amp (b) (if the magnitude exceeds the Vref voltage), the voltage coming out of the summing junction (c) is attenuated, slowing down the acceleration and softening the step.

This concept is preferable to simply reducing the power input, because it does not diminish the torque margin. If system friction increases with time or temperature changes, the acceleration signal will be reduced, and there will be less power attenuation to the motor. In other words, this circuit limits the maximum acceleration during a pulse. *If system or motor friction levels change you still have the capability to drive the load without introducing disturbances.* This aspect is a major advantage to the soft stepping concept. You are, in effect normalizing the performance for a maximum operational disturbance, without compromising torque margin.

4.0 SAMPLE HIGH REFLECTED INERTIA SYSTEM

For our sample system we have constructed a geared actuator, and coupled an inertial load directly to the output shaft. The following describes the test system:

Set-up Description:

- 25 mm Diameter Stepper Motor
- Two-Phase Bipolar.
- 6 Watts Per Phase (at 20 VDC)
- 30° Per Pulse (at motor)
- Holding Torque at Motor: 50 mNm
- Motor Inertia: 2.4E-07 kgm^2
- Gearbox Ratio: 10:1

- Load Inertia: 1.03E-03 kgm^2
- Inertia Factor: 44
- Inertia Factored Response Rate: 45 Pulses Per Second (PPS)
- Operational Pulse Rate: 17 PPS

While the magnitude of the inertia is not high, in and of itself, the Inertia Factor (ratio of reflected load inertia to the motor inertia) is quite high. [1] As a general rule, it is desirable to keep the Inertia Factor below 10:1, where practical.

4.1 Kinematics of Classic Step Motion

In Figure 4 we present the kinematics of a classical stepper motor. We have taken our sample actuator (with load inertia), and stepped the motor at a low pulse rate. The top curve is the demodulated analog output of the Resolver, providing the motor position versus time. The middle curve is the differentiated position signal, providing motor velocity information. The bottom curve is the output of the rotary accelerometer, after some filtering and gain. Significant performance characteristics may be derived from the analysis of these three signal, in particular the Rotary Acceleration signal [3].

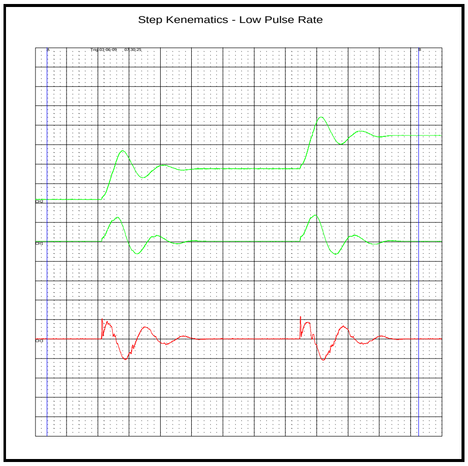

Figure 4

As the motor position crosses the stable step point, the velocity is at a maximum, and the acceleration crosses zero. The acceleration is at zero at this instant, because the motor torque is at zero. As the motor overshoots, the peak the velocity falls off, while the acceleration goes negative, trying to stop the motor at the stable position. The system overshoots and undershoots at the stepping oscillatory response until the damping of the system settles the motor out. The consequence of this under-damped characteristic is that the system experiences the maximum instantaneous velocity, and hence the maximum instantaneous kinetic energy and angular momentum at the crossover point. High load inertia systems will have low stepping oscillatory frequencies, and typically low Eigen frequencies as well. We should note hat there is a slight time lag in the acceleration signals and velocity signals shown here, due to filters (a) and (f).

4.2 Demonstration Conventional Performance

In our example, we have taken the system previously described and stepped at a pulse rate of 17 pulses per second; a pulse rate that coincides with the peak of the first undershoot. Figure 5 shows, once again, the Position, Velocity, and Acceleration signals as described. Refer to Table 1 for a tabulation of the peak to peak measurements of the position, velocity, and acceleration for “Conventional” performance.

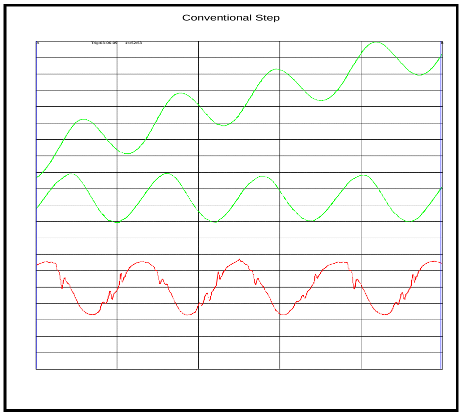

Figure 5

4.3 Demonstration Soft Step Performance

When we incorporate the Soft Stepping Circuit, with identical conditions, a dramatic improvement in the stepping characteristic occurs. Figure 6 shows that the peak overshoot to peak undershoot is reduced by 85%. The peak to peak velocity is reduced by 57%. The peak to peak acceleration is reduced by 52%. The kinetic energy of the load is reduced by an impressive 82% with the incorporation of the Soft Step circuitry. Refer to Table 1 for a tabulation of the peak to peak measurements of the position, velocity, and acceleration for “Soft Step” performance. The tabulated performance values only represent the measured voltages from the test circuitry.

With the Soft Step Circuitry implemented, the step characteristic is significantly more stable, with fewer disturbances. As a side benefit, the system efficiency has increased with the Soft Step, because the power attenuation at the start of the pulse reduces dynamic power input. As mentioned, if the system friction increases for any reason, the magnitude of the Soft Step voltage attenuation will automatically be reduced, providing torque margin when needed, but not at the sacrifice of introduction of instability.

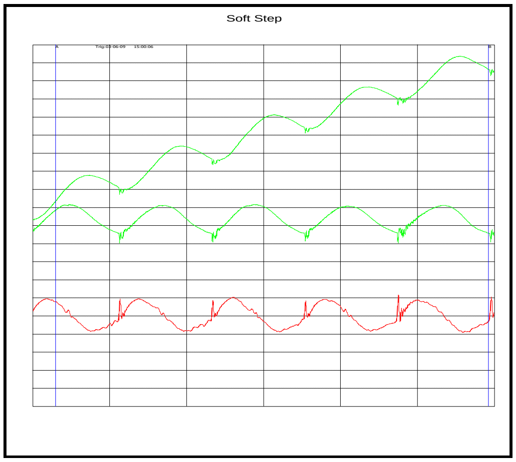

Figure 6

Conventional vs. Soft Step Comparison			
Parameter	**Conventional**	**Soft Step**	**Soft Step Reduction**
Over to Undershoot	712 mV	100 mV	85%
P-P Velocity	8.57 V	2.56 V	57%
P-P Acceleration	15.88 V	7.63 V	52%

Table 1

5. OTHER APPLICATIONS FOR SOFT STEP CONCEPT

We have shown the advantages of incorporating the Soft Step feedback concept while driving a high reflected inertial load. However, there are other potential applications for using this same concept to increase reliability or optimize stepping characteristics within a stepper motor driven mechanism.

5.1 Hard Stop Impact Torque Limits

In some applications, the gear ratio may be a rather high figure for step resolution, or inertial isolation purposes. In these systems, there is a potential to yield or damage the gearbox or system instrumentation, if the stepper motor drives into a hard stop. The motor holding torque reflected to the output could cause permanent damage, or result in a mission critical failure. With the incorporation of the Soft Step concept, if the actuator drives into a hard stop, a large negative acceleration would be generated. The electronics could easily be configured such that in such an event, the voltage (and power) input is attenuated, <u>limiting the amount of torque output, and potentially eliminating a system level failure.</u>

5.2 Critically Damping a Step Profile

For our demonstration system, we have shown an example of step softening that achieved a specific level of load disturbance attenuation. In theory, the level of step profile compensation can be as desired by specific system requirements. What we have achieved through acceleration attenuation could be also thought of as controlling the damping ratio, in the desire to achieve optimum step characteristics.

In cryogenic applications in particular, it is desirable to have the most efficient means of motion. The Soft Step concept can be utilized to set the level of damping to achieve the desired motor displacement in the most energy efficient means. By setting the gains and levels of attenuation, you can achieve desired torque capacity output while controlling the step profile. This can provide <u>minimum settling time and pulse width</u> for a specific set of system conditions.

6. CONCLUSION

We have defined and demonstrated the potential for instability and significant overshoot when driving high load inertia at oscillatory resonant frequencies. In our demonstration we have shown the three states of kinematic motion under these conditions. In addition to a key diagnostic tool, a Rotary Accelerometer may be used to compensate for these system instabilities, and attenuate overshoot, peak velocity and acceleration while increasing torque margin. In our demonstration we have reduced positional ringing displacement by 85% with the Soft Step circuit. Other potential applications for the Soft Step concept include hard stop damage protection and critically damping step profiles.

7. REFERENCES

[1] CDA InterCorp: “Stepper Motor Engineering Reference Data”, © 2000

[2] Ramakant Gayakward and Leonard Sokoloff, “Analog and Digital Control Systems”, Prentice Hall, ©1988, pp 161-163

[3] Scott Starin and Fred Crosno: “System Characterization and Motor Step Verification through Rotary Acceleration Signals”, NASA/CP 2002-211506 Proceedings of the 36th Aerospace Mechanisms Symposium, Glen Research Center April, 2002. pp 141-146

Back to Contents