HEAVY MOVABLE STRUCTURES, INC.
TWENTIETH BIENNIAL SYMPOSIUM

October 7-10, 2024

PID Controller Manual Tuning Methods for Heavy Movable Structures

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Introduction

Automated control of a process such as oil refining, chemical processing, electrical generation, traction, and motive power applications requires continuous monitoring and control. The goals of properly applying process control are to achieve the desired level of control and system stability. One of the most widely used forms of automated industrial control is the Proportional-Integral-Derivative (PID) controller.

PID controllers are closed-loop control controllers which employ feedback from that the process being controlled to dictate the control systems response to the systems behavior.

A PID controller continuously samples, calculates and applies a correction factor to minimize the difference between a desired “setpoint” of a process variable. This “difference” is called the “error value”. The error value is minimized by applying correction factors. The correction factors are based upon the historic, current and future (expected) values of the error value. The correction applied is based upon a weighted sum of the current (Proportional), historic (Integral) and future (Derivative) functions.

Proper configuration of a PID controller requires an understanding of the process being controlled and the process variables. A key factor in understanding the process being controlled is knowing how the process will respond to changes in the control terms.

PID controllers have been widely used in the heavy movable structures industry in various forms. PID controllers have been typically applied to control span position, skew, and speed. Other PID controlled systems include drive load sharing, hydraulic valve control, etc.

Designing PID mathematical models for heavy movable structures is a difficult exercise. This is due to heavy movable structures having customized components, varying wear levels of machine parts and the influence of external elements such as temperature changes, wind and ice loads, etc.

Although applying PID control can be complex, modern PID controllers are sophisticated enough to provide users with a simplified control experience through the use of function blocks, auto-tuning features pre-defined control modes, etc. Users are only required to apply a series of preset control modes and “autotune” the PID controller(s) without studying, constructing, and calculating PID controller models. This simplification allows the user to achieve the desired precision control and system operating stability without the burden of applying advanced mathematics to a structure and continuously correcting for changes in the system.

In this paper, we will focus on a number of popular PID manual tuning methods that can be easily applied in the field without an in-depth understanding of the control system or higher math. We will briefly touch on the general ideas of PID control, associated terminologies, and control system performance evaluation. We will also discuss case studies of the tuning methods application to movable bridges.

Control System Basics

A control system is a mechanism which takes deliberate action on a process or part of a process to produce a desired output and desired performance. There are two types of control systems: open-loop and closed-loop.

- **Control Feedback Loop Types**
  - **Open-loop systems** do not monitor or correct the output from errors or changes. They are simpler and less expensive to construct. However, the lack of feedback means it cannot compensate for changes which may occur to the system.
  - **Closed-loop systems** monitor the output and compensates for the effects of errors or changes. This type of control is more complicated than open loop control.

Compensation for errors and changes is critical for the process control industry and heavy movable structure operation, where unaddressed errors could be catastrophic.

- **Elements that determine control system performance:**
    - **Transient response** is the short-term response of the process from a steady state condition due to a perturbation/change.
    - **Steady-state error** is the difference between the input and output of a system between the input and the output after any transients have effectively disappeared.
    - **Stability** means the system output is behaving within expected parameters.

Figure 1, below, illustrates these elements.

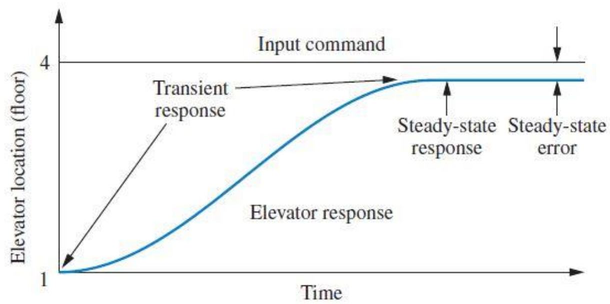

Figure 1 – Elevator response when the elevator is required to stop on the 4th floor. (Graphic Courtesy of Control Systems Engineering, 7th Edition)

The ideal control system should have a reasonable transient response, a steady-state error value within the system design tolerance and be stable.

- **Damping Types**:
    - **Overdamped** – the system moves slowly toward it's final value (equilibrium).
    - **Underdamped** – the system moves quickly toward it's final value but oscillates around it prior to reaching stability.
    - **Critically Damped** – This is the "sweet spot" between an overdamped response and an underdamped response. The system moves quickly to it's final value and does not oscillate around the final value.

Types of damping are best explained in graphical terms, as shown in Figure 2 below:

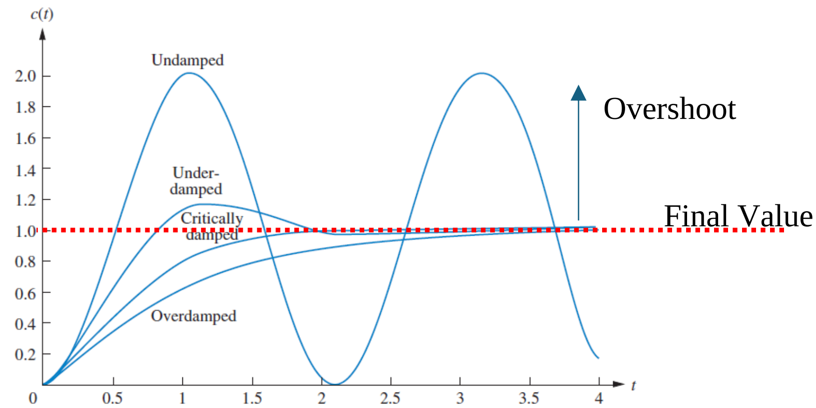

Figure 2 – Example of damping responses. (Graphic Courtesy of Control Systems Engineering, 7th Edition)

Proportional - Integral – Derivative (PID) Control Theory

A block diagram for PID control is illustrated in Figure 3 below:

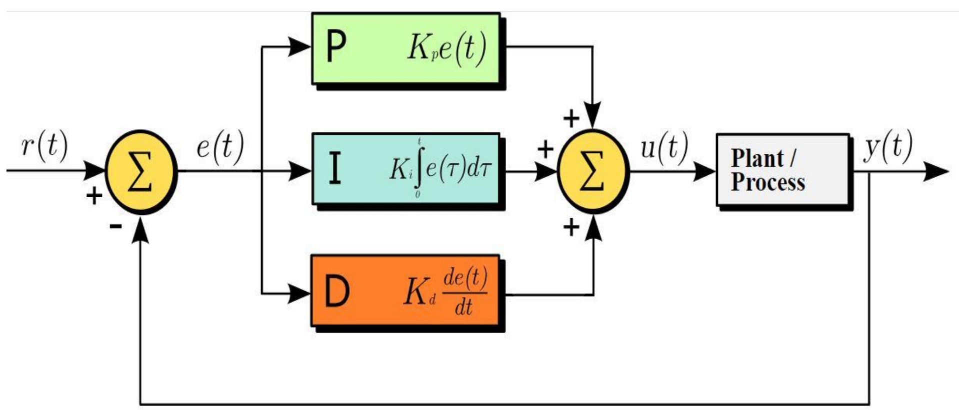

Figure 3 – PID control block diagram with a feedback loop (Courtesy Wikipedia).

Mathematically the block diagram shown in Figure 1 is expressed as equation 1, shown below:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \qquad (1)$$

Where:

K_p is the proportional gain,

K_i is the integral gain,

K_d is the derivative gain

$e(t)$ is the error

τ is the variable of integration for time

Understanding PID components and terminologies:

- **PID Individual Terms include:**
  - $\boldsymbol{K_p}$ **(Proportional gain) –** This element reacts to only the "present state" of the system. It requires an error signal and leaves behind an error between the measured value and the setpoint (droop). The Integral and Derivative gains compensate for this error. Increasing K_p will increase the speed of the response (reduce transient period) and magnitude. Conversely, reducing K_p reduces the speed of the response and magnitude. An excessive K_p value will result in control loop oscillation.
  - $\boldsymbol{K_i}$ **(Integral gain)** – This element considers the present and past state of the system. It sums the instantaneous error over time. The integral system response will continually increase over time unless the error is zero. The effect of the integral response is to drive the steady-state error to zero.
  - $\boldsymbol{T_i}$ **(Integral Time) –** This element controls how quickly the integral gain affects the control output.
  - $\boldsymbol{K_d}$ **(Derivative gain) -** This element considers the future state of the system. It causes the output to decrease if the process variable is increasing rapidly by damping the control response. A small K_d change can greatly affect the control loop output and its stability.
  - $\boldsymbol{T_d}$ **(Derivative Time) –** This element controls how quickly the derivative gain affects the control output.

Tuning PID controllers

Regulating motor speed and torque, load sharing, positioning, and high inertia compensations are key requirements for a properly controlled movable structure.

Control system performance for heavy movable structures can be analyzed by electrical chart recordings, strain gauge measurements, and/or data trending. Operating behavior can also be understood by observing machinery (gears, shafts, pinons) reactions, noise level, skew conditions during movements, overhauling performance, etc. The goal of these observations and analysis is to provide stable operations. Stable operation is a basic requirement in the heavy movable structures industry.

PID control systems must be properly configured so their gain constants (K_p, K_i, and K_d) match the characteristics of the structure. There are several ways these constants can be selected. They include manual tuning (heuristic) methods, mathematical methods and computer aided tuning. We'll focus on two manual tuning methods below in addition to the auto-tune function already provided by the drive/ PLC manufacturers. In some cases, the auto-tuned PID controllers may provide acceptable system performance and additional tuning become optional.

It is worth noting that these tuning procedures should be performed by experienced personnel who have a good understanding of controlling heavy movable structures. Additionally, these tuning approaches should be employed at a point when there will be no significant changes to the system's dynamic (after final balancing is completed). If the structure dynamics change too much, the control loop may be unable to compensate for the changes.

Auto-Tuning as a PID Tuning Method for Heavy Movable Structures

PID control methods are utilized by most, if not all, VFD manufacturers. This means the setup of the drive is, in large part, the setup of the PID control constants. Most VFD manufacturers include a tuning method “built-in” to the drive. The tuning method built into the drive is most often what is utilized for motor/drive tuning and is presented below.

1. Drive Auto-Tune (also known as ID run)
   The auto-tune function/ algorithm provided by the drive manufacturer allows the drive to identify the motor characteristics and construct the motor and feeder approximate equivalent circuit model. Alternatively, the motor and feeder cable characteristics can be obtained and manually entered into the drive setup parameters.

   Without accurate motor characteristics, the motor control cannot be properly optimized which, in most cases, leads to operating instability.

   Depending on the drive manufacturer and the drive model, differing types of auto-tune features are provided. Two that are most applicable to heavy movable structures are described below:

   a. Static Auto-Tune
      This method is best where the motors cannot be easily disconnected from the machinery. This is considered the minimum for tuning a drive/motor combination.

   b. Auto-Tune without Load
      When the motor and drives are installed and prior to connecting to the machinery, or if the machinery may be disconnected from the motor, the VFD can be auto-tuned without load. This is achieved by constructing motor equivalent circuit that matches the measured drive field conditions from the VFD library. This method is superior to static tuning and in some instances, will yield acceptable drive control results requiring minimal or no additional tuning.

2. After the auto-tuning is complete, the motors and the motors coupled to the machinery, the movable structure is moved at a slow speed to ensure that the VFD and motor configuration can handle the load.

3. The drive input/output should be metered, trended and strain-gauge data gathered to observe the system’s transient response during speed change and stability.

4. Additional tuning may be necessary if the motor/drive output is not stable, or the performance is not desired. If this is the case, then one of the manual tuning methods described below should be performed.

5. A final evaluation over the complete range of speed for the structure shall be conducted to verify acceptable performance has been achieved. This evaluation should include power and strain gauge recordings for analysis.

Trial and Error Manual Tuning Method:

1. Set the K_i and K_d values (gains) to zero.

2. Increase the K_p from a small value until the output of the control loop oscillates.

3. Set K_p to approximately half of the previous value for a “quarter amplitude decay” type response.

4. Increase K_i from zero until the system output is stable.

5. Increase K_d from zero, only if adjusting K_p and K_i did not achieve the desired stable output, until the control loop responds to the disturbance and reaches the desired setpoints quickly.

Ziegler-Nichols Tuning Method:

1. Set the K_i and K_d values (gains) to zero.

2. Increase the K_p from 0 until the output of the control loop has stable and consistent oscillations. The gain value reached from this procedure is denoted as K_u (Ultimate Gain). The period of the oscillations at K_u is denoted as T_u. The oscillation in constant frequency and amplitude is considered a "stable" control condition.
3. Use the Ziegler-Nichols table (Table 1) below to set the PID gains depending on the type of controller and the desired behavior.
4. After applying the system values in Table 1 below, further adjustments may be made to fine-tune the system performance as desired.

Control Type	K_p	T_i	T_d	K_i	K_d
P	$0.5K_u$	-	-	-	-
PI	$0.45K_u$	$0.8\bar{3}T_u$	-	$0.54\frac{K_u}{T_u}$	-
PD	$0.8K_u$	-	$0.125T_u$	-	$0.1K_uT_u$
Classic PID	$0.6K_u$	$0.5T_u$	$0.125T_u$	$1.2\frac{K_u}{T_u}$	$0.075K_uT_u$
Some Overshoot	$0.3\bar{3}K_u$	$0.5T_u$	$0.3\bar{3}T_u$	$0.6\bar{6}\frac{K_u}{T_u}$	$0.1\bar{1}K_uT_u$
No Overshoot	$0.2K_u$	$0.5T_u$	$0.3\bar{3}T_u$	$0.40\frac{K_u}{T_u}$	$0.06\bar{6}K_uT_u$

Table 1 – Ziegler-Nichols Method.

The Ziegler-Nichols tuning method is not considered a mathematical tuning method as it requires physical use of the system to determine K_u from which the other control constants are calculated.

Movable Structure (Bridge) Drive Tuning Case Studies

The manual tuning methods described earlier in this paper are important methods for providing suitably operating bridges when auto-tuning methods do not provide satisfactory operation performance.

Two real-world examples of applying the manual tuning methods described above to movable bridges with step-by-step procedures to derive the desired system performance are presented below.

Case Study 1 – Norfolk Southern (NS) bridge B-210.21, Span Drive Vertical Lift Bridge, Lorain OH, August 2014

Tuning Method Applied: Trial and Error Manual Tuning Method

Controller Type: PI controller

Bridge information: NS bridge B-210.21 crosses the Black River in Lorain, Ohio. It is a span-drive vertical lift bridge featuring dual-span drive motors with silicon-controlled rectifier (SCR) drives. Two 100HP, wound rotor, induction type, main drive motors are used during normal operation. The main drive motors are controlled by SCR controller with tachometers. The tachometers provide closed-loop speed control feedback. The drives are arranged in a Master- Follower configuration. The SCR drives are of Bardic manufacture, model PL/XD with LA 102800 SCR trigger boards.

The motors and drives were installed as part of an electrical rehabilitation of the bridge which was designed and constructed by others. NS reported that since the rehabilitation, the drive system has operated in a seesawing, unstable manner.

The mechanical and electrical engineers instrumented the bridge with strain gauges and power recording devices to investigate the reported "seesawing" condition. The strain gauges were connected to the primary reducer output shafts, and the power recorders were connected to the drives.

Based on the findings of this preliminary investigation, the Engineers made several recommendations to address the issue. The recommendations included improvements to structure imbalance, equalization of the operating rope tensions, and systematic drive tuning. At the conclusion of the mechanical portion of recommended improvements, it was determined that although the imbalance and rope tension adjustments provided some improvements which reduced the loading on the bridge machinery and extended its service life, the root cause of the operational issue was improper drive tuning.

The bridge baseline operational data from both mechanical (strain gauge data) and electrical (power recording) instrumentation were taken after the mechanical repairs and prior to the drive tuning, and can be seen in Figures 4 and 5:

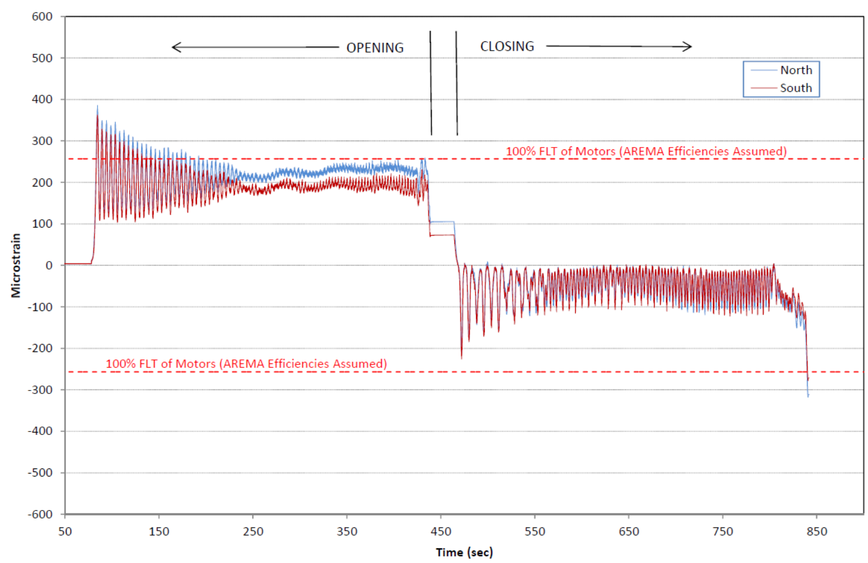

Figure 4 – Strain Guage baseline Measurement, dual motor half speed.

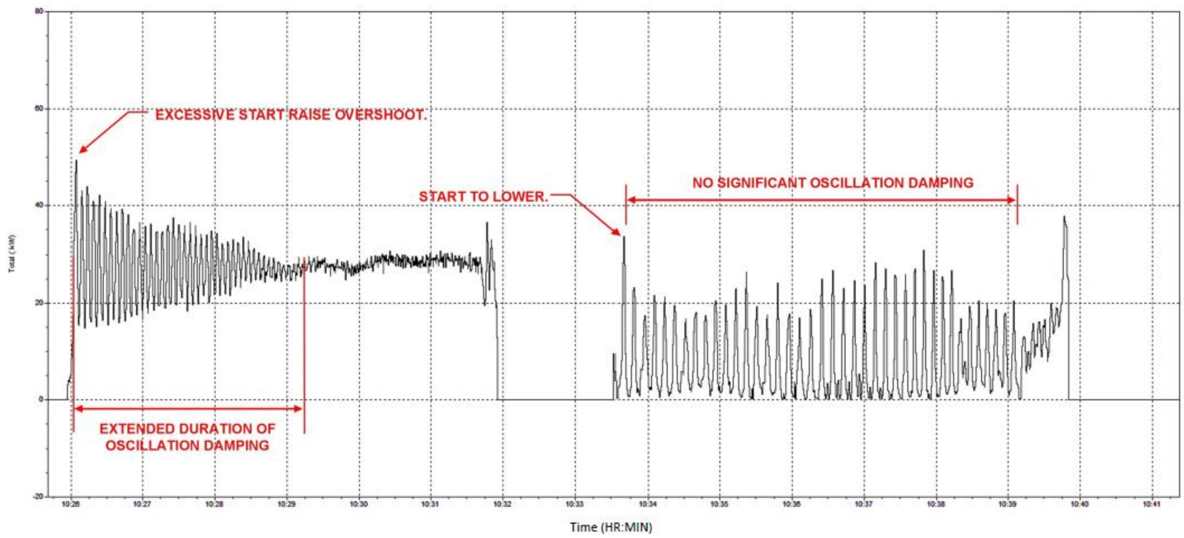

Figure 5 –Baseline Power Recording, Dual motor half speed. M1 Shown, M2 similar.

Manual tuning of the drives PID parameters was then performed.

During the tuning the bridge was operated in 10 ft increments during both raising and lowering.

The tuning was as follows:

1. The integral time constant (T_i =0) was disabled. The drive default operating speed was set to 50% full speed.
2. The proportional gain K_p value was changed in increments: 1, 2, 4, 8, 12 and 16. The operating performance both raising and lowering was recorded for each of gain setting. The operating performance for each setting was evaluated to determine the optimal K_p value (K_p =4). See Figures 6 and 7 for both strain gauge and power recording data for this tuning step.

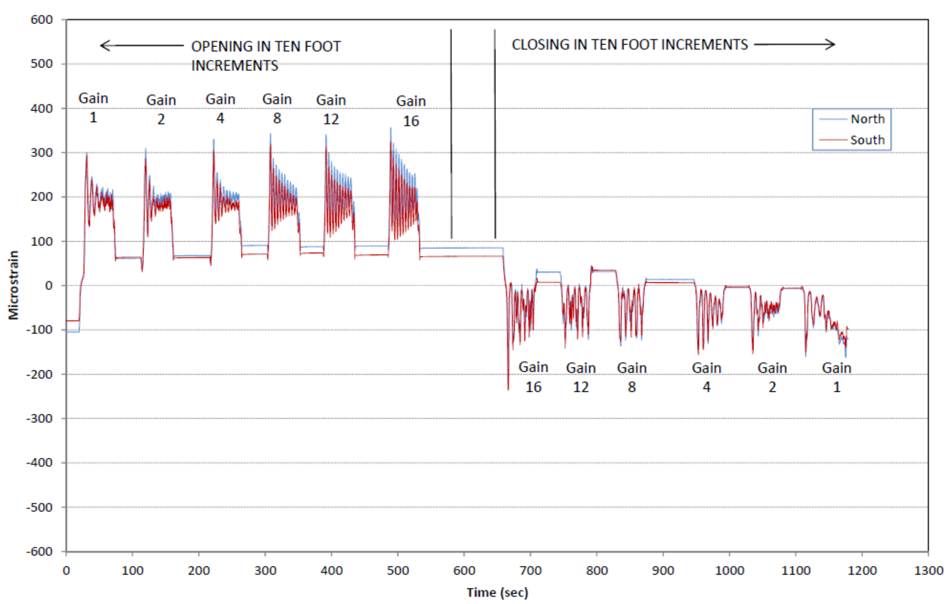

Figure 6- Strain Gauge Measurements During K_p Adjustments. Half speed.

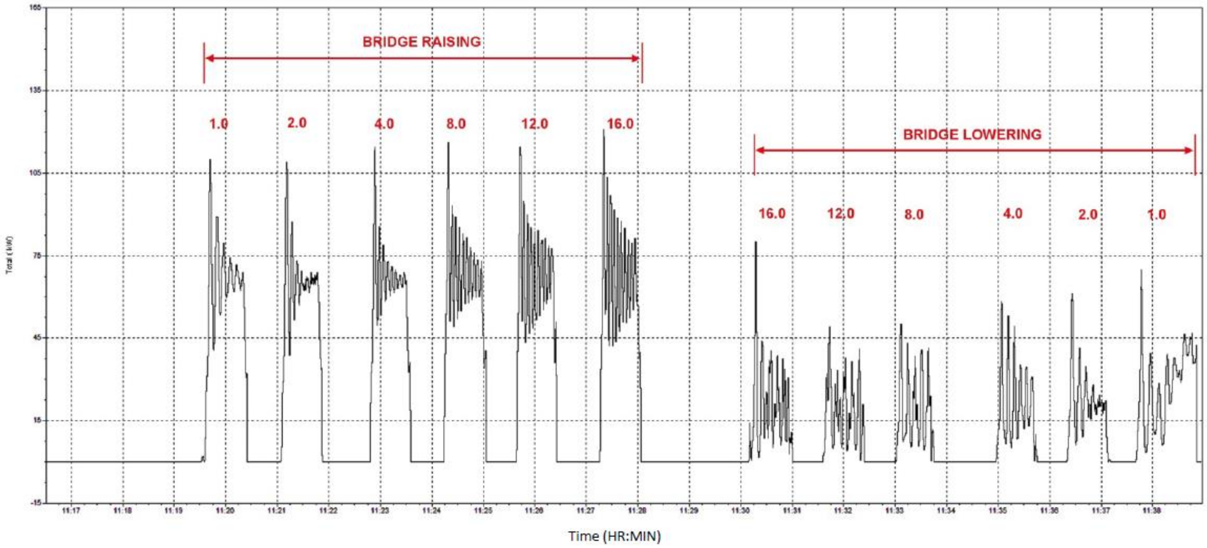

Figure 7- Power Recording During K_p Adjustments, half speed.

3. K_p was set to its optimum setting (4), with "quarter amplitude decay" type response, then T_i (integral time constant) was adjusted incrementally to values of 1s, 2s, 4, 8s, 12s, and 16s in both raising and lowering directions. Span performance was observed for both bridge raising and lowering for each T_i increment. Based on these observations the optimal T_i value was determined as 2s. See Figure 8 and 9 for both strain gauge and power recording data regarding this tuning step.

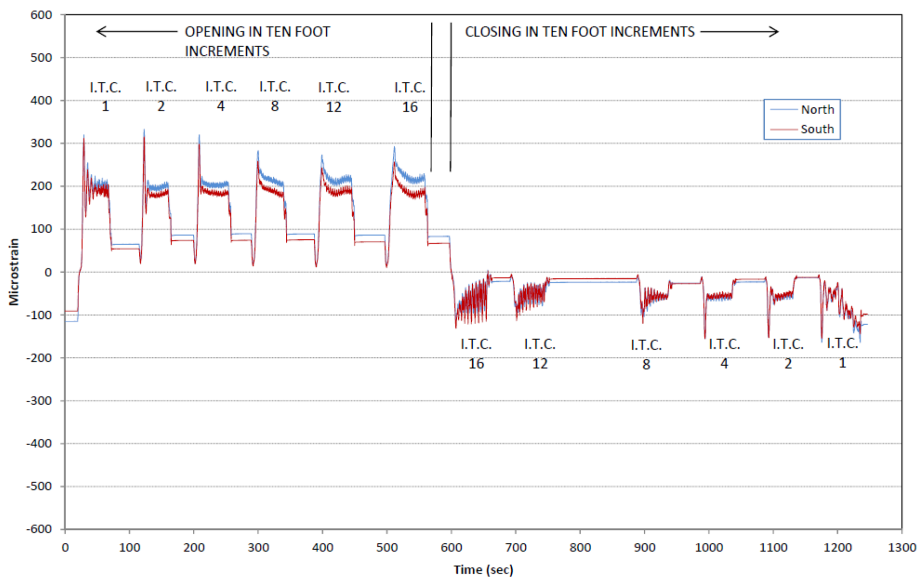

Figure 8- Strain Gauge Measurements During T_i Adjustments, half speed.

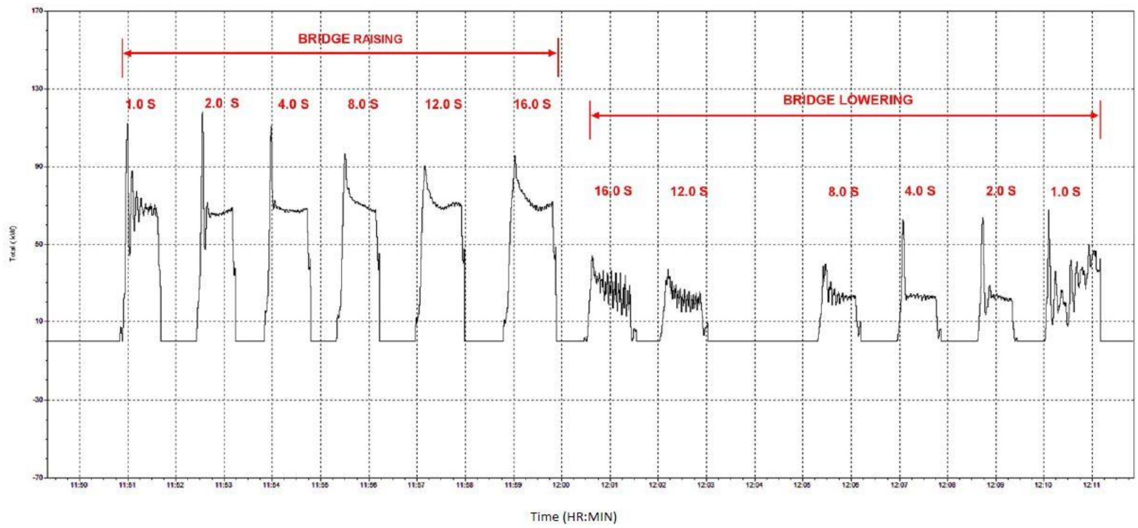

Figure 9- Power Recording During T_i Adjustments, half speed.

4. With the drive set to its optimal setting of K_p =4 and T_i =2s, there remained an issue with excessive accelerating torque. This was due to the short accelerating ramp time setting of the drive. Increasing the ramp time to 20 seconds eliminated this issue.
5. Additional operations were next performed at different bridge operating speeds: 50%, 75%, and 100% full speed to observe the final system operating performance. See Figures 10 and 11 for the strain gauge and power recording of the final condition after tuning.

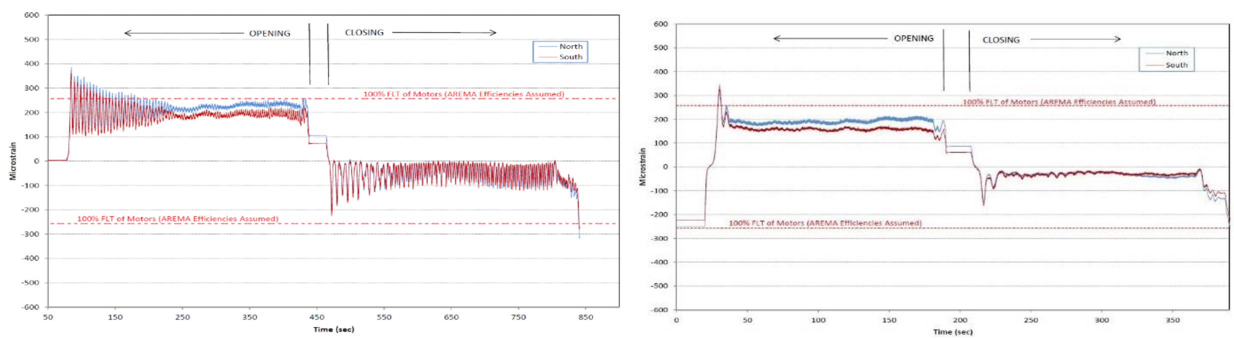

Figure 10 – Strain Gauge Measurement of the Bridge Operation, dual motor, full speed before and after drive tuning.

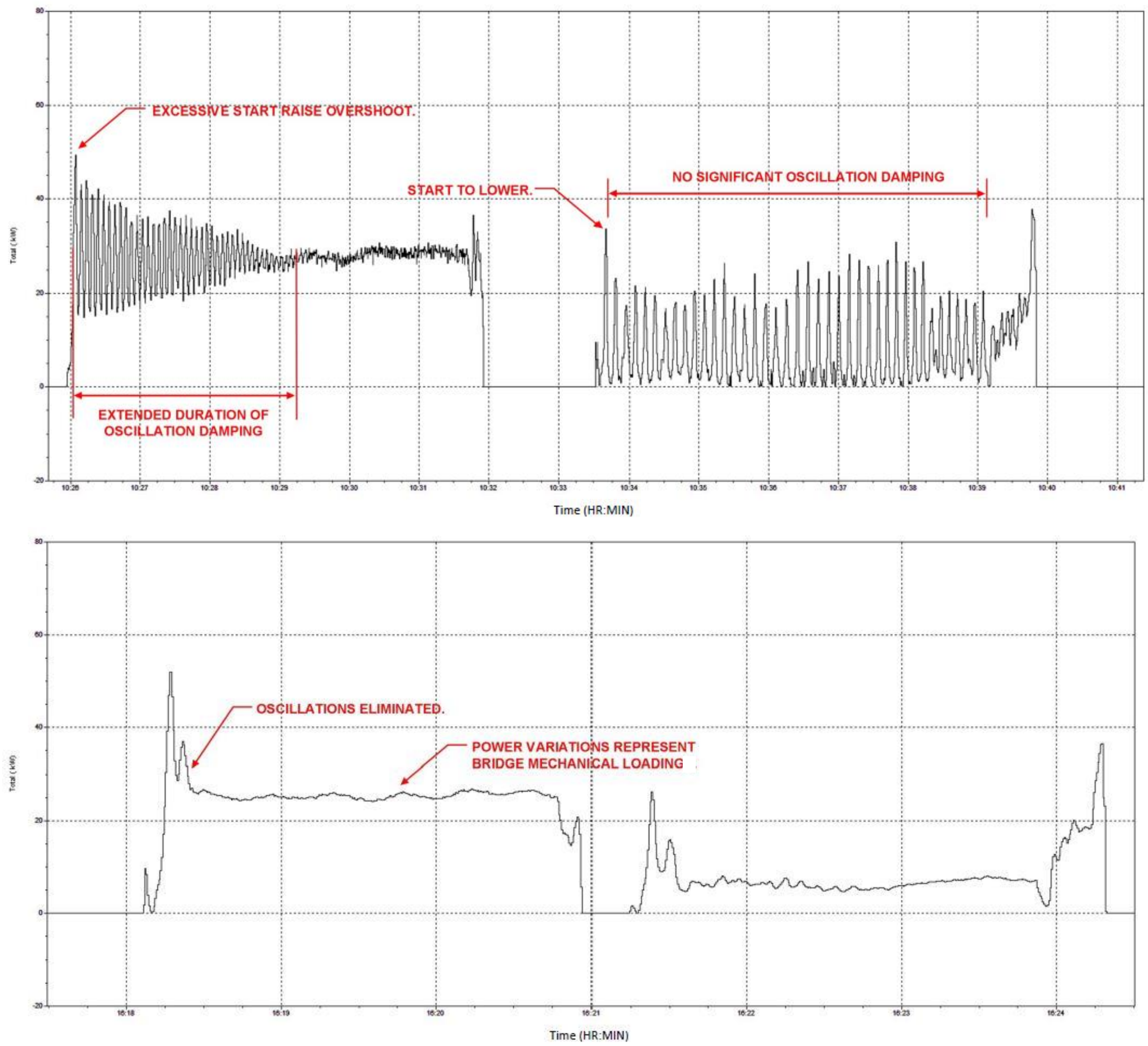

Figure 11- Final Power Recording of motor 1, motor 2 similar. Dual Motor Operation, Full Speed before and after drive tuning.

The poor operation of NS Bridge B-210.21 was eliminated through the systematic application of manual drive tuning and analysis of mechanical and electrical measurements. The improvement included dramatically reduced oscillating and peak loads, elimination of the objectionable 'seesaw' behavior and improved long-term durability of the system.

Case Study 2- Cow Bayou Swing Bridge, Orange, TX, January 2021

Tuning Method: Ziegler-Nichols Tuning Method

Controller Type: PI controller

Bridge information: The Cow Bayou bridge is a swing-span bridge that was rehabilitated, and its operating system changed to a VFD and 7.5 hp, squirrel cage, induction motor combination. The span motor drive controller is an Eaton SPX 9000 with encoder feedback. The drive was configured in speed control mode. It should be noted that in speed control mode, the drive only allows adjustment of K_p and T_i along with an additional droop setting. No derivative setting is available.

Bridge startup testing was performed by the control vendor and witnessed by the Engineer. During testing, it was found the bridge did not operate in a stable manner. It exhibited loud machinery noise, which was audible in the control house, some 100ft away. The engineer assessed that VFD drive tuning had not been performed correctly. The drive had been autotuned by the control vendor during the drive setup. However, the tuning parameters were not sufficient to control the bridge. Therefore, additional drive-tuning was performed.

See Figures 12 and 13 for initial strain gauge testing and baseline electrical recording below.

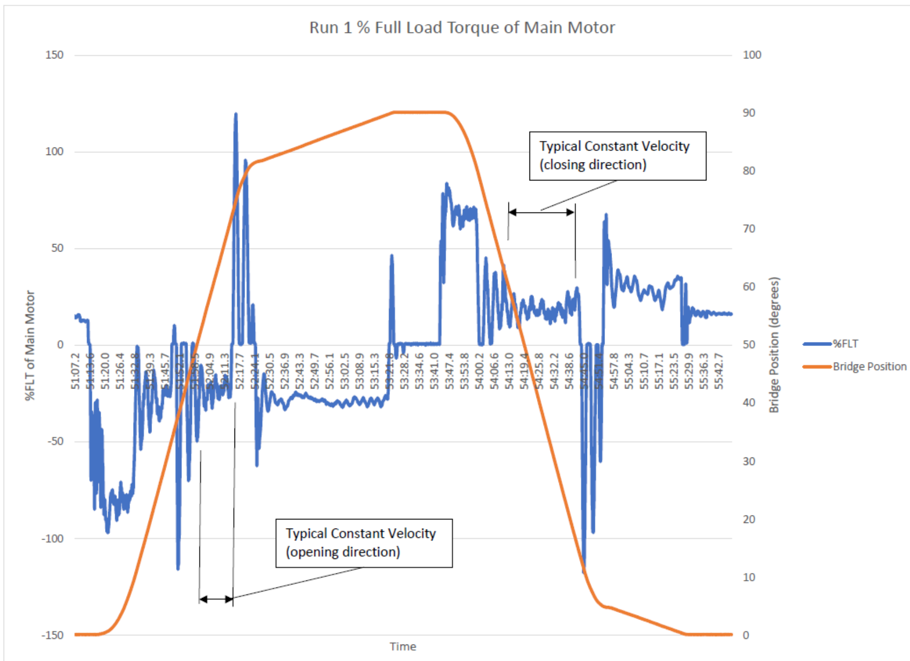

Figure 12- Strain Gauge Data, September 2020. Full-speed operation, preliminary bridge balancing.

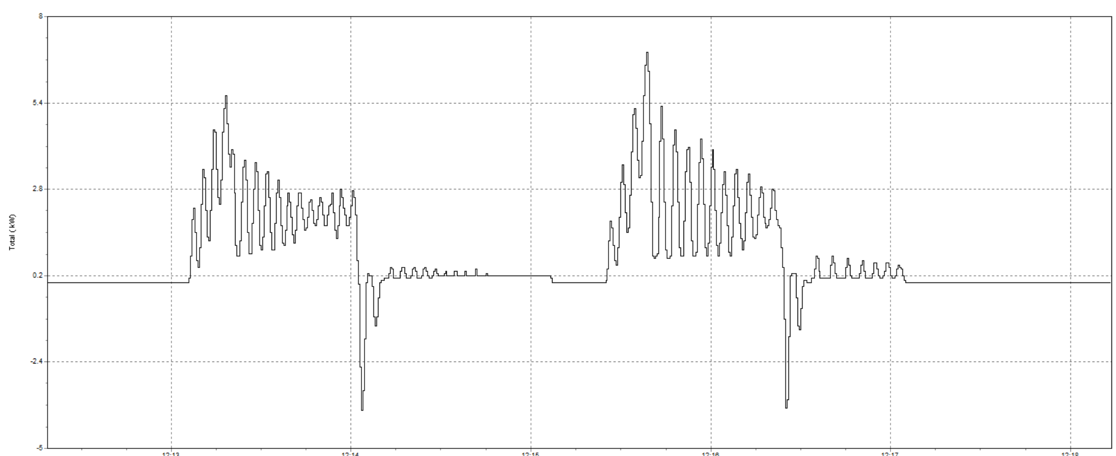

Figure 13- Initial Electrical Power Recording, October 2020. Preliminary bridge balance condition.

The chart recording shown in Figure 13 clearly indicates drive output power oscillations. A properly tuned drive is critical to achieving operating stability on swing span bridges due to their high inertia during span operation.

The control vendor and the Engineer returned to the bridge after additional span balancing was completed. A baseline power recording was taken prior to the drive tuning, shown in Figure 14 below. Although the magnitude of the drive output oscillations was reduced, the unstable behavior remained throughout the operation.

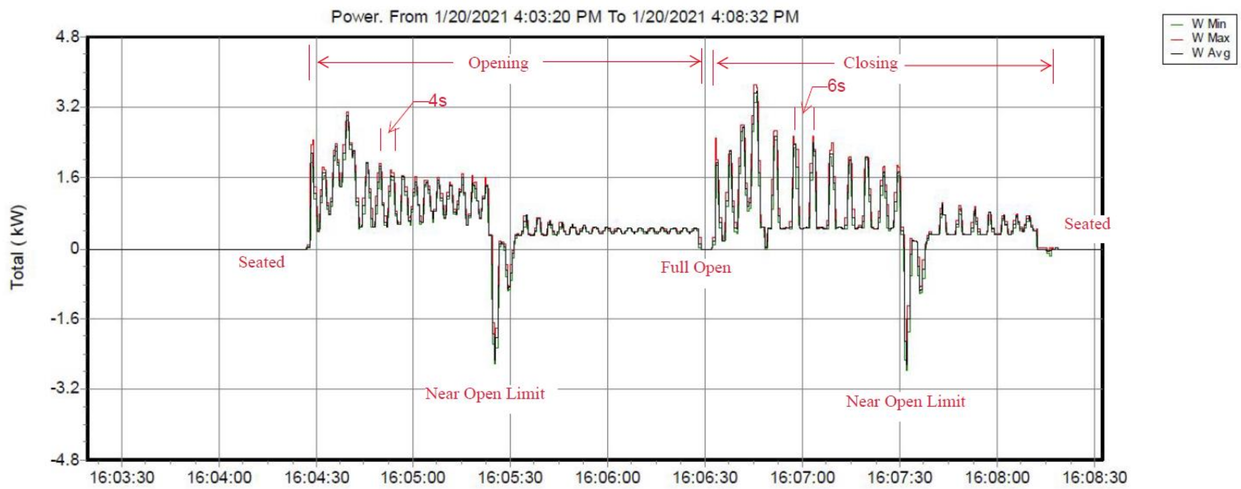

Figure 14- Baseline Power Recording Prior to Drive Tuning. Note the magnitude of power decreased after balancing.

Key parameters on the drive were investigated, and it was determined that the following parameters required adjustment from their initial auto-tuned values:

Droop = 0%, see description (1) below.

K_p =30,

T_i =100ms

(1) A drive should always be provided with a form of droop regulation to compensate for operating load variations. A VFD adjusts output speed within the droop percentage based on the motor's load. As the load increases, the VFD will output lower than the speed setpoint and vice versa. The droop setting buffer the VFD control response to slow the drives aggressive response to the loading change.

To rectify the operating issues, the drives were re-tuned as follows:

1. Baseline Testing was performed, and system behavior was observed. See Figure 14.
2. It was determined that, due to the machinery dynamics, the initial system behavior was close enough to be used as assumed “ultimate gain (K_u)” oscillation behavior. This system behavior was an almost constant oscillating frequency and small decaying behavior due to the short integral time (T_i). The T_i value does not affect determining the value of K_u. The small T_i value was retained to ensure the bridge could be closed during the tuning process to minimize disruption of the roadway traffic.
3. The Ziegler-Nichols Tuning Method for a PI controller was next applied, as shown in Table 1. Due to non-ideal machinery conditions and chart recorder data resolution (500ms per data point), the tuning was performed conservatively, with small incremental changes.

4. First parameter adjustments:
    a. Droop was adjusted from 0% to 3% to introduce load regulation as described above.
    b. The proportional gain K_p was adjusted from 30 to 15, half of the assumed K_u value. The reason for this adjustment was to observe the system's improvement as the proportional gain for P and PI systems are similar with values of $0.5K_u$ and $0.45K_u$ respectively.
    c. Measure the Oscillation period (T_u). Due to the recording device's resolution and the slightly different system dynamic for opening and closing the span, the value of the T_u could not be determined easily. The measured steady-state oscillation period was 4s for opening and 6s for closing (See Figure 14).
    d. T_i remained at 100ms, unchanged from the original setting, to simplify the tuning.

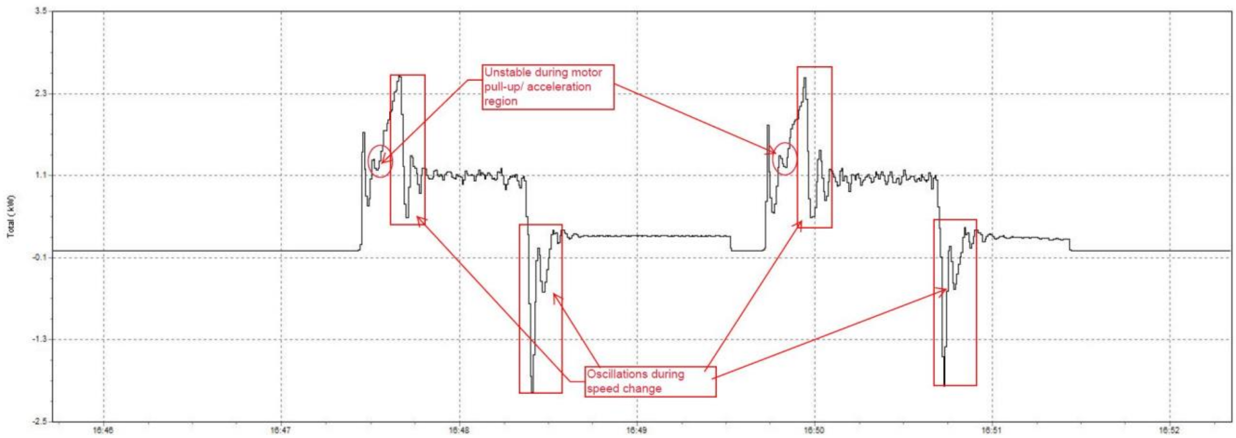

Figure 15- Drive Output Power Recording, Droop=3%, K_p =15, T_i =100ms.

The chart recordings of the bridge behavior showed the improved system's response due to the new settings. The peak power was reduced, with no obvious oscillatory behavior during the constant speed regions. However, instability occurs during the motor acceleration process. Additionally, two (2) to three (3) damping effects were observed during the speed changes. These were due to the movable structure's high inertia. The control system behavior was due to insufficient error detection and compensation. These caused the system to have an aggressive response for error correction (overshot), thus causing gear backlash issues.

5. The second adjustment:
    a. Droop=3%, K_p =15, were unchanged from the previous adjustment
    b. T_i was changed from 100ms to 500ms.
    c. The bridge was operated, and power recording of the drive output taken for analysis. Although some improvement was observed, the PID loop was found to still be sensitive to the speed change. See Figure 16.

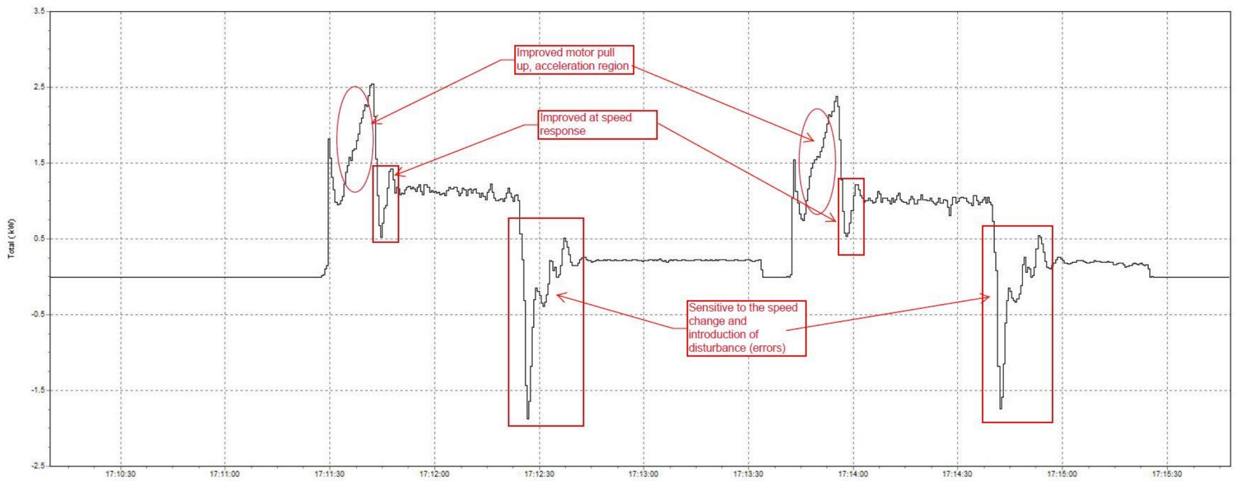

Figure 16- Drive Output Power Recording, Droop=3%, K_p =15, T_i =500ms.

6. The third adjustment:
   a. K_p =15, T_i =500ms, were unchanged from the previous adjustment.
   b. The droop setting was changed from 3% to 5%.
   c. A small improvement in the speed change response was observed. Power (torque) fluctuations were reduced at the constant speed regions. See Figure 17.

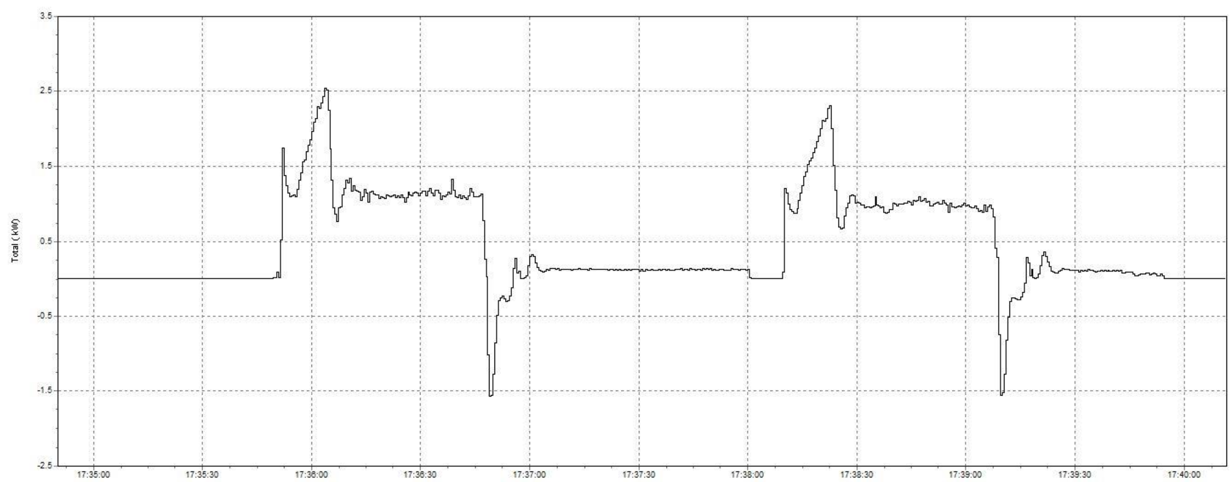

Figure 17- Drive Output Power Recording, Droop=5%, K_p =15, K_i =500ms.

7. The fourth adjustment:
   a. Droop=5%, was unchanged from the previous adjustment. This value was retained since increasing the droop value might introduce a lack of torque output.
   b. Per Ziegler-Nichols, $0.45K_u$=13.5 is expected to be the optimal value. K_p =13 was used as the VFD only allowed integer values. Due to the variation in open and closed machinery behaviors, a slight increase in T_i to 1000ms was introduced to the system.
   c. The bridge was operated, and power recording of the drive output taken for analysis. Some improvement was observed during the speed change. See Figure 18.

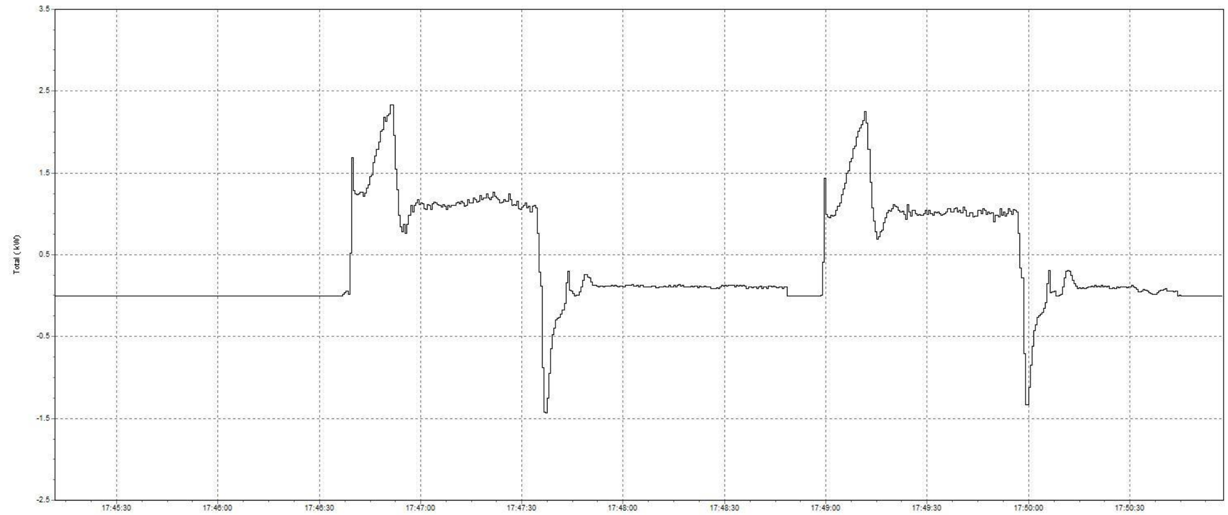

Figure 18- Drive Output Power Recording, Droop=5%, K_p =15, T_i =1000ms.

8. The 5th adjustment:
    a. Droop=5%, K_p =13, were unchanged from the previous adjustment.
    b. T_i was changed from 1000ms to 1500ms.

    Table 1 indicates the T_i value should be near 3300ms when using T_u=4 seconds. However, factoring in large errors with recording resolution and the error within the assumed "Ultimate Gain", this value was only be considered as the maximum adjustment value. It might not be the "optimal" value. Therefore, an additional integral time of 500ms was added to observe system behavior. See Figure 19.

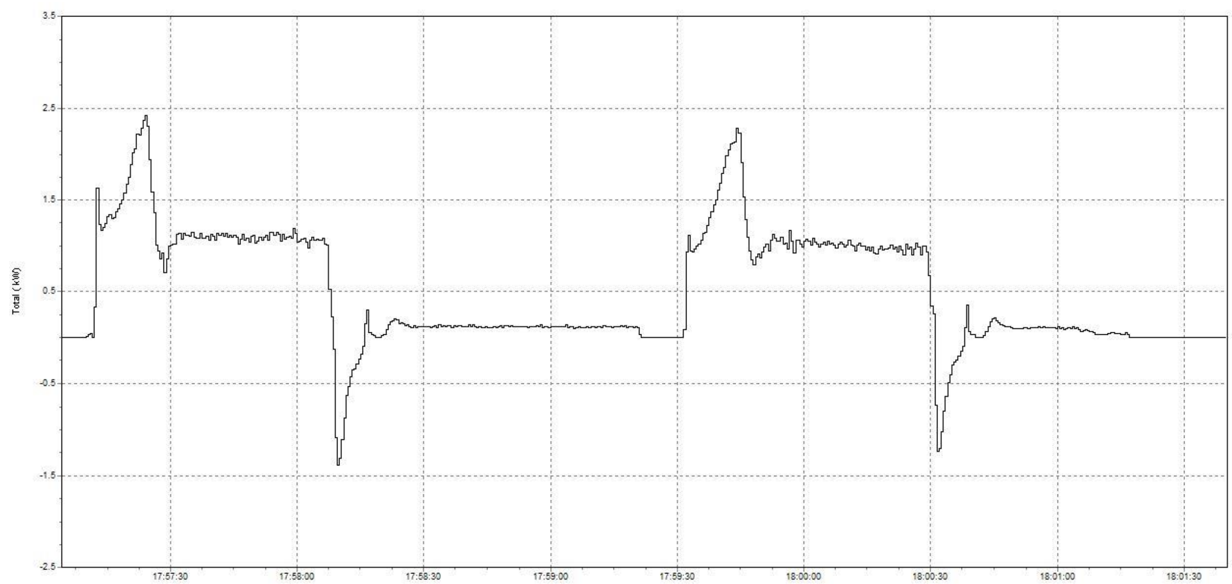

Figure 19- Drive Output Power Recording, Droop=5%, K_p =15, T_i =1500ms.

With the lack of K_d component in the control loop and the high system inertia, the peak power cannot be further reduced without increasing the acceleration time. This was not considered appropriate for this structure. The high and low constant speed regions were very stable. These tuning values were considered to the optimal values for this structure.

Strain gauge measurements were taken after the drive tuning and the final balancing to verify the control stability of the drive system. See Figure 20 below for the final operating condition.

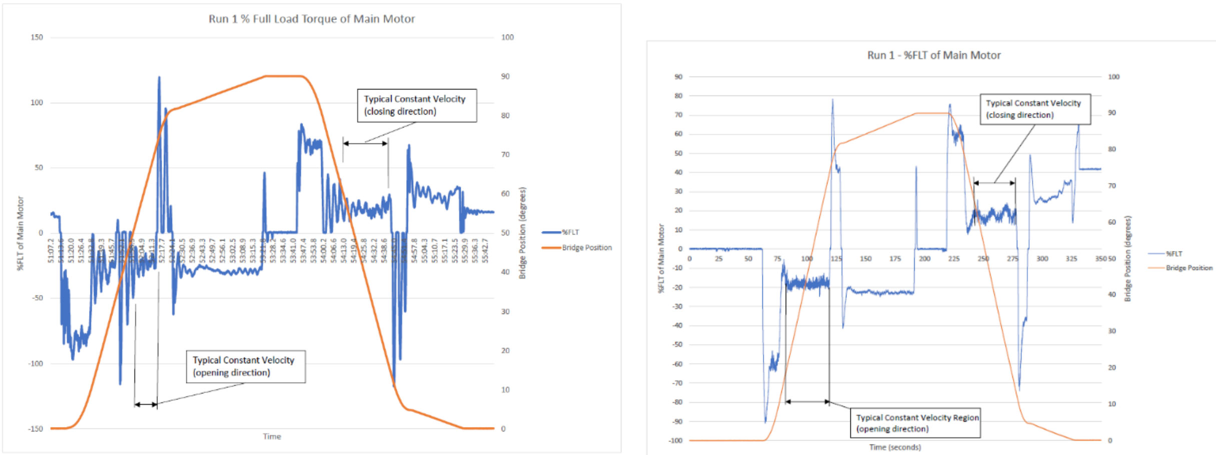

Figure 20- Strain Gauge Measurement of the bridge operation before and after drive tuning.

Conclusion

Proper control system tuning is a key facet of the movable structure testing and commissioning process. Although many tuning methods are available, only a few are used in practice. Knowledge of basic control system theory, these tuning methods, and movable structure behavior will allow the user to develop control systems that provide stable long-term performance for movable structures.

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