Water Start Up Time Model Validation Test

A Project Documentation

Presented to the Faculty

of Oregon Institute of Technology

in Partial Fulfilment for the Requirements for the Degree

of Master of Science

By

Daniel Lee

December 2015

I. Acknowledgements

This project would not have come into fruition without the help and most importantly patience of many extraordinary people.

To the Hydroelectric Design Center, I'd like to offer thanks to the turbo machinery section for providing data and their input into my project during my time there with special thanks to John Etzel for his guidance as my industry mentor.

To the Hydro Research Foundation, I'd like to offer my thanks for their guidance and support during the project and for allowing me to meet industry leaders and supporting my endeavor in school. I offer special thanks to Brenna Vaughn for her planning, commitment, and above all patience to make the Hydro Research Foundation a success in connecting the youth with hydro industry leaders.

To Oregon Tech, I would like to thank all the staff who made learning easier and the instructors for their guidance throughout these two years. I want to send special thanks to Hope Corsair for her guidance and support as my academic advisor. I would also like to thank Lee Sheldon for being my project advisor and bestowing his knowledge upon me in the duration of this project. Last but not least I offer special thanks for Richard Ellis for his diligence in support with constructing the water start up time model.

Daniel Lee

II. Executive Summary

This report is an Oregon Institute of Technology thesis project completed in partial fulfillment for the Masters of Science in Renewable Energy Engineering degree. The testing and research done for this report, investigate the phenomena of water start up time in the spiral case of hydro units. Water start up time is defined as the time it takes for water to accelerate from zero to rated velocity. From analysis of the literature there shows no published article of water start up time being measured and compared to theoretically calculated values. However a multiplier is used to create a buffer in the estimations of water start up time to use in the engineering and selection of governors for hydro units. The multiplier has also been widely used in computer model simulations which causes a dependence of this multiplier. In 2013 an article was published which challenges the hypothesis that water start up time has been over hypothesized and that the multiplier would be of a smaller value than what was hypothesized which would mean that the governing ability is more than what was expected. This proposal of a higher governing ability would mean that the hydro facilities that are currently standing has a higher stability rating than what was initially thought. The higher stability would allow for increased penetration of renewables onto the electrical grid. The lack of actual water start up time measurements as well as the infeasibility of testing on an actual hydro unit meant that a model would need to be designed, built, and tested.

The model had two testing parameters that were examined. One of the parameters was flow rate that was controlled by the number of wicket gates that was installed into the system and the other was the reference height from the forebay to tail water. There were one hundred results from the test trials. The data from the trials showed a trend for the multiplier which was not constant as previously hypothesized and instead illustrated a parabolic trend that tapers into a

linear digression. This result means that the range of testing was insufficient and the height range in which the trials were taking placed was subjected to higher variability. The results showed that the multiplier used in water start up time is not a constant and is variable based on the water level. The previous hypothesis stating that the water start up time is faster is false. In accordance with the results the trend showed that the actual water start up time is slower than what is hypothesized. This means at lower water levels the hypothesized governing ability is actually less than what is calculated to be using the current method of water start up time calculation for spiral cases.

The theoretical analysis showed that with increased water level and flow rate showed that the multiplier has less effect on water start up time. The value of the water start up time tapering off from the experimental data shows that the trend for water start up time for both theoretical and experimental share similarities. An increased testing range of the water level in the trials will hypothetically lower the variability of the multiplier and in turn conform to a linear equation. The linear equation is shown to approach zero with increased head in which a static value can be achieved for a specified range.

III. Contents

IV. List of Figures

V. Introduction

Purpose and Significance/Literature review

The importance of hydro power in the Pacific Northwest is clearly expressed by its 70 percent contribution to the total power production in the region [1]. The growth in variable renewable energy sources such as wind and solar cause grid instability. When variable energy sources are added to the grid, there needs to be reliable source of energy that can activate when variable energy sources dip below consumption levels. The unpredictability of wind and solar energy sources brings hydro power into play as it is reliable and renewable. This source of energy can curb the instability that wind and solar bring to the grid. The controller of the applications for hydro power is the governor system that allows for the opening and closing of the wicket gates. The wicket gates are located in the spiral that resides between the penstock and the draft tube as shown in figure 1.

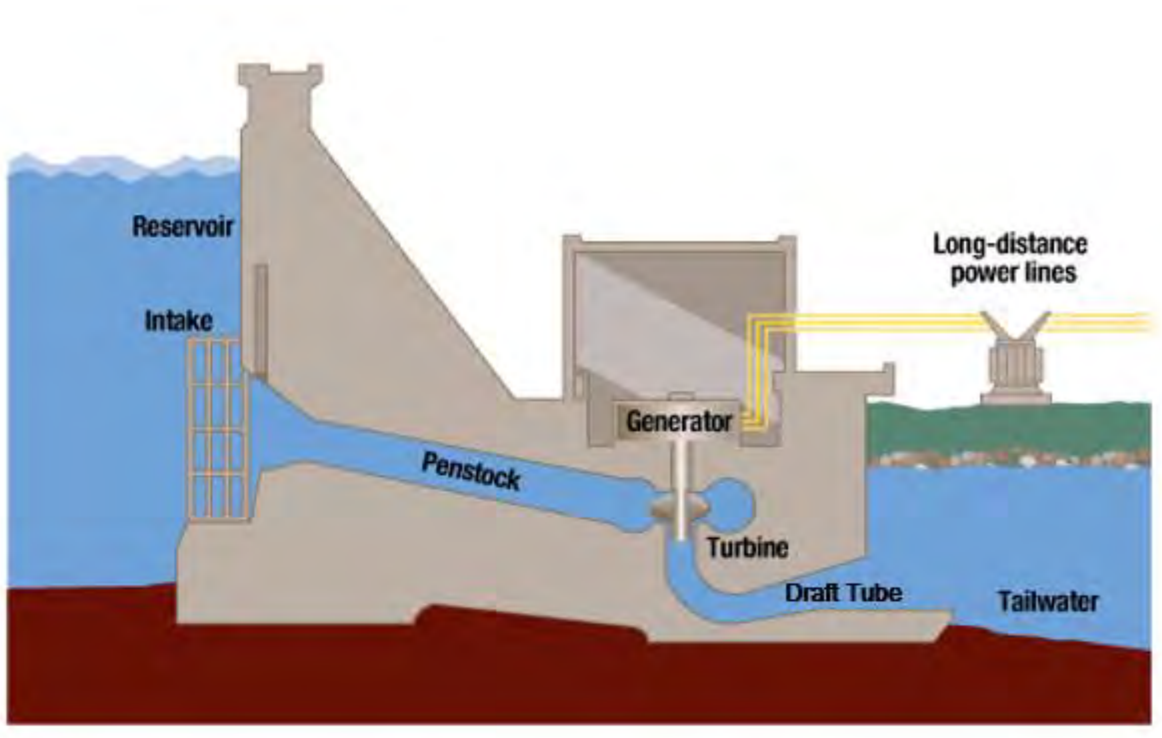


Figure 1. Hydro facility layout

When determining the governing ability, the water start-up time, sometimes referred to as water running up time, or water inertia constant, is needed for the assessment as shown in equation 1. The mechanical start up time is expressed as "T_m", which is the time the mechanical unit takes to obtain rated rotational velocity from zero. The water start up time is expressed by "T_w".

$$Governing\ Ability = \frac{T_m}{T_w} \qquad \text{Equation 1}$$

The governor's ability to control the speed of the large rotating turbines is primarily rated by the mechanical start up time to water start up time ratio [2]. The designer of a governor system aims for the value of four, meaning the mechanical start up time is four times that of the water start up time. According to equation 1, the faster the water start up time design the greater the governor ability [2].

The origin of water start up time was first brought up by hydro engineer, Charles Jaeger. The proposed equation was derived from pressure rise in short rigid pipe or the effects of water hammer [3]. The equation used was the idealized running up time of a pipe line defined as equation 2.

$$\theta_*(s) = \frac{L(ft)*v_o(\frac{ft}{s})}{g(\frac{ft}{s^2})*H_o(ft)} \qquad \textit{Equation 2}$$

The "θ_*" shown in equation 2 is the time which is required by the pressure constant "H_o" to accelerate water from zero to steady state rated velocity expressed as "v_o" [3]. The "L" term is the length of the intake to the outlet [3].

The equations used to calculate water start up time shown as equation 4 is derived from equation 3, the water hammer equation. Water hammer is the pressure surge when a fluid is forced to abruptly stop or change direction from current velocity. Water start up time relates to water hammer by having the opposite effect, which is when fluid is abruptly allowed to accelerate towards rated velocity [2]. One is brought to an abrupt stop and the other is allowed to accelerate as fast as possible towards rated velocity.

$$WaterHammer(H_w) = -\frac{L(ft)}{g\left(\frac{ft}{s^2}\right)}\frac{dV}{dt} \qquad \textit{Equation 3}$$

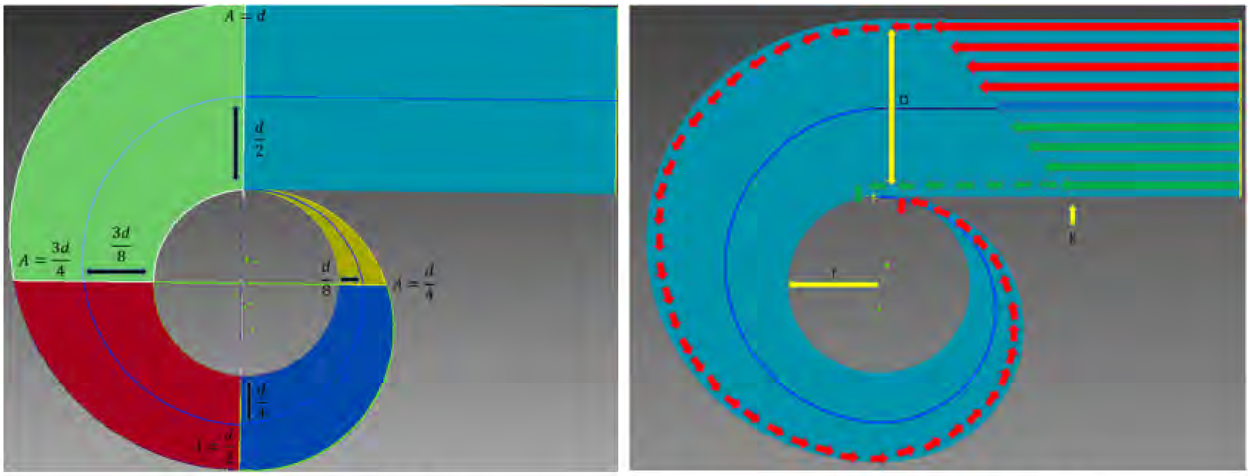
$$Water\ Start\ \ Up\ Time(T_w) = \frac{L(ft)v\left(\frac{ft}{s}\right)}{g\left(\frac{ft}{s^2}\right)h(ft)} \qquad \textit{Equation 4}$$

$$v\left(\frac{ft}{s}\right) = \frac{Q\left(\frac{ft^3}{s}\right)}{A(ft^2)} \qquad \textit{Equation 5}$$

Equation 5 is used to transform equation 4 into equation 6, which is the common form used when calculating water start up time.

$$Water\ Start\ \ Up\ Time(T_w) = \frac{L(ft)Q\left(\frac{ft^3}{s}\right)}{A(ft^2)g\left(\frac{ft}{s^2}\right)h(ft)} \qquad \textit{Equation 6}$$

The subject of uncertainty that Lee Sheldon's research addresses is the law of continuity in the calculation of water start up time. The law of continuity states that when a fluid enters a single point, it will have to leave in the same amount through the exit. This is represented by equation 5 with "Q" as the flow rate and "A" as the area of the orifice. The case for water start up time in a spiral case for a hydro turbine behaves differently as the water enters through multiple points and discharges through multiple orifices at different rates. The effect in the hydro turbine has water enter through the penstock from one point and leaves multiple points through the wicket gates at different rates. This varied set up is where the 0.5 multiplier for the length over area ratio expressed as "L/A" of the spiral case comes from. The fifty percent multiplier assumes that any water molecule within the spiral case has an equal fifty percent chance to leave the spiral case, which is a value that is used for getting closer to the actual water start up time [2]. The examination of the spiral case presented as figure 2 shows that this theory is incorrect [2]. A water molecule starting at the inner radius of the spiral has a greater chance to exit through the wicket gates than a water molecule starting at the outer radius of the spiral case. This shows that there is bias in which not all water molecules within the spiral case have an equal chance of discharging through the wicket gates.



Traditional Spiral Case Stream Tube Spiral Case

Figure 2.Simple geometric calculation and multiple stream tube application [2]

The research proposed a new method of calculating the water start up time using stream tubes, which will account for the bias that is dependent on the starting location of the molecule. The research results shows that the 0.5 multiplier for the length over area should be closer to 0.398, when using actual spiral case geometries [2] [4]. A smaller multiplier would result in a decreased overall value of water start up time, which would increase the value of the governing ability. This would mean that that the stability of the grid would need to be revaluated with a likely chance that there is more stability on the grid than originally defined.

To prove that the proposed method of evaluating water start up time was more accurate, an experimental verification of the water start up time on the facility would have to be done. However with the size of the facilities it is not feasible to perform the test, as the wicket gates would need to be instantaneously opened in which the facilities cannot perform. The infeasibility of this option has left a lack of water start up times for comparison.

There has also been a hypothesis that full load rejection can be used to calculate water start up time. Full load rejection is a test used for power systems to determine if it can handle a sudden loss of load and by using the governor to return to stable operation [5]. The equation starts with calculating the full closing time of the servomotor defined by equation 7 and represented by "T_k".

$$T_k = 0.25 + T_f \qquad \textit{Equation 7}$$

The servomotor minimum closing time is labeled as "T_f" measured from 75 percent to 25 percent closing. The next step is to calculate the mechanical start up time denoted as "T_f" using equation 8 [6]. The "WR^2" is denoted as the fly wheel effect of rotating parts. The "n" is expressed as the rotational speed of the machine. The "P_r" denotes the turbine full gate capacity at rated head or at rated power.

$$T_m = \frac{WR^2n^2}{1600000P_r} \qquad \textit{Equation 8}$$

The next step is to calculate a ratio between the minimum servo motor closing time and mechanical start up time shown as equation 9.

$$R = \frac{T_k}{T_m} \qquad \textit{Equation 9}$$

The next step is to determine the theoretical speed rise percentage (S_r) which is based on three equations: the design specific speed and the type of turbine. Equation 10 is used for Kaplan turbine units and equations 11 and 12 are used for Francis turbine units with a specific speed: equation 11 if the value is below 60 and equation 12 if the value is over 60 [6].

$$S_r = -6.0289 * R^2 + 38.202 * R + 1.7211 \qquad \textit{Equation 10}$$

$$S_r = -6.0042 * R^2 + 42.28 * R + 2.3987 \qquad \textit{Equation 11}$$

$$S_r = -7.5864 * R^2 + 42.248 * R + 1.919 \qquad \textit{Equation 12}$$

The final step to acquire water start up time uses the full load rejection test data speed rise including the effects of water hammer (S_r') in equation 13 [6].

$$T_w = (\frac{S_r'}{S_r} - 1) * T_f \qquad \textit{Equation 13}$$

The method shown using full load rejection is a way the U.S Bureau of Reclamation obtains water start up time values. However this method does not match the definition of water start up time, which requires an instantaneous gate opening [6]. A full load rejection is an instantaneous gate closure while water start up time require an instantaneous gate opening [2]. From the report, hydro turbine-governor model validation in pacific northwest by Dmitry Kosterev, "there is a significant difference in amount and speed of the recorded and simulated governor responses" in for models such as that of The Dalles and John Day hydro facilities located on the Columbia river. This means that there is a gap between what is simulated and what happens under real life test conditions, and a model test is further justified due to constants that are used in calculations that are not validated, such as water start up time. [7]

From the literature review it is learned that water start up time represent a large factor in determining the governing ability and in turn the grid stability. However there is a gap in the research where there is no actual water start up time values to compare to or unpublished results of these tests.

Hypothesis

The results of the experiment would yield results that are comparative to the geometric calculation method and the stream tube method. This experiment will yield definitively accurate water start up time data for a model test in which a true multiplier can be obtained for the length over area ratio of the water start up time equation. With the results, a comparative theoretical value can be compared to in order define and gauge where the current stability of the grid resides.

VI. Methodology

Experimental Design

The experimental procedure starts with the design of the instantaneous gate opening. The reason for the design is because life sized hydro facilities are not equipped to perform an instantaneous gate opening and so a model test is required to confirm the behavior of water in water start up time.

In order to be able to perform an instantaneous gate opening, a piece of elastic with tension around the end of the draft tube would be used. The elastic would be pulled off, effectively making the gate disappear. This option would have no debris leftover that would affect the water flow after the gate opening. This option would also allow the elastic to be reused, which is more economical.

The system would also be designed to be modular in order to test for a larger array of variables such as material, shape, and size of the model. The modularity allows the system to be more economical and serve for more than just a single type of test. The design of the coupling system allows for parts to be interchangeable.

The hypothesis for how the water will react to an instantaneous gate opening is that the velocity of the water will shift from one steady state to another. This assumption is based on the principle in Bernouli's principle that a drop in pressure will conversely increase in velocity to compensate for the transition from potential to kinetic energy. This brings up the need for a pressure transducer to measure the two pressures at the start and end of the model. This will allow for verification of the steady states as water start up time is the duration it takes for water to reach rated velocity from zero. [2]

The experiment was also designed to have a sensitivity analysis to have a wide array of data to compare and contrast with a single variable alteration. The sensitivity analysis will be done with referenced water level and the amount of wicket gates, which will alter the flow rates and patterns. The number of trials will be at a minimum of three per variable change which will allow for more data to analyze and decrease the risk of using outliers in the analysis.

The water level reference parameter is done by changing the starting water level of the upper reservoir right before the start of the experiment. The water level reference will be 10 centimeters, 15 centimeters, 20 centimeters, 30 centimeters, 35 centimeters, and 40 centimeters. This parameter will change the flow rate of the system and is one of the sensitivity analyses.

The number of wicket gates that will be tested is 10 gates, 15 gates, and 20 gates, all with the same porosity of 30.8 percent. The porosity was determined by analyzing the area that is open to discharge from a vertical and horizontal view. The porosity can be any number, and varies from facility to facility, but the number chosen was to represent comparable porosities from a hydro facility and to justify the results obtained. The design of the wicket gates were represented by number of slits that were equally spaced from each other. The number of wicket gates is the other parameter that affects the flow rate.

Equipment Selection

Acrylic material was selected to be used due to the light weight and easiness to cut and mold to a desired shape. The acrylic also had a low roughness factor to decrease the effects of friction acting within the fluid column. The translucence of the material also allowed for visibility of large bubbles are air pockets within the model that could affect the measurement results.

The square orifice design was chosen instead of a rounded or circular orifice design was due to the initial design of the spiral which had square orifices. This allowed for the measurement of the length and area of the orifice to be as accurate as possible as well as the ability to couple to the spiral case. The rounded orifice design was considered due to less friction acting on the water column in comparison to the square orifice; the rounded orifice design resulted in less friction due to less of the surface area exposed, which lowered the contact the water column had with the sides of the model.

The USB-6009 data acquisition unit figure 3 was used because it had the ability to record data.

Figure 3.National Instruments USB-6009

USB-6009 can acquire up to 14000 points per second, which allows the analysis of data points within a hundredth of a millisecond from one another; this capability is necessary, since timing is the main variable to be measured in this model test. The system uses a lab view set up with a data acquisition assistant. The block diagram operates with the data acquisition assistant that sends to a write to measurement file that is controlled by a true false condition statement, which is controlled by the record button. The recording functions starts recording and writing the test data to a file, which then creates new files in ascending order every time the program restarts. The entire program exists within a while loop with a time delay, which is set at one millisecond to cap the amount of data points recorded to 1000 points per second. The points per second was chosen based on the error the pressure transducer based on linear hysteresis, which had a max error percentage of two. The block diagram and front panel is shown in figure 4 and figure 5.

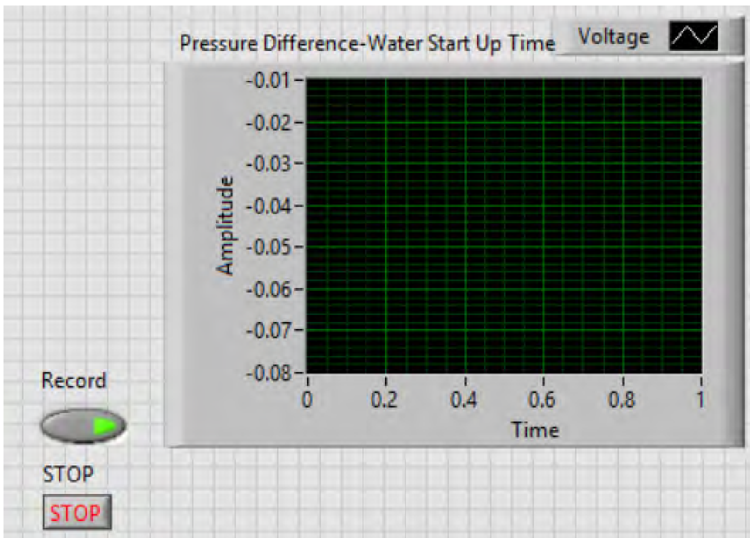


Figure 4. Labview front panel water start up time

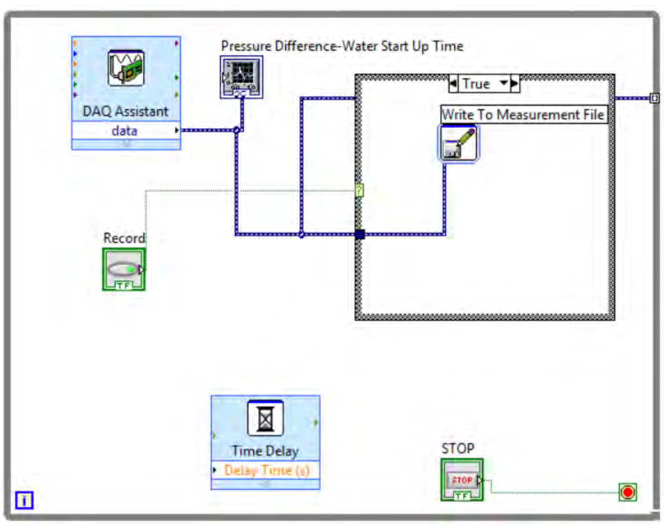


Figure 5. Labview block diagram water start up time

Figure 6.Omega PX409-10WDWUV

The selection of the pressure transducer was selected based on the specification that it was wet to wet rated, meaning that the device was designed to measure the pressure difference between liquid mediums. The range of the pressure transducer's operation was chosen to be 10 inches of water. The device operates with linear hysteresis in which the accuracy of the device will vary depending on the range of the pressure measurement. The absolute accuracy of the pressure measurement is not of high importance due to the scope of the project: focusing on the the relation and behavior of all the data points as a whole rather than the accuracy of each data point. The pressure transducer that was selected was the Omega PX409-10WDWUV as shown in figure 6.

Experimental procedure

The system is arranged as shown in figure 7 as an Autocad design file and figure 8 as the actual set up. The upper and lower reservoir is filled to the appropriate water levels with the upper reservoir filled slightly above the rated water level and the end of the draft tube sealed with a balloon which simulates the gate. Next, air bubbles are purged from the pressure transducer lines by bleeding the valves. Next the Lab view data collection program is initiated and with the program running. After the gate is fully open, the water flow will take from 1 to 2 seconds to reach rated flow; the program is then stopped.

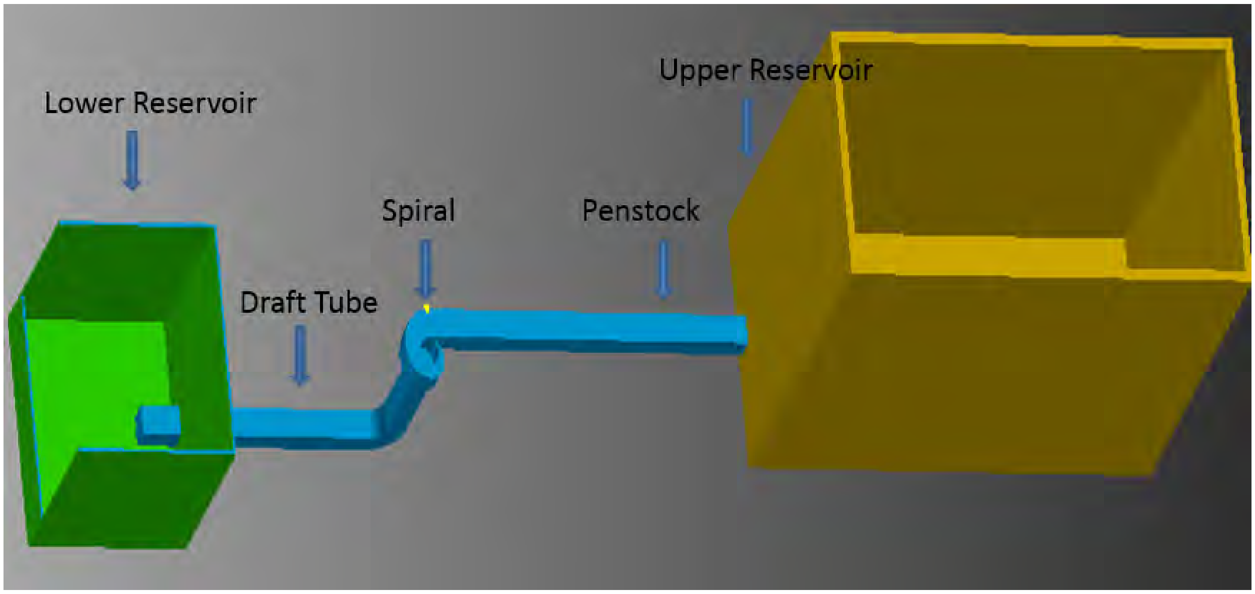


Figure 7. Cad design file layout

Figure 8. Real world layout

The experiment was designed with several sensitivity analyses to obtain data over a wide variety of parameters. The parameters that are set to change are the differential water levels and the number of wicket gates. The sensitivity will show variation of the test results to allow for examination of a trend.

An example of the data plot is shown as figure 9 which shows the sudden change in the pressure and the momentum of the water trying to equalize the upper reservoir discharge rate with the rated flow rate until the pressure approaches steady state. The water start up time is measured is by finding the difference between the last crescent before the pressure drop and the first crescent after the pressure drop. This method is repeatable but comes with inaccuracy as the water start up time should be a larger value than what is obtained. This is because the recovery of the pressure drop takes a longer duration than what is perceived to be the last crescent after the pressure drop from the first crescent.

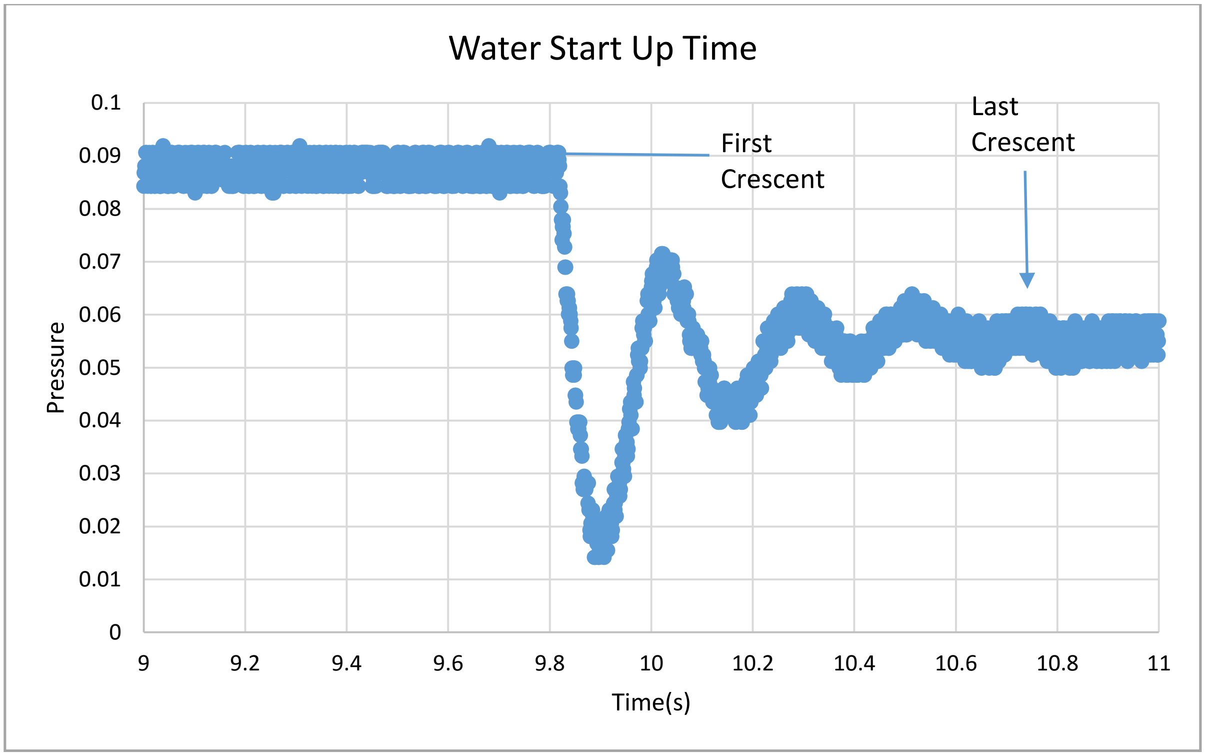


Figure 9. Example of water start up time data

For calculations the water start up time equation is transformed to fit the needs of finding the length over area ratio as shown in equation 14. The transform changes the length over area portion by factoring out the three components that make it up. The two components that can be have the length over area ratio measured easily are the penstock and draft tube. Due to the simplicity of the shape of the penstock and the draft tube the length and area of the orifice can easily be calculated. The component that cannot be easily measured is the spiral case. The spiral case which cannot have the length over area ratio calculated due to the behavior of water on the orifice. The three components are split between the spiral case and penstock with the draft tube. The length over area is clearly defined with the penstock and draft tube with "X" representing the multiplier for the spiral case length over area ratio. The equation to determine the multiplier for the length over area ratio is shown as equation 15. The water start up time is denoted by "T_w". The length and area is equated as "L" and "A" respectively and subscripted by the corresponding part of the model. The gravitational constant, flow rate, and rated head is "Q", "G", and "H_w" respectively.

$$T_w(s) = [\left(\frac{L_{Penstock+Draft\,Tube}(ft)}{A_{Penstock+Draft\,Tube}(ft^2)}\right) + X\left(\frac{L_{Spiral\,Case}(ft)}{A_{Spiral\,Case}(ft^2)}\right)]\frac{Q(\frac{ft^3}{s})}{G\left(\frac{ft}{s^2}\right)H_w(ft)} \qquad \textit{Equation 14}$$

The length of the penstock was measured to be 32.43700787 inches, with a measured orifice area opening of 3.875 $inch^2$ yielding a length over area ratio of 8.370840741 $inch^{-1}$. The length of the draft tube was measured to be 28.57205 inches with a measured orifice area opening of 3.875 $inch^2$ yielding a length over area ratio of 7.373432258 $inch^{-1}$. The length over area ratios of the penstock and draft tube can be summed because they do not have a multiplier factor that is associated and the whole value of each is used.

$$X = \frac{\frac{T_W(s)G\left(\frac{ft}{s^2}\right)H_W(ft)}{Q(\frac{ft^3}{s})} - 15.744273}{7.744029289} \qquad \textit{Equation 15}$$

VII. Analysis

Test Runs

The amount of usable data where the water start up time is identifiable and can be justifiably used is 100 results. The flow rate was calculated from a water drop test in which the water is filled to highest level in the reservoir and discharged through the model while it is watered. The rated flow rate will vary for each height and gate tested as shown in figure 10.

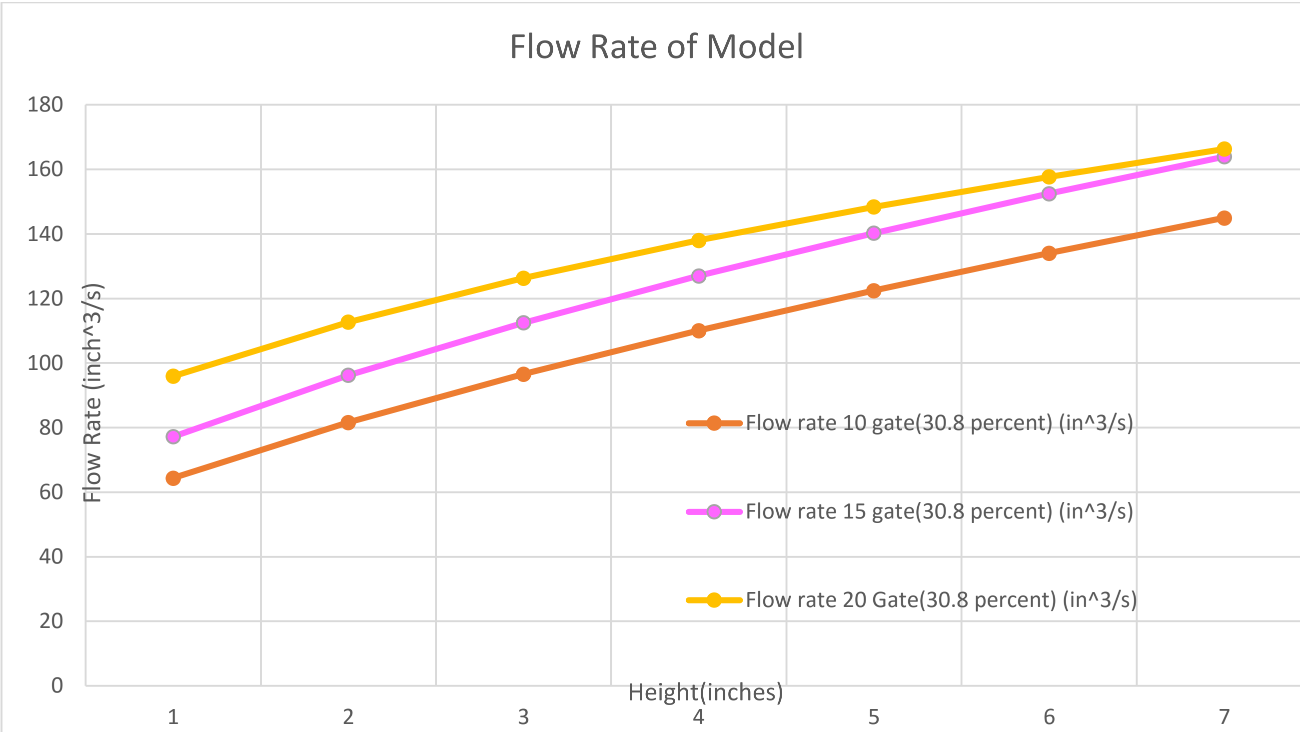


Figure 10. Measured flow rate

The flow rate was as hypothesized, with the amount of gates affecting the flow rate. As the number of gates increase, the less coarse the orifices is, which results in less head loss occurring when the water is discharged through the gates. During testing there was also leakage within the model, however the leakage was minuscule as shown from the results of a leak test where the entire system was filled and a leakage test was performed. The multiple leakage tests showed that of the 31.96 gallons spilled over the course of a maximum of 56.83 seconds, the greatest amount of water that leaked from the major sites of the system being the coupled parts was 0.0833 gallons: 0.261 percent of the total water spilled. Another factor to take note in is that a single trial lasts no more than 2 seconds; the leakage test was over the course of 56 to 57 seconds.

10 gate

The first test with 10 gates yielding 19 results, showed that the multiplier for the spiral case varies in a linear digression with all values being above the 0.5 modifier that is commonly used, shown in figure 11. The results were expected to yield results such as that of a horizontal line but from this data it shows that the multiplier is not constant.

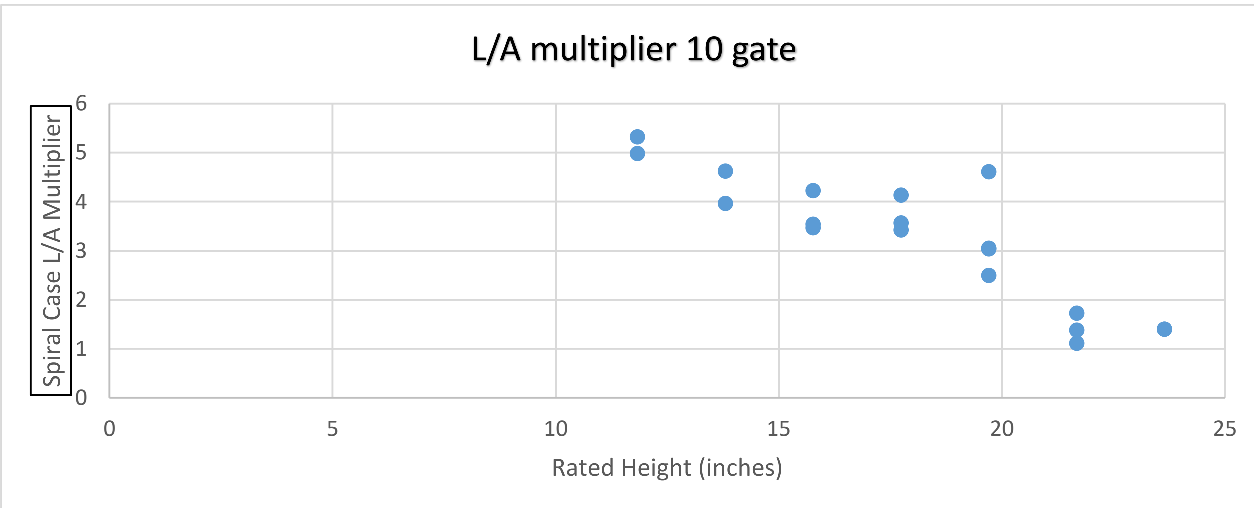


Figure 11. L/A multiplier 10 gate

Figure 12 shows a comparison to the between the theoretical value of water start up time and the experimental water start up time. The results show that the actual water start up time is slower as opposed to faster based on what was originally hypothesized.

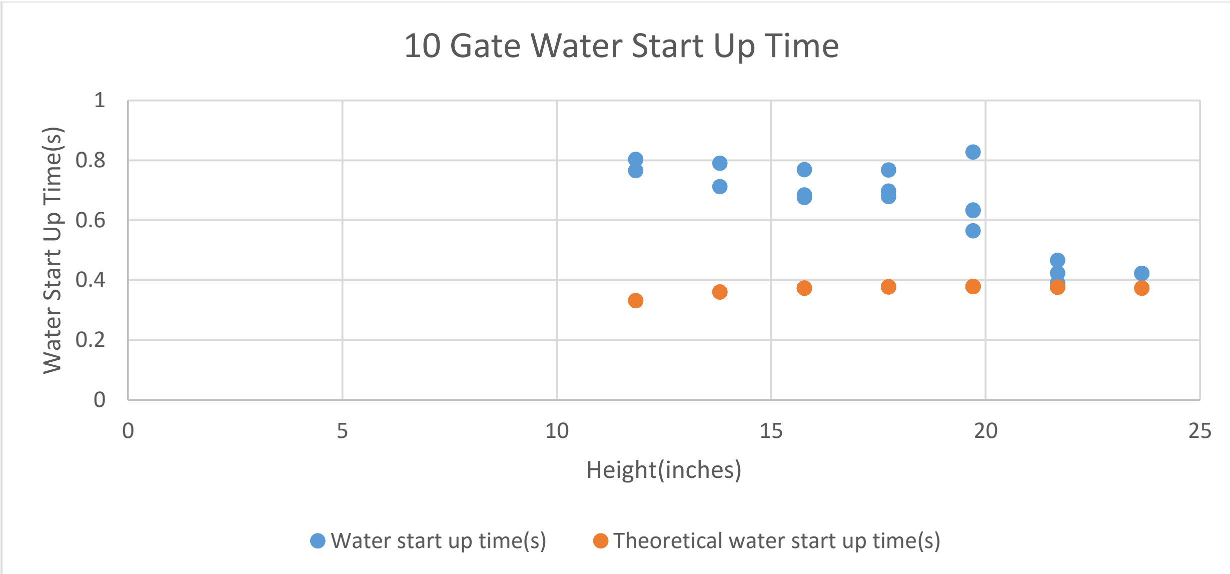


Figure 12. 10 gate theoretical and measured water start up time

15 gate

For the 15 gate testing, 24 results were gathered. As in the testing from the 10 gate test, there was no constant in the multiplier and by the trend it showed a parabolic relationship with negative values. The negative value for the multiplier would mean that spiral component decreases the overall length over area value of the entire apparatus. However the multiplier follows a trend, but a majority of the values are positive which lead to believing that the negative values are error values from the measurement.

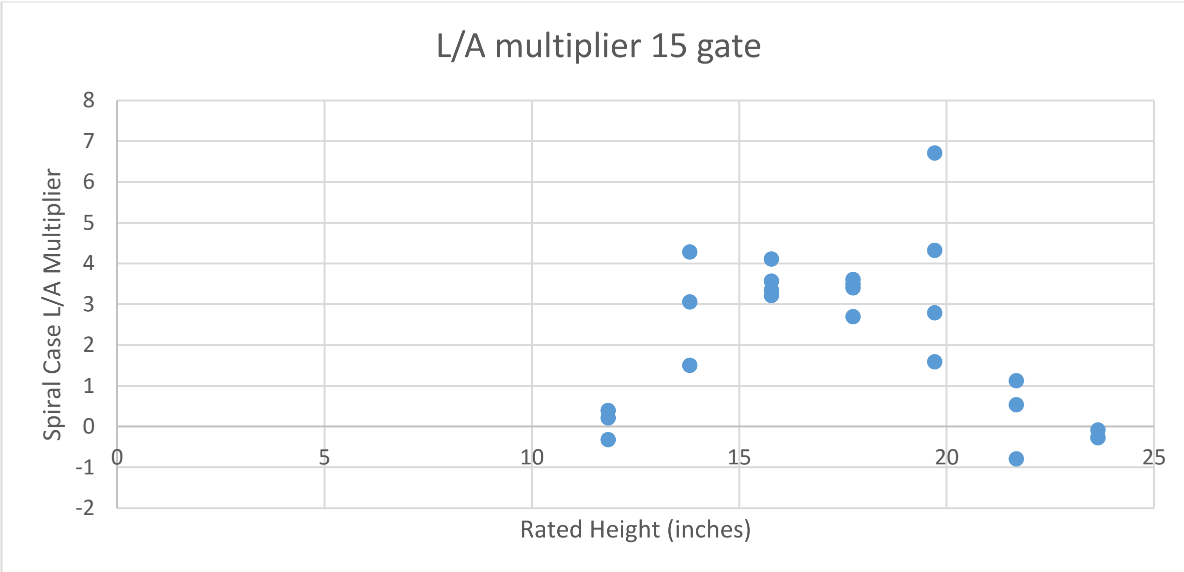


Figure 13. L/A multiplier 15 gate

The comparison of the theoretical value of water start up time and experimental value of 15 gate shown in figure 14 shows that even though the values are quite different, the trend was the same which was parabolic with the vertex of both data sets occuring near the same height.

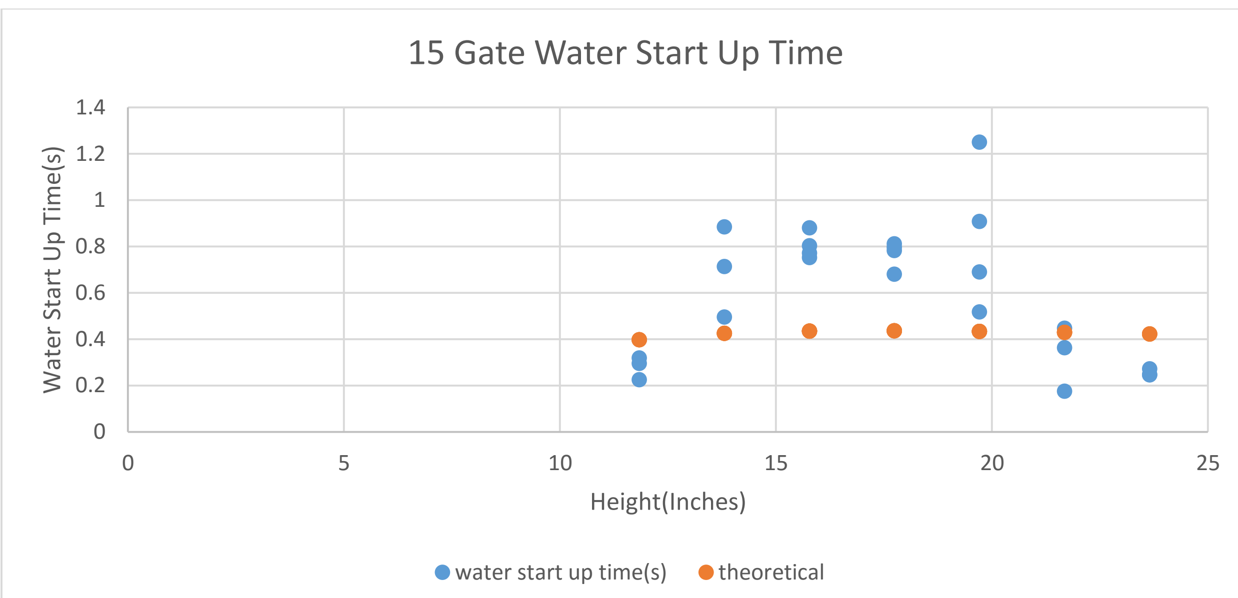


Figure 14. 15 gate theoretical and measured water start up time

20 gate

The 20 gate test was done twice to verify if the trend of the parabolic curve resulting in 60 data points. In the secondary trials the same type of trend appeared verifying that the parabolic trend was not an error. Figure 15, shows a parabolic trend; however as the height passes 20 inches there seems to be a curtailment. The curtailment could mean that the testing range of heights in the project was too small. This alludes to the possibility that higher heights or heads reach a point of stability.

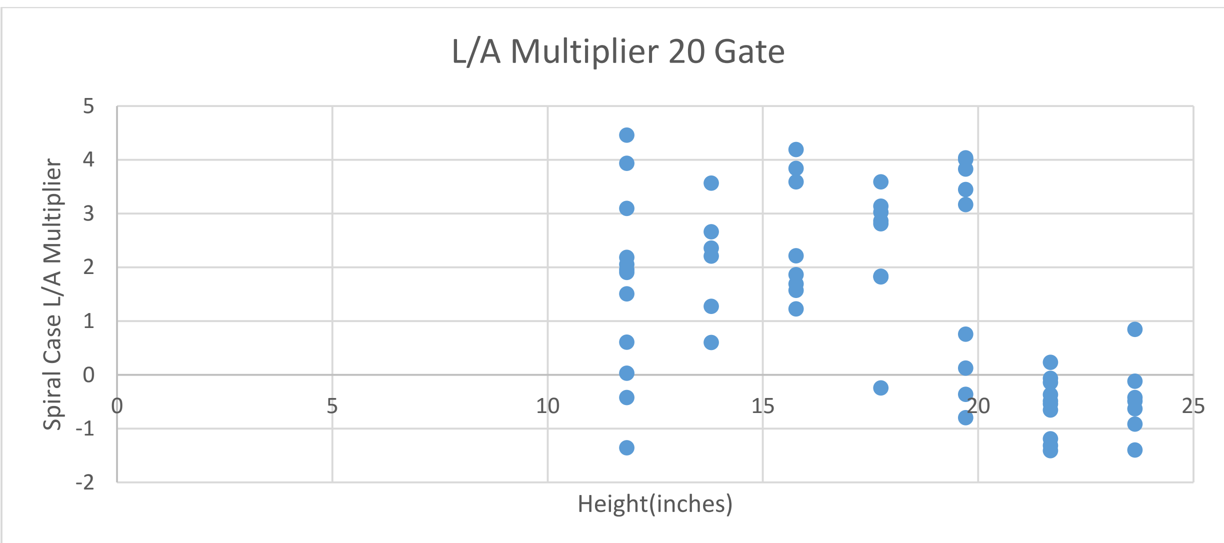


Figure 15. L/A multiplier 20 gate

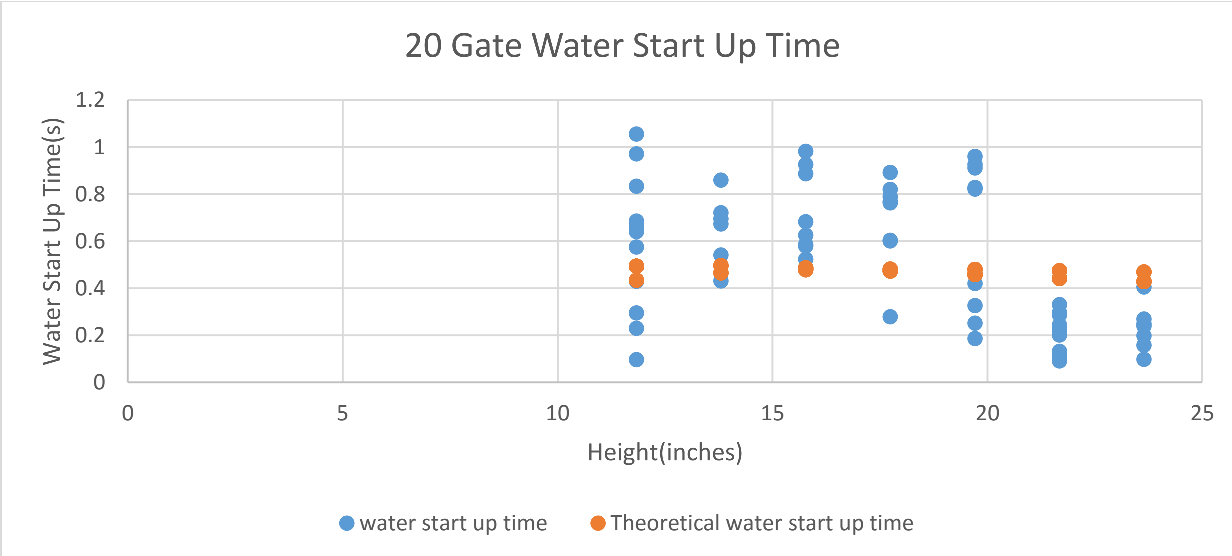


Figure 16. 20 gate theoretical and measured water start up time

Consolidated Results

The total number of results from the test is 100 data points and when graphed together, shown in figure 17, the parabolic trend seems more apparent along with a linear trend that appears after 20 inches in height.

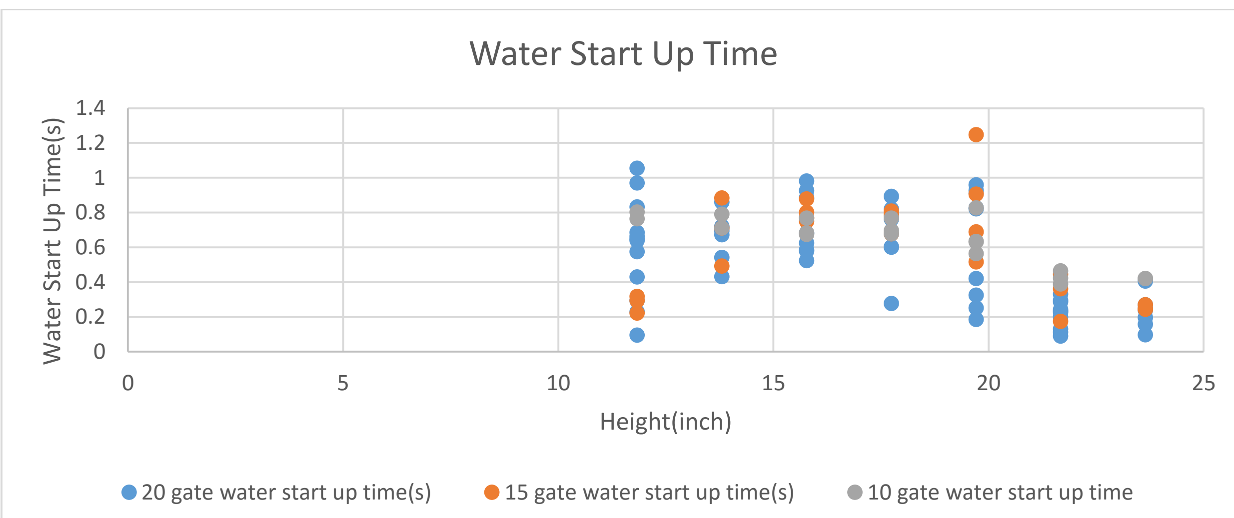


Figure 17. Consolidated water start up time comparison

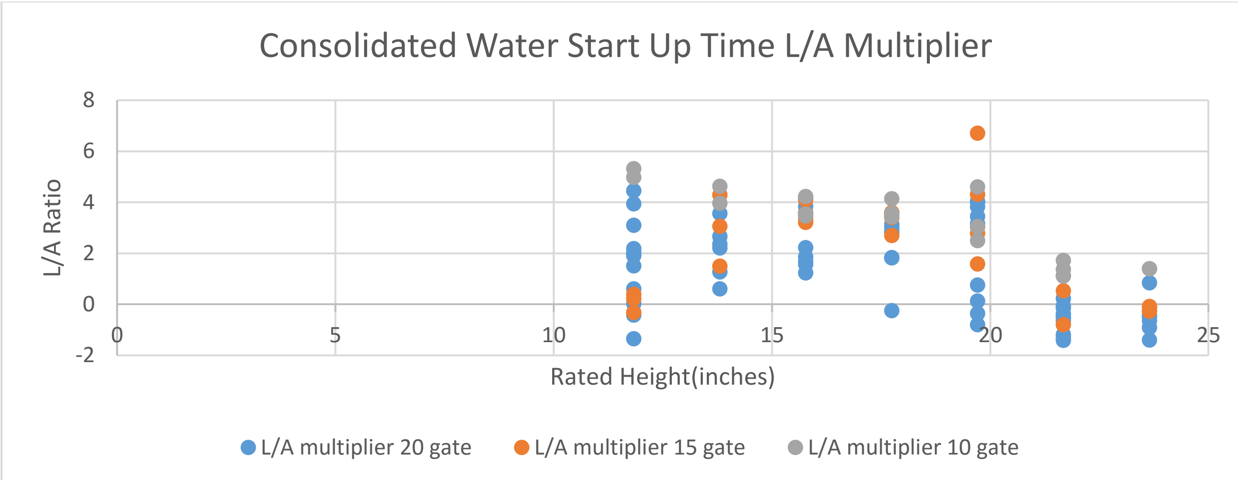


Figure 18. Consolidated water start up time multiplier comparison

The current number of tests shows that there is no proof that the trend of water start up time starts to curtail as the height increases due to the restrictions in the model. However with the data from the model, a theoretical water start up time can be hypothesized by examining if the trends that are showing in the test are true. Figure 19 and 20 show a theoretical trend of water start up time for 1.0, 0.5, and 0.4 multipliers for the length over area ratios. At low heads there is at first very little variance, which causes the data to be indistinguishable. Then results shift to having great variances with increases in head. Then as the head increases further, the data becomes more distinguishable with less variances in between the multiplier values. The theoretical plot also follows a linear trend similar to what the experimental data shows. This is proof that the data that was acquired was an accurate representation of water start up time. The problem shown in figure 18 is that some of the length over area multipliers are in the negative region. The reasoning for the negative multipliers is that to keep the procedure repeatable, accuracy was lost. The method for determining the water start up time was measuring the time between the first crescent, which signals the instantaneous gate opening and the last crescent, which signals when the fluid column has reached rated velocity. The water start up time is hypothesized to be longer because the steady state is a horizontal line which happens after the last crescent which is difficult to define how much discrepancies between points is allowed. This means most of the results gathered for the multiplier would increase due to the slower water start up time. A method that was not repeatable but accurate involving the use of french curves is discussed in the future considerations section.

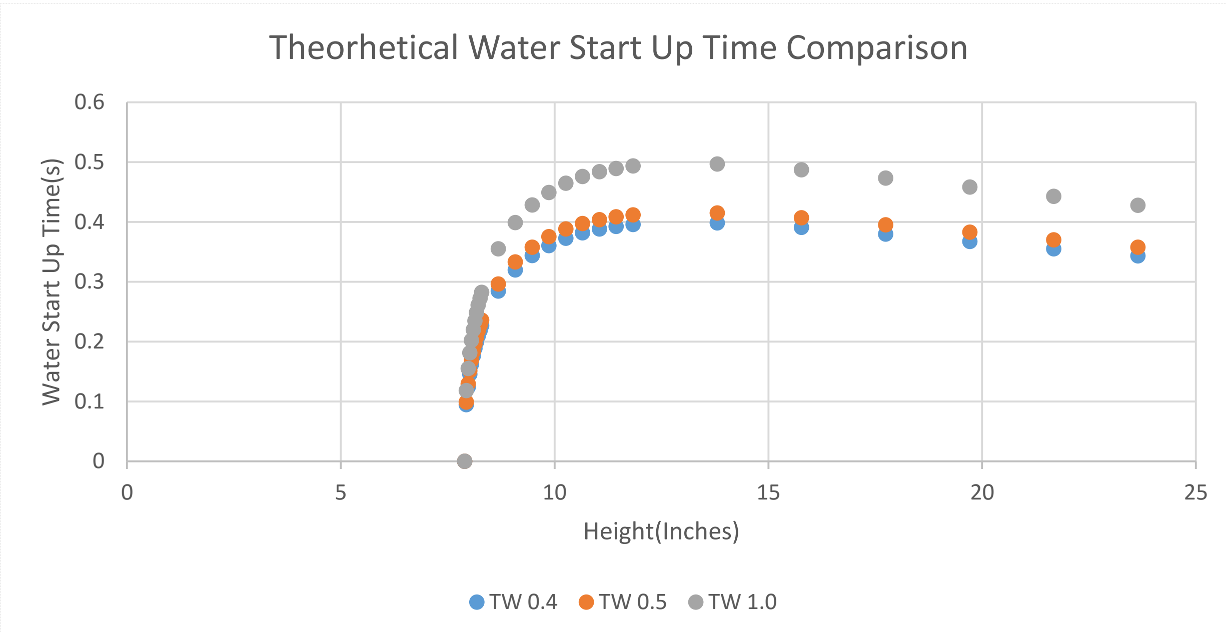


Figure 19. Theoretical water start up time comparison with varying multipliers

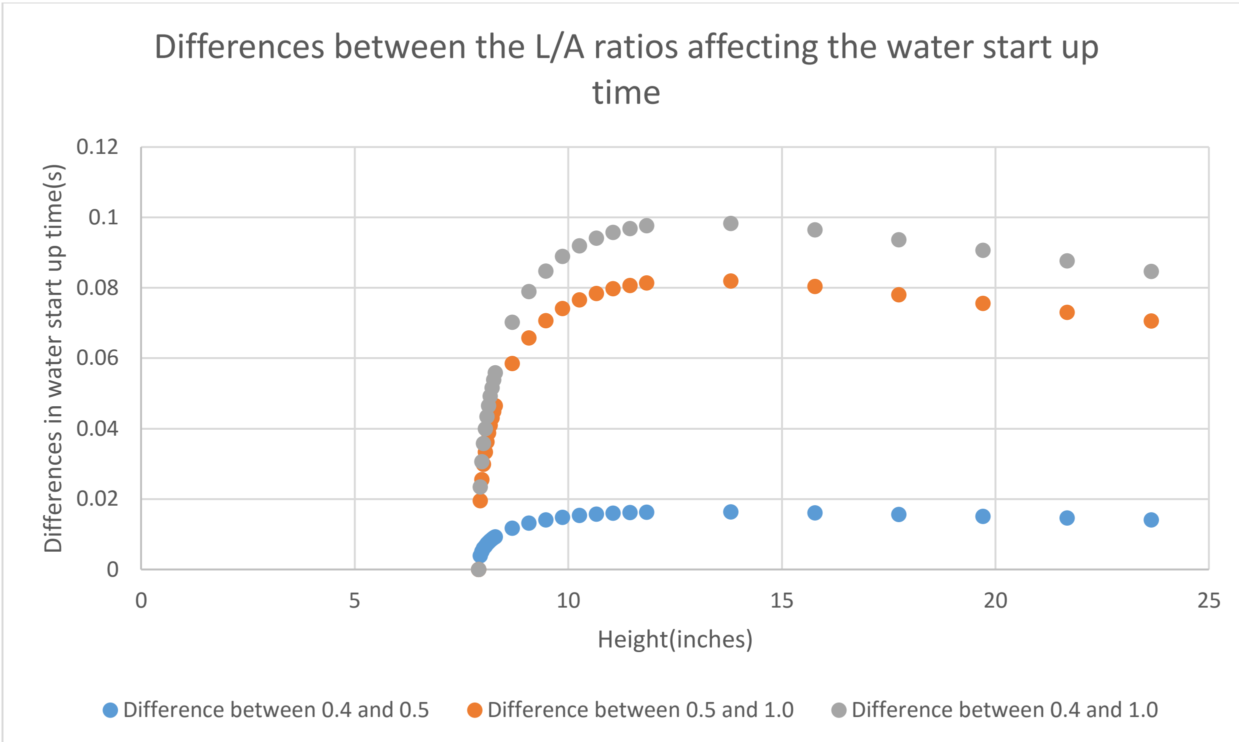


Figure 20. Differences in theoretical water start up time comparison with varying multipliers

Figure 21 and 22 show that, with the bounds expanded to 1400 inches, the water start up time will at first exponentially slow down, exponentially speed up, then slowly increase in speed as the height increases. The results show that the testing range was done where the results would vary greatly. This means that although the trend is accurately measured, the actual values of water start up time is more difficult to distinguish in terms of calculating the length over area ratio in that region of testing.

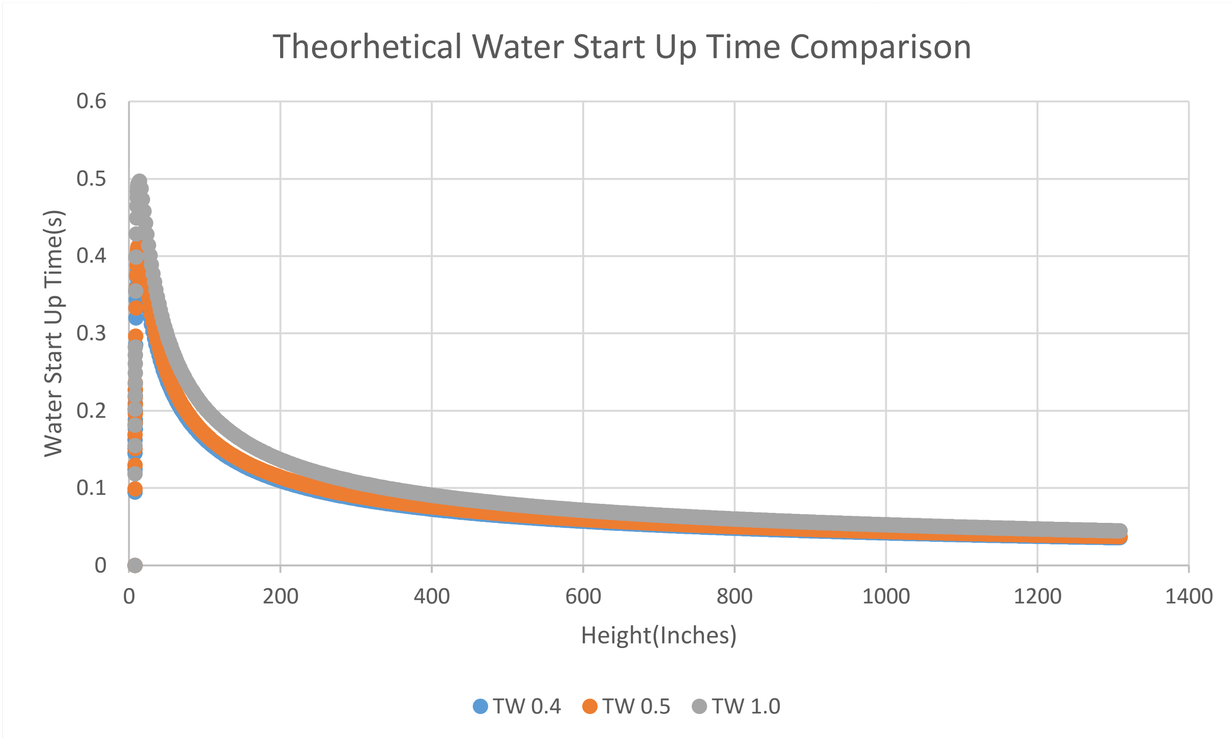


Figure 21. Theoretical water start up time comparison expanded bound

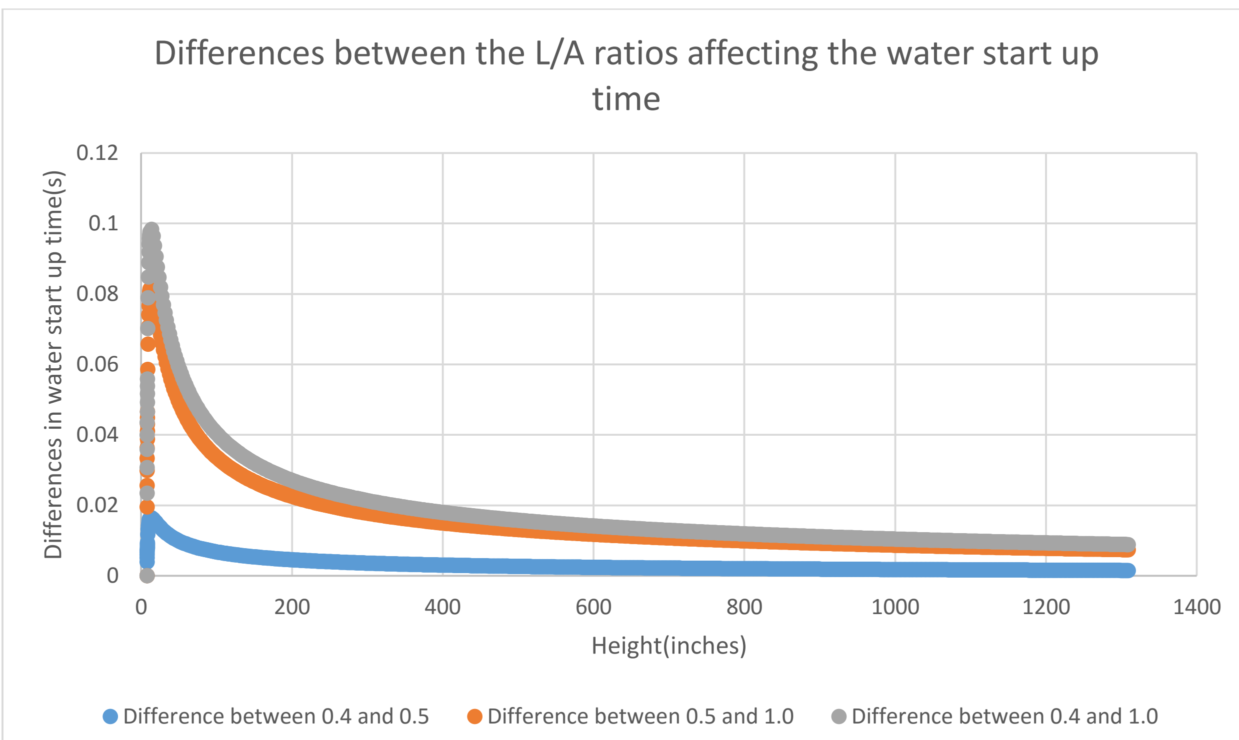


Figure 22. Differences in theoretical water start up time comparison expanded bound

VIII. Conclusion

Evaluation

In this project, accurate trends of water start up time were measured as well as the water start up time values which now allow for comparison with theoretical values. A true multiplier for the length over area for spiral cases was not discovered; what was discovered is that water start up time has a trend in which the values show large variability at low head, hypothesized to have low variability at high head. This hypothesis alludes to the idea that the length over area ratio component of the spiral case has little difference in affecting the water start up time that is not at low heads. Another hypothesis is that there is an equation that determines the length over area multiplier based on the height or reference head of the hydro unit. Most of the actual water start up time values in the data are slower than the hypothesized value of water start up time meaning, that very low head units run the possibility of a lowered governing ability and the need for accurate measurement of water start up time. The need for accurate water start up time values targets units such as micro hydro which have extremely low head; and in which water start up time variability is at its highest. The lack of data for higher head and the data of actual water start up time being greater than what is theoretically hypothesized does not mean that this is true in all ranges and that there is still a possibility that water start up time is hypothesized to be lower than what is rated on currently operating hydro units and that there is undocumented stability on the grid.

IX. Future Consideration

Leakage

Water discharging at non determinate locations within the systems allows for error. The leakage areas within model allow for minute changes within the flow rate calculations and affects the value of water start up time by accelerating the water column slightly before the instantaneous gate opening. When leaks occur, the value of water start up time does not match the true definition of water start up time, which is water accelerated through a fluid column from zero to rated. With leakage, the starting point of the water is not zero due to preliminary fluid flow. A large portion of the leakage were at the modular coupler sites shown in figure 23.

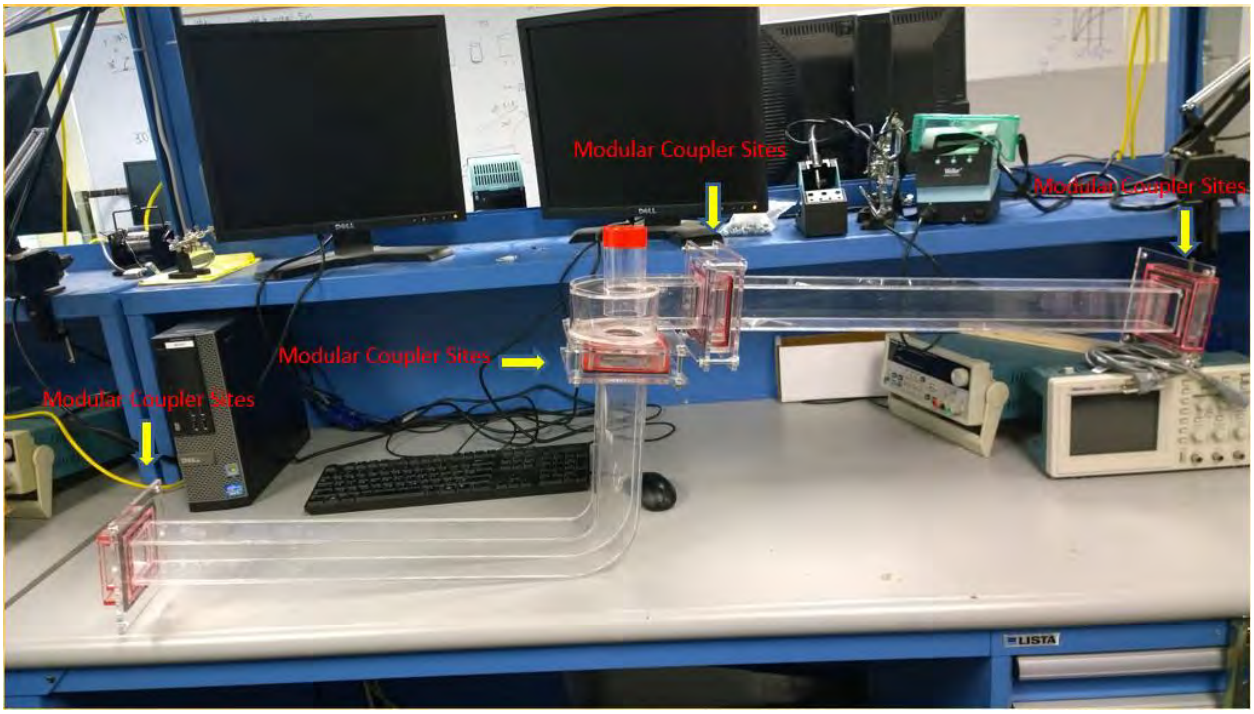


Figure 23. Coupler sites on model

The couplers were made from acrylic which matches the material used for the model, however acrylic cannot withstand high pressure on the face of the material and is subject to fractures and shattering. A proposed strategy is to switch to a material that does not shatter or fracture under the rated conditions, such as a steel or aluminum.

Another proposed solution is to form the entire model from upper reservoir to lower reservoir with no connections. This would be the easiest and quickest solution to leakage within the system. However the drawbacks of this course of action includes decreasing the amount of sensitivity analysis and further testing different parameters as well as limiting the ability of the model as a teaching tool. If modularity is a factor that cannot be sacrificed, then different types of seals can be researched and explored to stop leaks within the model.

Surge tank

For future research, if the model is equipped with the modular ability to add in attachments, this will allow for the installation and testing of surge tanks. The surge tanks at hydro facilities are usually installed between the power house and the upper reservoir to compensate for pressure changes in the system such as low pressure at high load and high pressure at low load. With the setup it is possible to measure the effect surge tanks have on water start up time based on head, location or even number of surge tanks. Figure 24 illustrates a concept drawing of the relative size and placement of the surge tank relative to the current model.

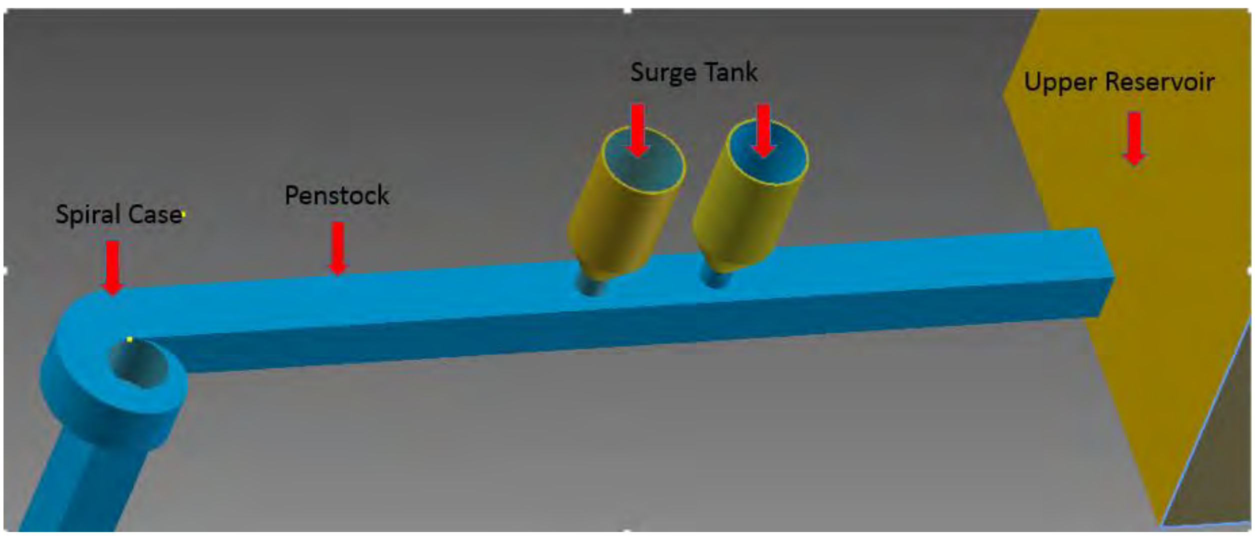


Figure 24. Surge tank model

French Curve Analysis

The French curve analysis is a method that was proposed as the primary method of determining the water start up time by use of French curves. This method was rejected due to the increased rate of bias and lack of repeatability. However, this method does hold merit in that it can produce results closer to that of the actual water start up time because it is a tool used for approximating curves.

Larger Reservoirs

The ideal set up is to have the largest surface area water possible on the upper and lower reservoir. The larger the surface area, the slower the change in height of the forebay and tail water in respect to each other due to the sheer volume of water to height ratio. A changing height, as the test goes on, will have a varied rated flow rate and in retrospect the rated velocity. The drawback would be storage and cost of fabricating the larger reservoirs. It is due to the lack of the range of measurements that a larger reservoir is needed to test. The larger reservoir would allow for a higher flow rate and a larger range of testing heights. The results allude to a hypothesis, that larger heights would yield data that has less variance by extending the test range outside the volatile region.

Increased Trial Count

The suggestion for more results is necessary to decrease the variance in data and separate usable data from the outliers. The increased count would also decrease the standard deviations of the data from each other. Due to time and costs the number of tests were less than originally planned.

IX. References

[1] Pacific Northwest Waterways Association, "The role of hydropower in the Northwest," Pacific Northwest Waterways Association, 14 1 2013. [Online]. Available: http://www.pnwa.net/new/Articles/Hydropower.pdf. [Accessed 15 2 2015].

[2] L. Sheldon, "Calculating Water Start Up Time for Spiral Cases of Hydraulic Turbines," Hydro Review, 1 3 2013. [Online]. Available: http://www.hydroworld.com/articles/hr/print/volume-32/issue-2/articles/calculating-water-startup-time-for-spiral-cases-of-hydraulic-tur.html. [Accessed 2 2 2014].

[3] C. Jaeger, Technische Hydraulik, Germany: Verlag Birkhauser, Basle, 1949, pp. 331-335.

[4] U.S. Department of Interior's Bureau of Reclamation, "Selecting Hydraulic Reaction Turbines," *Engineering Monograph,* vol. 20, 1976.

[5] S. Nakano, K. Tsubouchi, H. Shiraiwa, K. Hayashi and H. Yamada, "Load Rejection Tests and Their Dynamic Simulations With a 150 kW Class Microsteam Turbine," *ASME J.Eng. Gas Turbines Power,* vol. 135, no. 5, 2013.

[6] US Bureau of Reclamation, "Selecting Hydraulic Reaction Turbines," *Engineering Monograph,* no. 20, 1976.

[7] D. Kosterev, "Hydro Turbine-Governor Model Validation in Pacific Northwest," *IEEE Transactions on Power Systems,* vol. 19, no. 2, pp. 1144-1149, 2004.

[8] Tennessee Valley Authority, "Hydro Electric Power," Tennessee Valley Authority, [Online]. Available: http://www.tva.gov/power/hydro.htm. [Accessed 12 2 2015].

Appendix A-Data tables from water start up time trials

The tables in appendix A, shows the variables used to calculate the multiplier value of the length over area and the value of the water start up time recorded from the experimental trials.

Table 1. 10 gate water start up time results

Rated height (inches)	Water start up time(s)	Rated flow rate(in^3/s)	Gravitational constant	L/A penstock and draft tube	L/A spiral case	Multiplier
11.83562992	0.803	64.39051509	385.92	15.744273	7.744029279	5.322467476
11.83562992	0.766	64.39051509	385.92	15.744273	7.744029279	4.983544118
13.80413386	0.712	81.63720231	385.92	15.744273	7.744029279	3.966639547
13.80413386	0.79	81.63720231	385.92	15.744273	7.744029279	4.623912788
15.77263779	0.676	96.60837023	385.92	15.744273	7.744029279	3.466963729
15.77263779	0.685	96.60837023	385.92	15.744273	7.744029279	3.540189236
15.77263779	0.769	96.60837023	385.92	15.744273	7.744029279	4.223627295
17.74114173	0.697	110.0870379	385.92	15.744273	7.744029279	3.564599599
17.74114173	0.679	110.0870379	385.92	15.744273	7.744029279	3.420039584
17.74114173	0.768	110.0870379	385.92	15.744273	7.744029279	4.134808546
19.70964567	0.828	122.4844537	385.92	15.744273	7.744029279	4.606767876
19.70964567	0.565	122.4844537	385.92	15.744273	7.744029279	2.497732349
19.70964567	0.634	122.4844537	385.92	15.744273	7.744029279	3.051053457
19.70964567	0.632	122.4844537	385.92	15.744273	7.744029279	3.035015164
21.6781496	0.39	134.0494158	385.92	15.744273	7.744029279	1.109971099
21.6781496	0.423	134.0494158	385.92	15.744273	7.744029279	1.375922035
21.6781496	0.466	134.0494158	385.92	15.744273	7.744029279	1.722464164
23.64665354	0.422	144.9464597	385.92	15.744273	7.744029279	1.397789042
23.64665354	0.422	144.9464597	385.92	15.744273	7.744029279	1.397789042

Table 2. 15 Gate water start up time results

Rated height (inches)	Water start up time(s)	Rated flow rate(in^3/s)	Gravitational constant	L/A penstock and draft tube	L/A spiral case	Multiplier
11.8356299	0.318	77.209834	385.92	15.744273	7.744029	0.39618675
11.8356299	0.224	77.209834	385.92	15.744273	7.744029	0.32189998
11.8356299	0.294	77.209834	385.92	15.744273	7.744029	0.21284545
13.8041338	0.712	96.237205	385.92	15.744273	7.744029	3.05643021
13.8041338	0.884	96.237205	385.92	15.744273	7.744029	4.28591994
13.8041338	0.494	96.237205	385.92	15.744273	7.744029	1.49812346
15.7726377	0.751	112.51805	385.92	15.744273	7.744029	3.21320524
15.7726377	0.802	112.51805	385.92	15.744273	7.744029	3.5694779
15.7726377	0.77	112.51805	385.92	15.744273	7.744029	3.34593430
15.7726377	0.879	112.51805	385.92	15.744273	7.744029	4.10737995
17.7411417	0.679	127.02038	385.92	15.744273	7.744029	2.69307230
17.7411417	0.781	127.02038	385.92	15.744273	7.744029	3.40304003
17.7411417	0.81	127.02038	385.92	15.744273	7.744029	3.60489360
17.7411417	0.795	127.02038	385.92	15.744273	7.744029	3.50048658
19.7096456	0.689	140.24668	385.92	15.744273	7.744029	2.79234145
19.7096456	1.249	140.24668	385.92	15.744273	7.744029	6.71431395
19.7096456	0.907	140.24668	385.92	15.744273	7.744029	4.3191093
19.7096456	0.517	140.24668	385.92	15.744273	7.744029	1.5877356
21.6781496	0.362	152.49822	385.92	15.744273	7.744029	0.5313767
21.6781496	0.175	152.49822	385.92	15.744273	7.744029	-0.7933592
21.6781496	0.446	152.49822	385.92	15.744273	7.744029	1.1264452
23.646653	0.271	163.97280	385.92	15.744273	7.744029	-0.0854957
23.646653	0.245	163.97280	385.92	15.744273	7.744029	-0.2723493
23.646653	0.246	163.97280	385.92	15.74427	7.744029	-0.2651626

Table 3. 20 Gate water start up time results

Rated height (inches)	Water start up time(s)	Rated flow rate(in^3/s)	Gravitational constant	L/A penstock and draft tube	L/A spiral case	Multiplier
11.83563	0.097	84.3101	385.92	15.74427	7.744029	-1.35449
11.83563	0.23	84.3101	385.92	15.74427	7.744029	-0.42403
11.83563	0.295	84.3101	385.92	15.74427	7.744029	0.030698
11.83563	0.649	95.93249	385.92	15.74427	7.744029	1.957169
11.83563	0.43	95.93249	385.92	15.74427	7.744029	0.610689
11.83563	0.665	95.93249	385.92	15.74427	7.744029	2.055542
11.83563	0.641	95.93249	385.92	15.74427	7.744029	1.907983
11.83563	1.056	95.93249	385.92	15.74427	7.744029	4.459533
11.83563	0.576	95.93249	385.92	15.74427	7.744029	1.508343
11.83563	0.686	95.93249	385.92	15.74427	7.744029	2.184657
11.83563	0.834	95.93249	385.92	15.74427	7.744029	3.094607
11.83563	0.971	95.93249	385.92	15.74427	7.744029	3.936926
13.80413	0.674	105.6383	385.92	15.74427	7.744029	2.35604
13.80413	0.721	105.6383	385.92	15.74427	7.744029	2.662106
13.80413	0.86	105.6383	385.92	15.74427	7.744029	3.567282
13.80413	0.432	112.6825	385.92	15.74427	7.744029	0.604259
13.80413	0.542	112.6825	385.92	15.74427	7.744029	1.275805
13.80413	0.695	112.6825	385.92	15.74427	7.744029	2.209865
15.77264	0.887	123.9688	385.92	15.74427	7.744029	3.590922
15.77264	0.587	123.9688	385.92	15.74427	7.744029	1.688777
15.77264	0.926	123.9688	385.92	15.74427	7.744029	3.8382
15.77264	0.982	123.9688	385.92	15.74427	7.744029	4.193267
15.77264	0.579	126.312	385.92	15.74427	7.744029	1.569951
15.77264	0.626	126.312	385.92	15.74427	7.744029	1.862425
15.77264	0.524	126.312	385.92	15.74427	7.744029	1.227694
15.77264	0.683	126.312	385.92	15.74427	7.744029	2.217129
17.74114	0.893	140.3505	385.92	15.74427	7.744029	3.592262
17.74114	0.821	140.3505	385.92	15.74427	7.744029	3.138707
17.74114	0.769	140.3505	385.92	15.74427	7.744029	2.811139
17.74114	0.602	138.0092	385.92	15.74427	7.744029	1.823476
17.74114	0.764	138.0092	385.92	15.74427	7.744029	2.861288
17.74114	0.604	138.0092	385.92	15.74427	7.744029	1.836288
17.74114	0.789	138.0092	385.92	15.74427	7.744029	3.021444
17.74114	0.279	138.0092	385.92	15.74427	7.744029	-0.24574
19.70965	0.927	155.3297	385.92	15.74427	7.744029	3.82876

Table 4. 20 Gate water start up time results-continued

Rated Height (inches)	Water start up time(s)	Rated flow rate(in^3/s)	Gravitational constant	L/A penstock and draft tube	L/A spiral case	Multiplier
19.70965	0.822	155.3297	385.92	15.74427	7.744029	3.164797
19.70965	0.96	155.3297	385.92	15.74427	7.744029	4.037434
19.70965	0.912	148.3663	385.92	15.74427	7.744029	4.004577
19.70965	0.326	148.3663	385.92	15.74427	7.744029	0.125114
19.70965	0.187	148.3663	385.92	15.74427	7.744029	-0.7951
19.70965	0.421	148.3663	385.92	15.74427	7.744029	0.754037
19.70965	0.252	148.3663	385.92	15.74427	7.744029	-0.36478
19.70965	0.828	148.3663	385.92	15.74427	7.744029	3.448476
21.67815	0.296	169.235	385.92	15.74427	7.744029	-0.14355
21.67815	0.234	169.235	385.92	15.74427	7.744029	-0.53933
21.67815	0.113	169.235	385.92	15.74427	7.744029	-1.31174
21.67815	0.132	169.235	385.92	15.74427	7.744029	-1.19046
21.67815	0.0909	157.7271	385.92	15.74427	7.744029	-1.41048
21.67815	0.226	157.7271	385.92	15.74427	7.744029	-0.48514
21.67815	0.243	157.7271	385.92	15.74427	7.744029	-0.36871
21.67815	0.331	157.7271	385.92	15.74427	7.744029	0.234033
21.67815	0.201	157.7271	385.92	15.74427	7.744029	-0.65638
21.67815	0.287	157.7271	385.92	15.74427	7.744029	-0.06734
23.64665	0.239	182.2827	385.92	15.74427	7.744029	-0.488
23.64665	0.098	182.2827	385.92	15.74427	7.744029	-1.39954
23.64665	0.249	182.2827	385.92	15.74427	7.744029	-0.42335
23.64665	0.158	166.3119	385.92	15.74427	7.744029	-0.91356
23.64665	0.406	166.3119	385.92	15.74427	7.744029	0.843668
23.64665	0.198	166.3119	385.92	15.74427	7.744029	-0.63014
23.64665	0.27	166.3119	385.92	15.74427	7.744029	-0.11997

Appendix B-10 gate water start up time graphs

The graphs in appendix B are the 10 gate water start up time results from each trial. The "H" denotes the reference height which is in centimeters. To obtain the forebay to tail water height, add 20.06 centimeters the reference height. In the graphs if there is a missing number in the sequence it means that the data produced an error and was left out of the analysis.

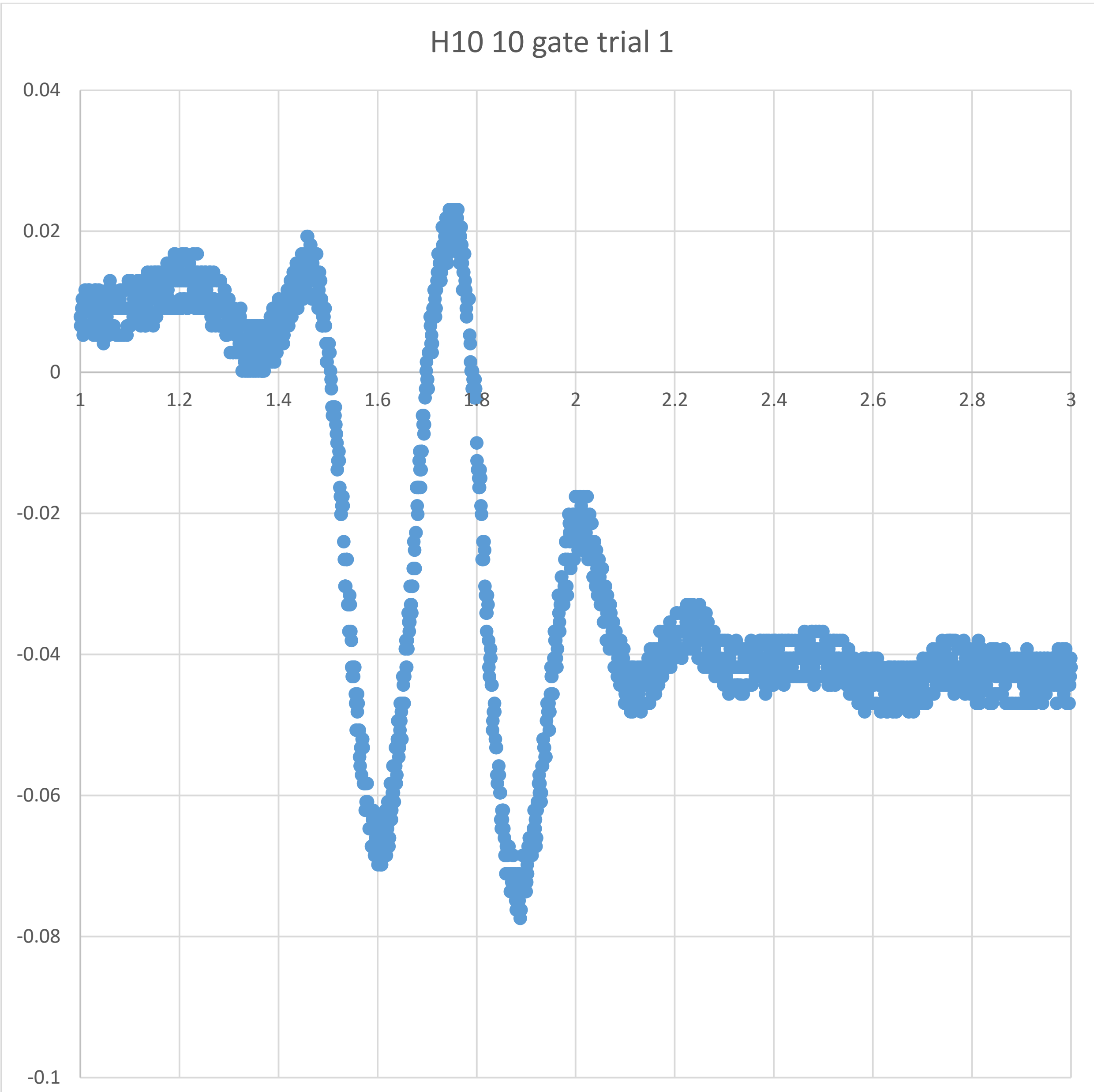


Figure 1. H10 10 Gate trial 1

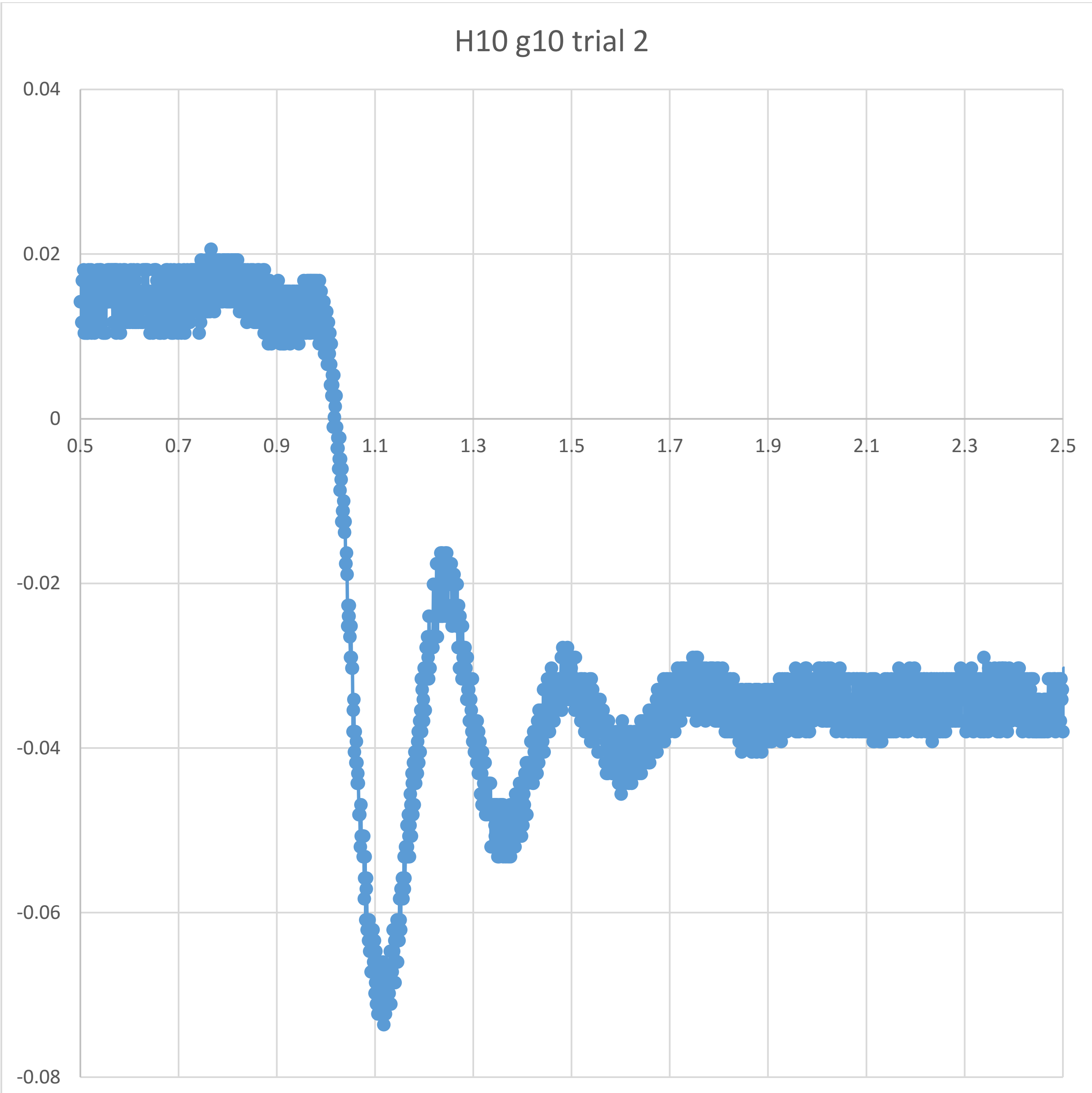


Figure 2. H10 g10 trial 2

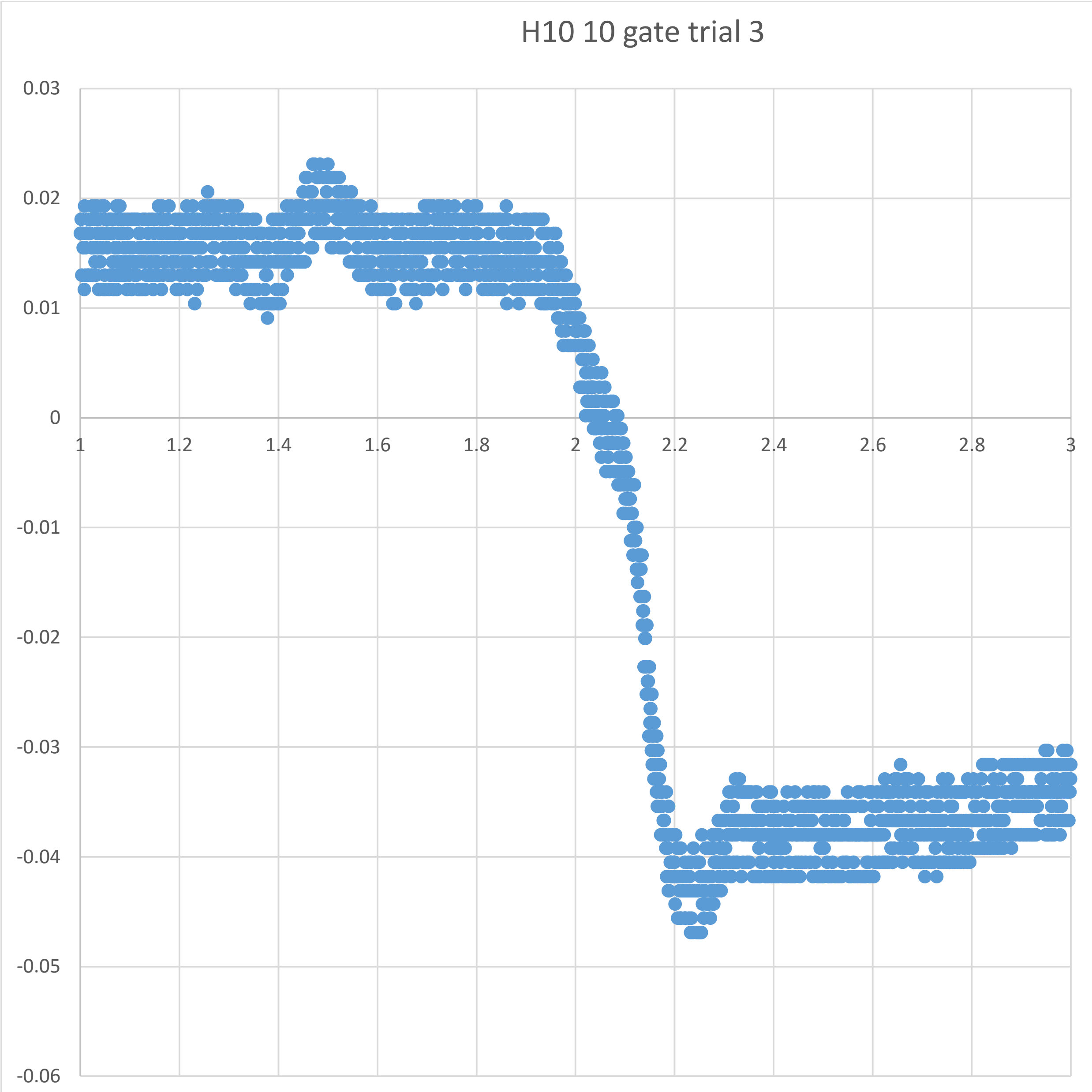


Figure 3. H10 10 gate trial 3

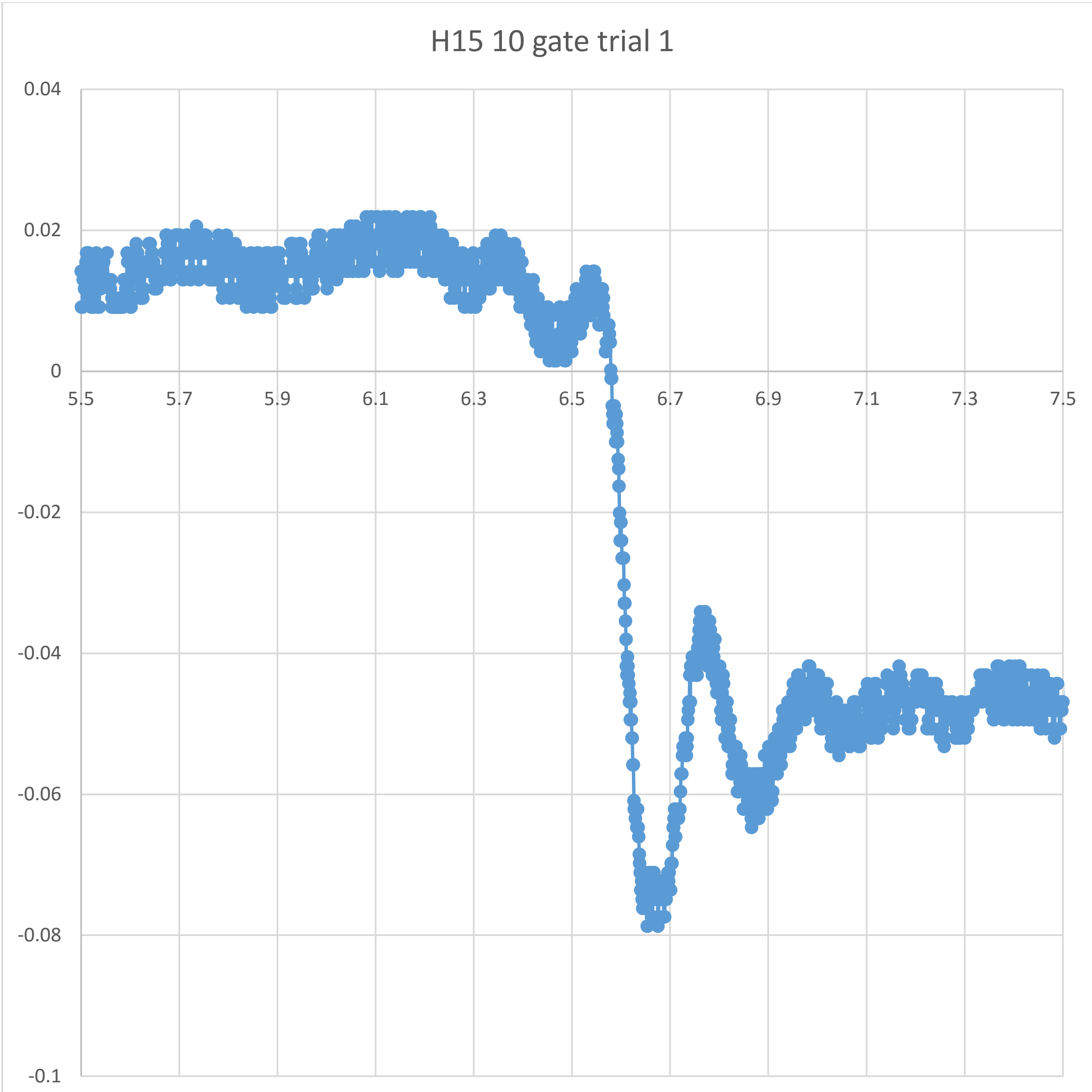


Figure 4. H15 10 gate trial 1

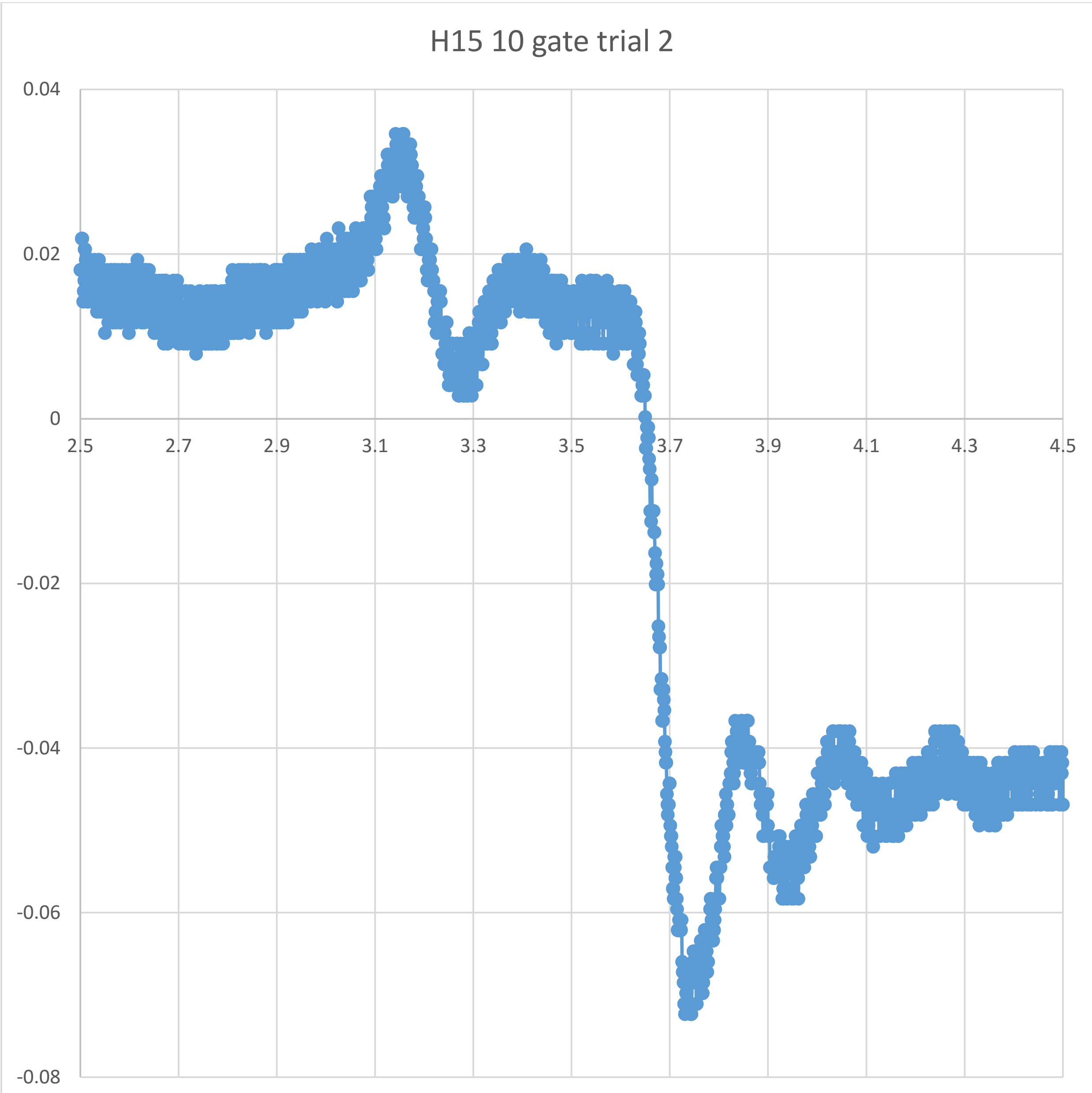


Figure 5. H15 10 gate trial 2

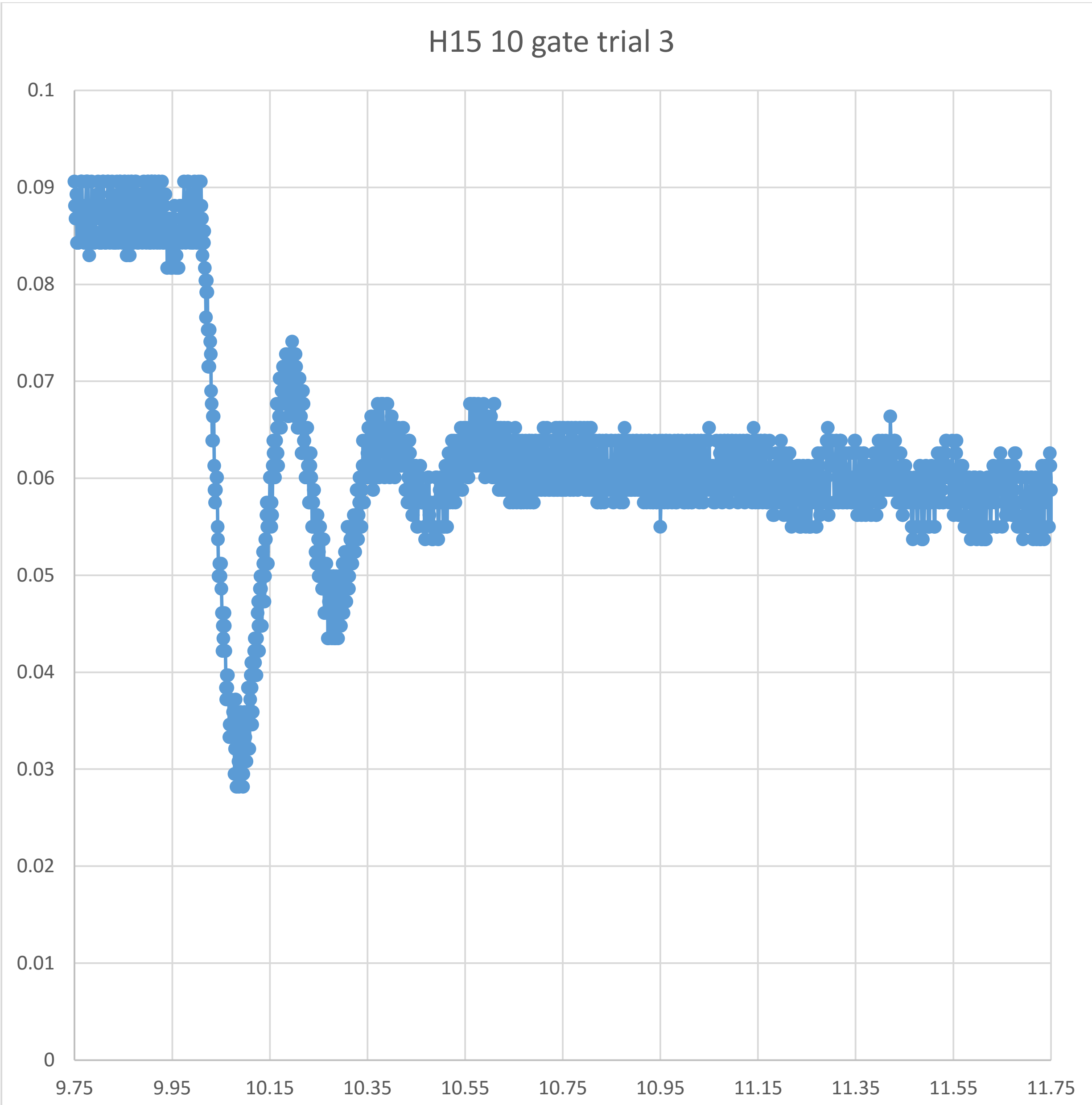


Figure 6. H15 10 gate trial 3

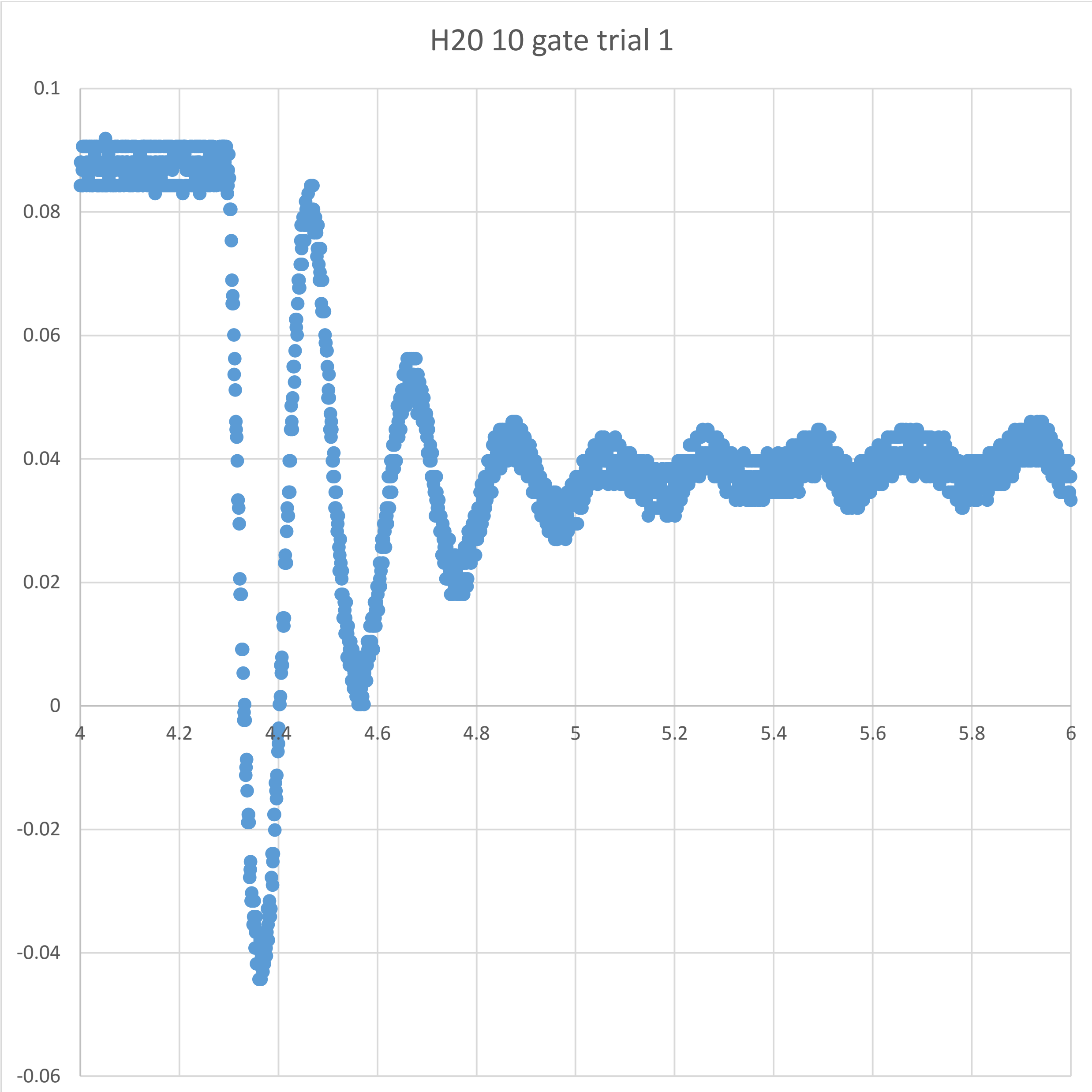


Figure 7. H20 10 gate trial 1

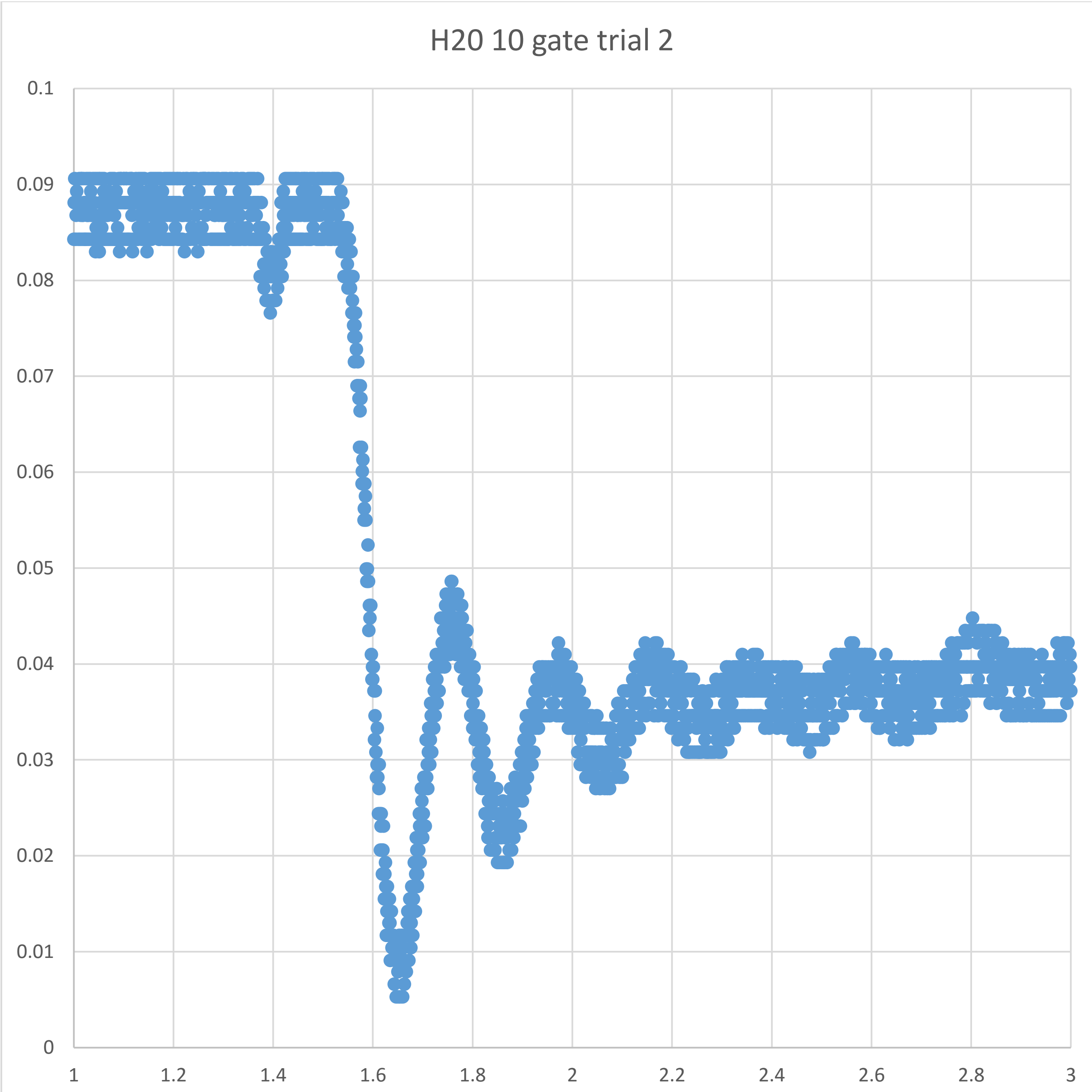


Figure 8. H20 10 gate trial 2

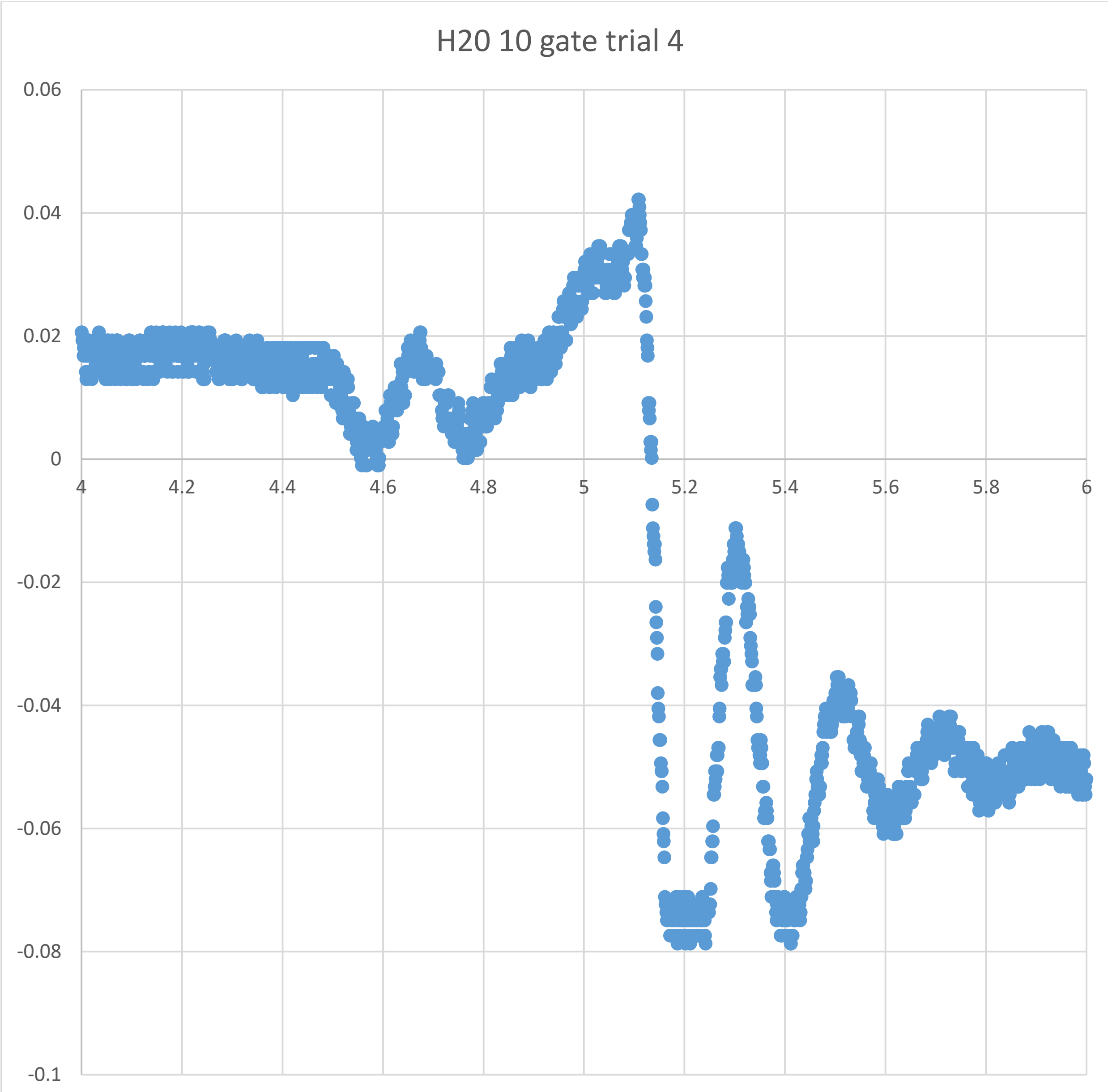


Figure 9. H20 10 gate trial 4

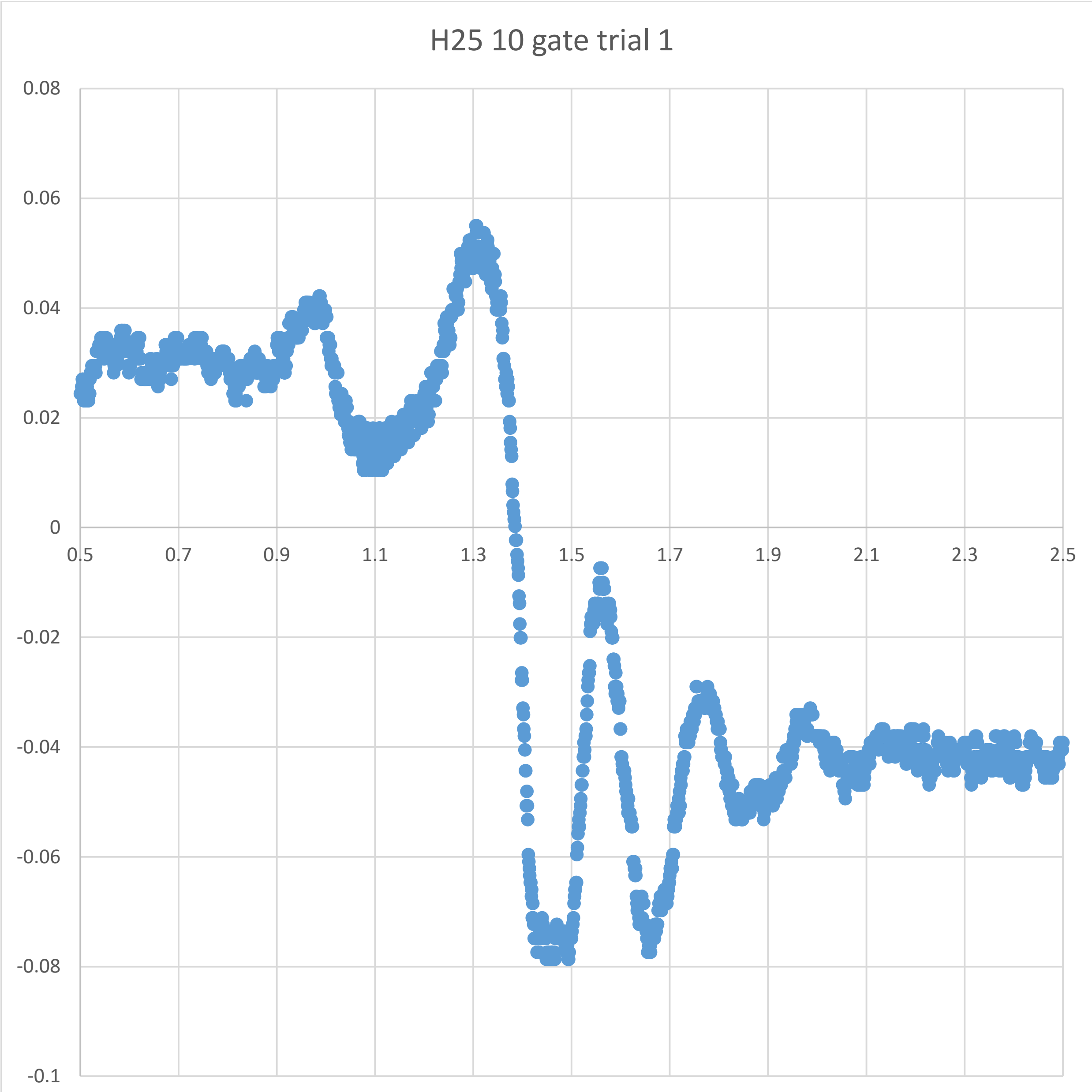


Figure 10. H25 10 gate trial 1

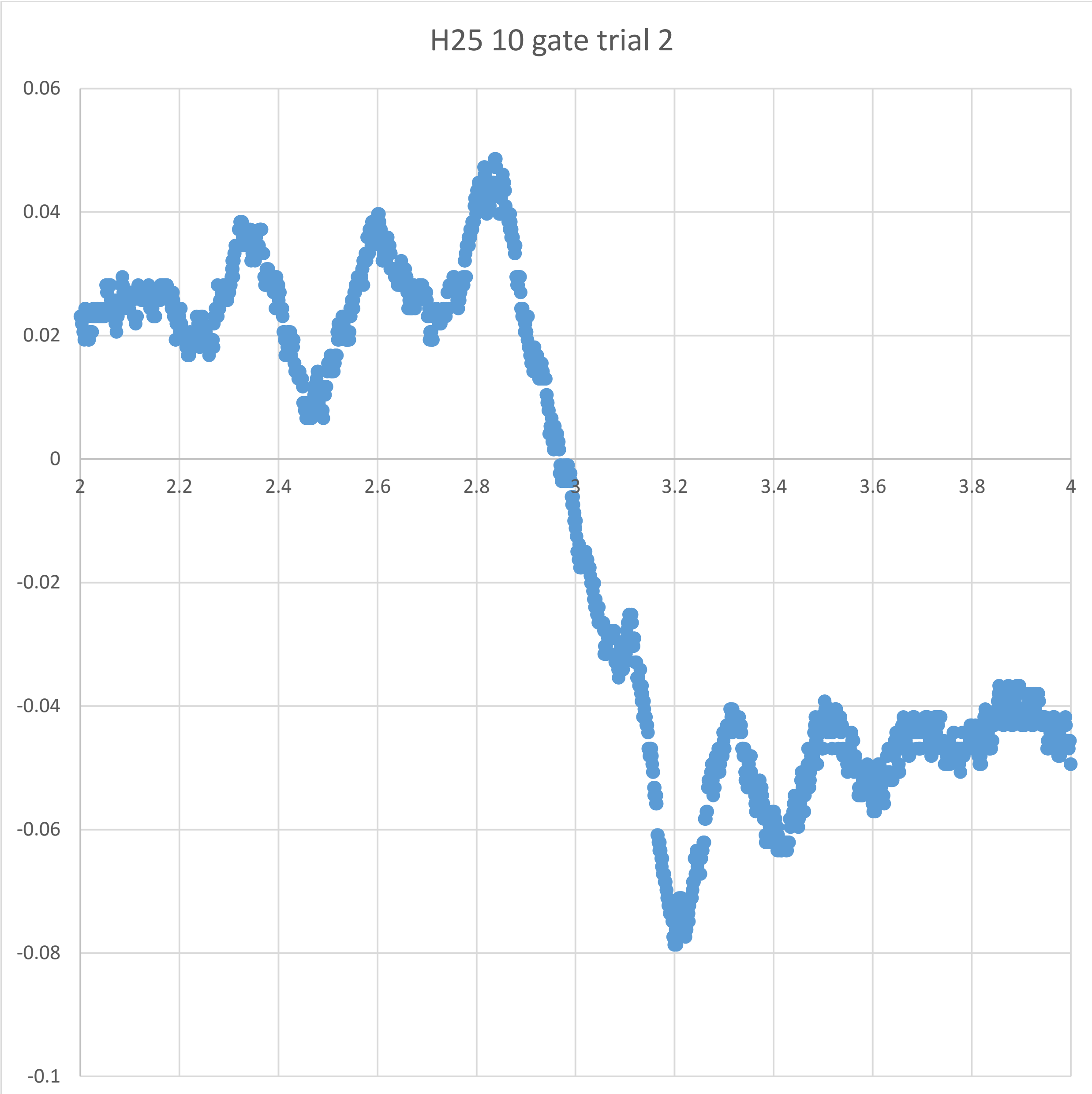


Figure 11. H25 10 gate trial 2

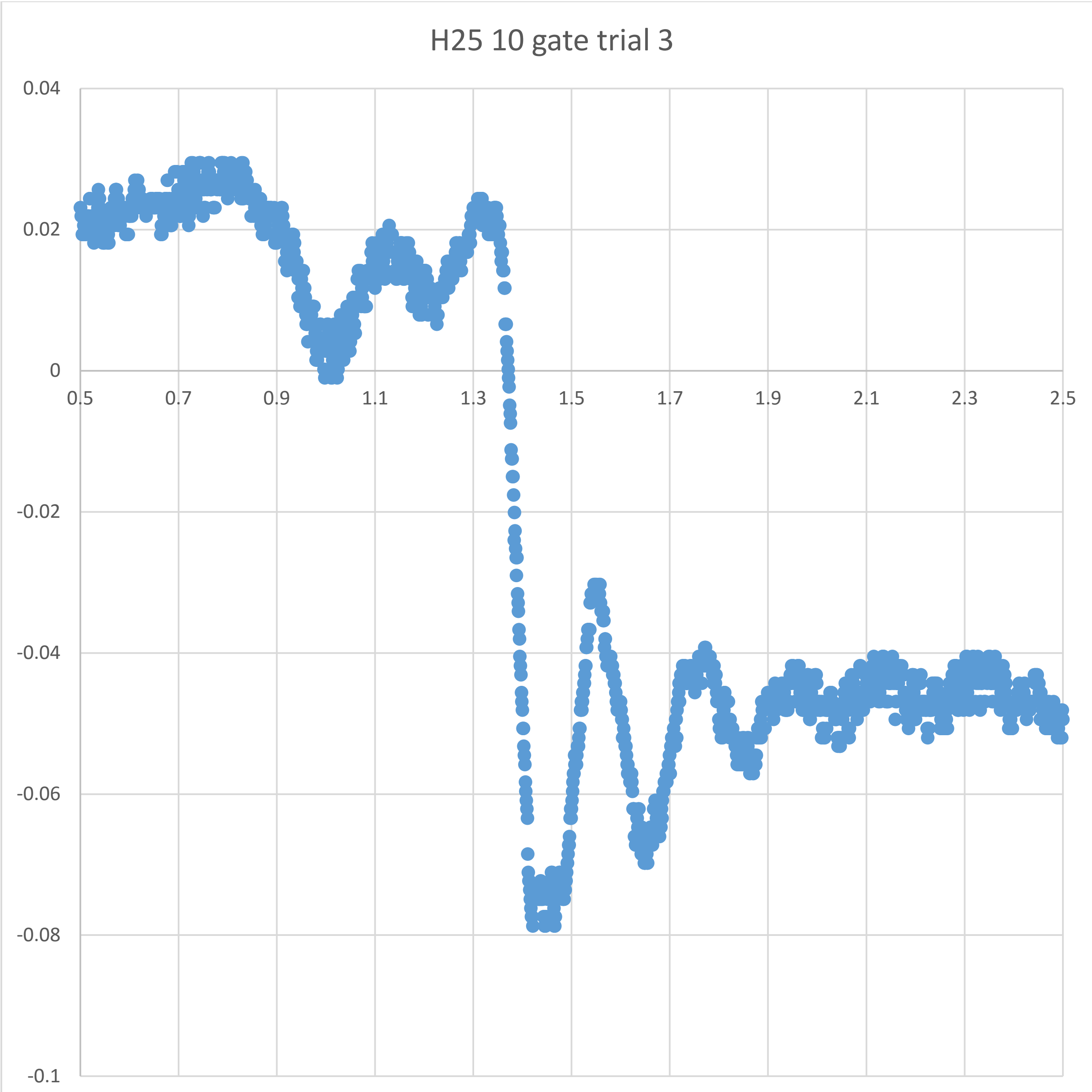


Figure 12. H25 10 gate trial 3

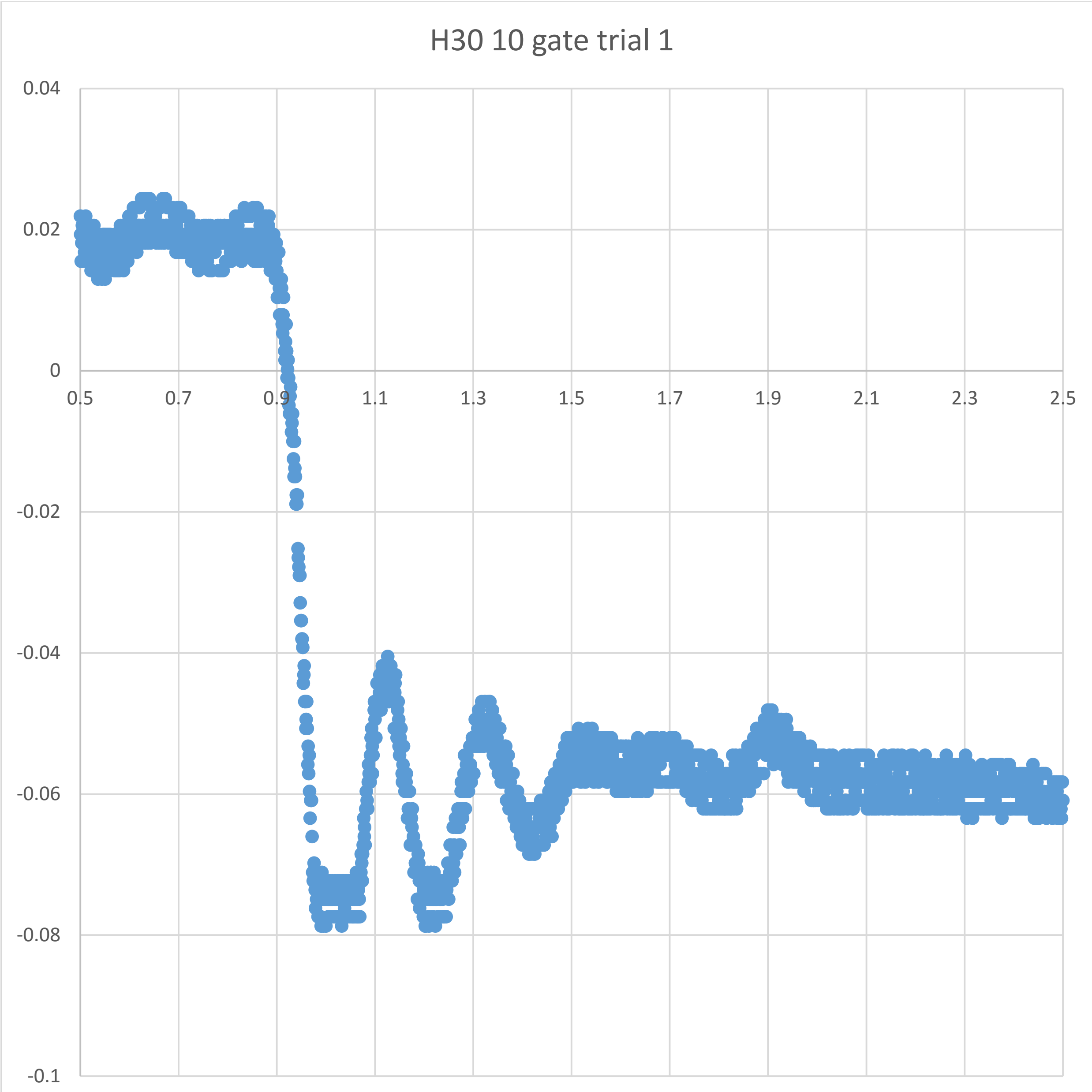


Figure 13. H30 10 gate trial 1

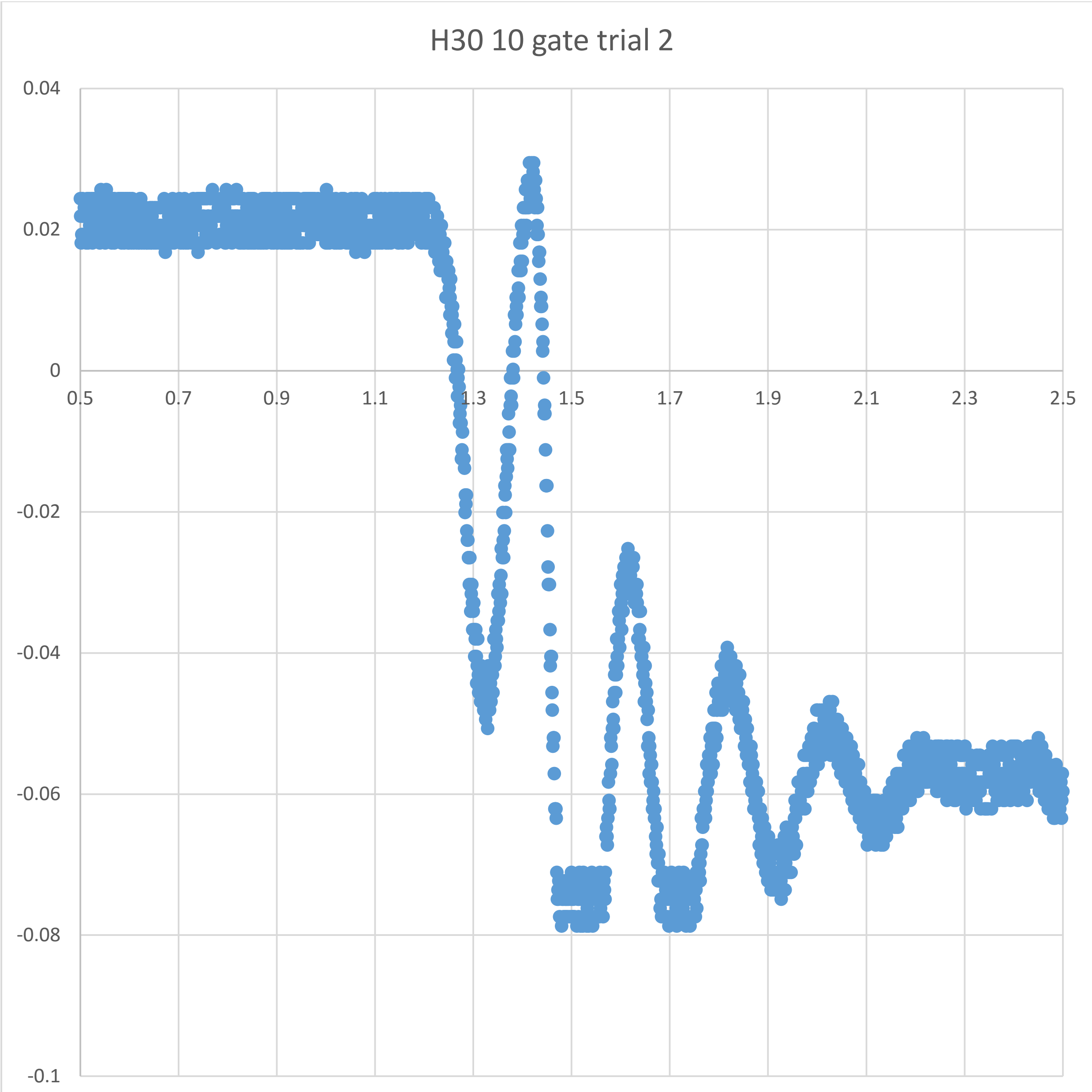


Figure 14. H30 10 gate trial 2

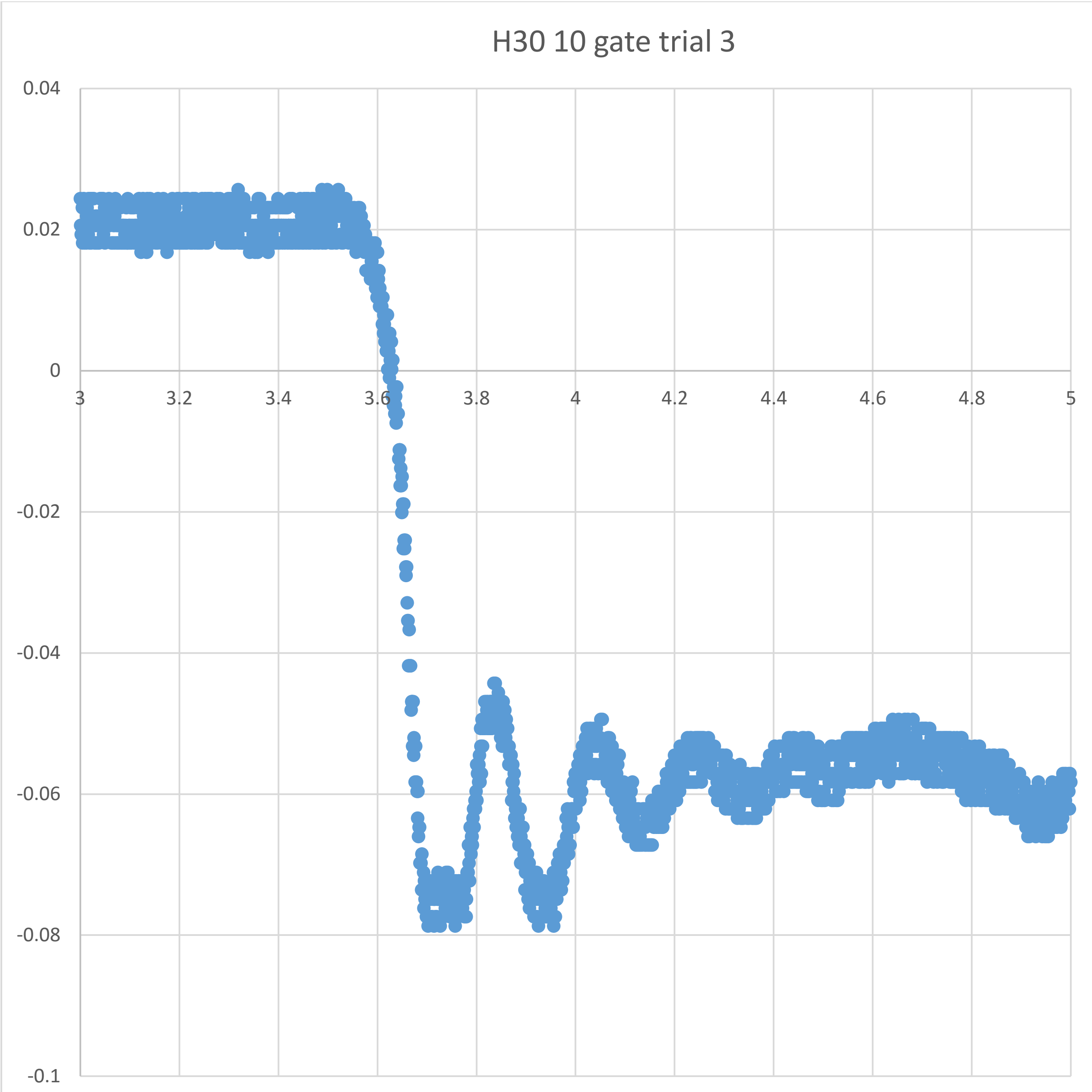


Figure 15. H30 10 gate trial 3

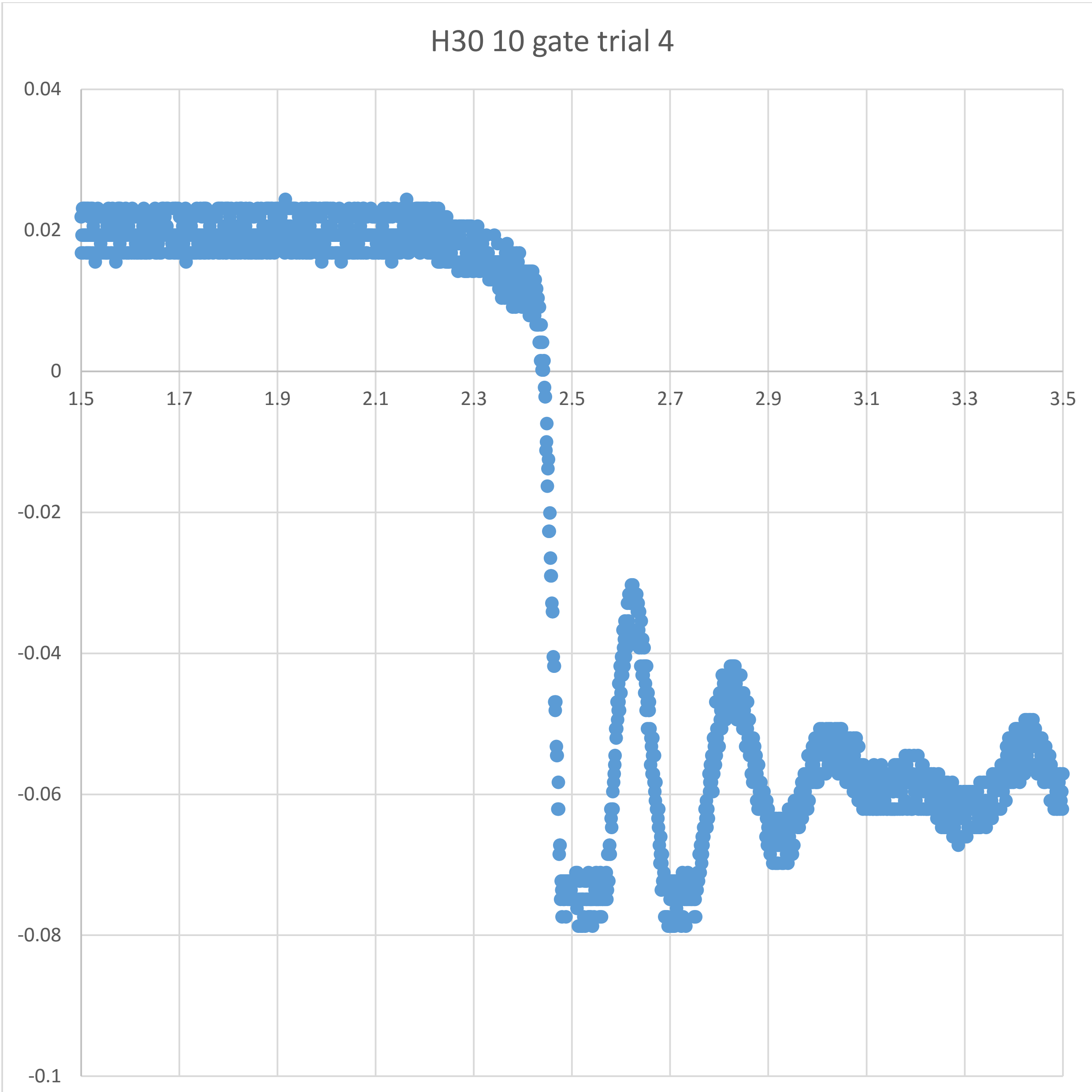


Figure 16. H30 10 gate trial 4

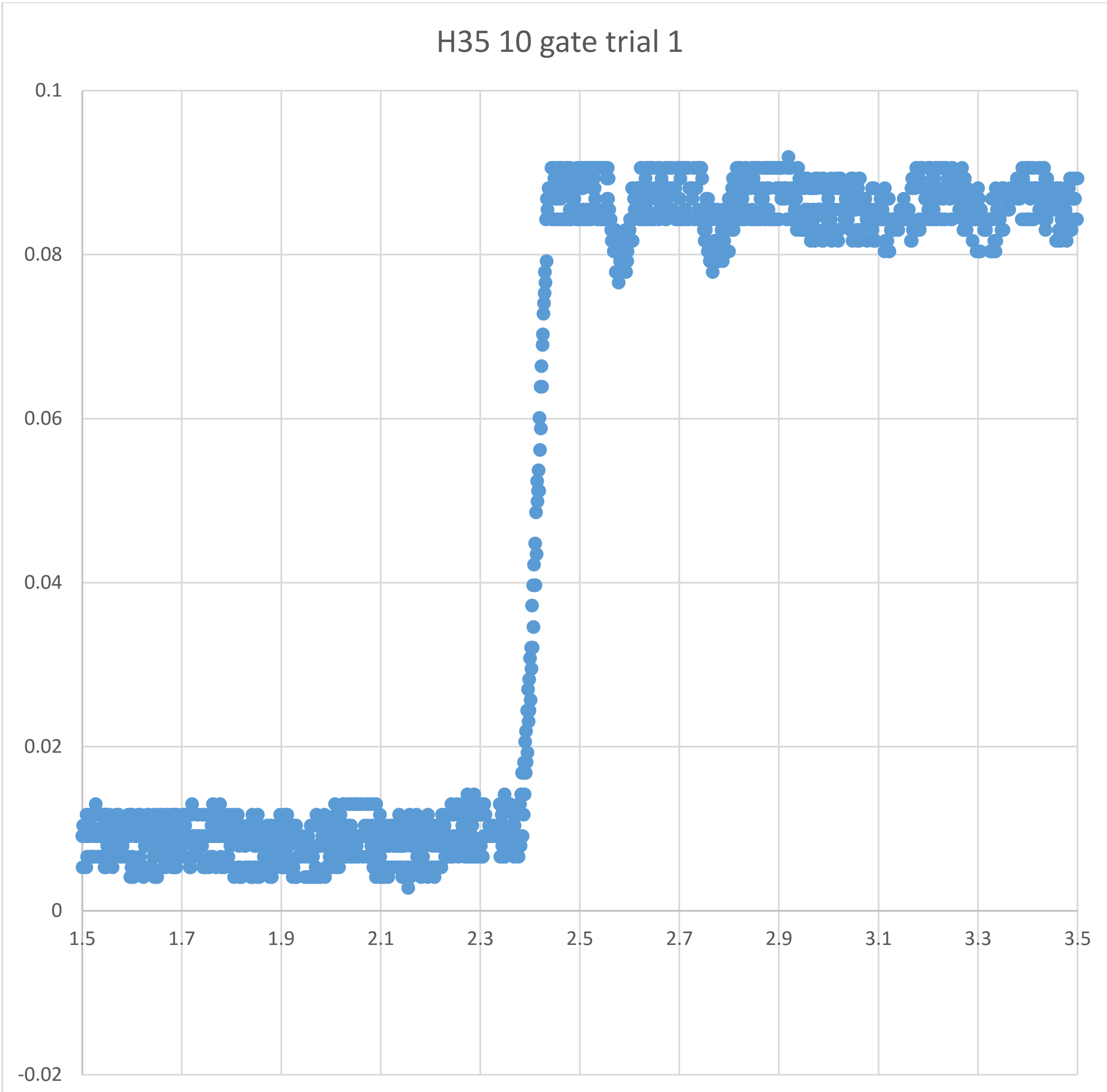


Figure 17. H35 10 gate trial 1

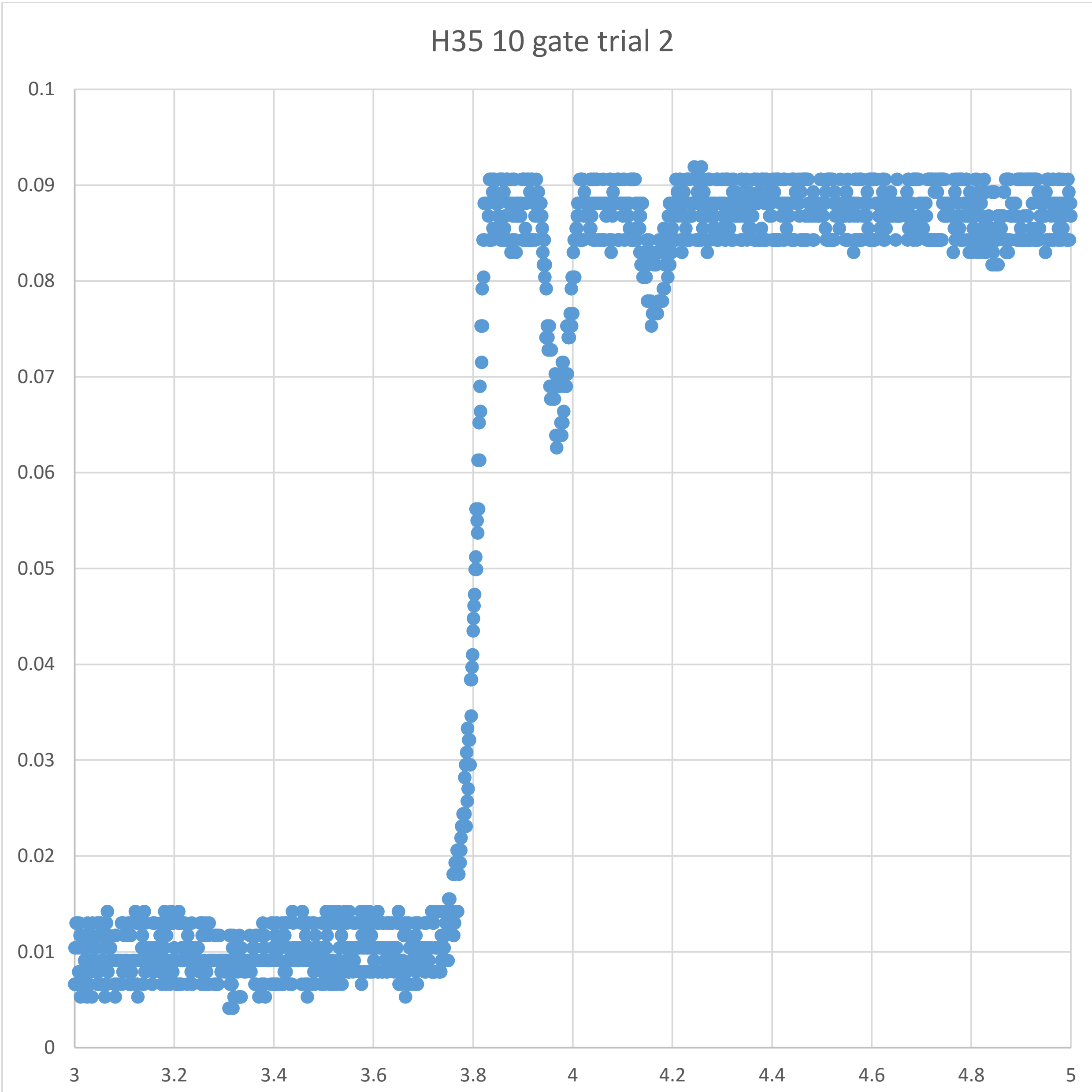


Figure 17. H35 gate trial 2

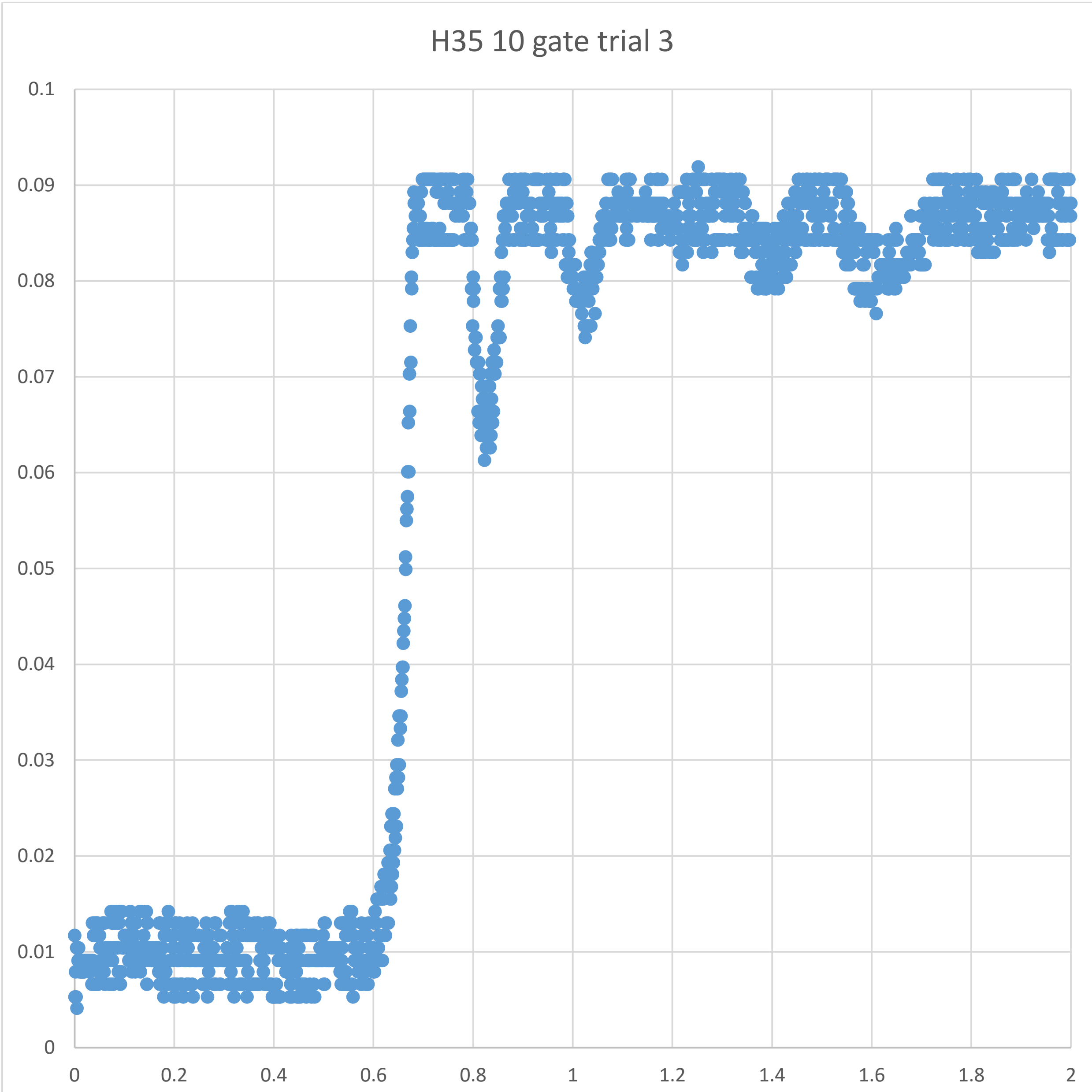


Figure 18. H35 10 gate trial 3

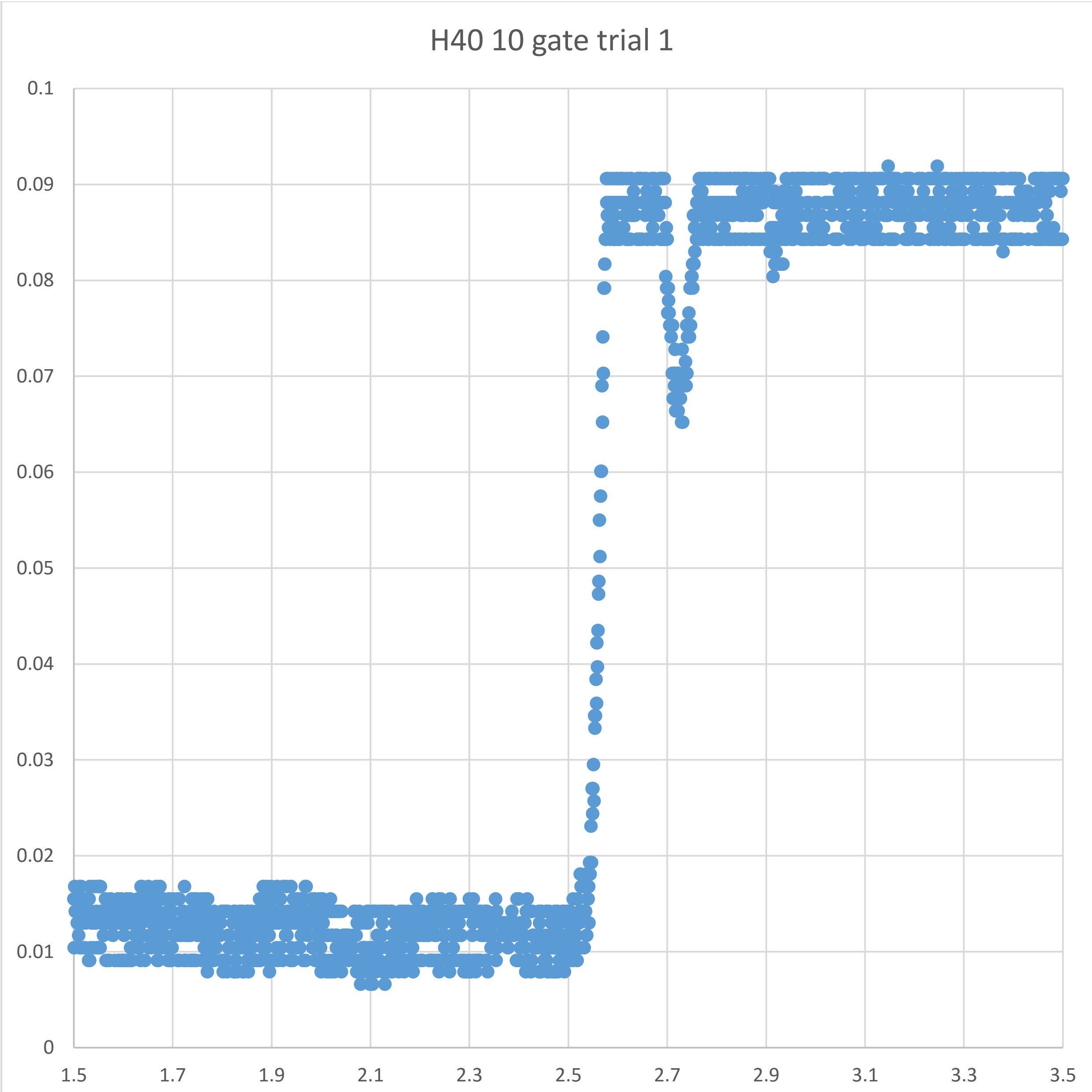


Figure 19. H40 10 gate trial 1

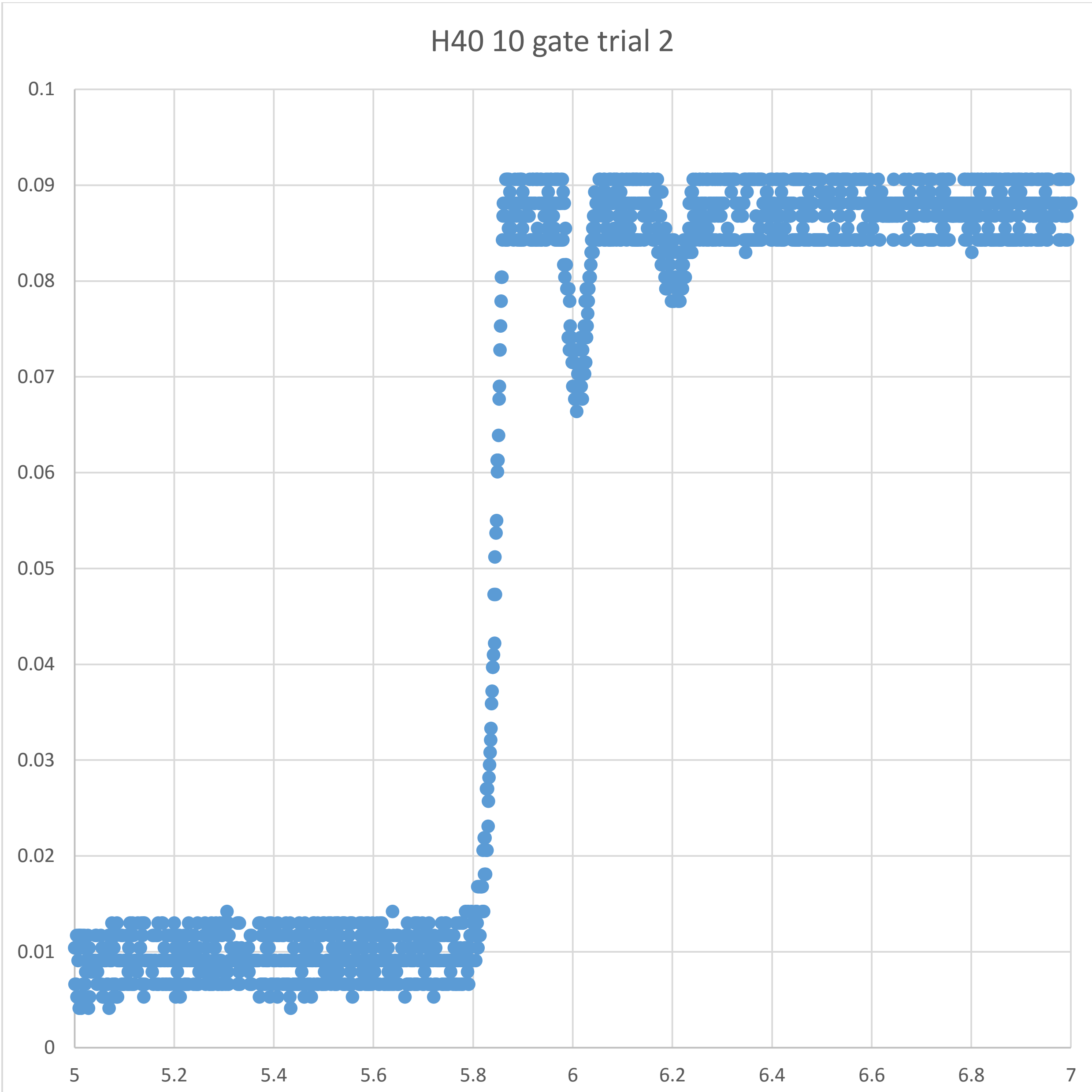


Figure 20. H40 10 gate trial 2

Appendix C-15 gate water start up time graphs

The graphs in appendix C are the 15 gate water start up time results from each trial. The “H” denotes the reference height which is in centimeters. To obtain the forebay to tail water height, add 20.06 centimeters the reference height. In the graphs if there is a missing number in the sequence it means that the data produced an error and was left out of the analysis.

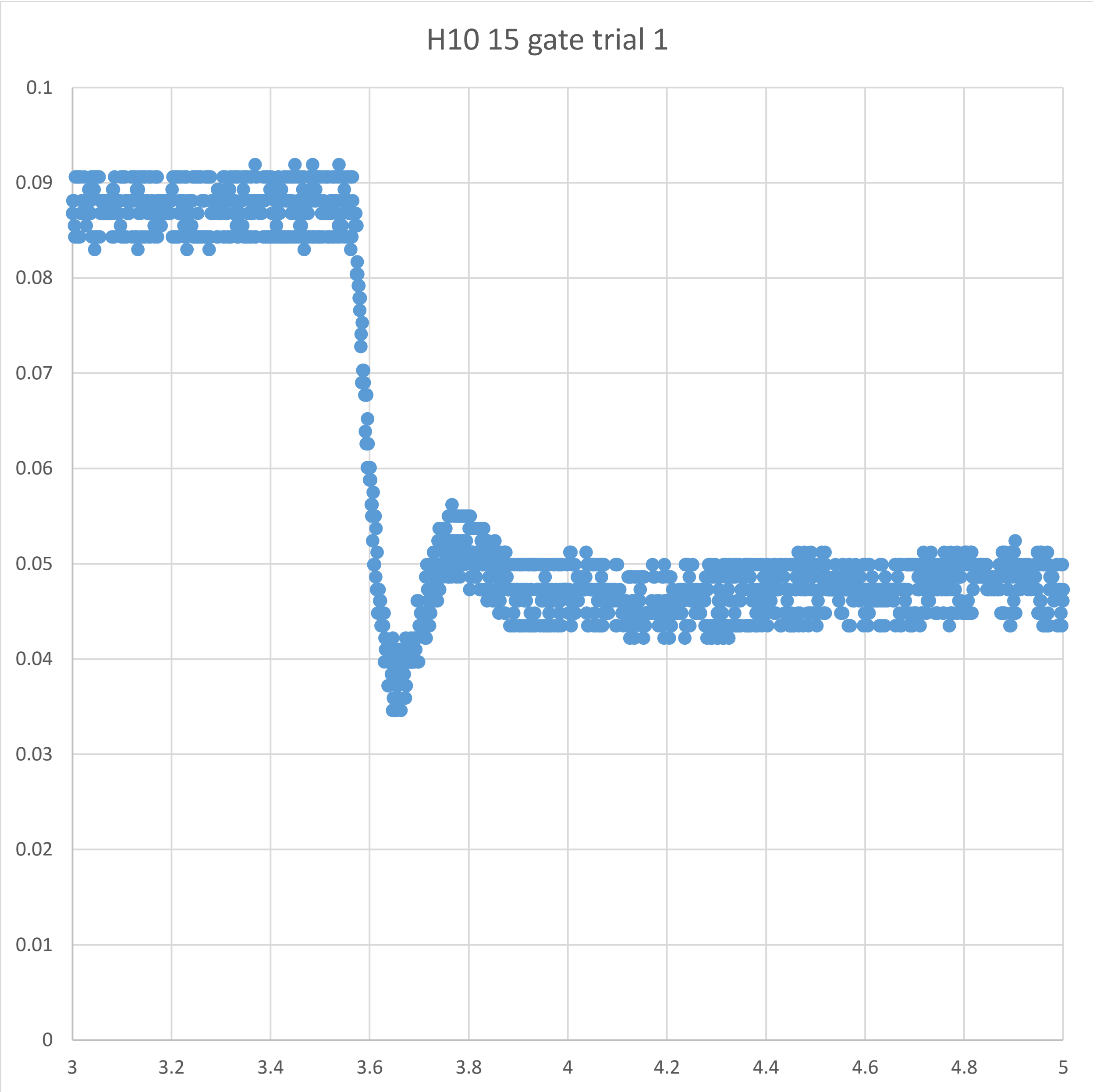


Figure 1. H10 15 gate trial 1

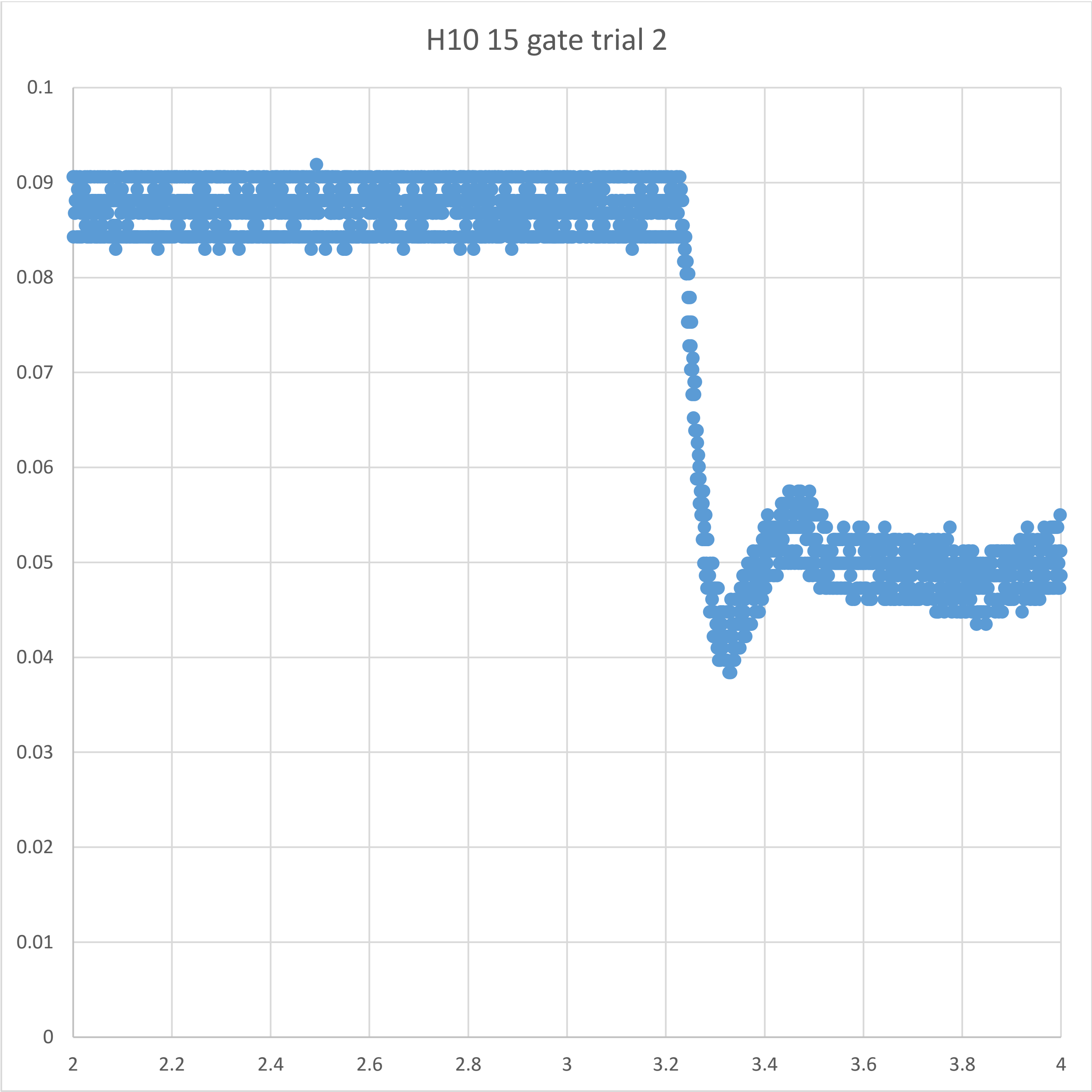


Figure 2. H10 15 gate trial 2

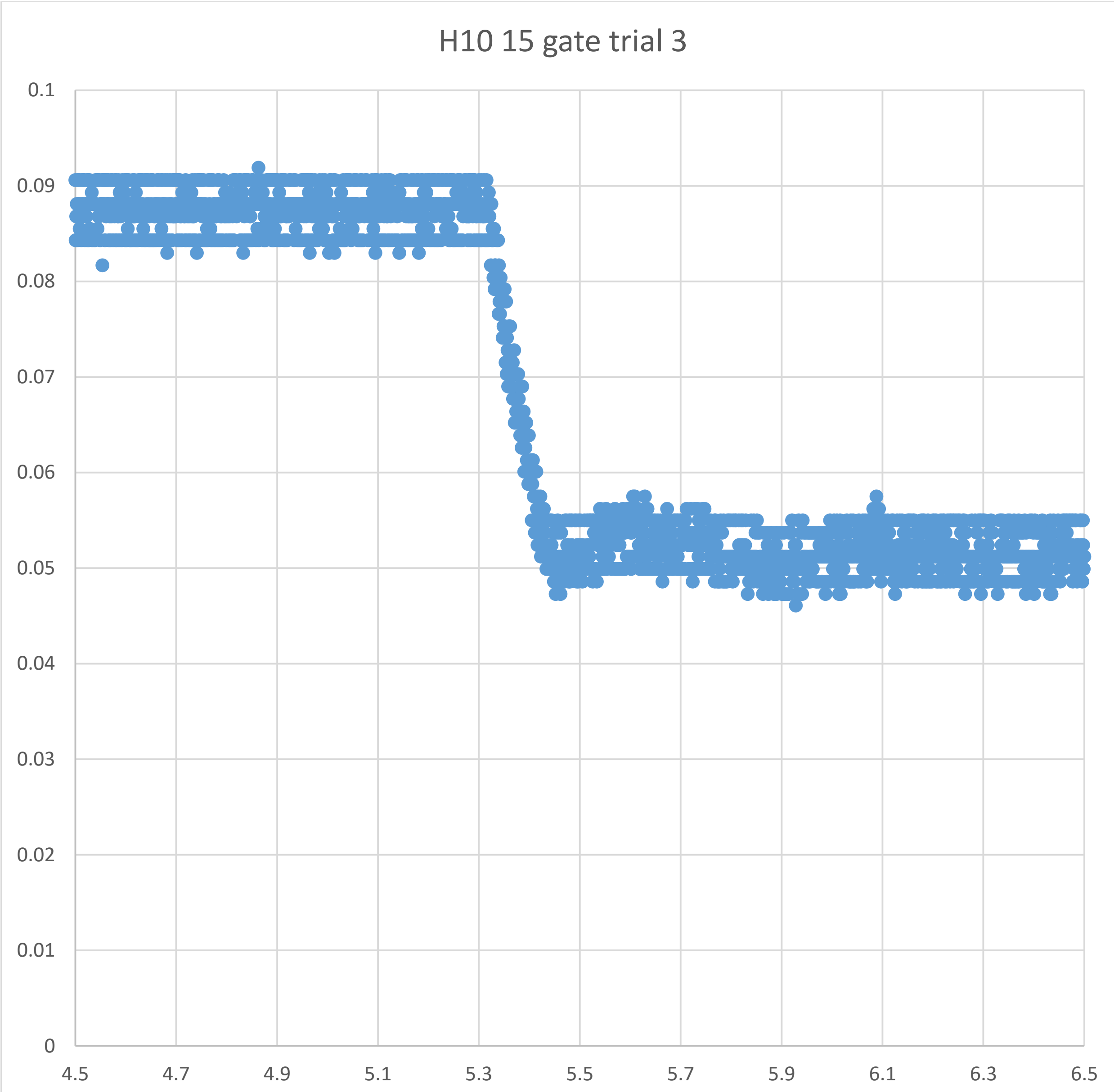


Figure 3. H10 15 gate trial 3

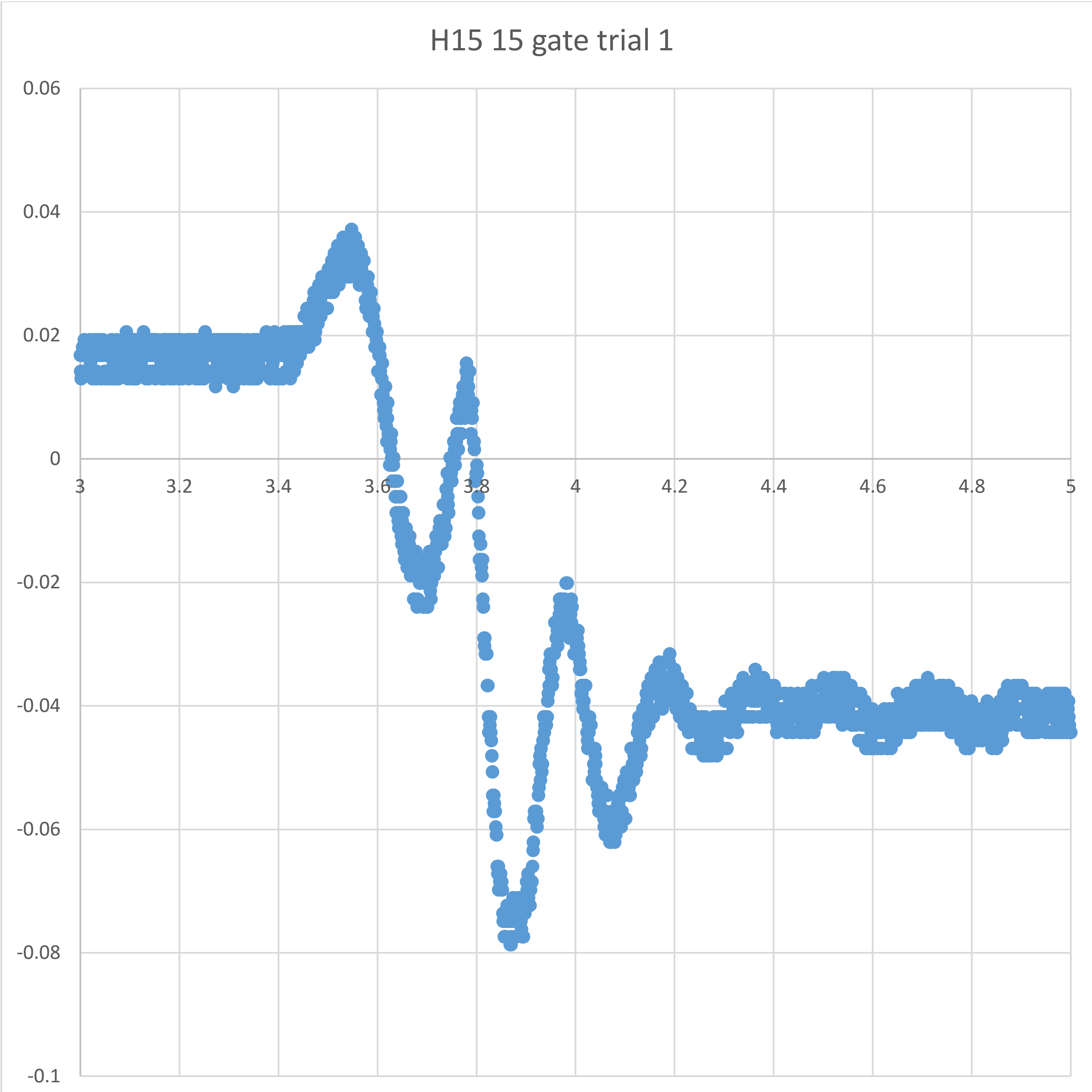


Figure 4. H15 15 gate trial 1

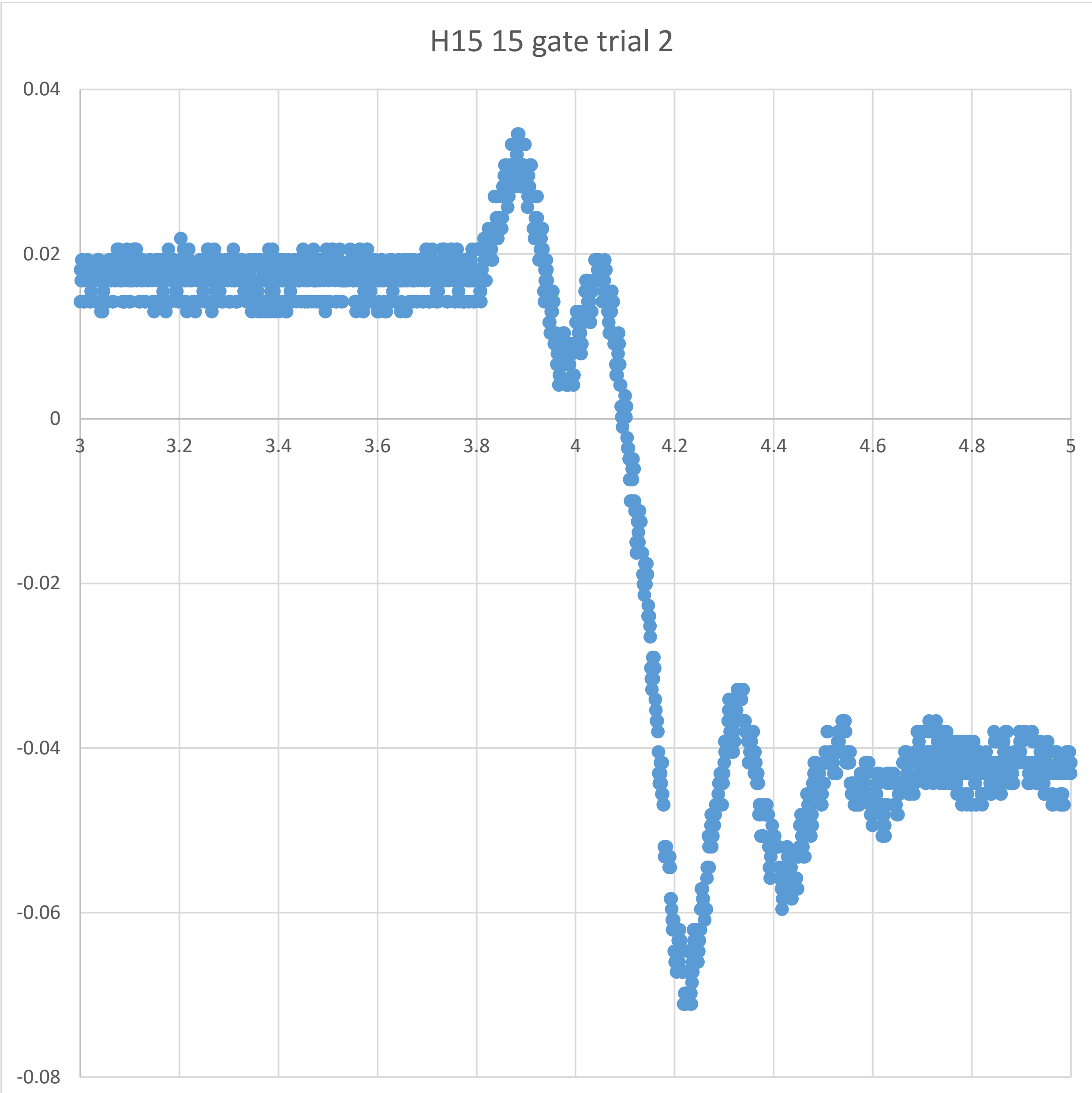


Figure 5. H15 15 gate trial 2

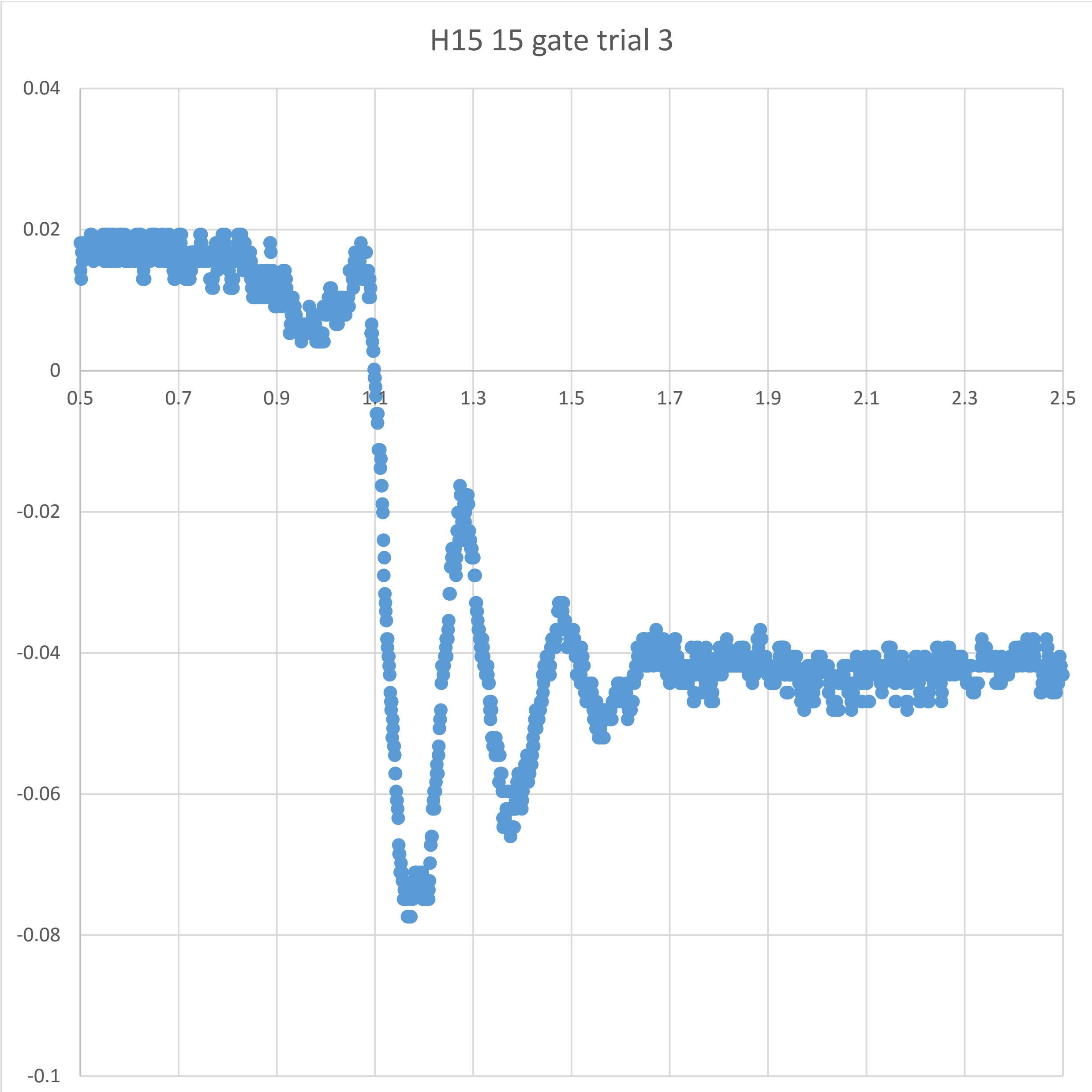


Figure 6. H15 15 gate trial 3

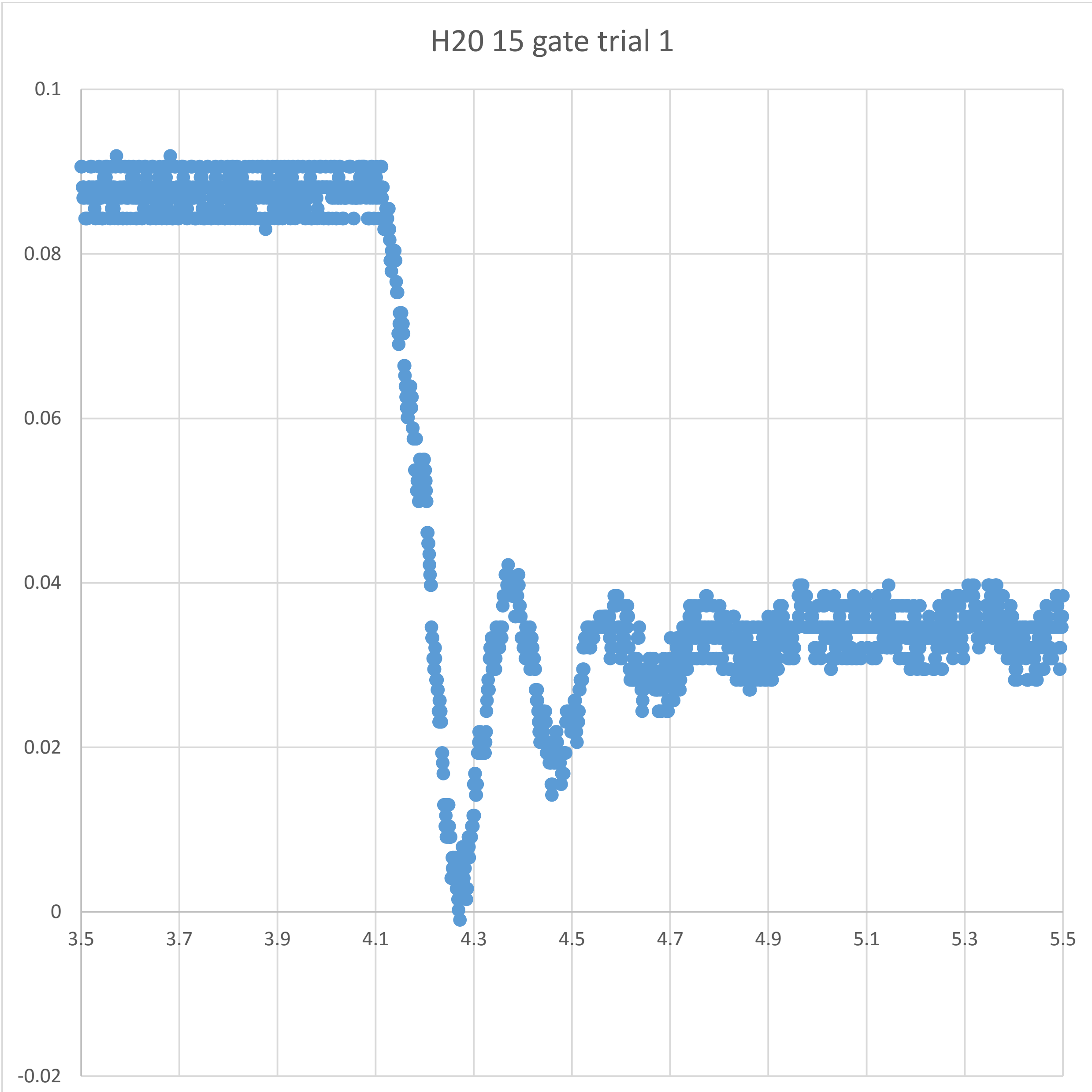


Figure 7. H20 15 gate trial 1

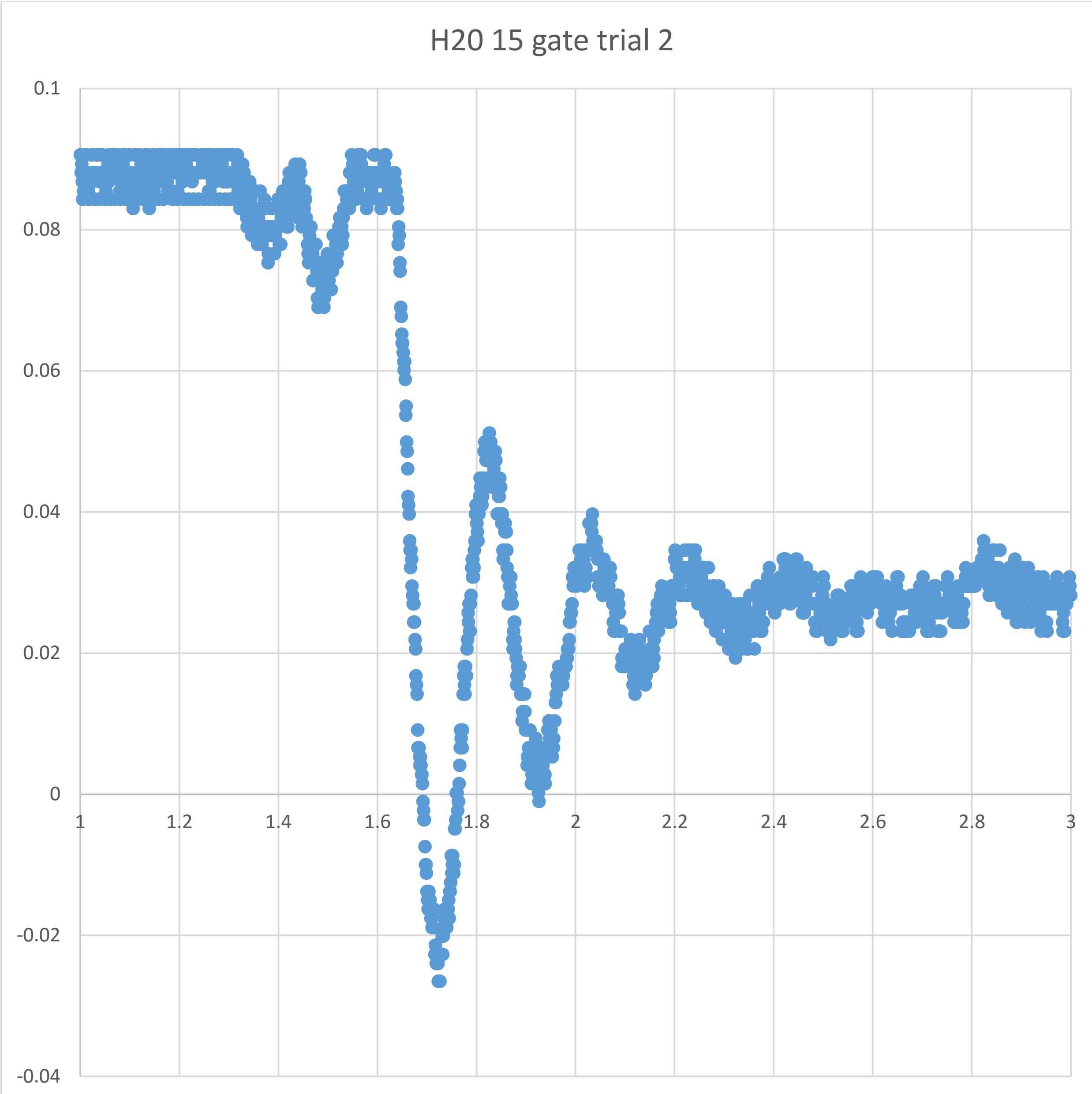


Figure 8. H20 15 gate trial 2

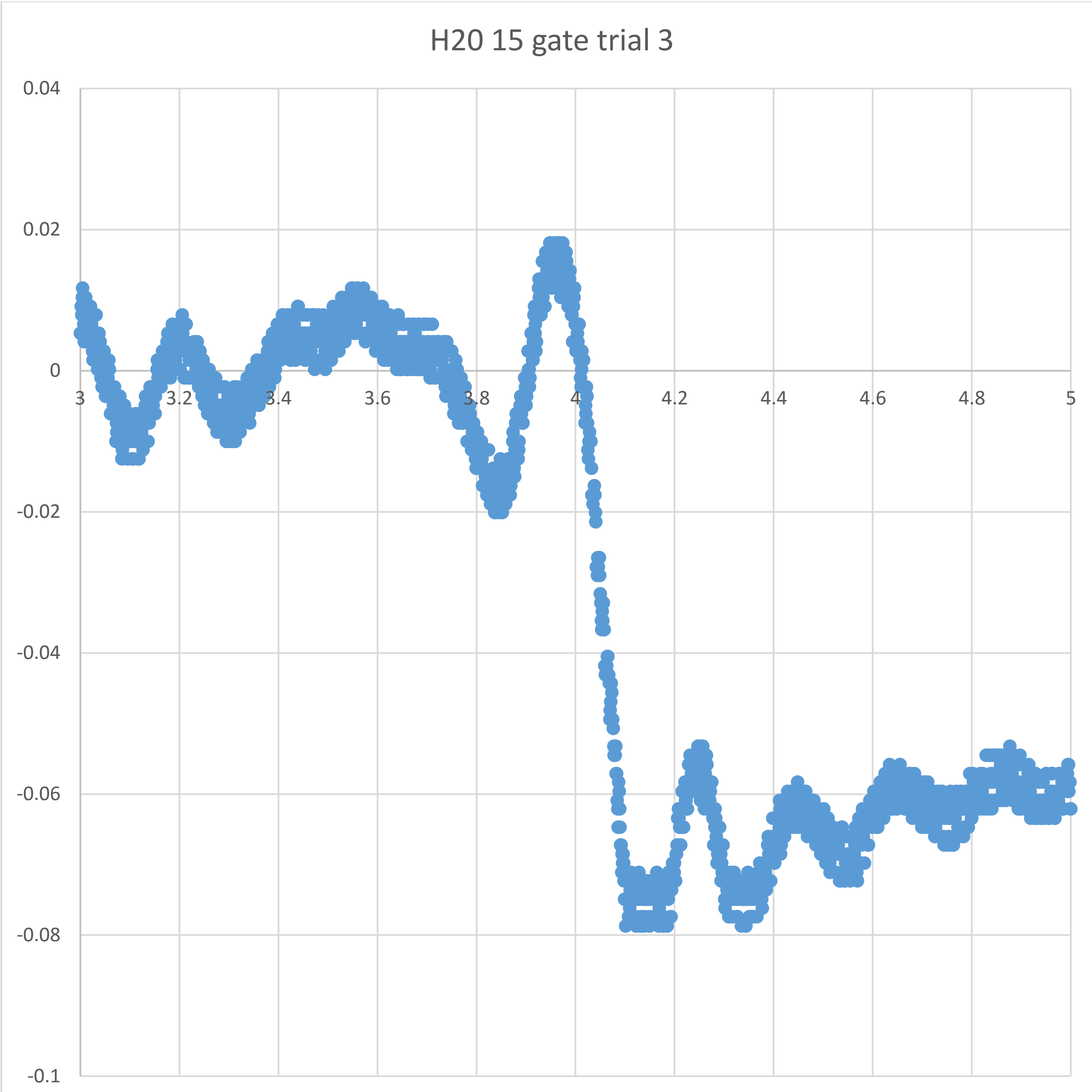


Figure 9. H20 15 gate trial 3

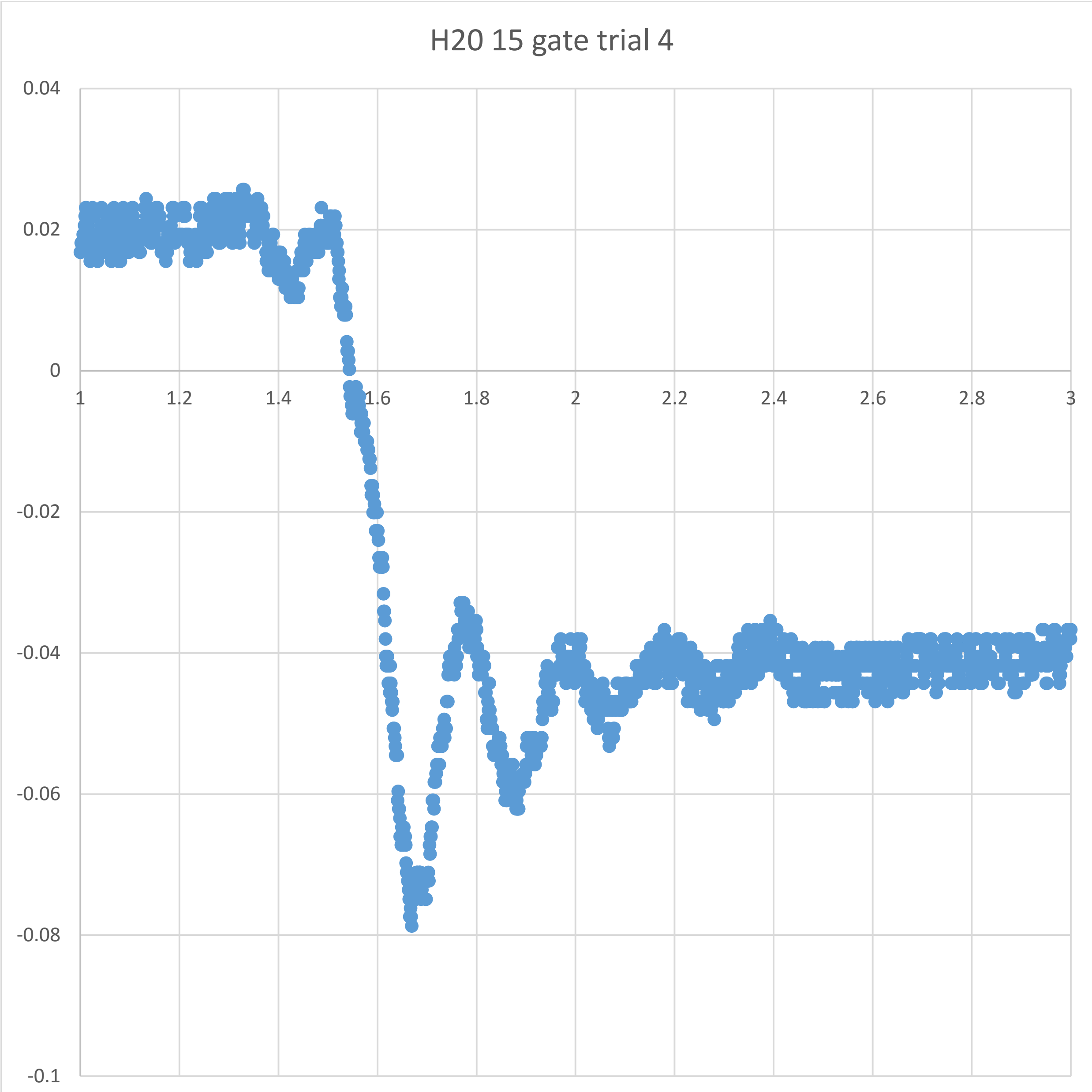


Figure 10. H20 15 gate trial 4

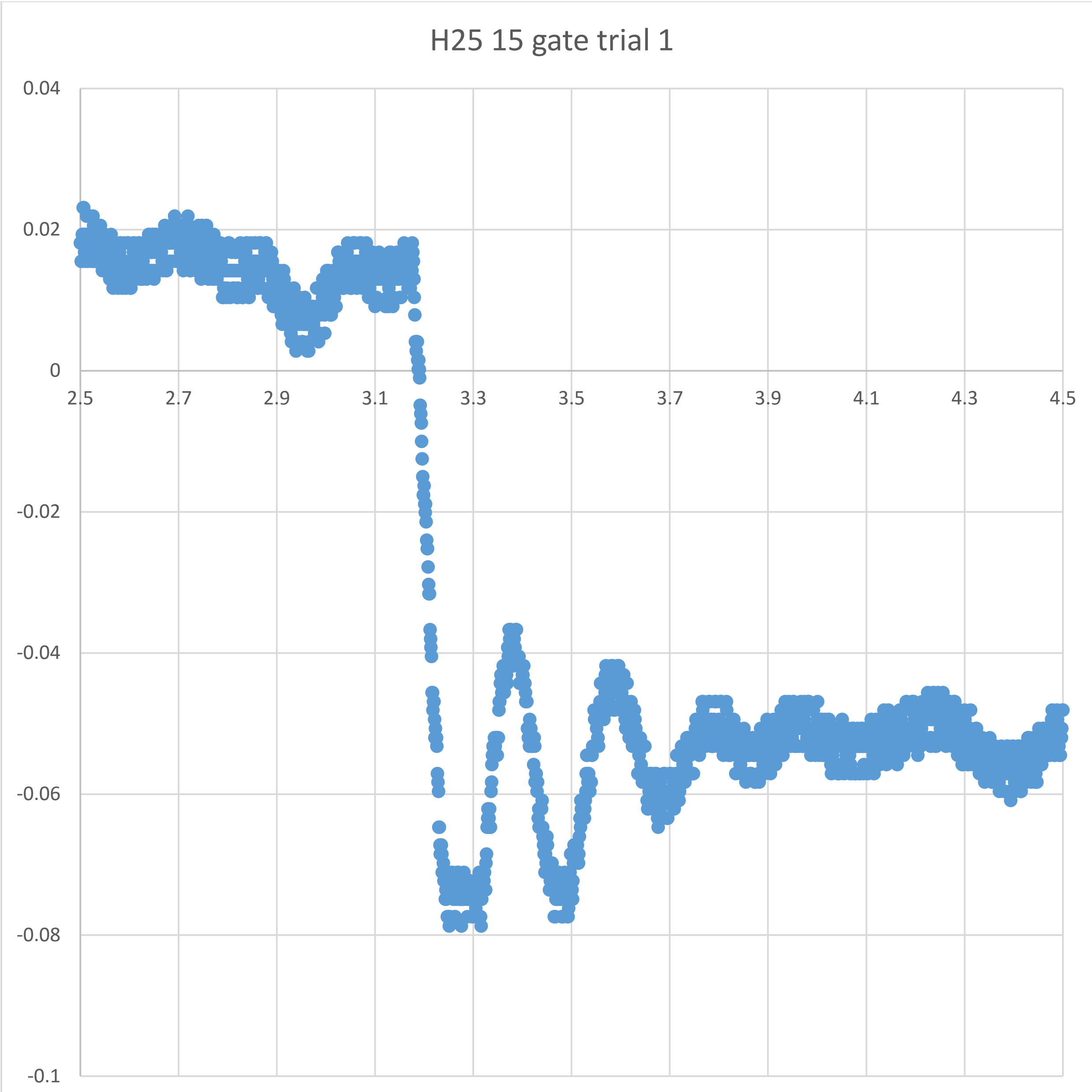


Figure 11. H25 15 gate trial 1

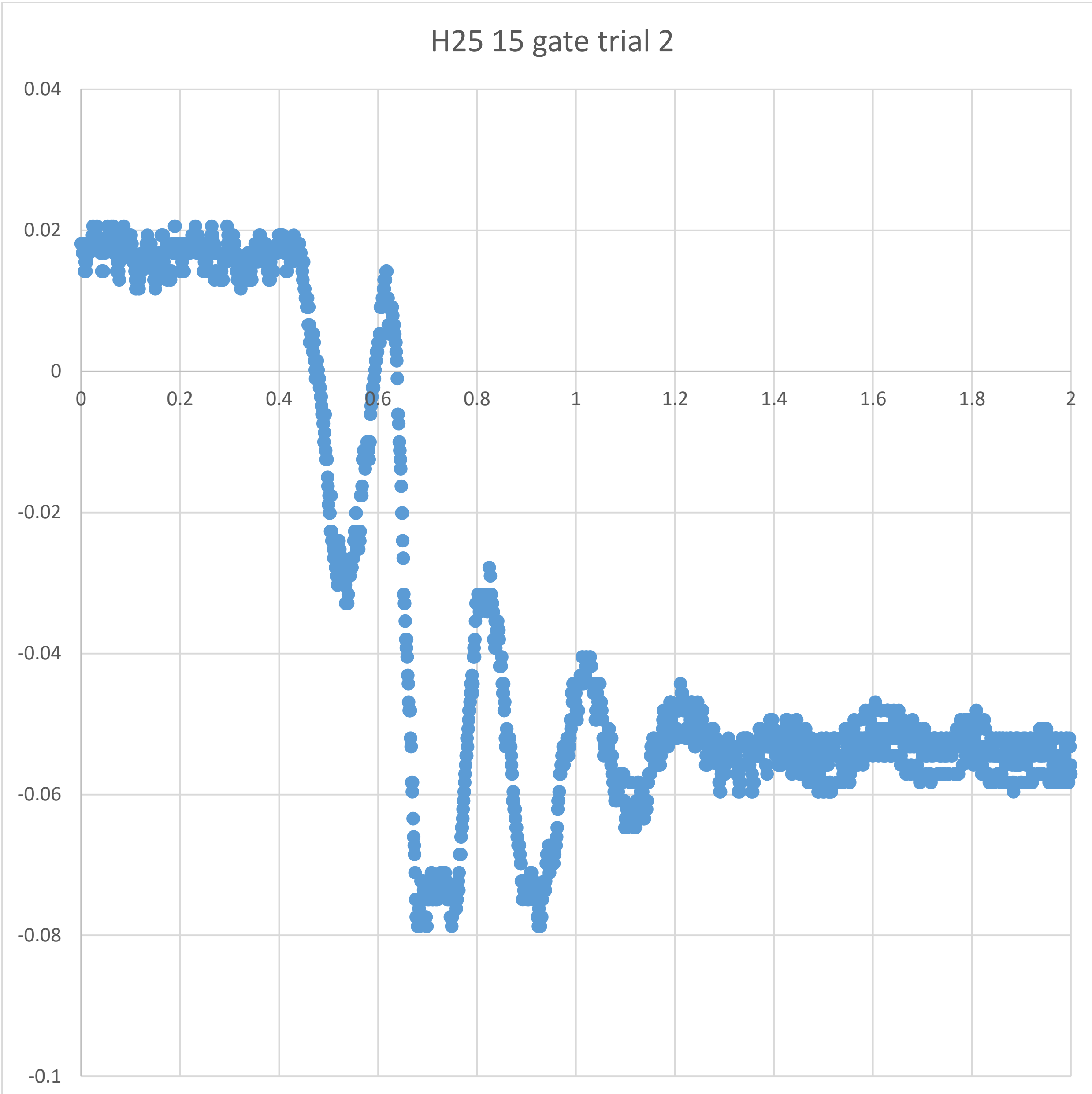


Figure 12. H25 15 gate trial 2

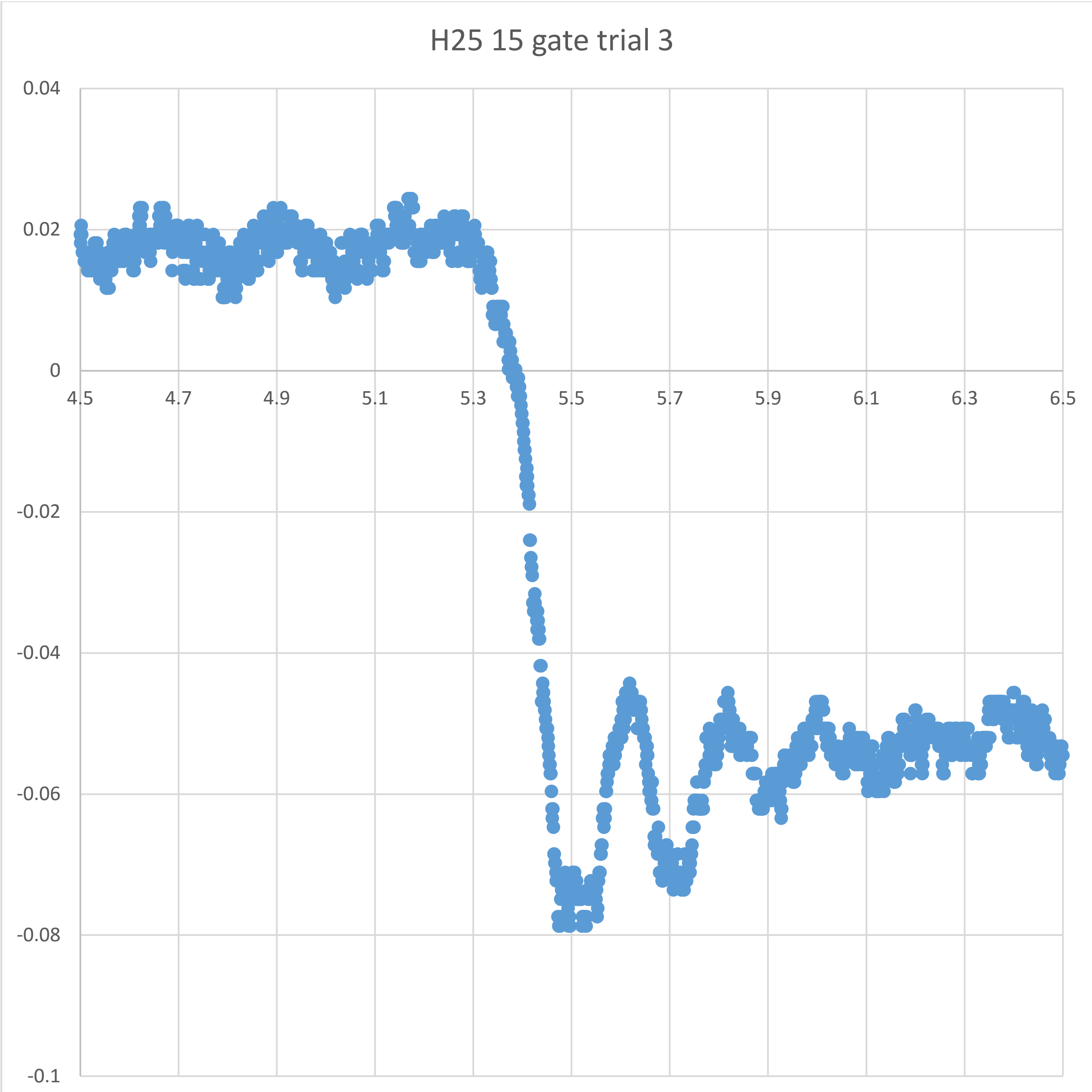


Figure 13. H25 15 gate trial 3

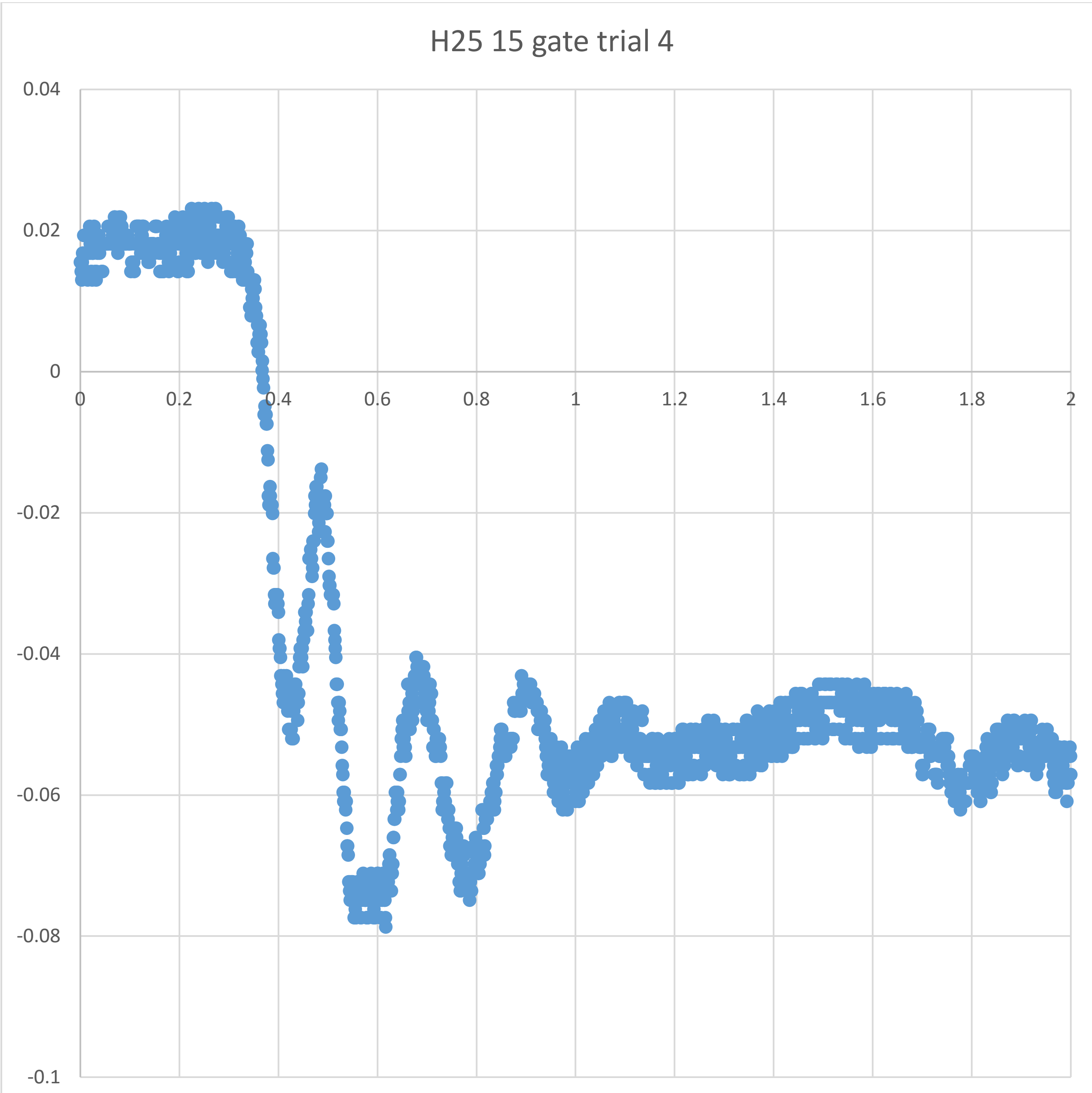


Figure 14. H25 15 gate trial 4

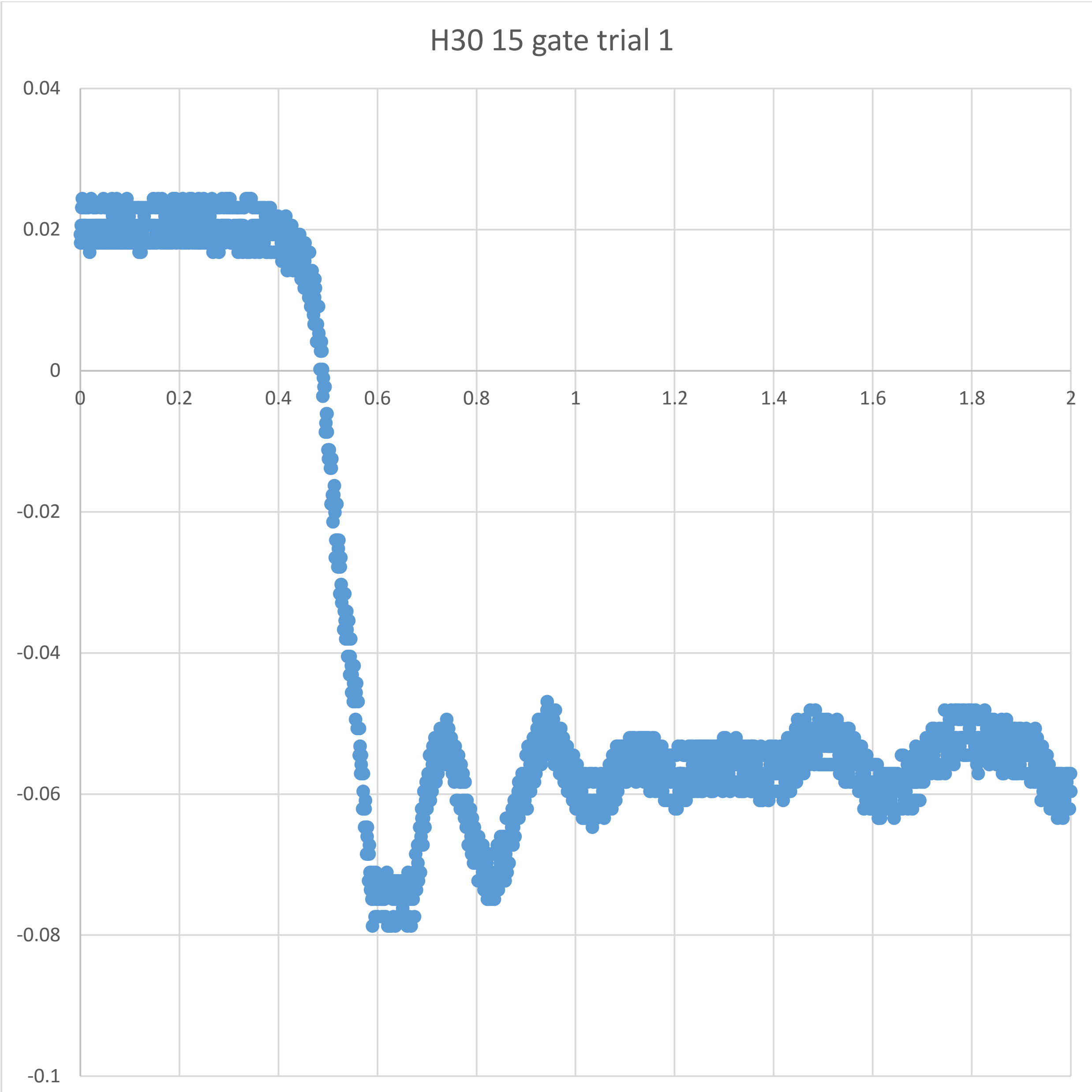


Figure 15. H30 15 gate trial 1

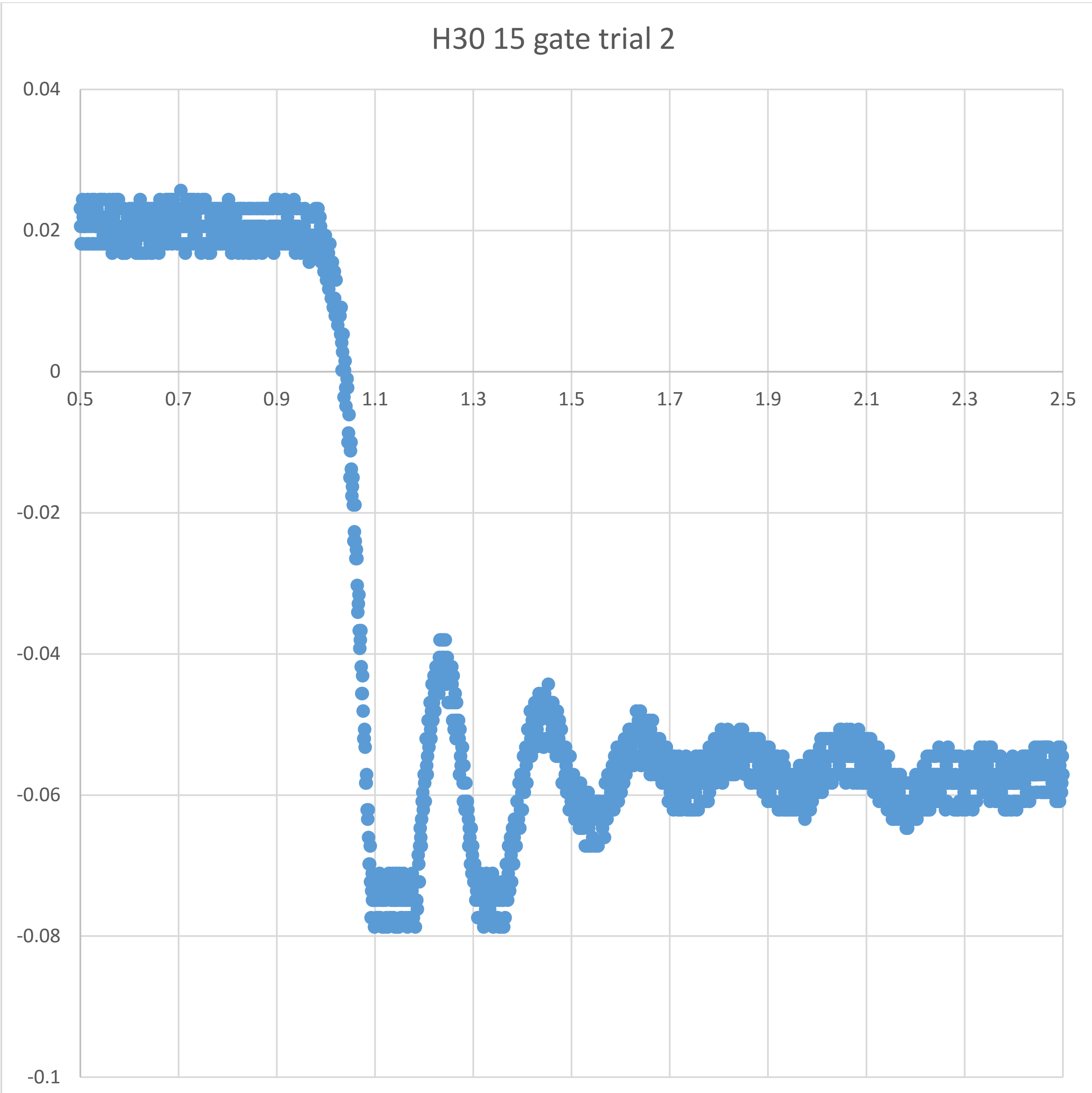


Figure 16. H30 15 gate trial 2

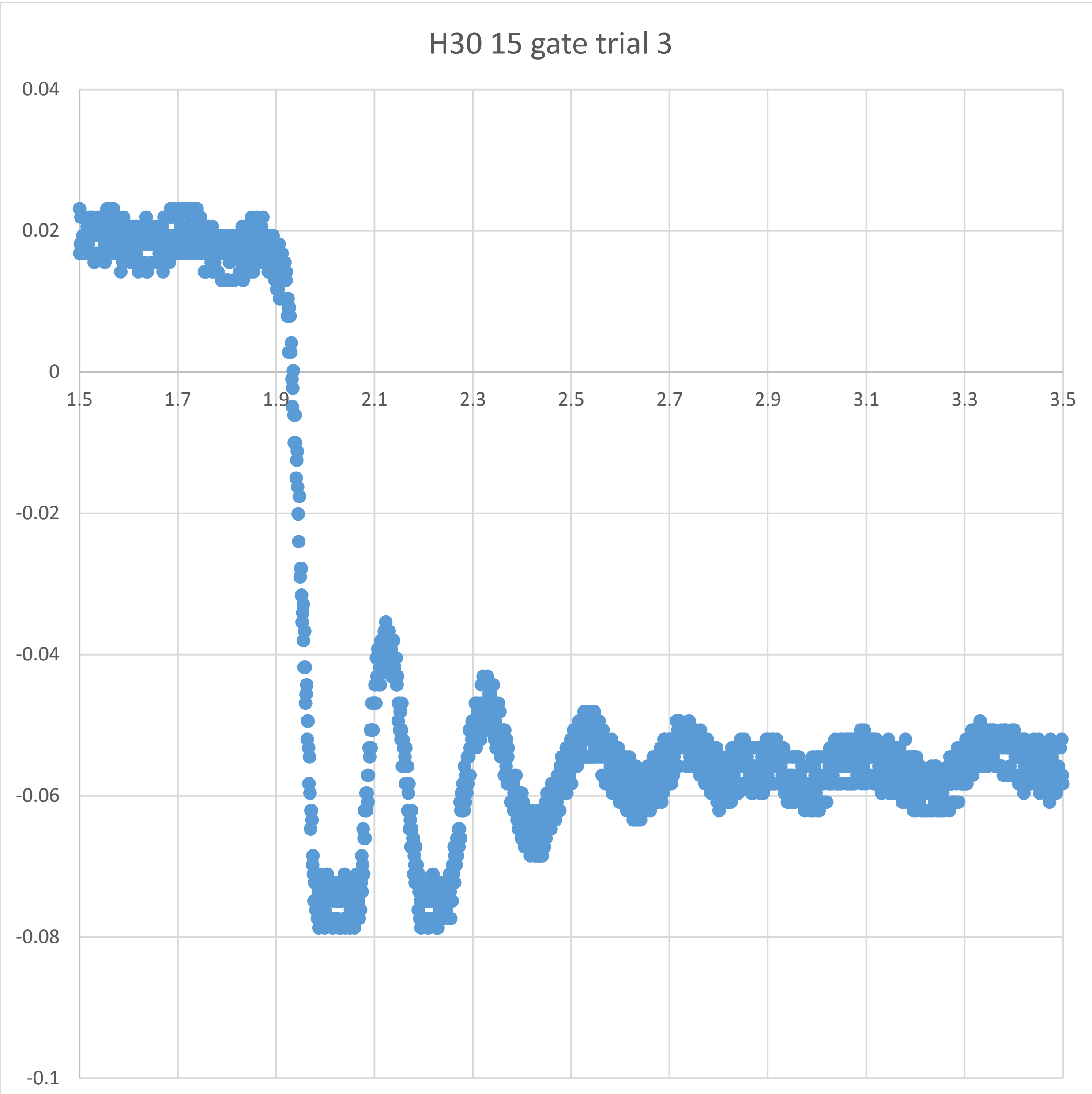


Figure 17. H30 15 gate trial 3

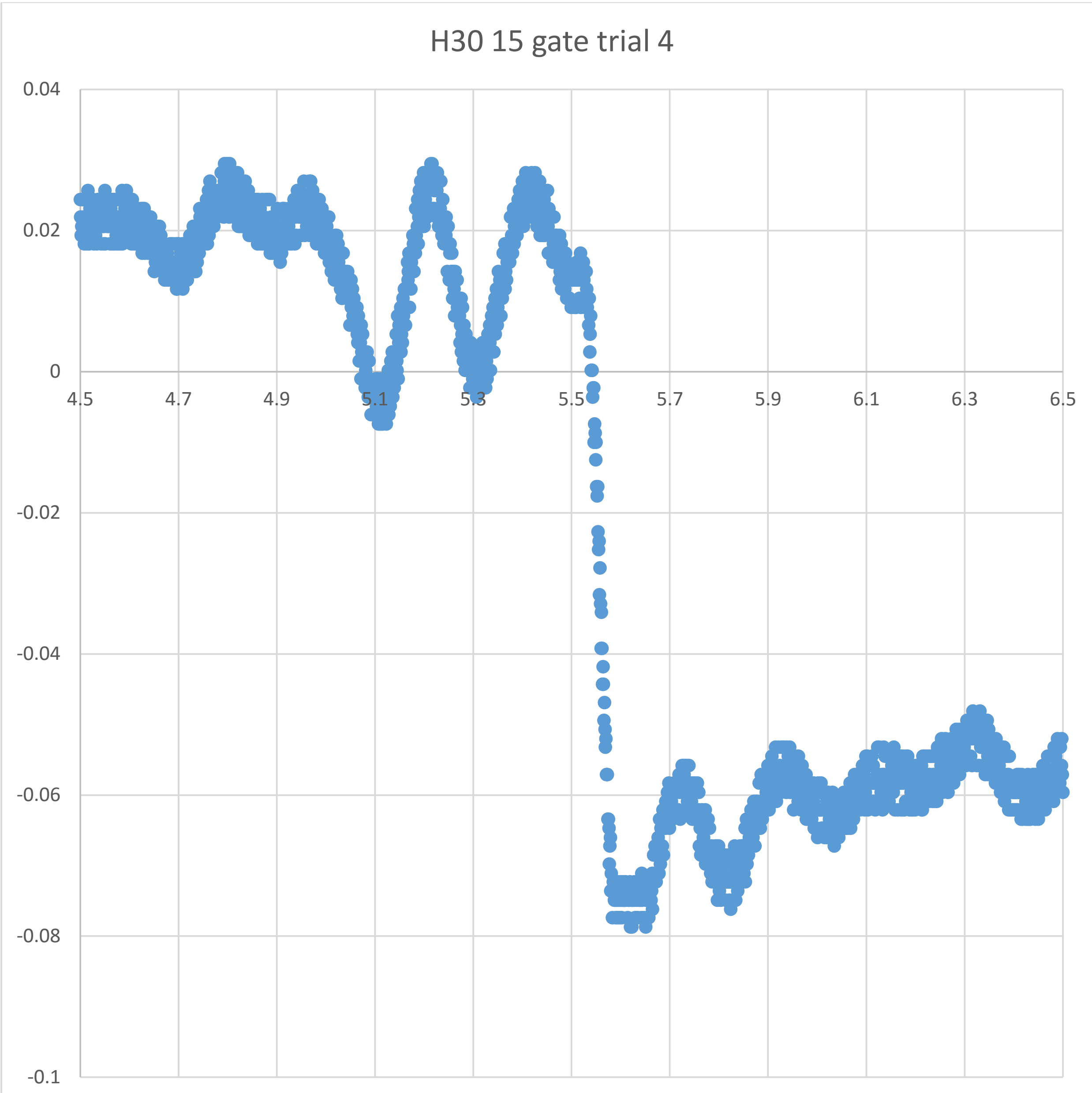


Figure 18. H30 15 gate trial 4

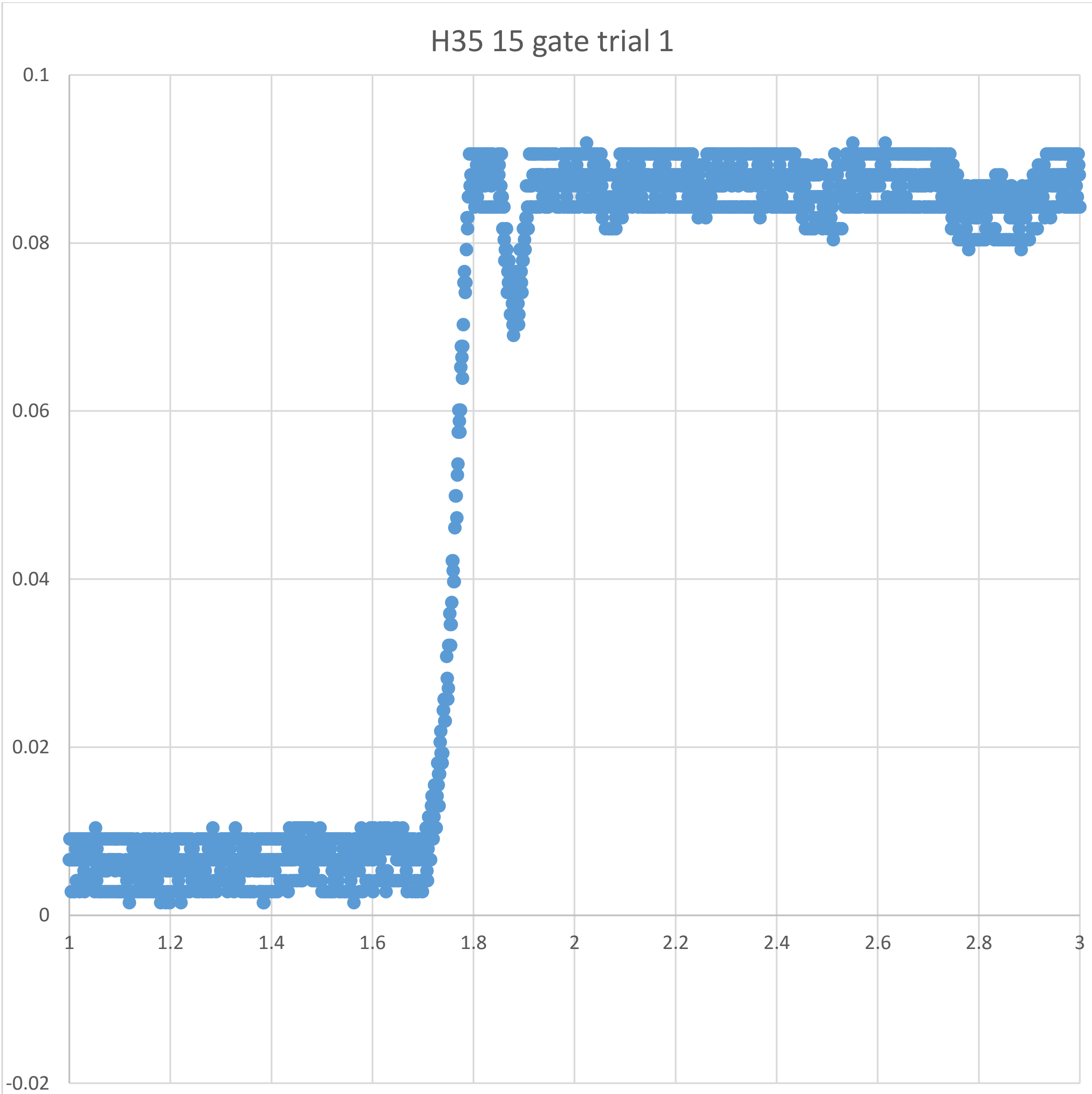


Figure 19. H35 15 gate trial 1

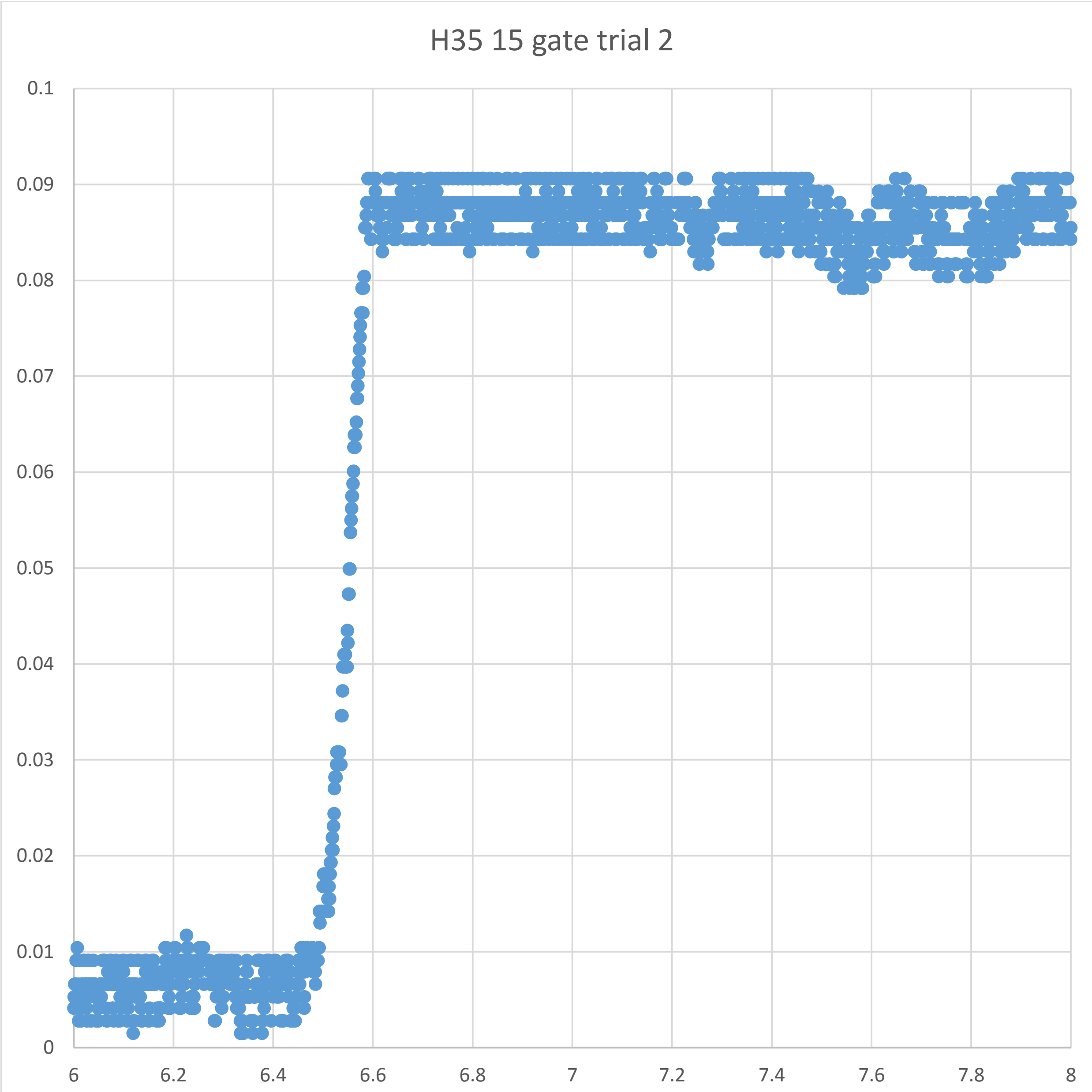


Figure 20. H35 15 gate trial 2

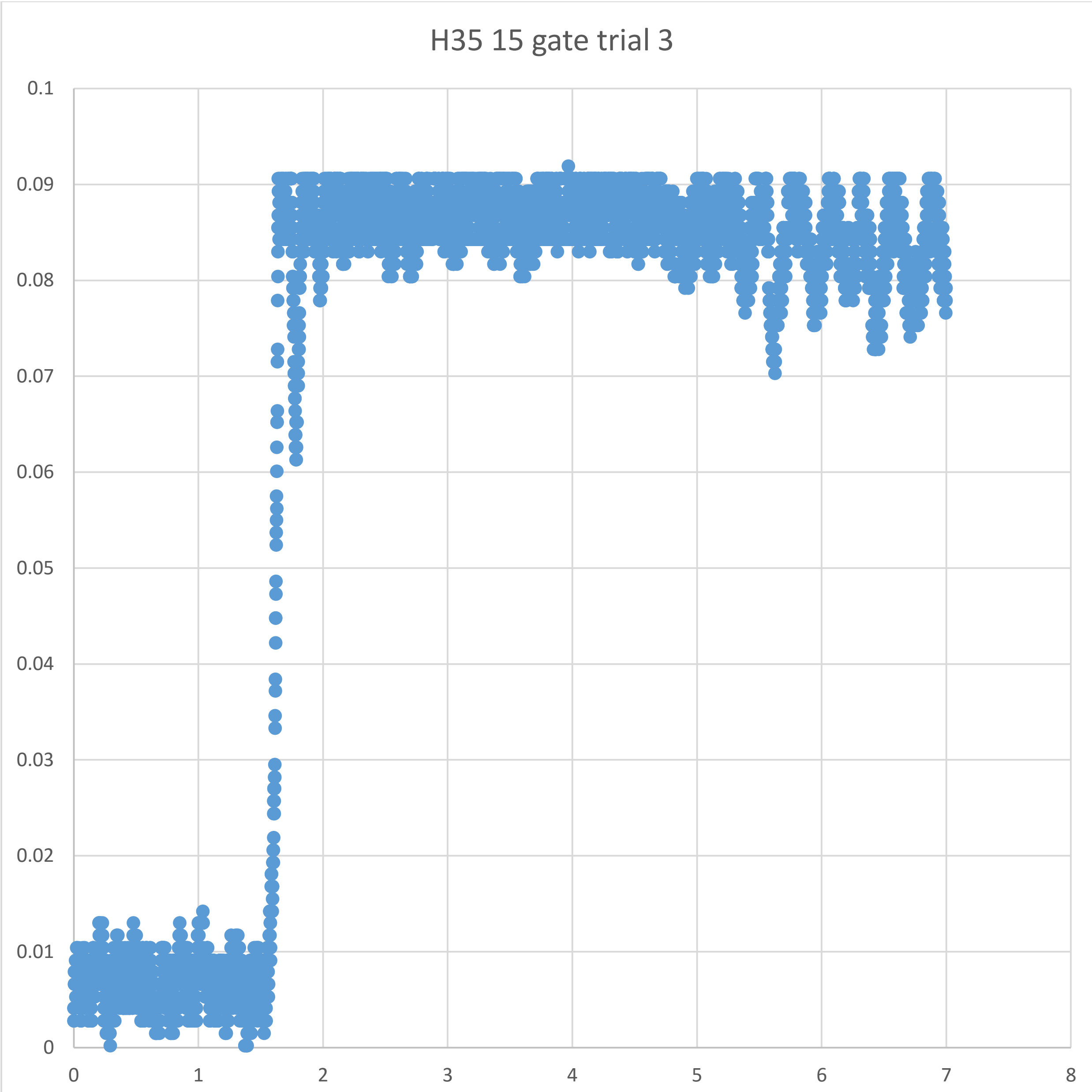


Figure 21. H35 15 gate trial 3

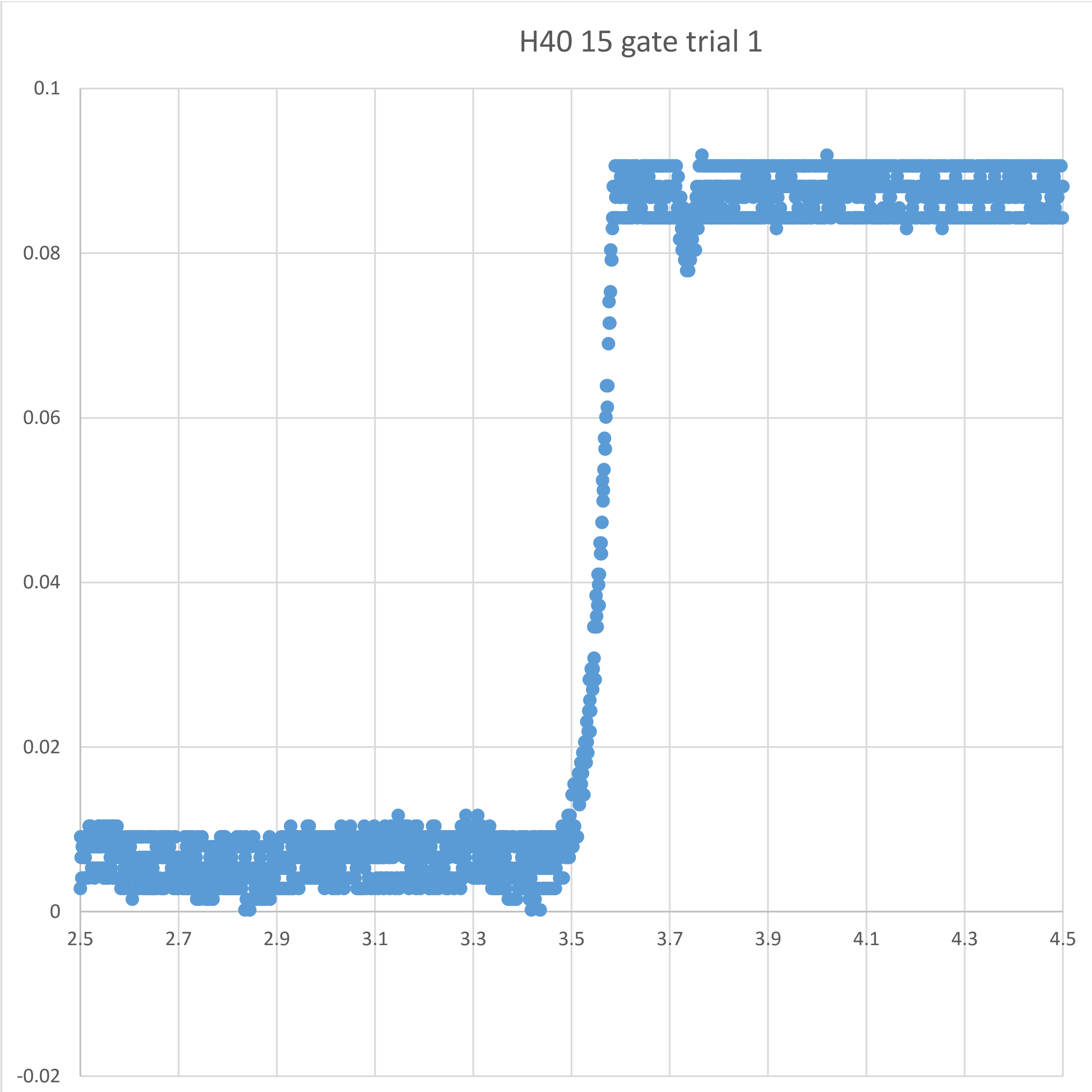


Figure 22. H40 15 gate trial 1

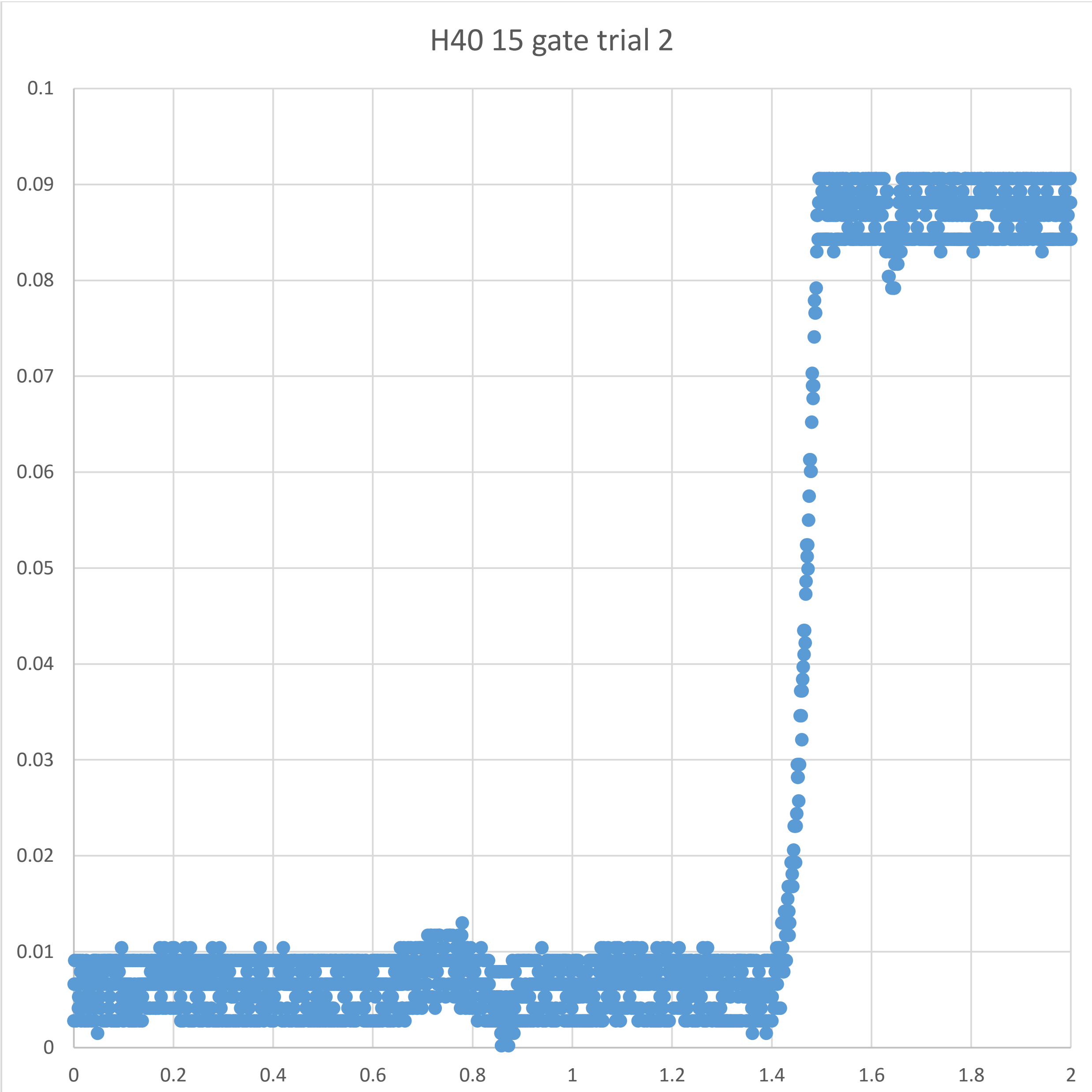


Figure 23. H40 15 gate trial 2

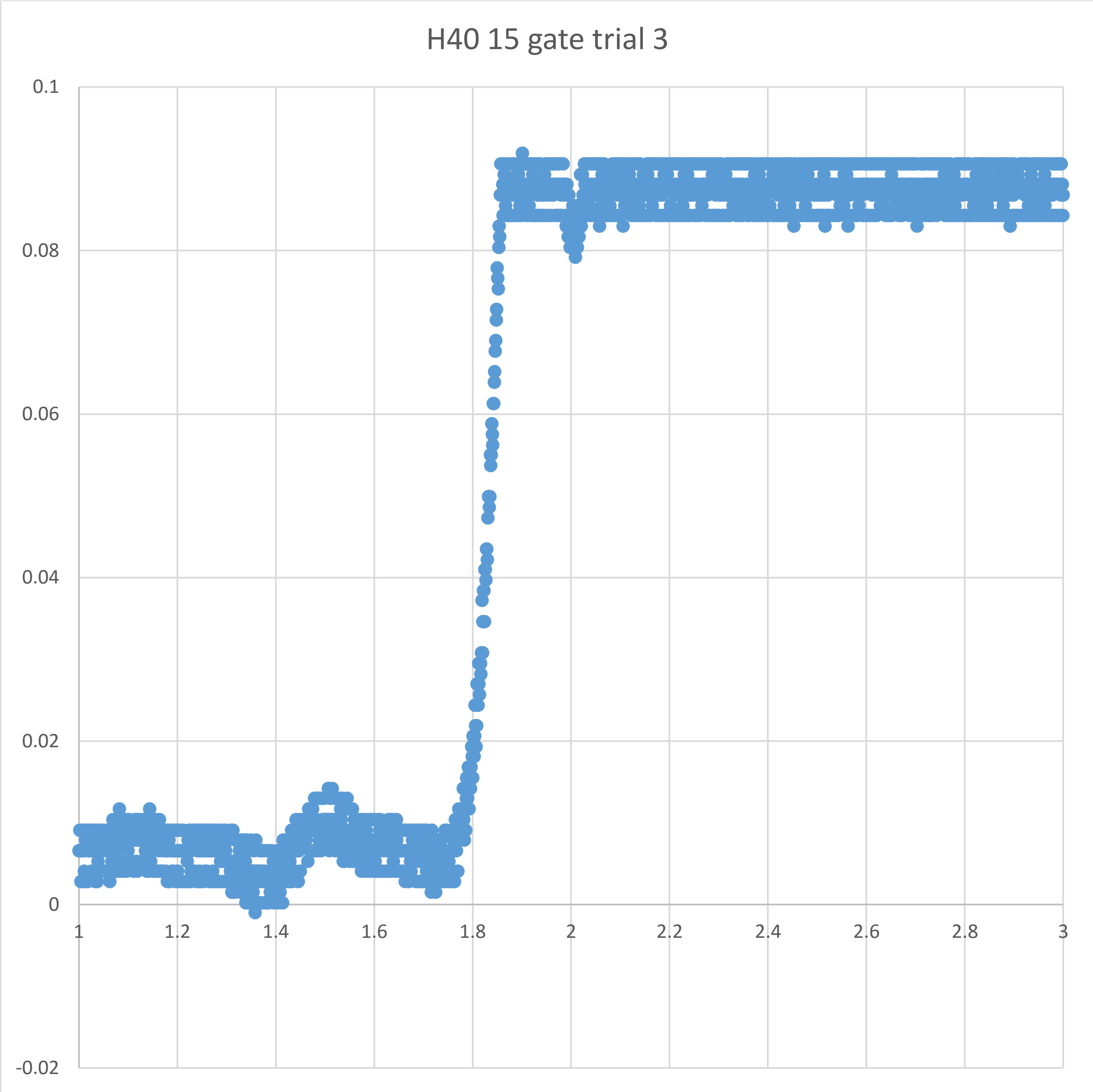


Figure 24. H40 15 gate trial 3

Appendix D-20 gate water start up time graphs first set

The graphs in appendix D are the 20 gate water start up time results from each trial. The "H" denotes the reference height which is in centimeters. To obtain the forebay to tail water height, add 20.06 centimeters the reference height. In the graphs if there is a missing number in the sequence it means that the data produced an error and was left out of the analysis.

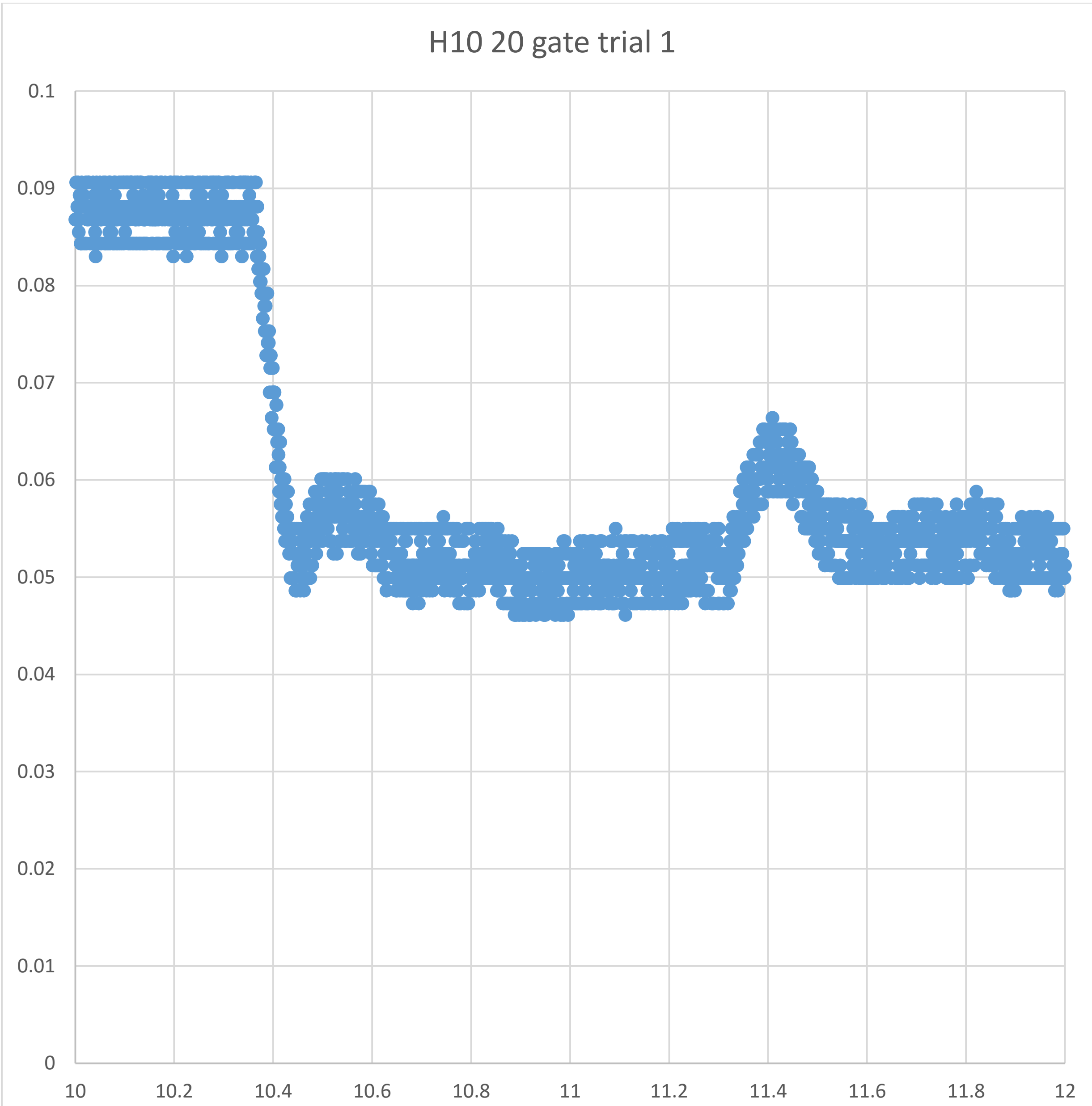


Figure 1. H10 20 gate trial 1

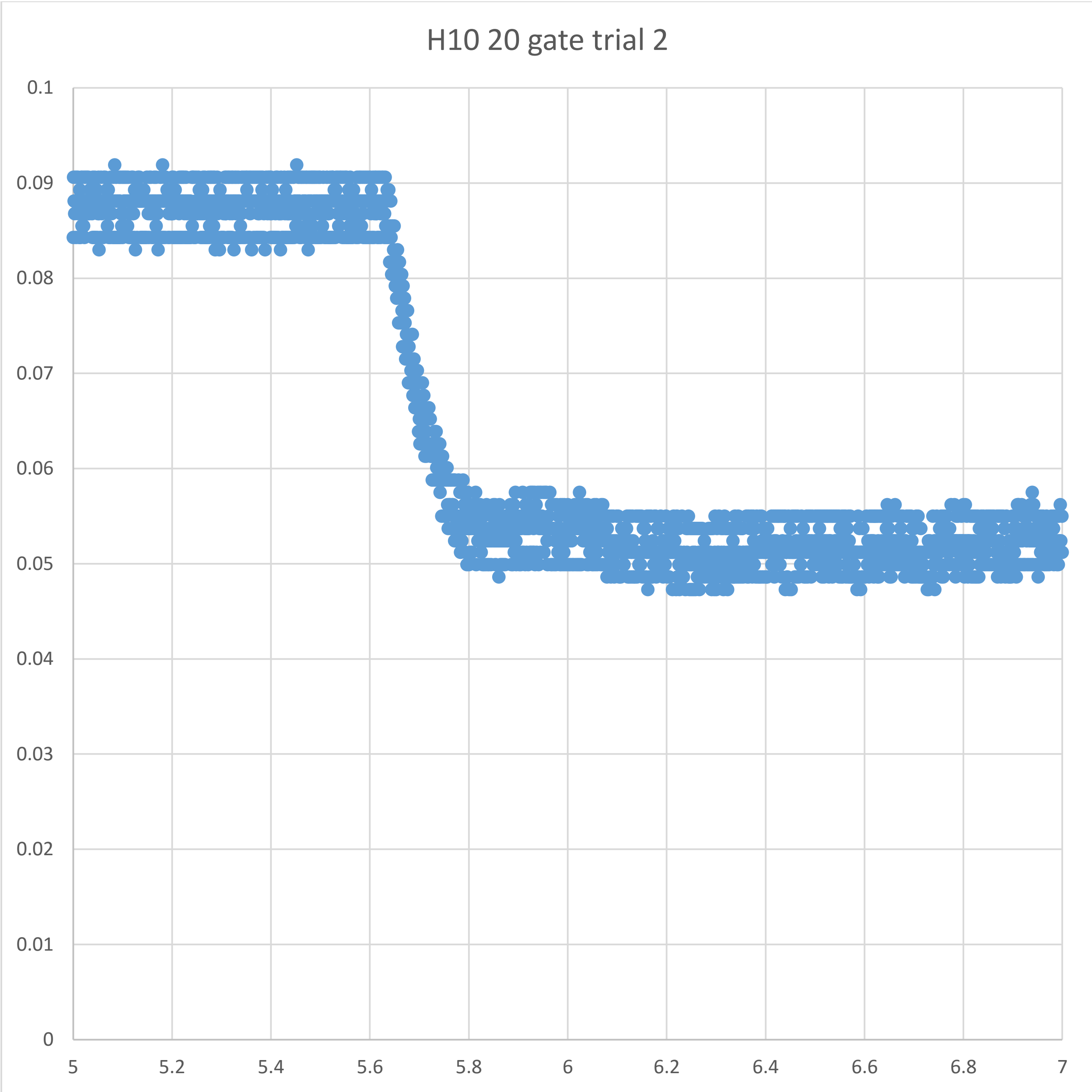


Figure 2. H10 20 gate trial 2

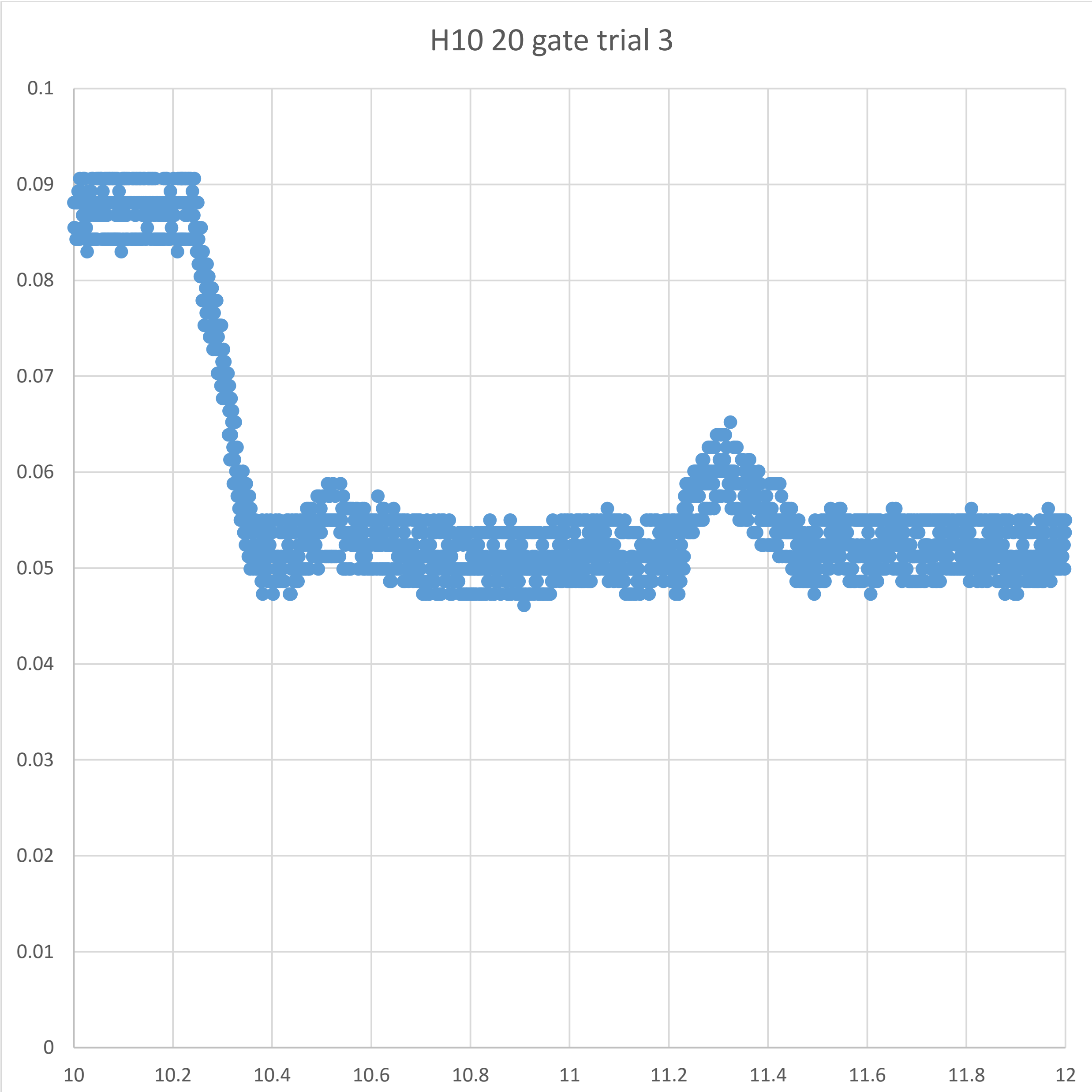


Figure 3. H10 20 gate trial 3

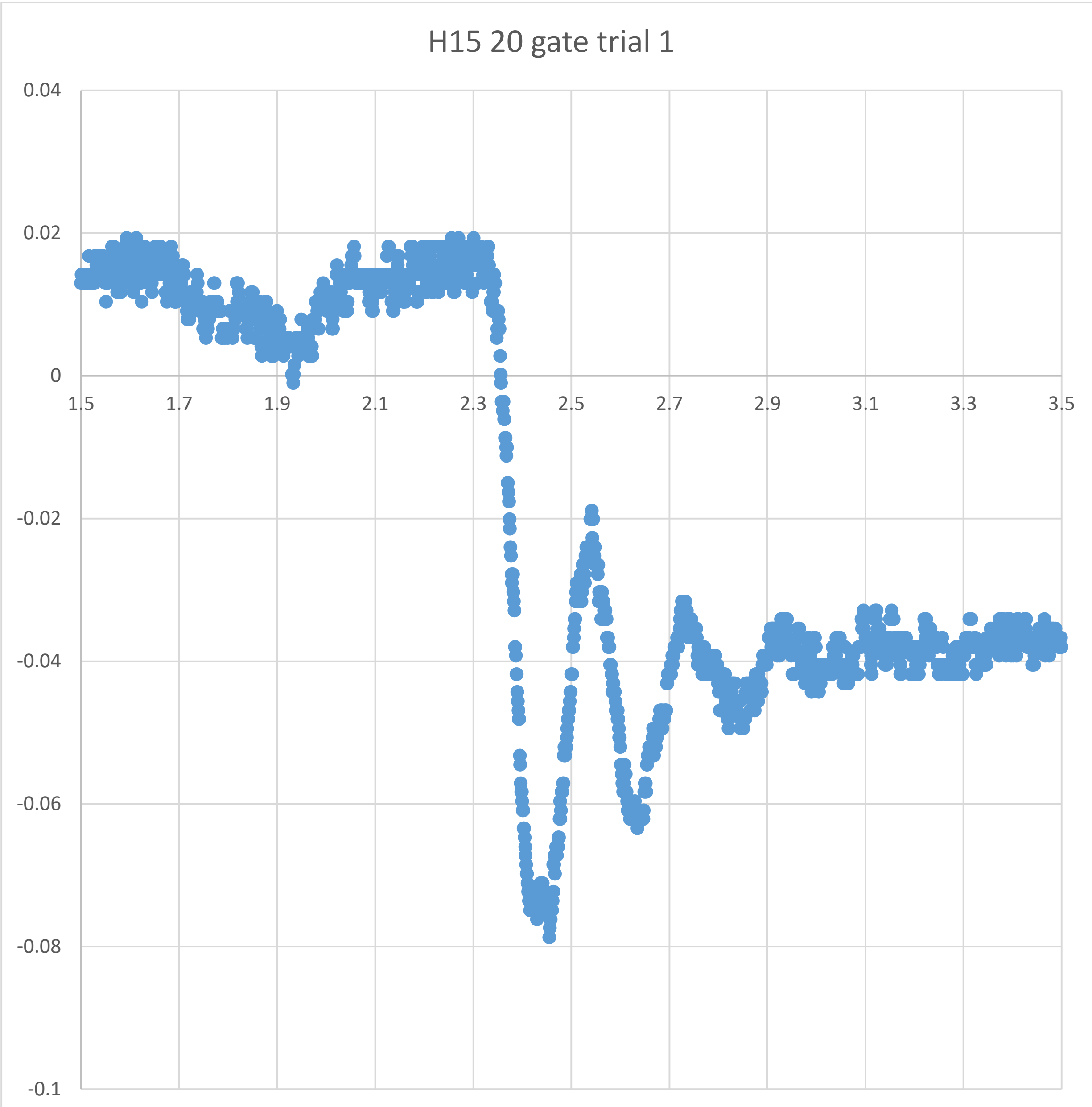


Figure 4. H15 20 gate trial 1

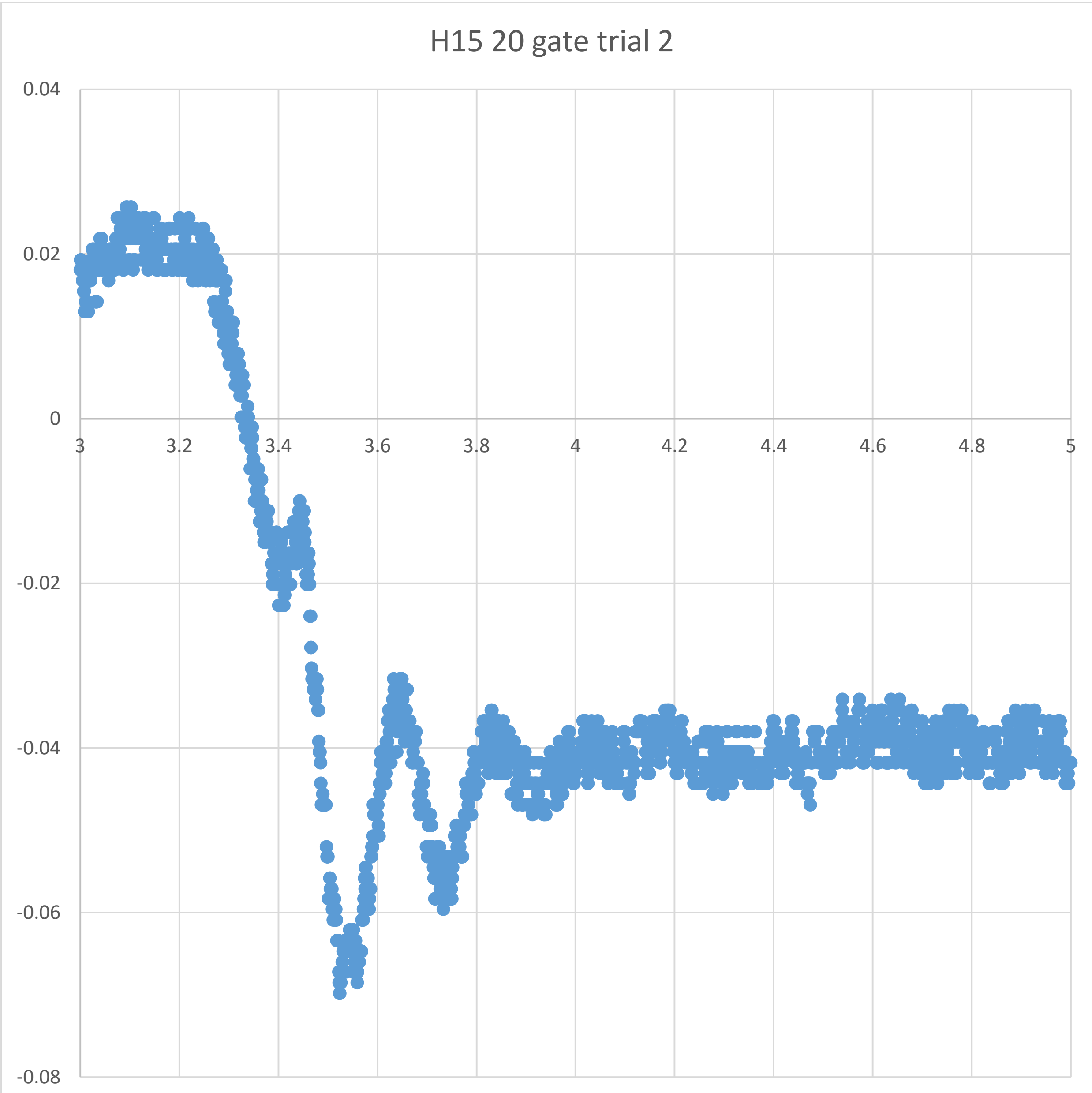


Figure 5. H15 20 gate trial 2

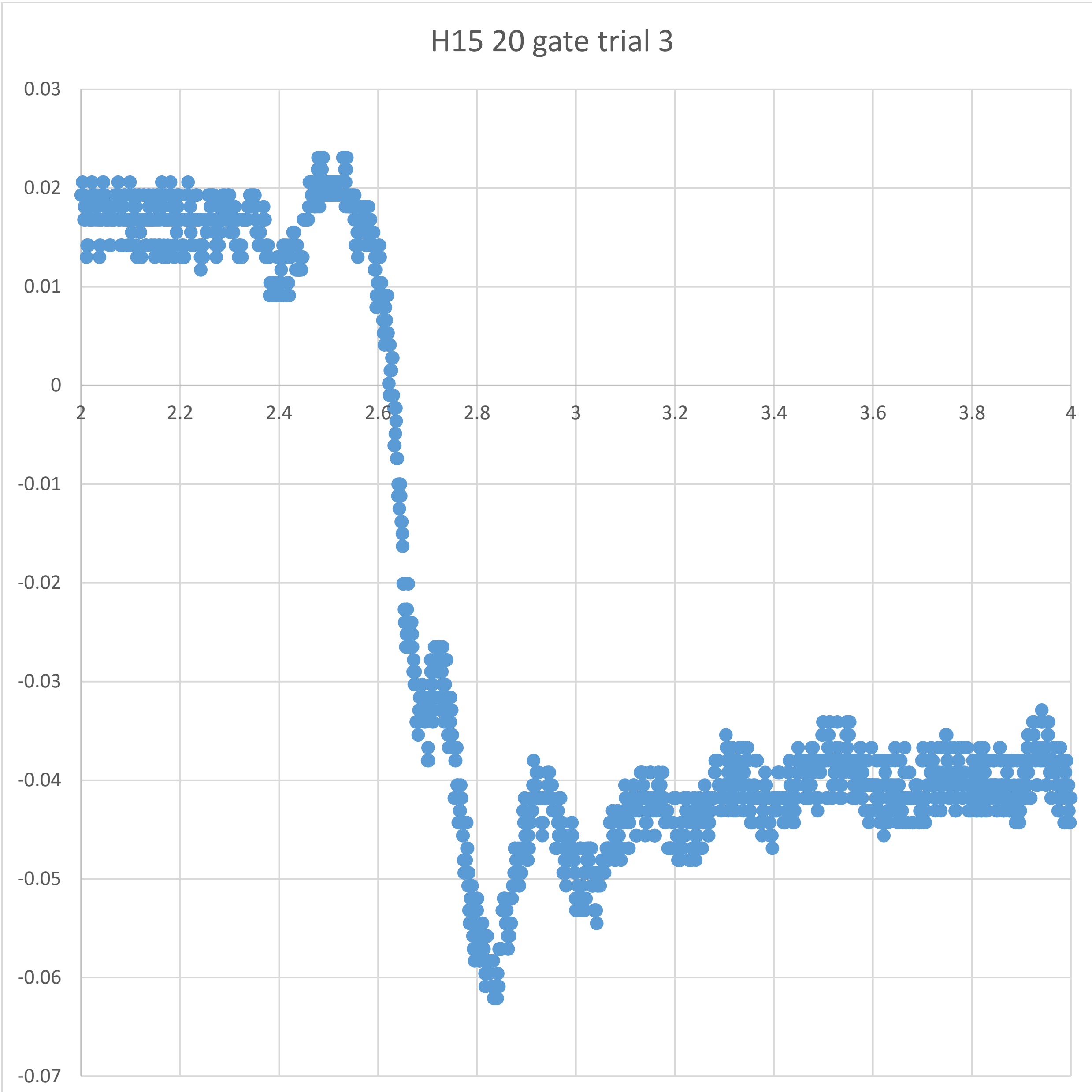


Figure 6. H15 20 gate trial 3

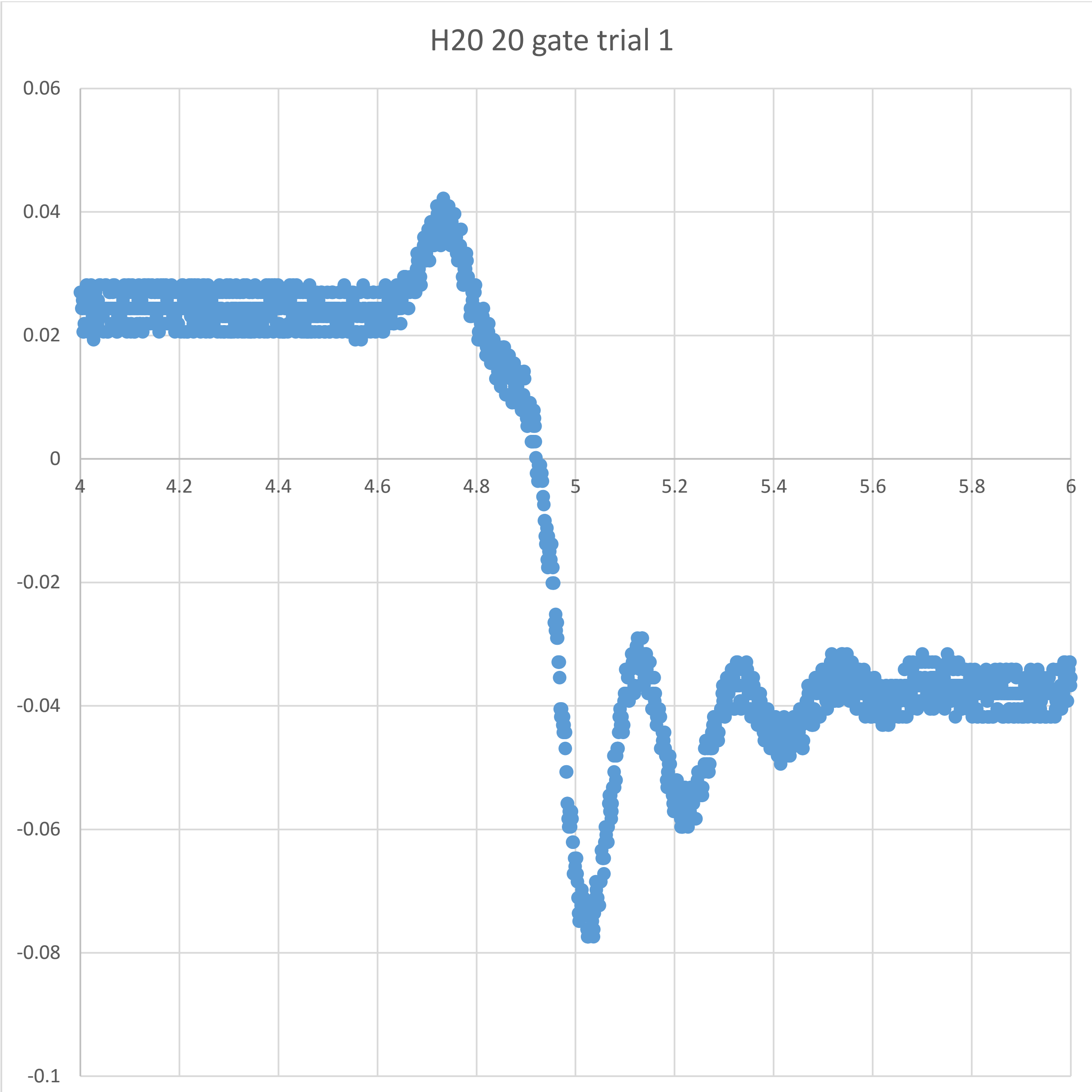


Figure 7. H20 20 gate trial 1

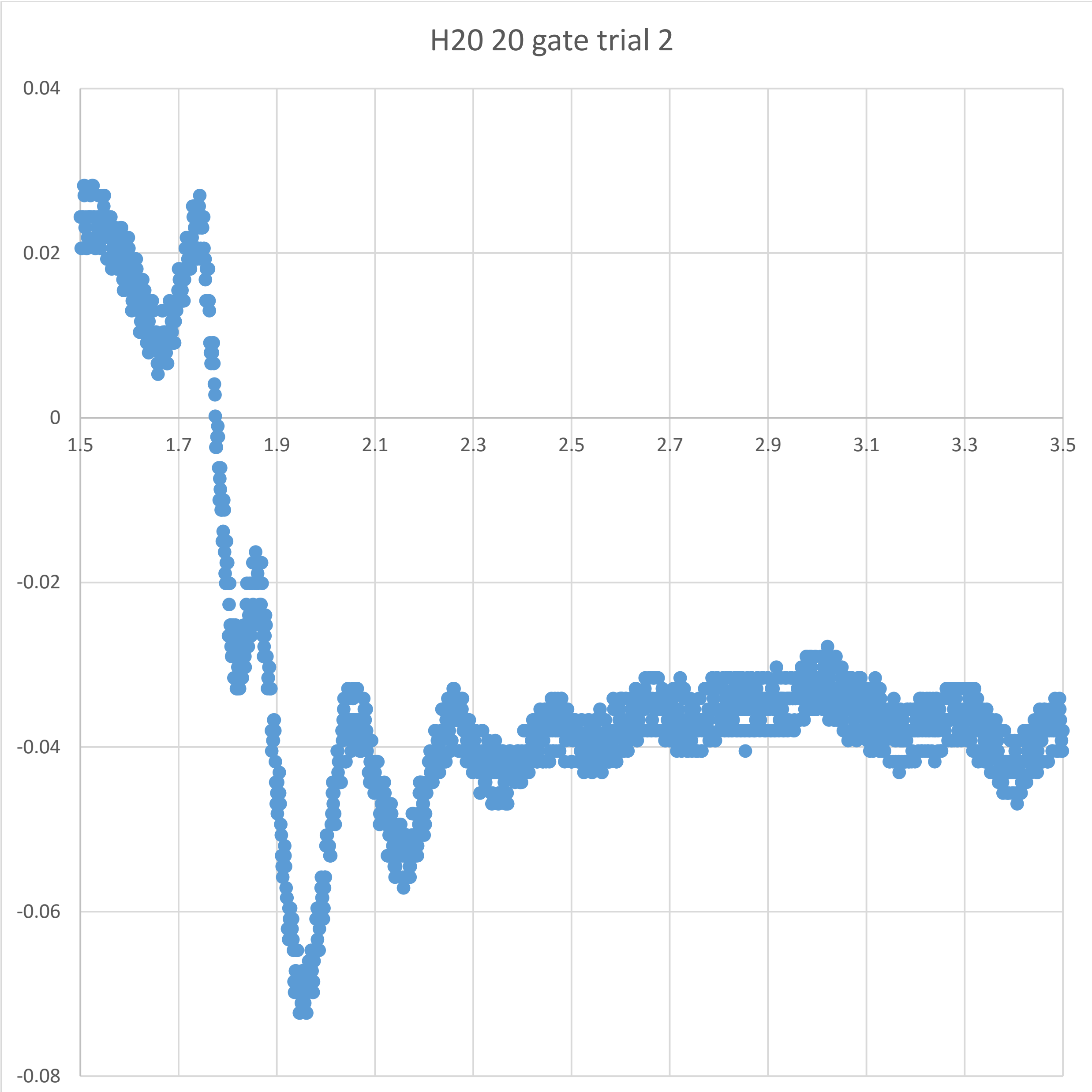


Figure 8. H20 20 gate trial 2

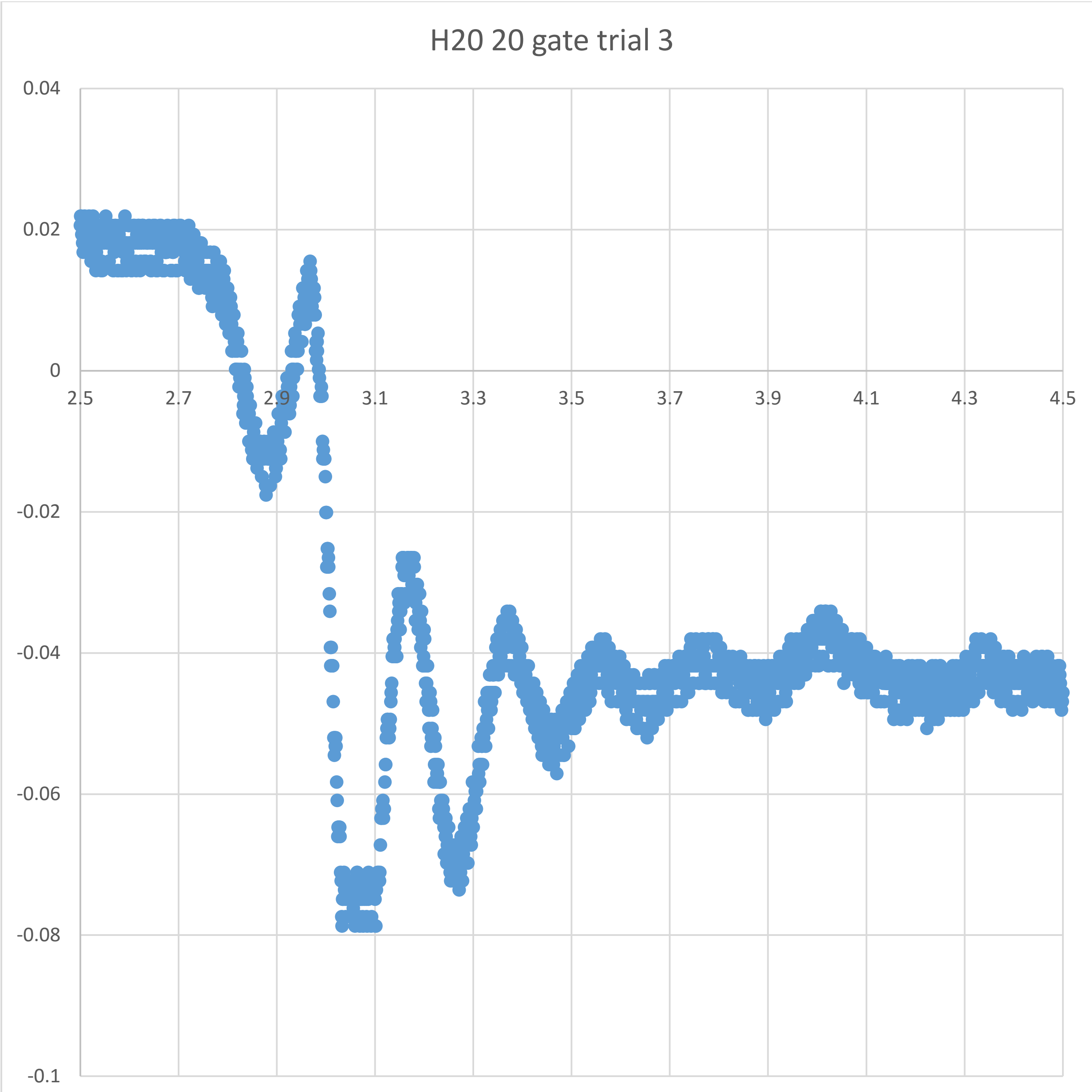


Figure 9. H20 20 gate trial 3

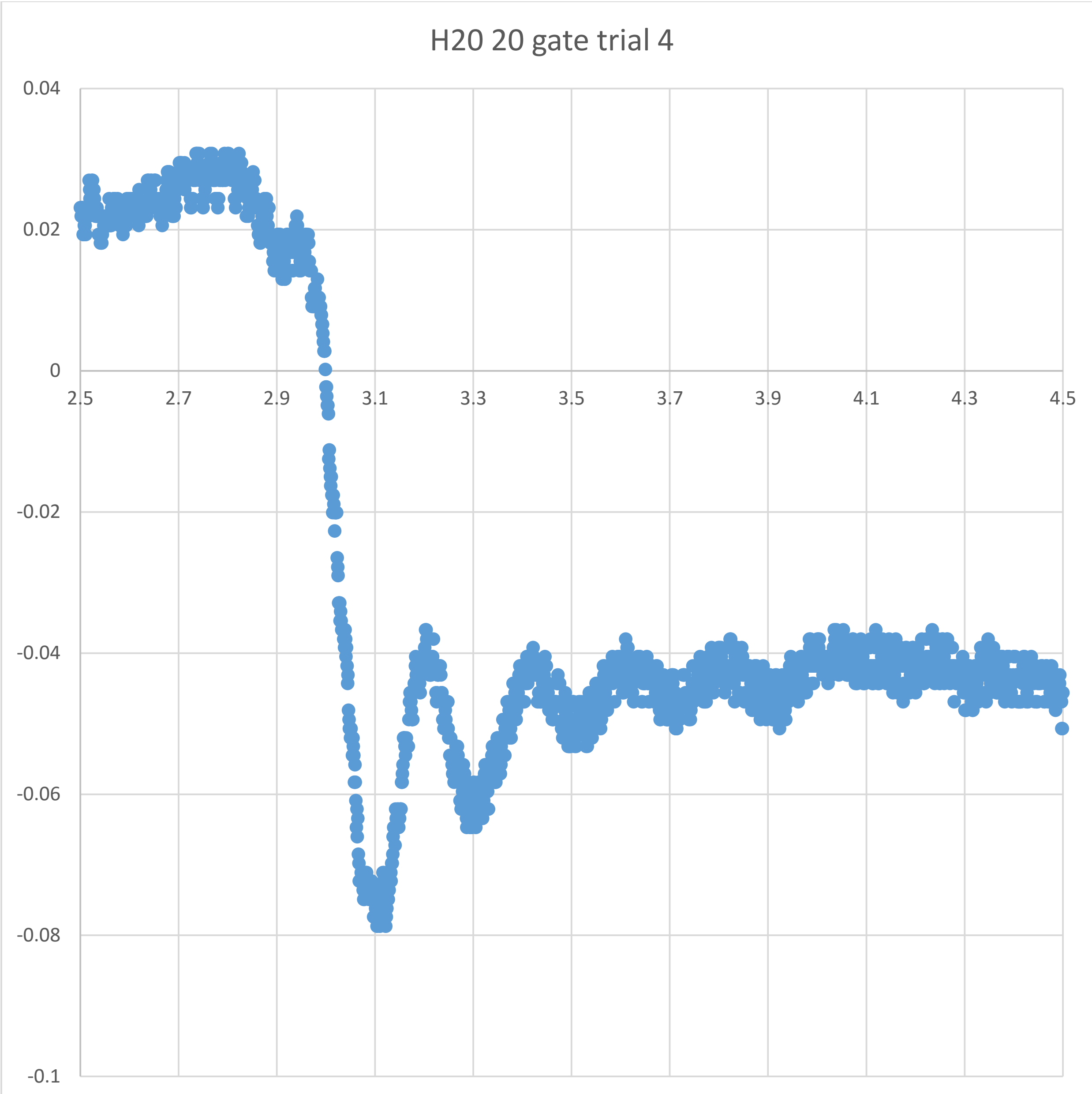


Figure 10. H20 20 gate trial 4

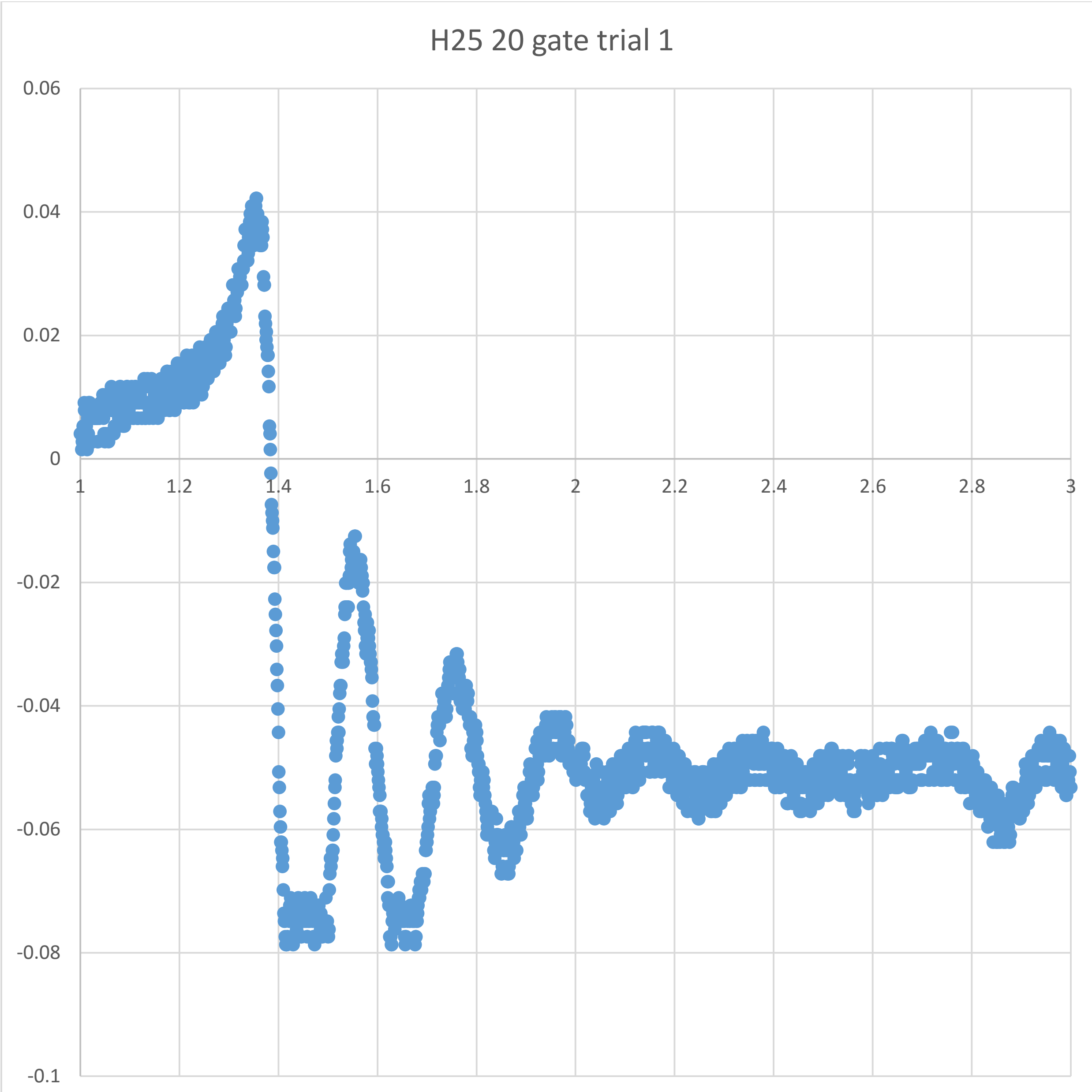


Figure 11. H25 20 gate trial 1

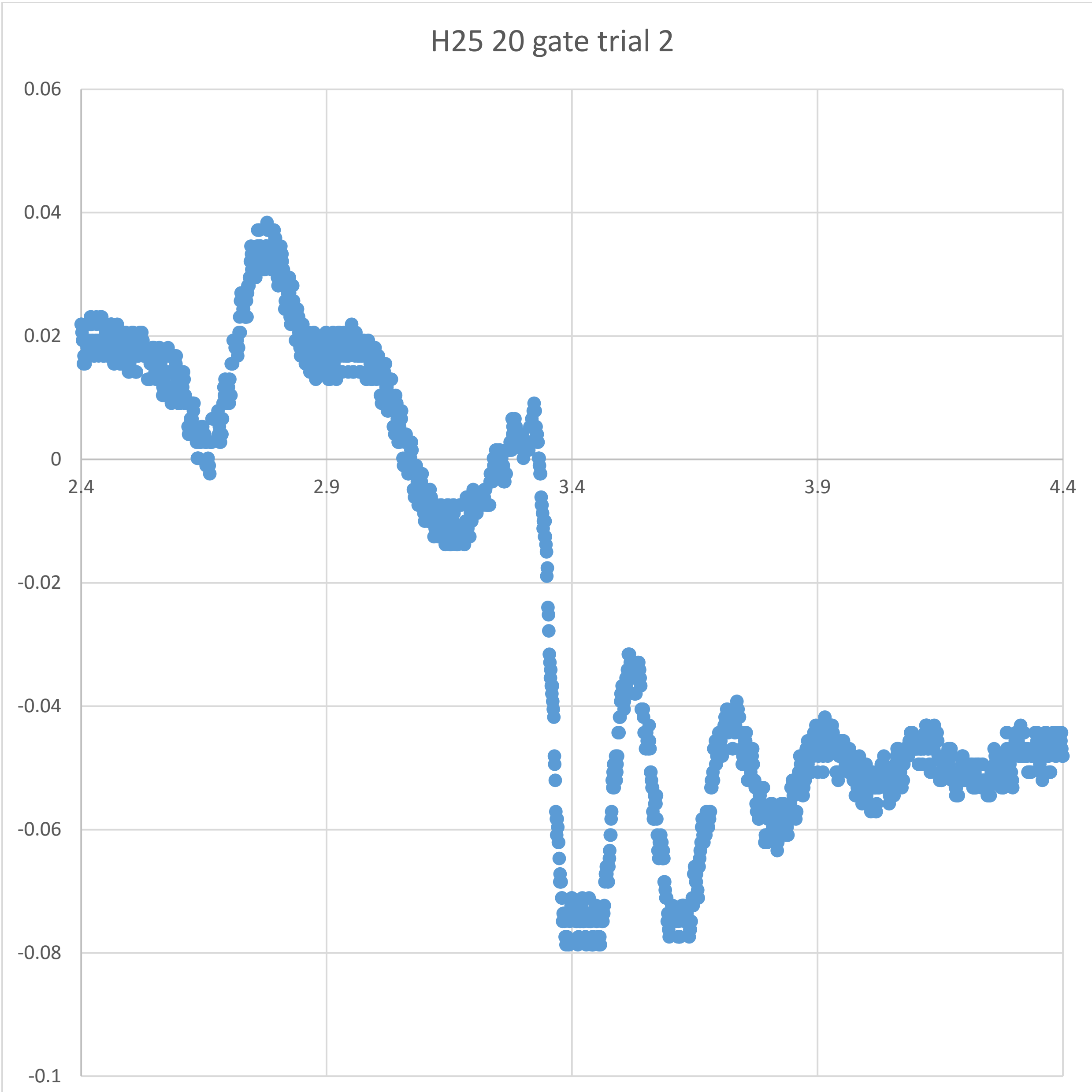


Figure 12. H25 20 gate trial 2

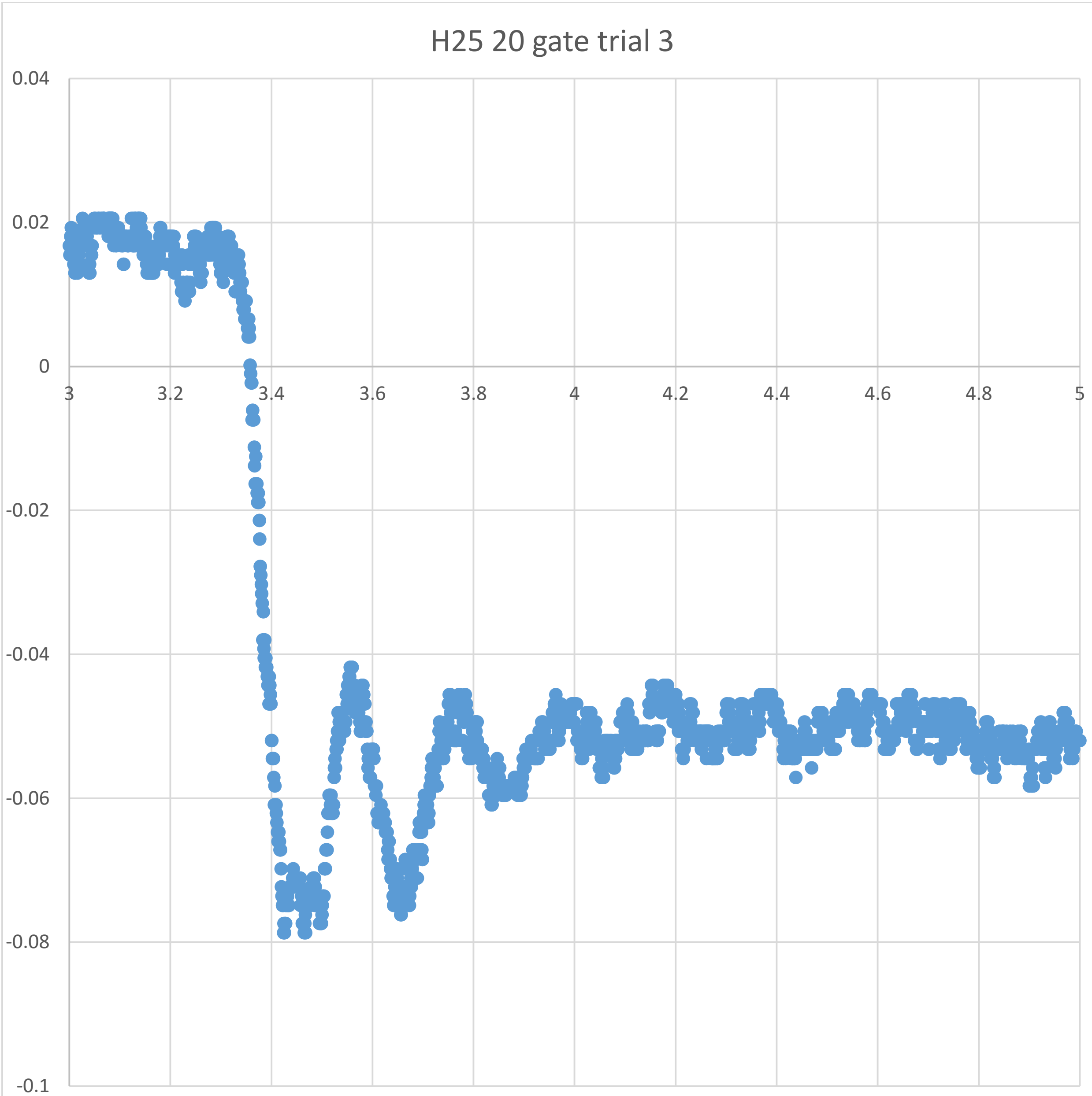


Figure 13. H25 20 gate trial 3

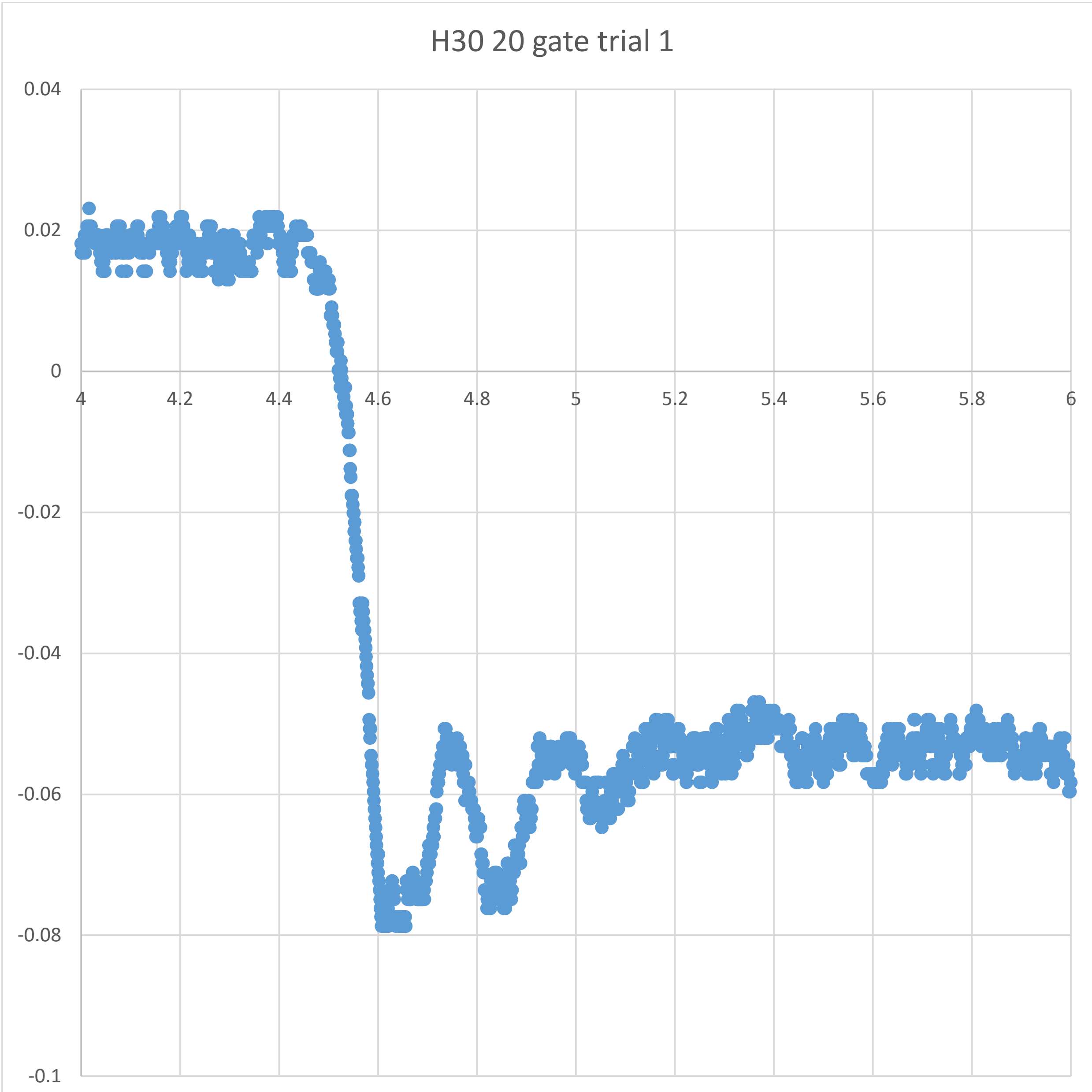


Figure 14. H30 20 gate trial 1

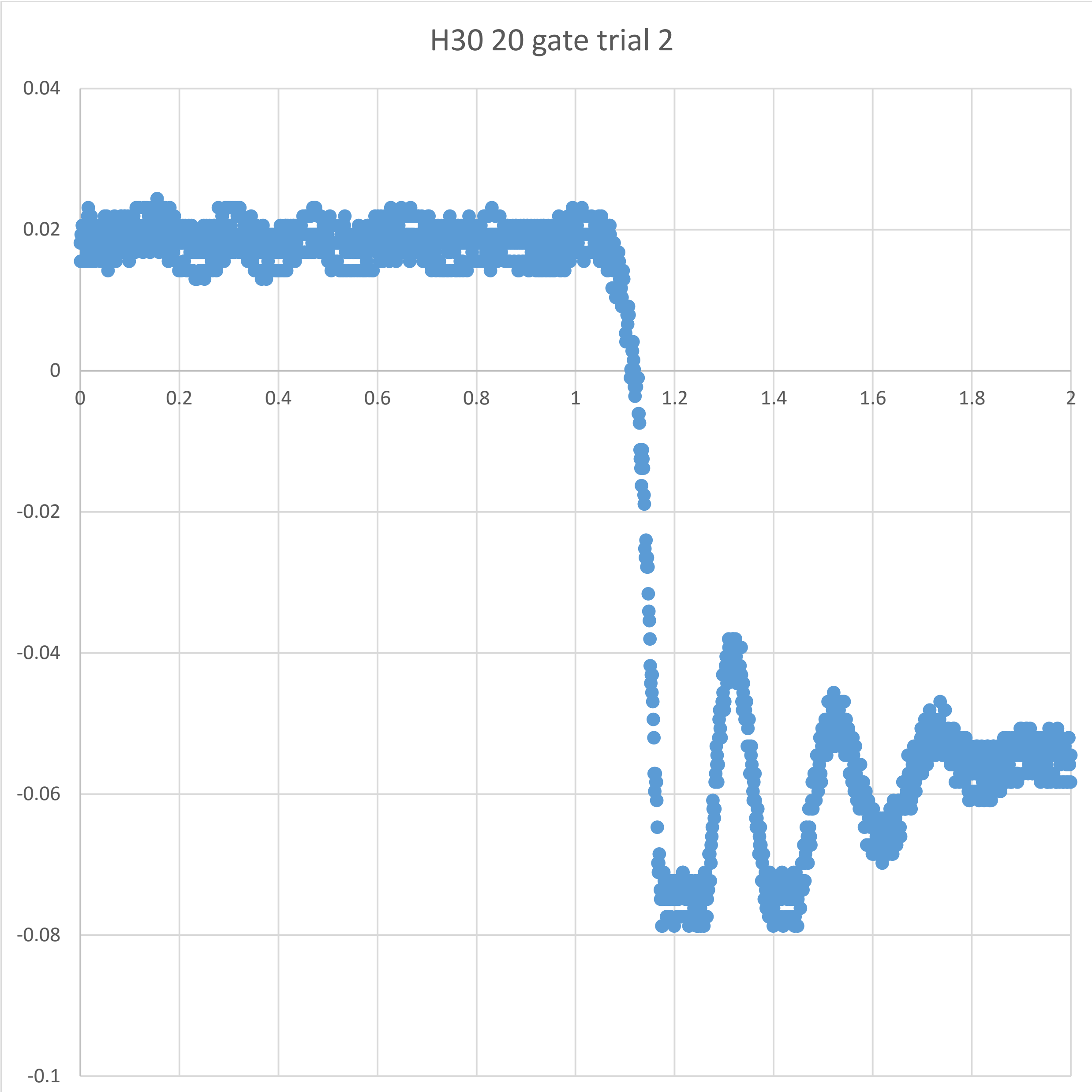


Figure 15. H30 20 gate trial 2

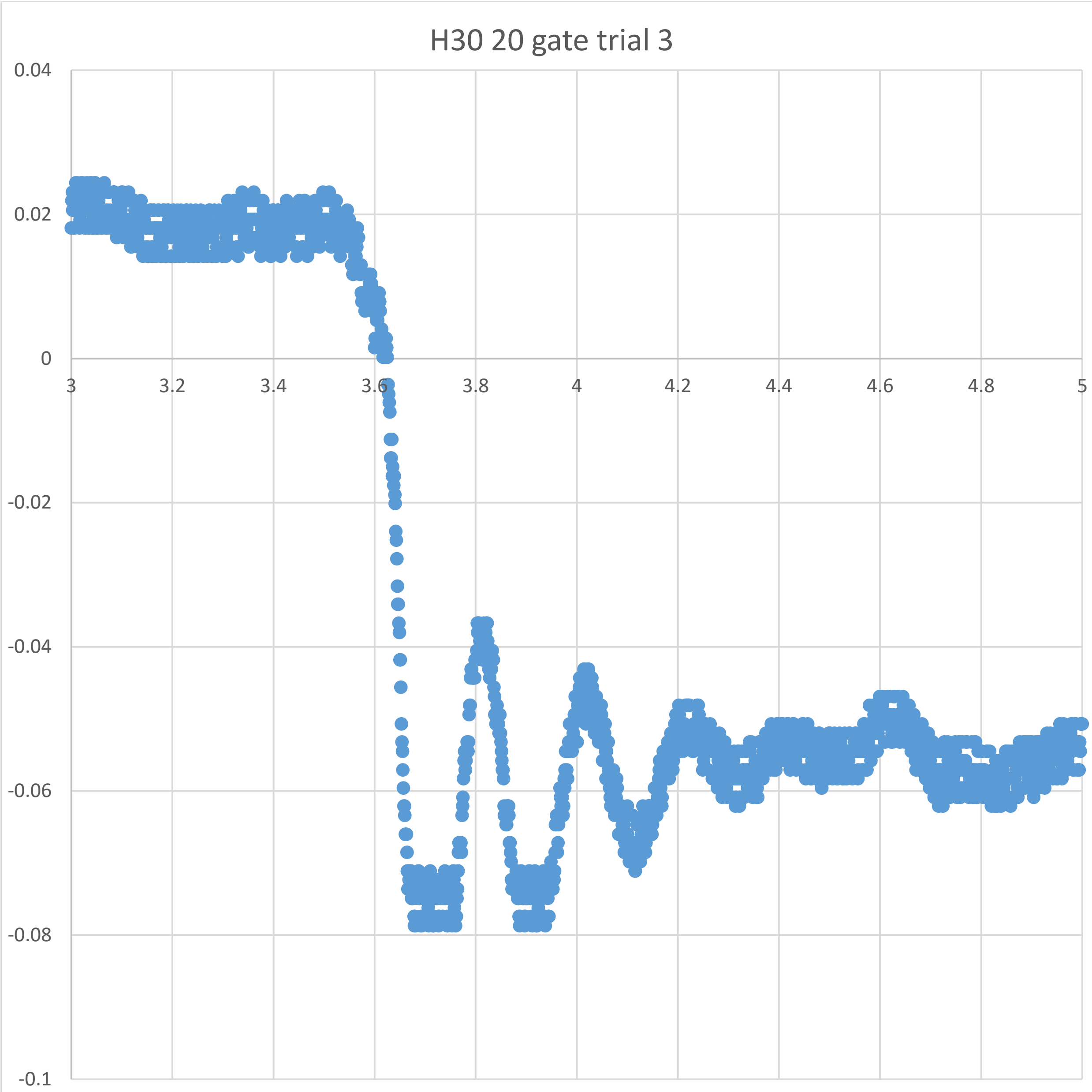


Figure 16. H30 20 gate trial 3

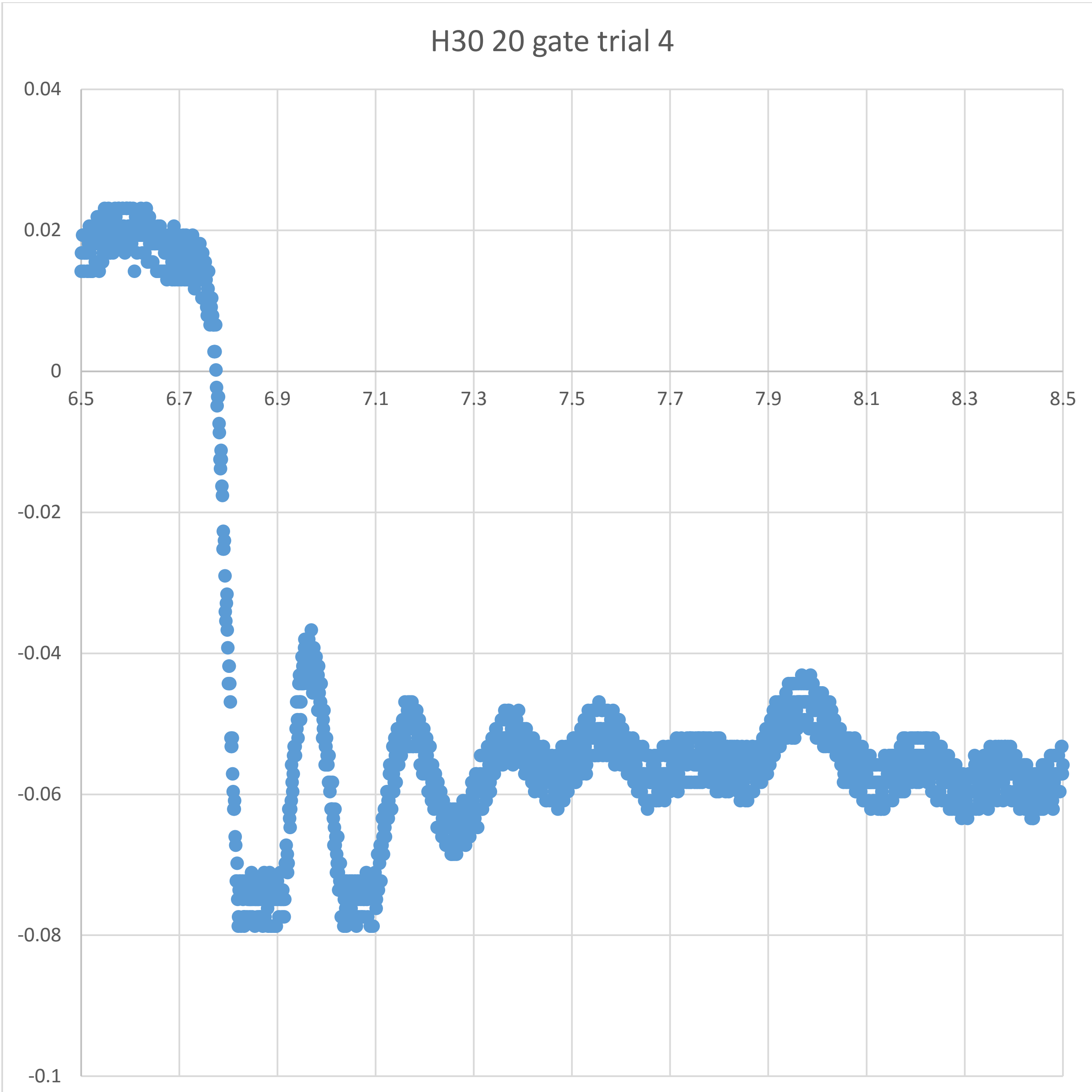


Figure 17. H30 20 gate trial 4

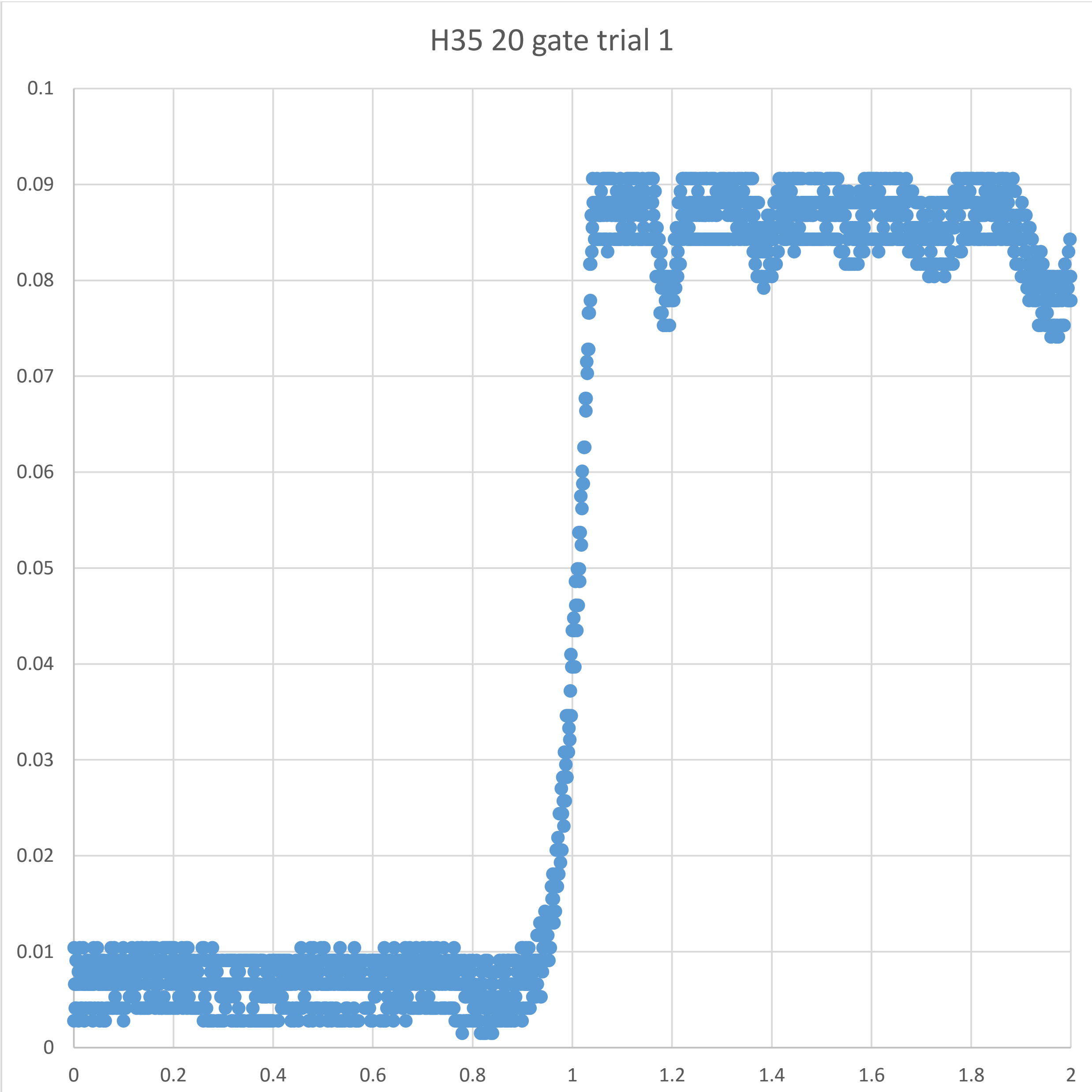


Figure 18. H30 20 gate trial 1

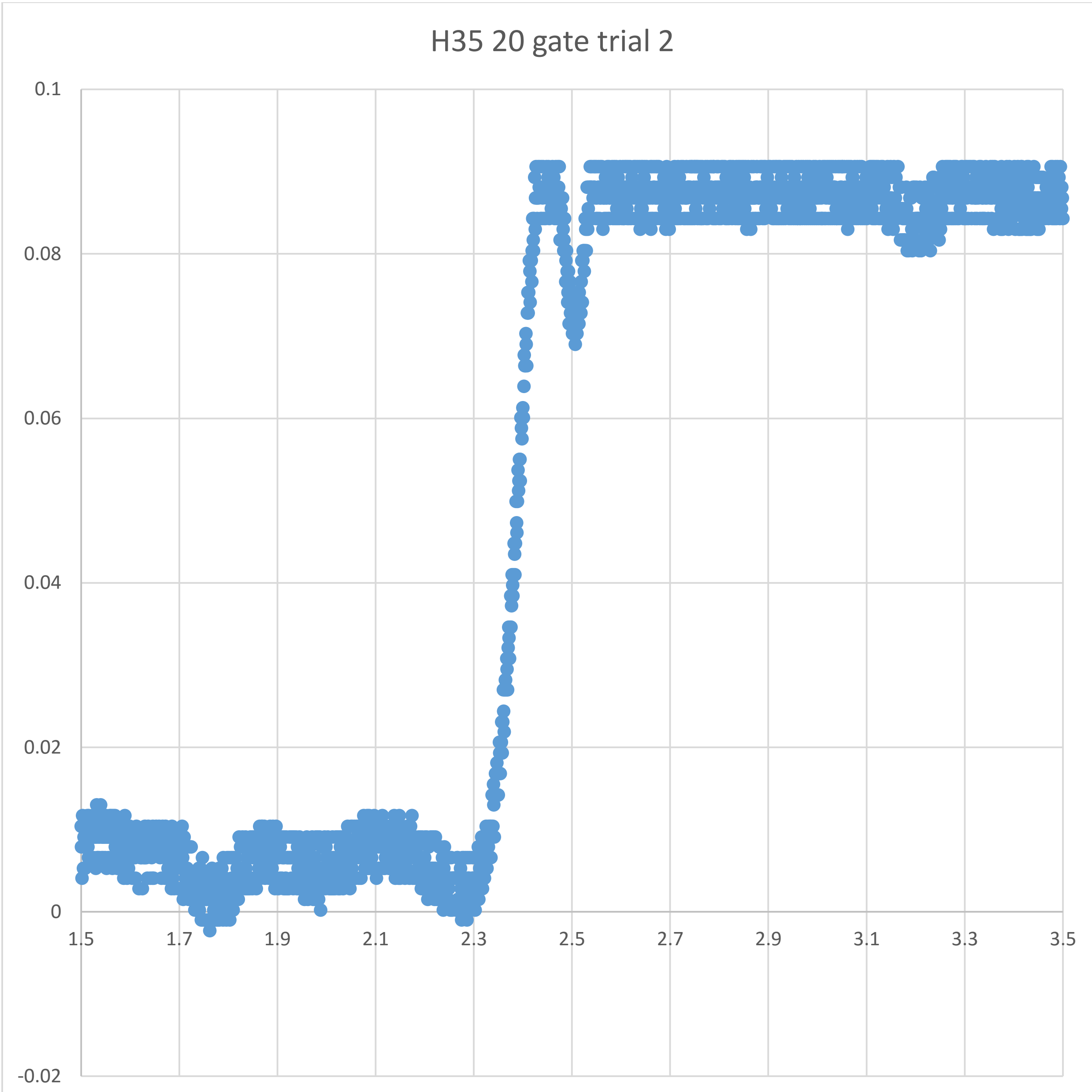


Figure 19. H35 20 gate trial 2

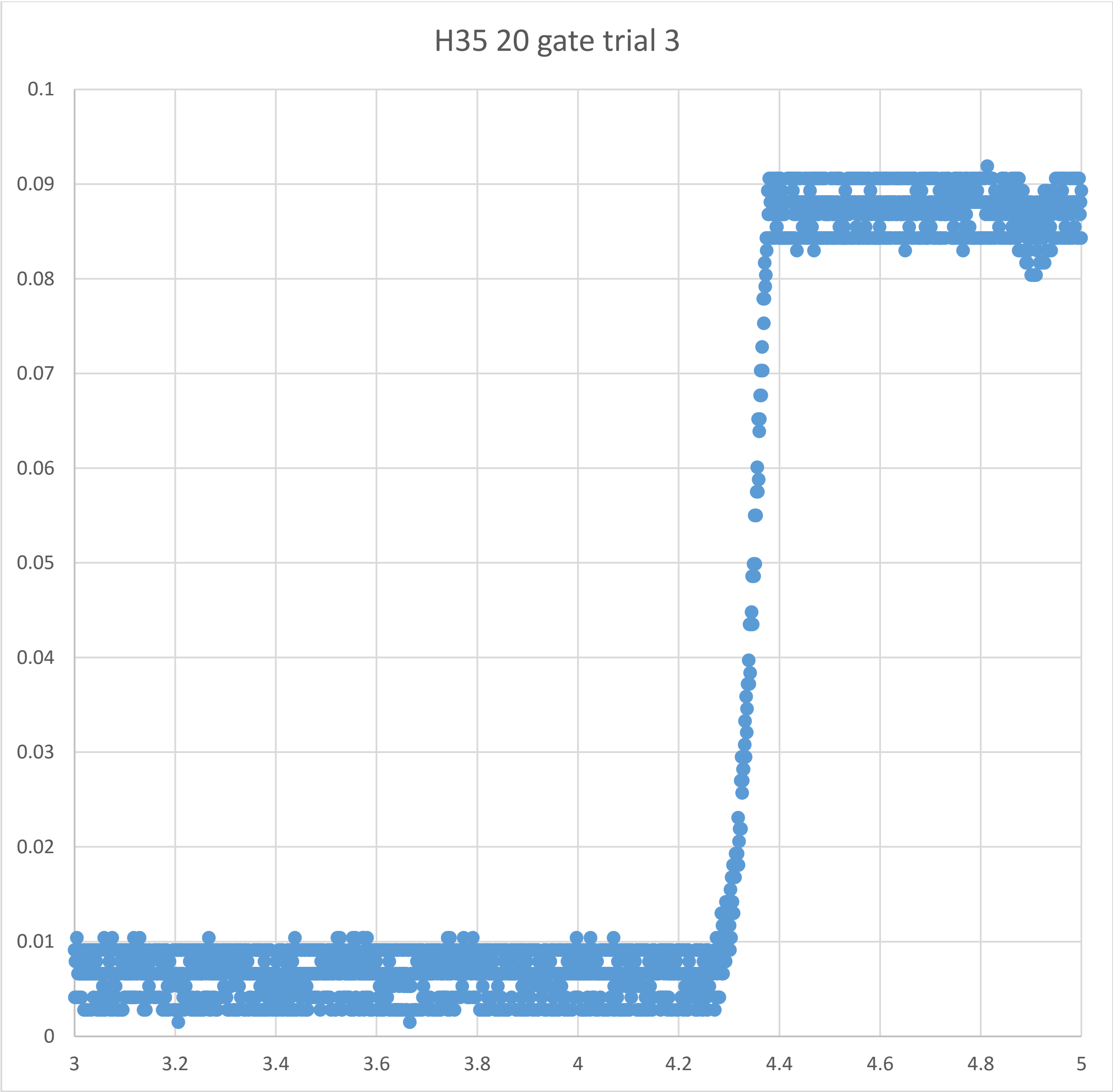


Figure 20. H35 20 gate trial 3

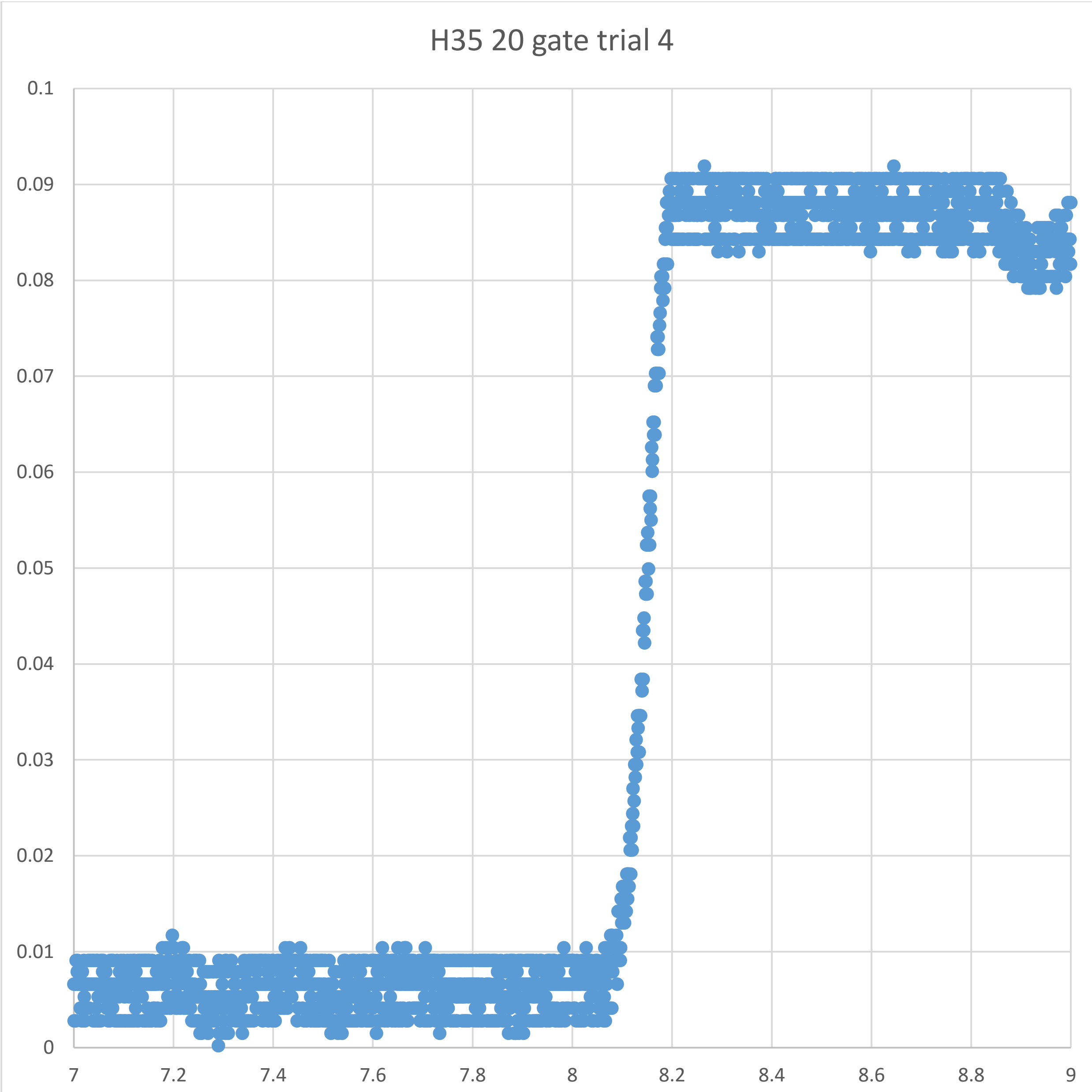


Figure 21. H35 20 gate trial 4

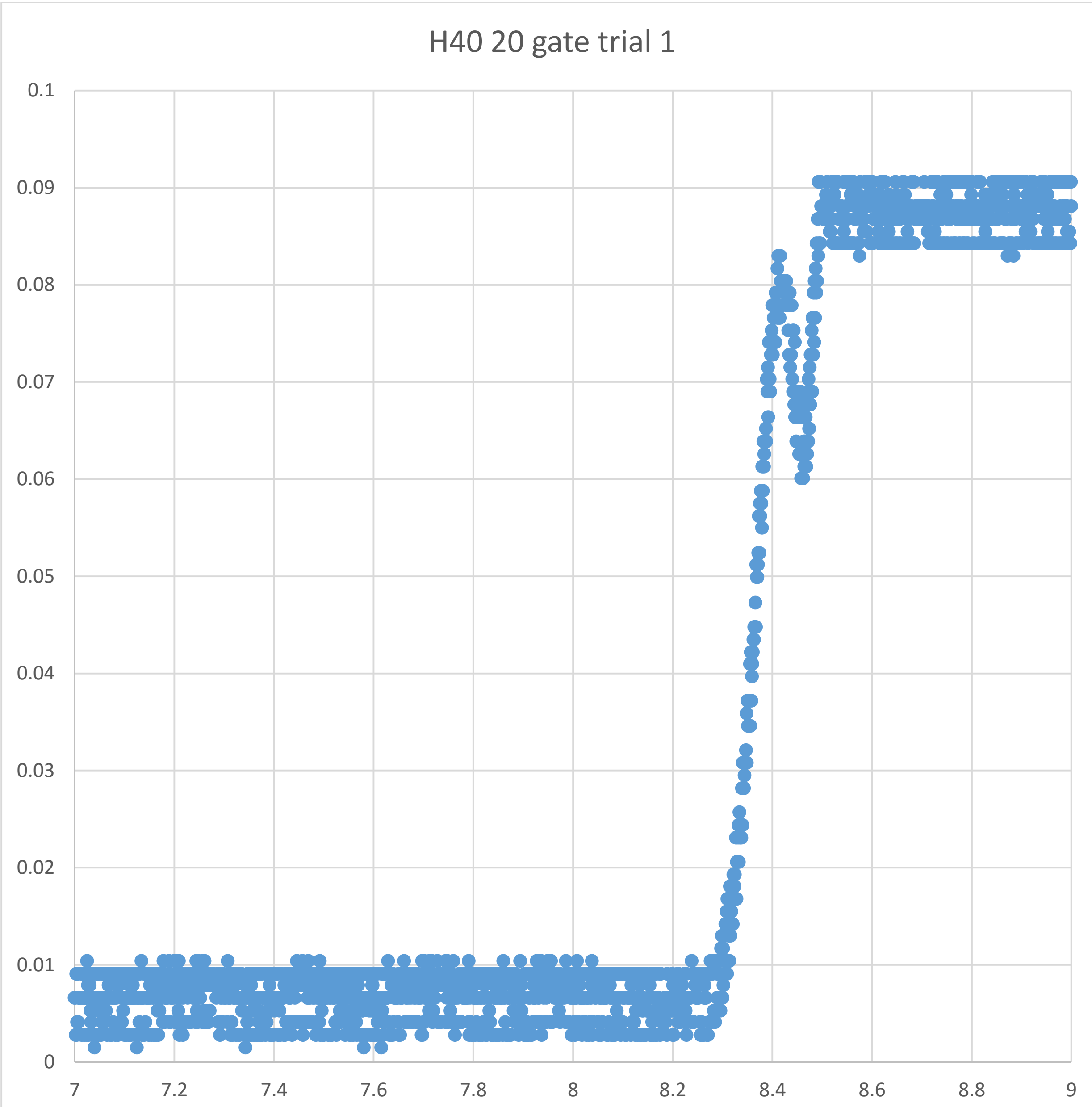


Figure 22. H40 20 gate trial 1

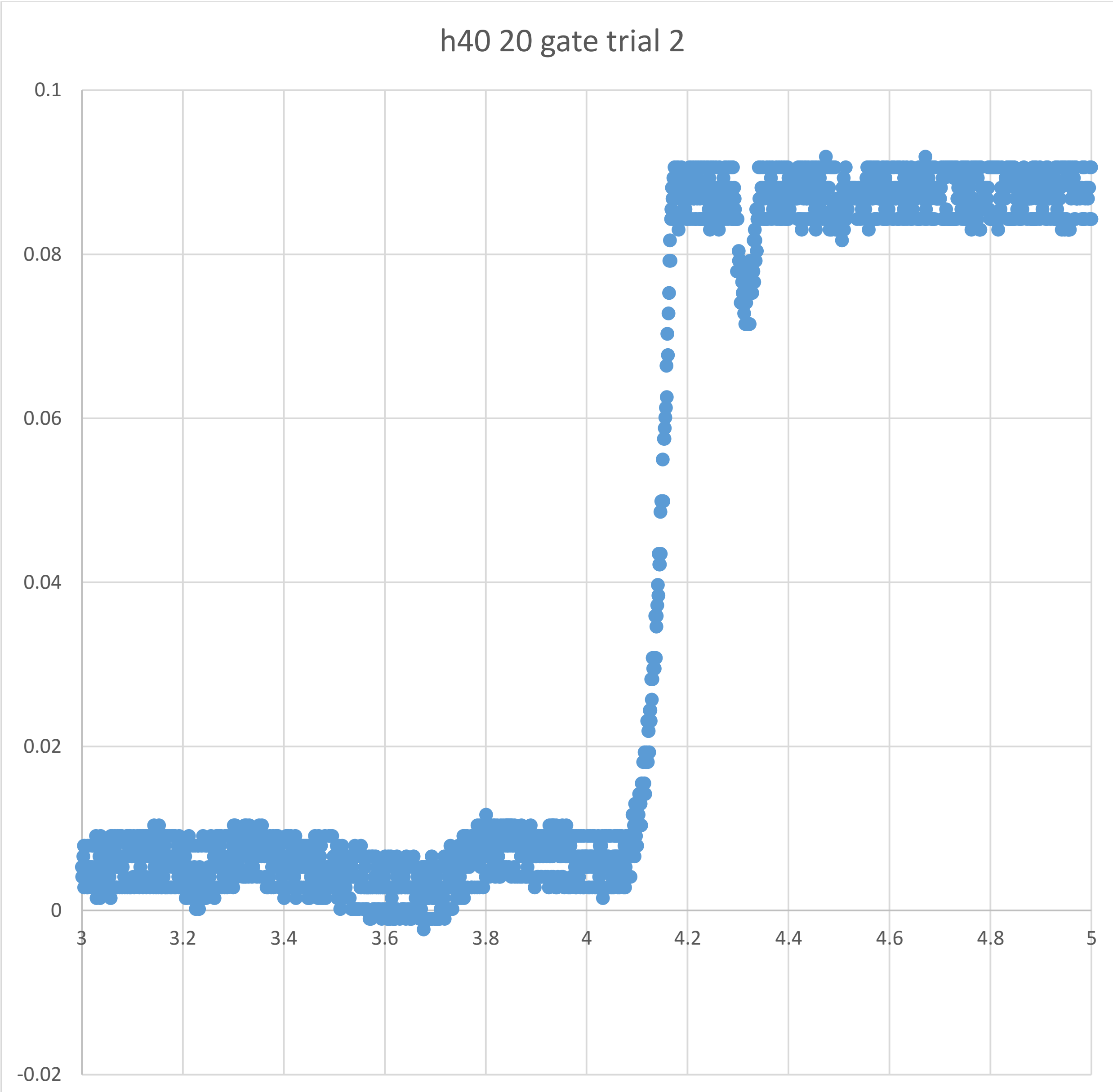


Figure 23. H40 20 gate trial 2

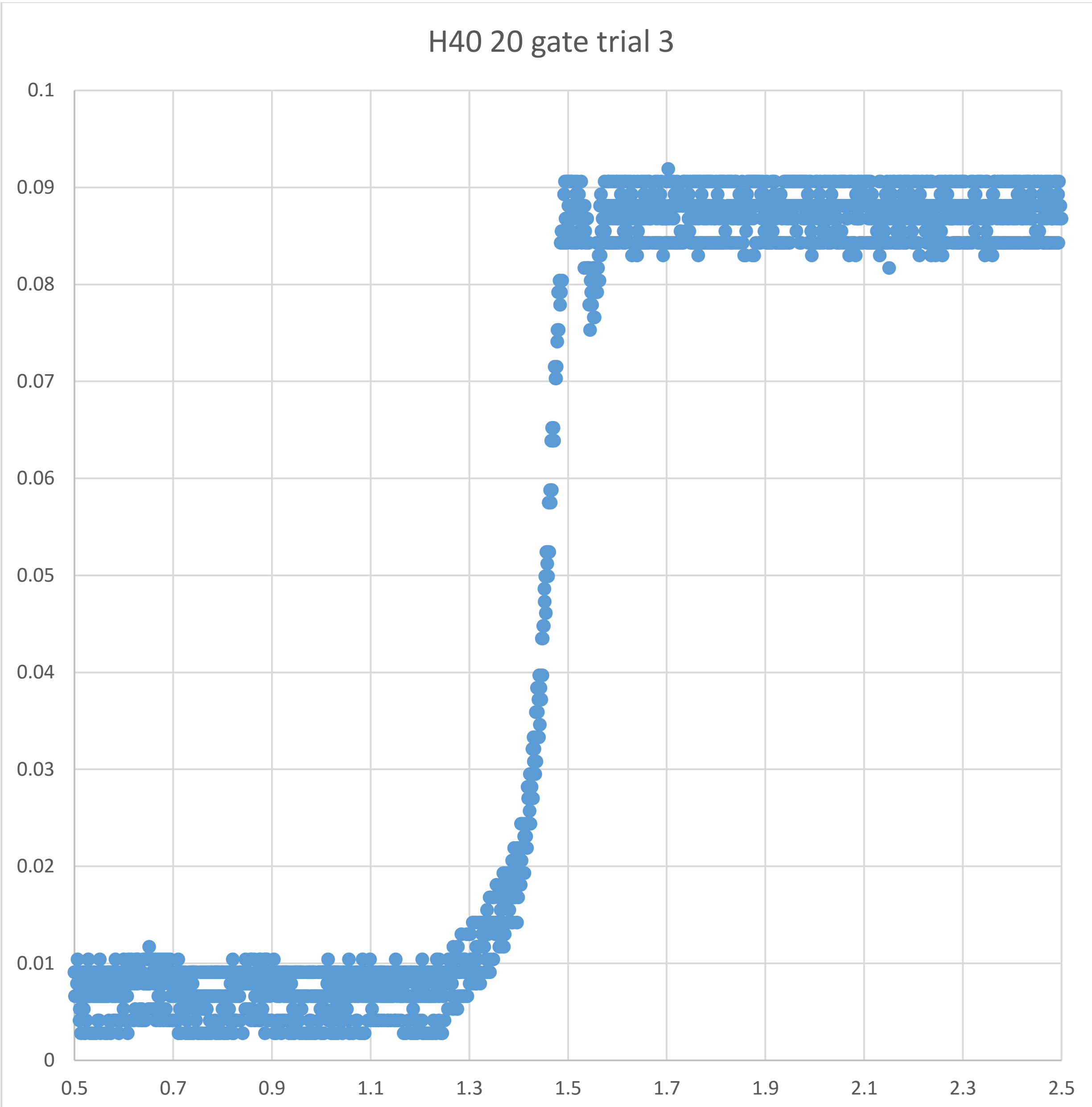


Figure 24. H40 20 gate trial 3

Appendix E-20 gate water start up time graphs second set

The graphs in appendix E are the 20 gate water start up time results from each trial. The “H” denotes the reference height which is in centimeters. To obtain the forebay to tail water height, add 20.06 centimeters the reference height. In the graphs if there is a missing number in the sequence it means that the data produced an error and was skipped. The second set was an extra set done for the 20 gate in order to justify the trend in data was appearing.

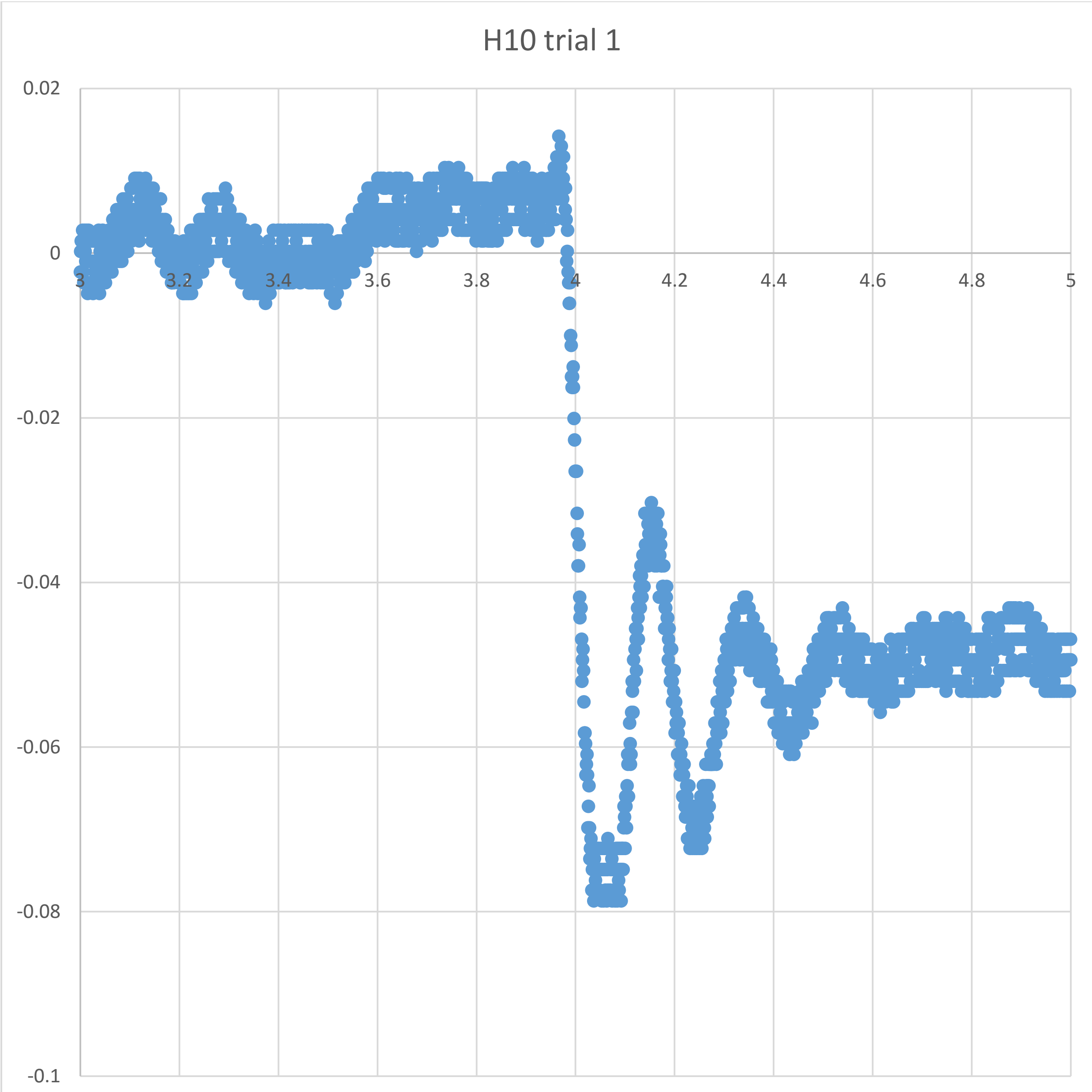


Figure 1. H10 trial 1

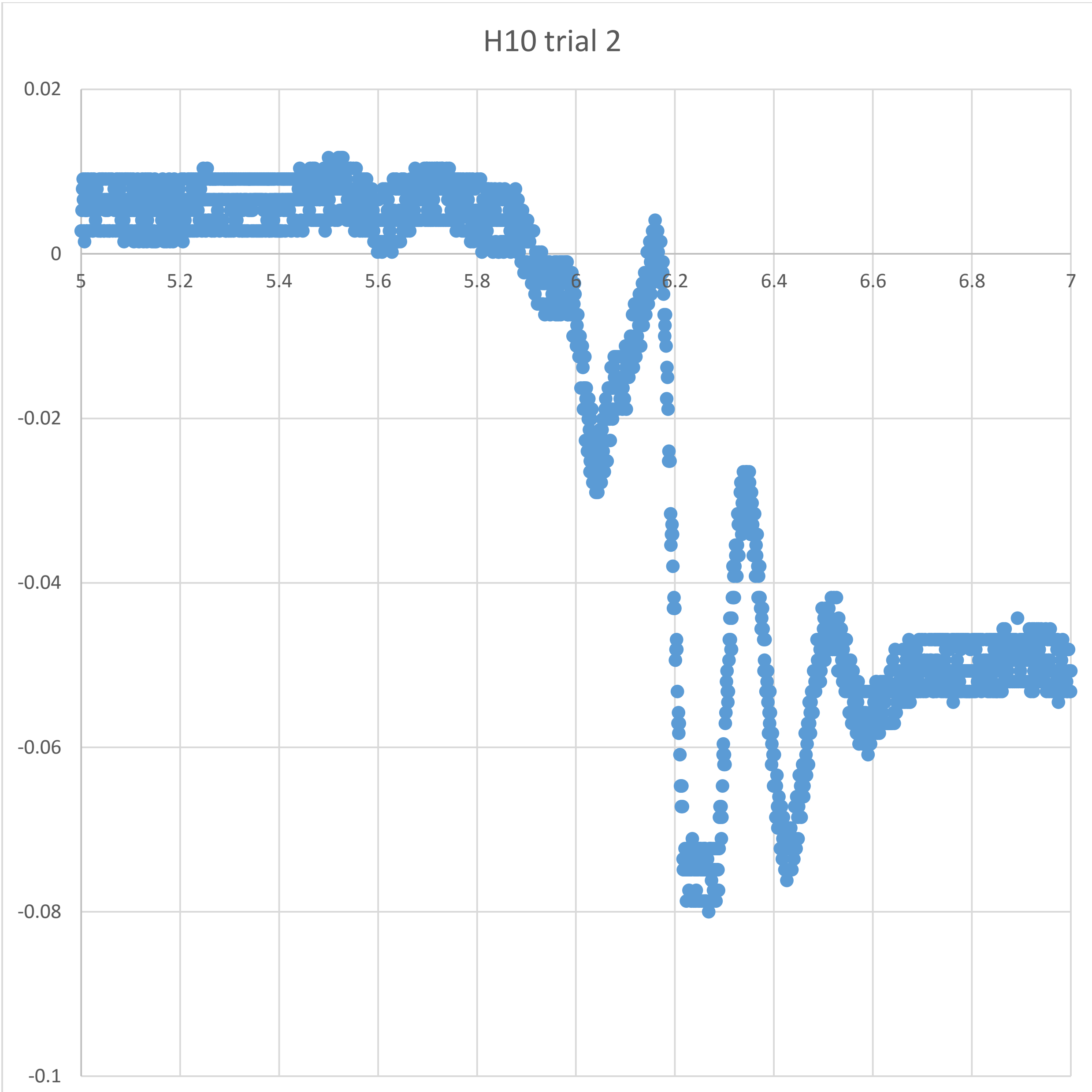


Figure 2. H10 trial 2

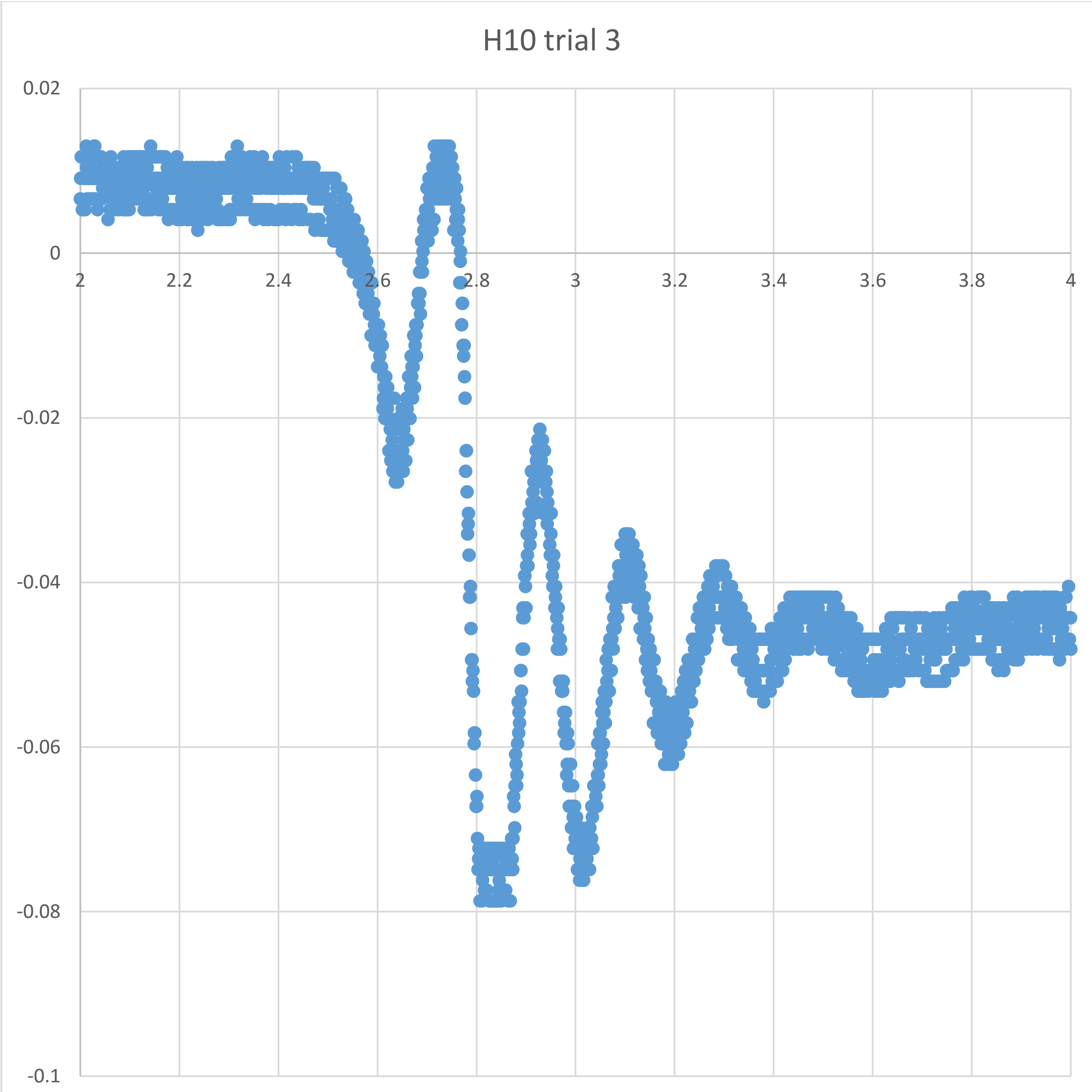


Figure 3. H10 trial 3

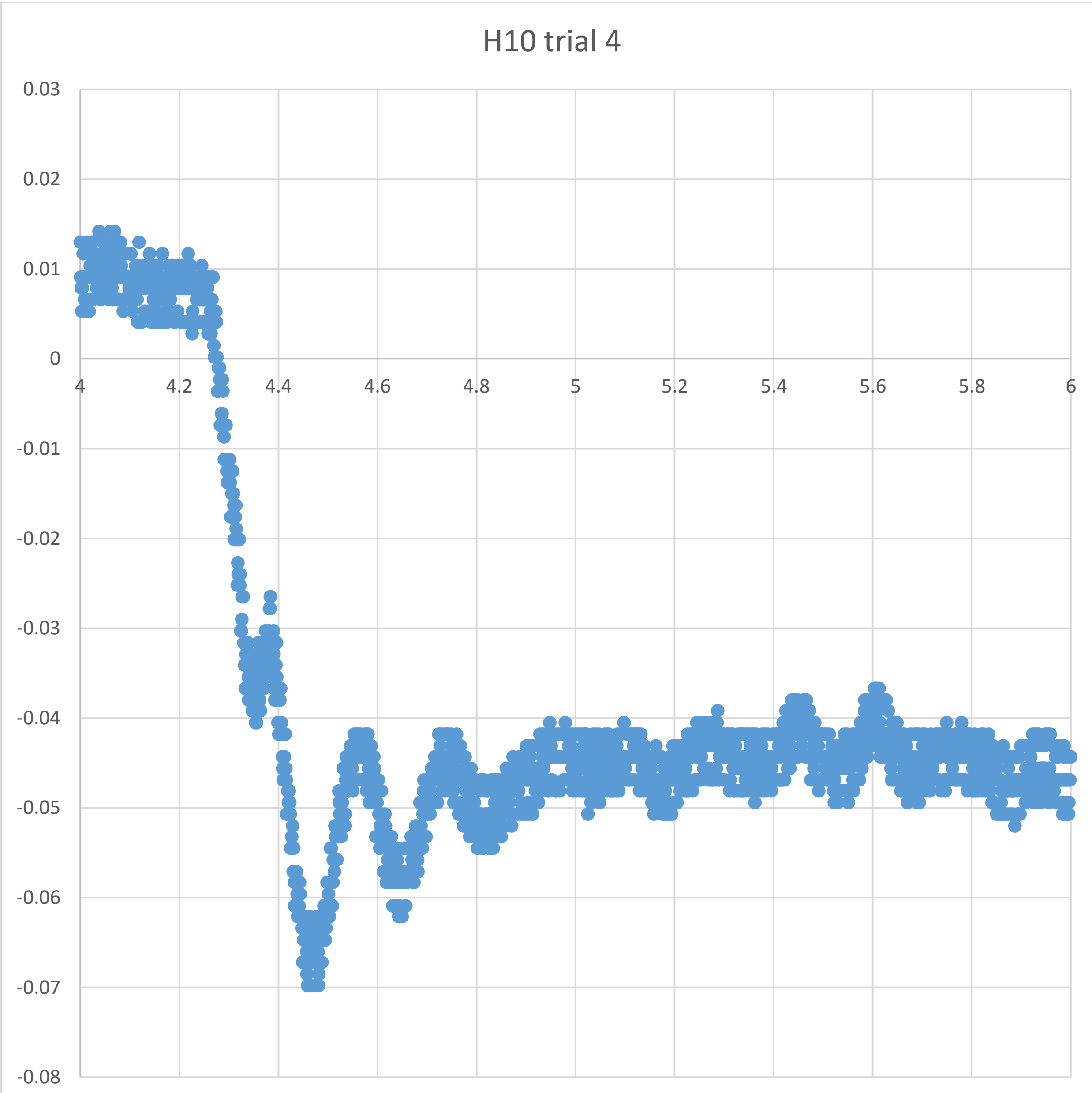


Figure 4. H10 trial 4

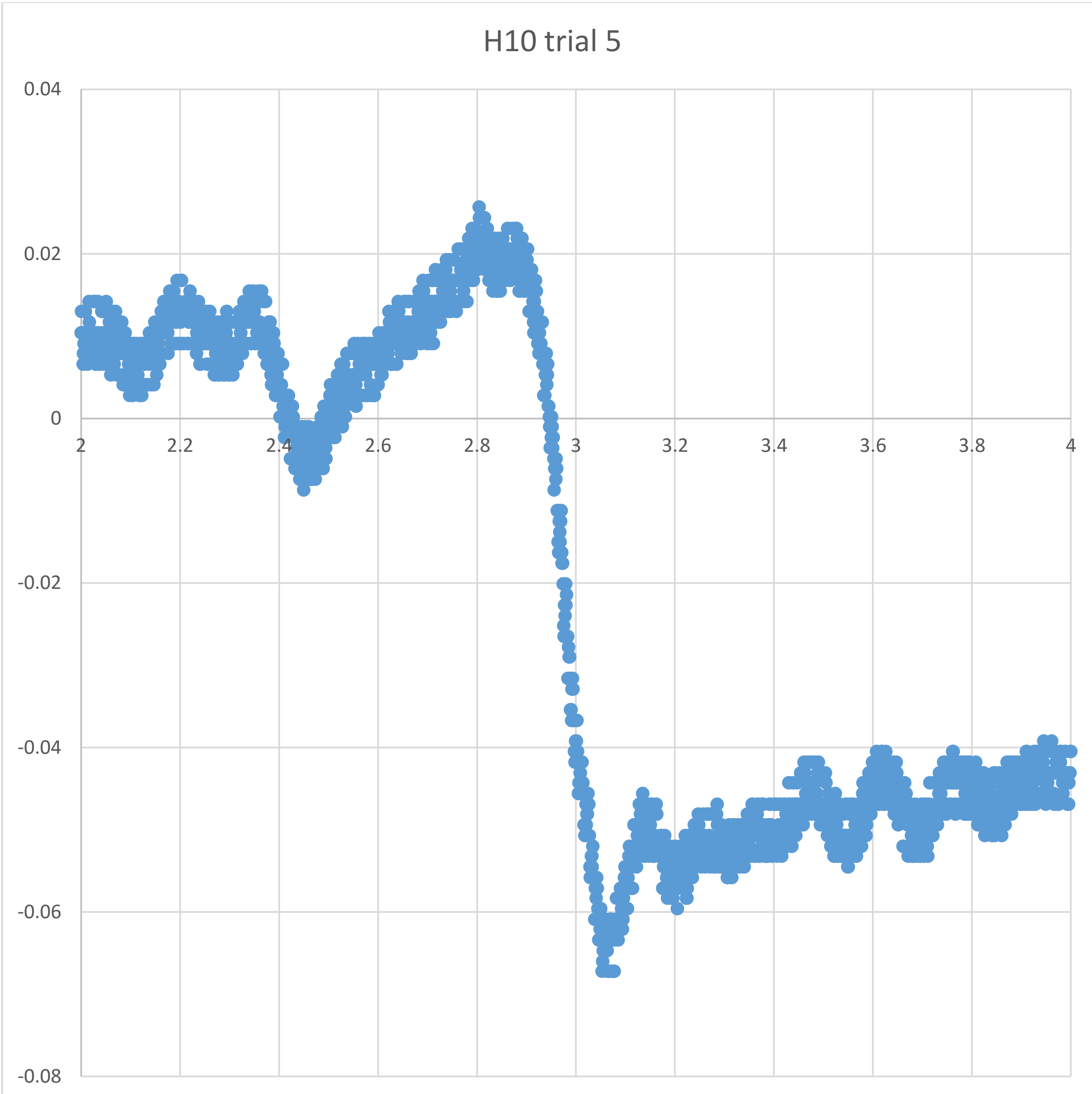


Figure 5. H10 trial 5

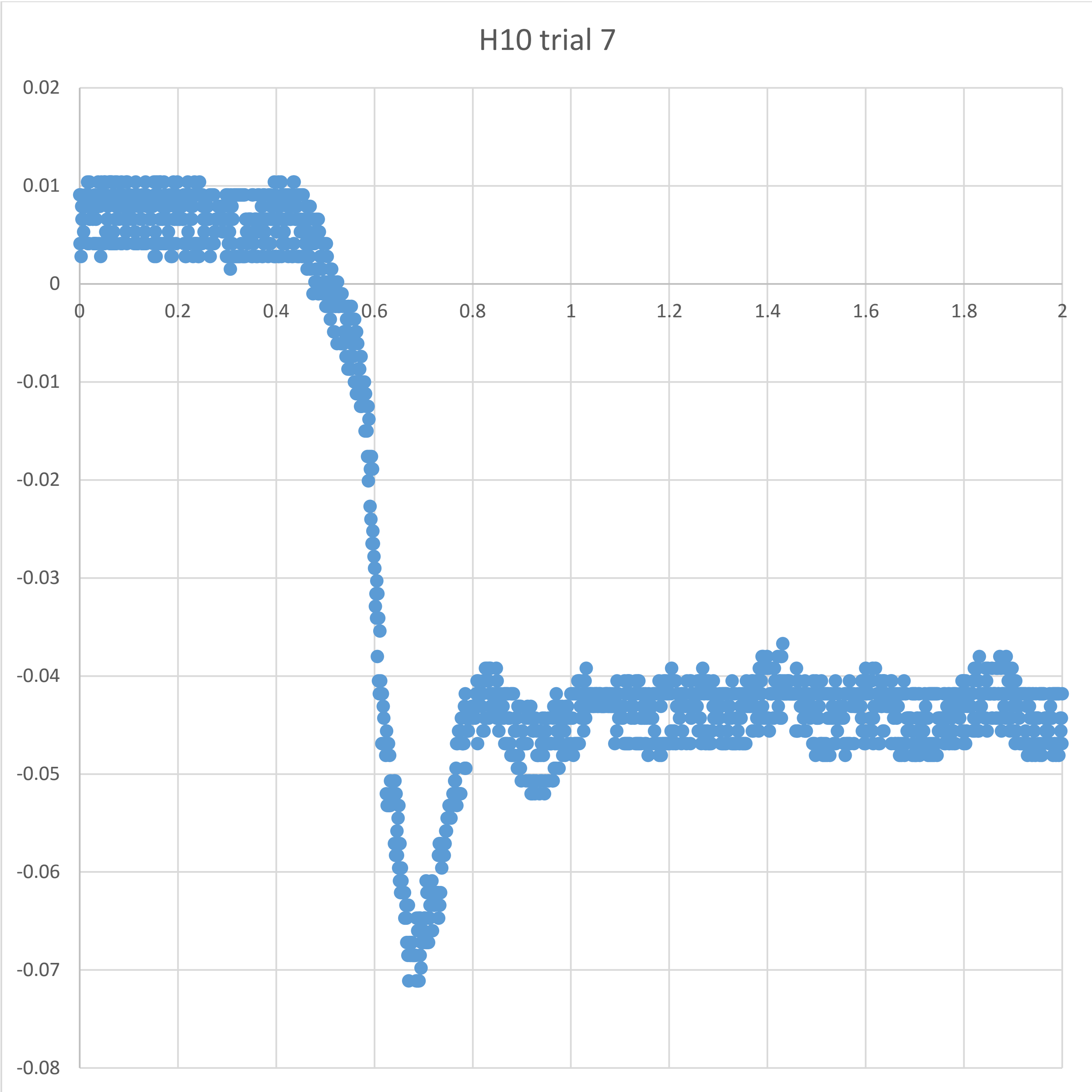


Figure 6. H10 trial 7

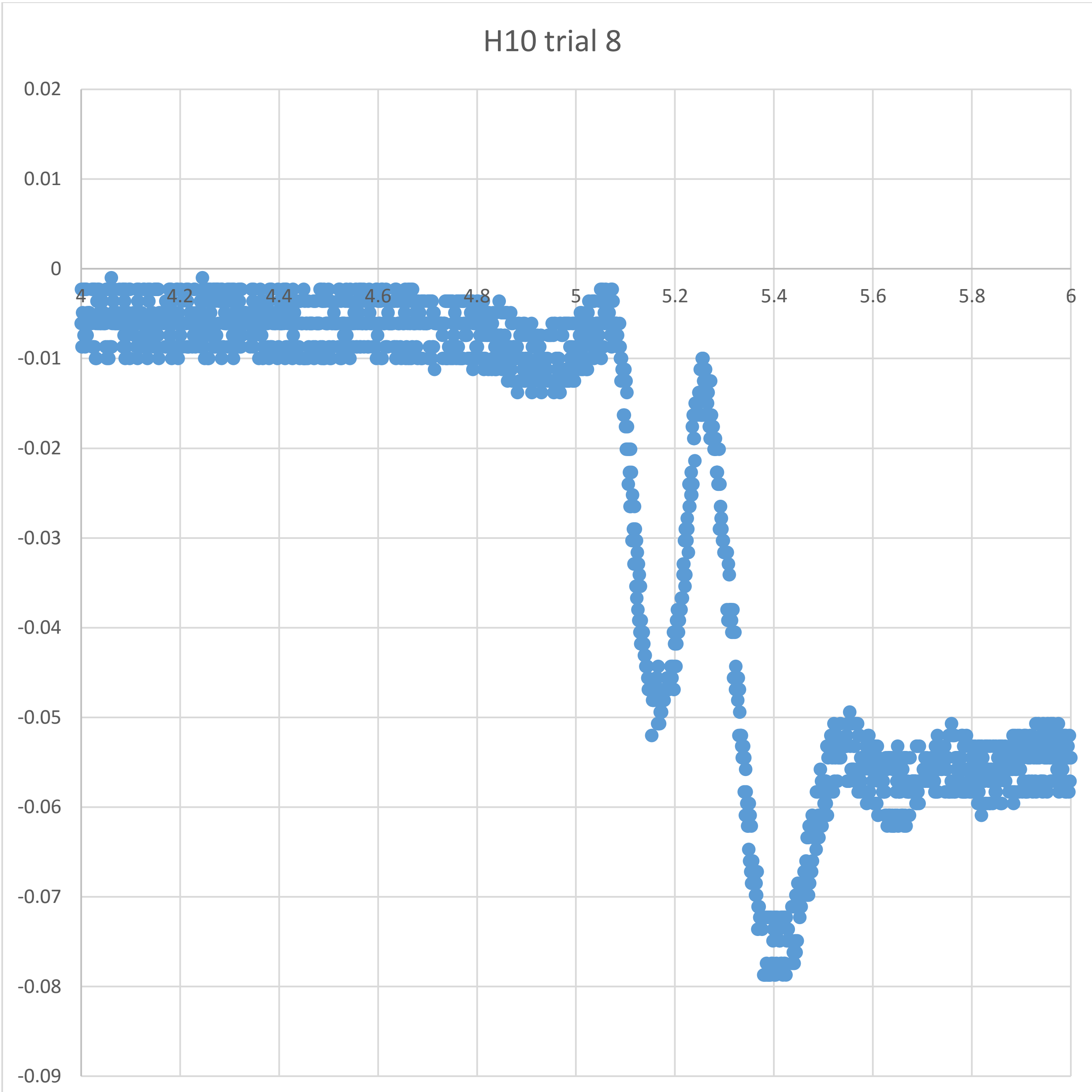


Figure 7. H10 trial 8

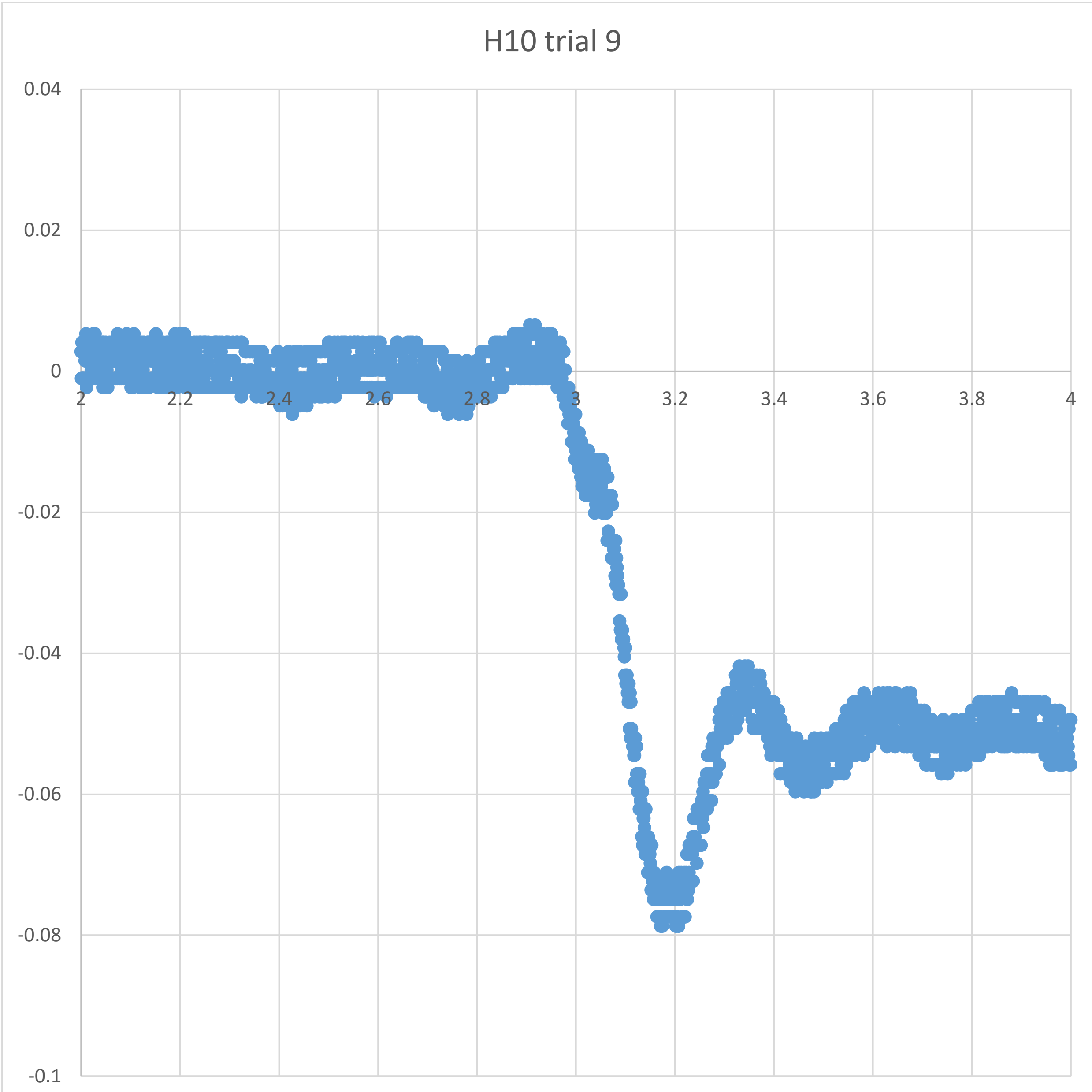


Figure 8. H10 trial 9

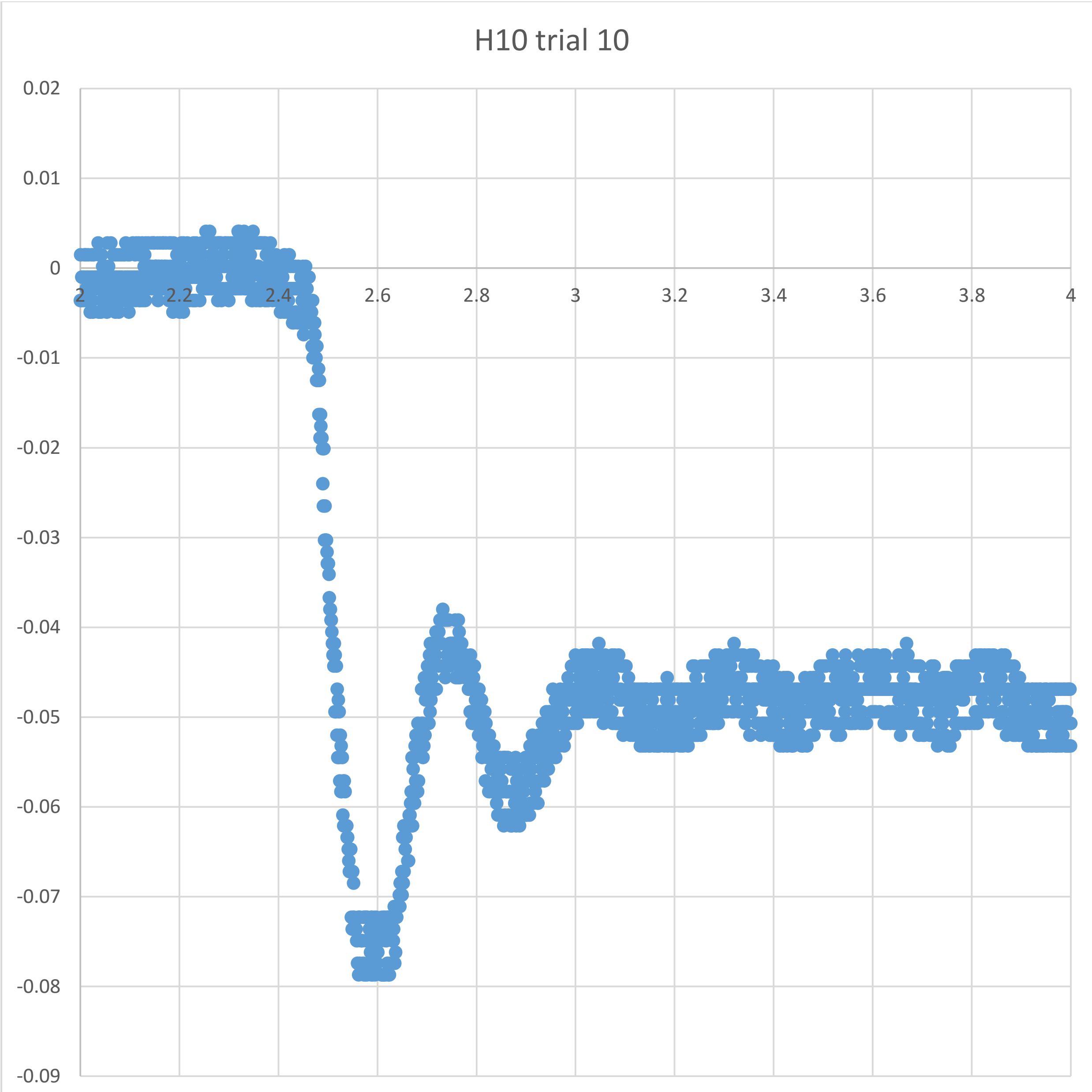


Figure 9. H10 trial 10

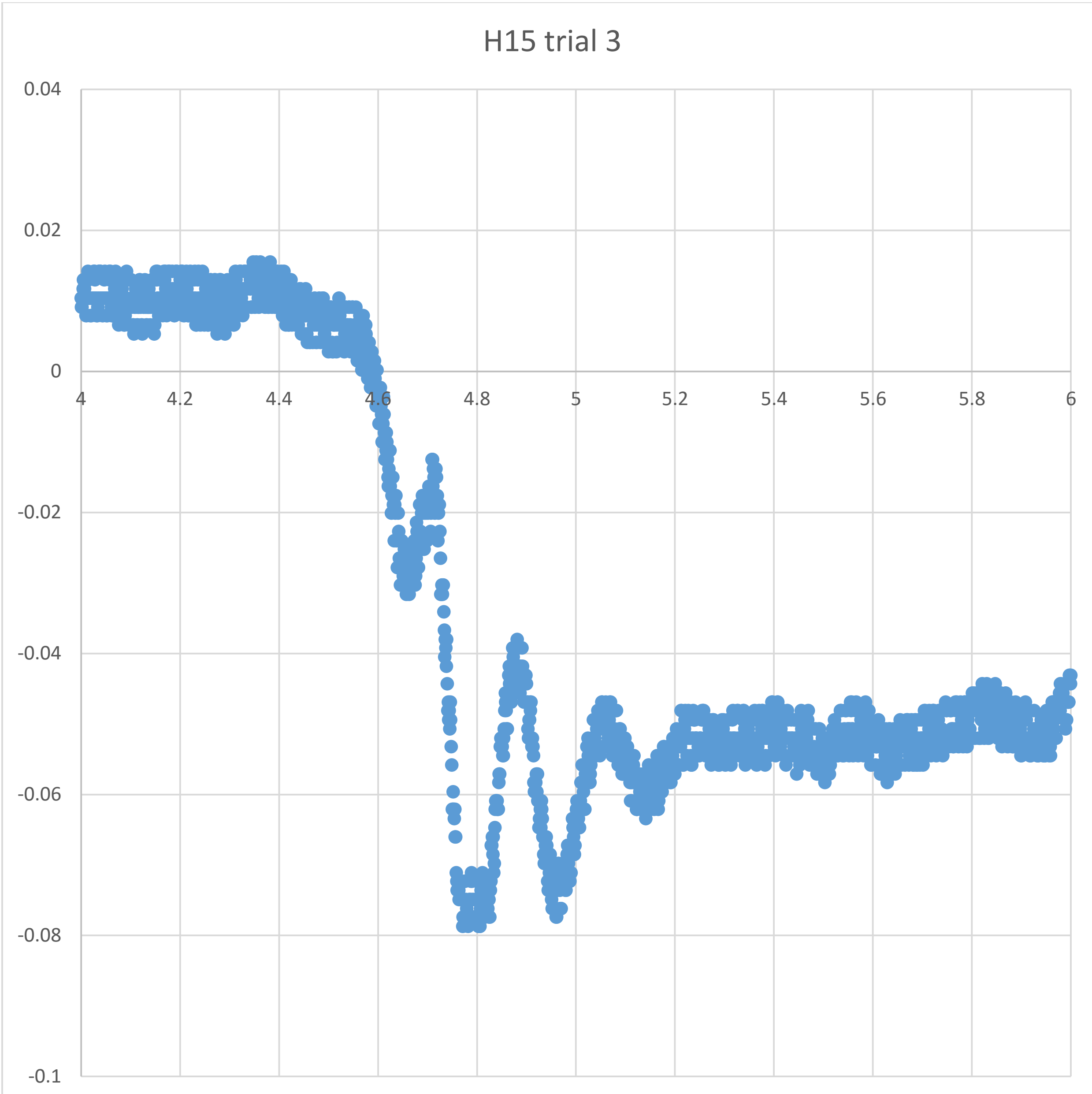


Figure 10. H15 trial 3

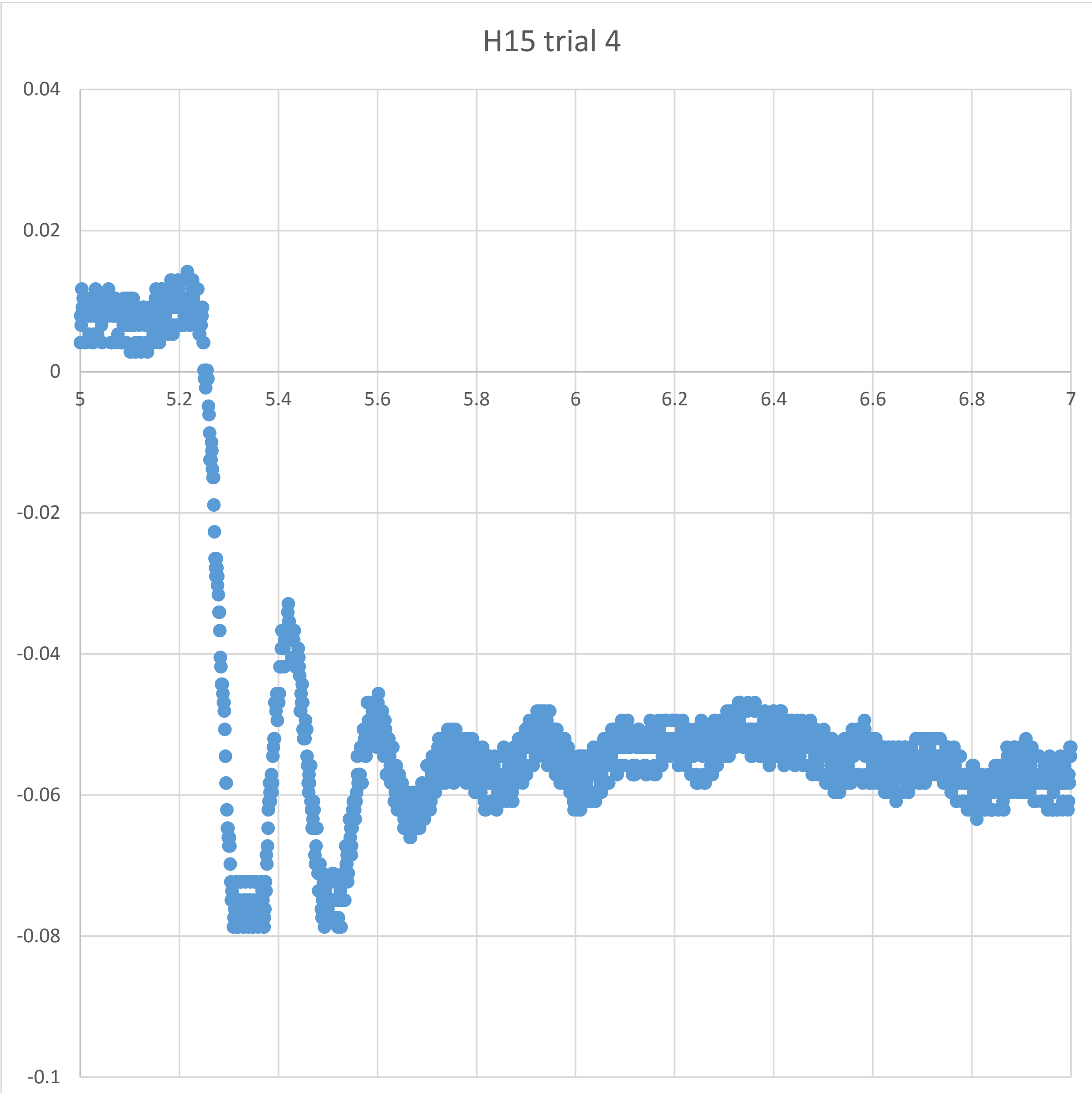


Figure 11. H15 trial 4

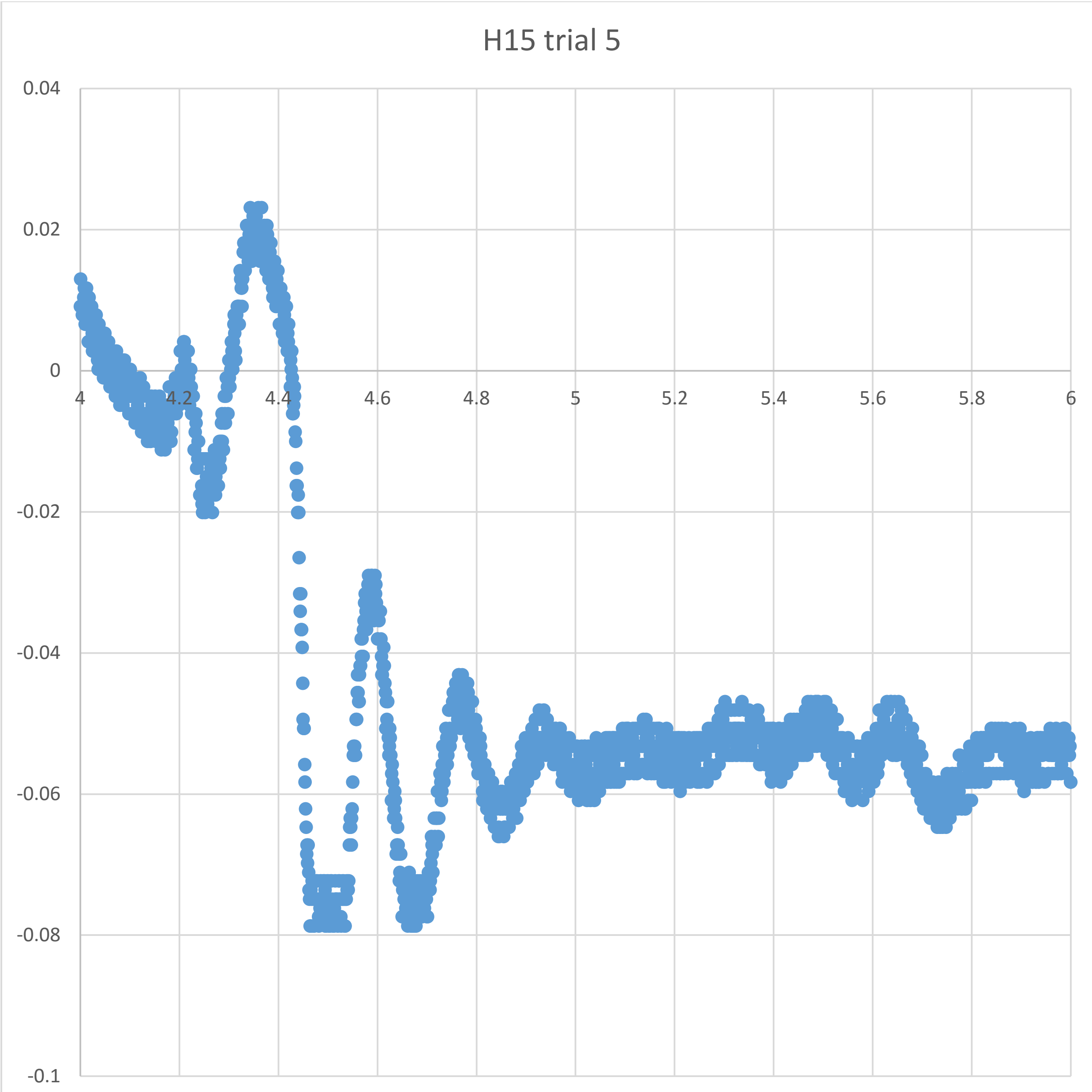


Figure 12. H15 trial 5

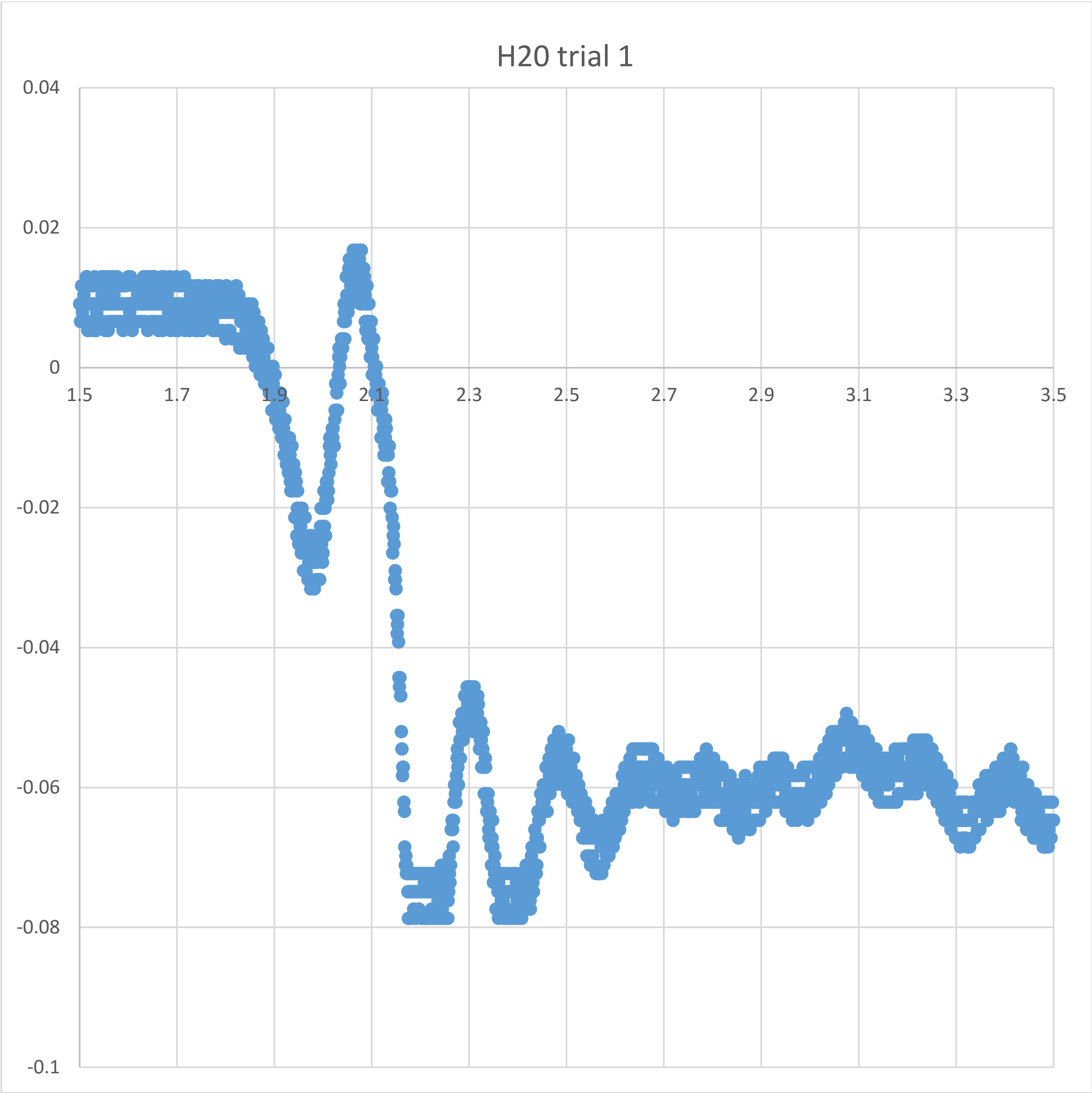


Figure 13. H20 trial 1

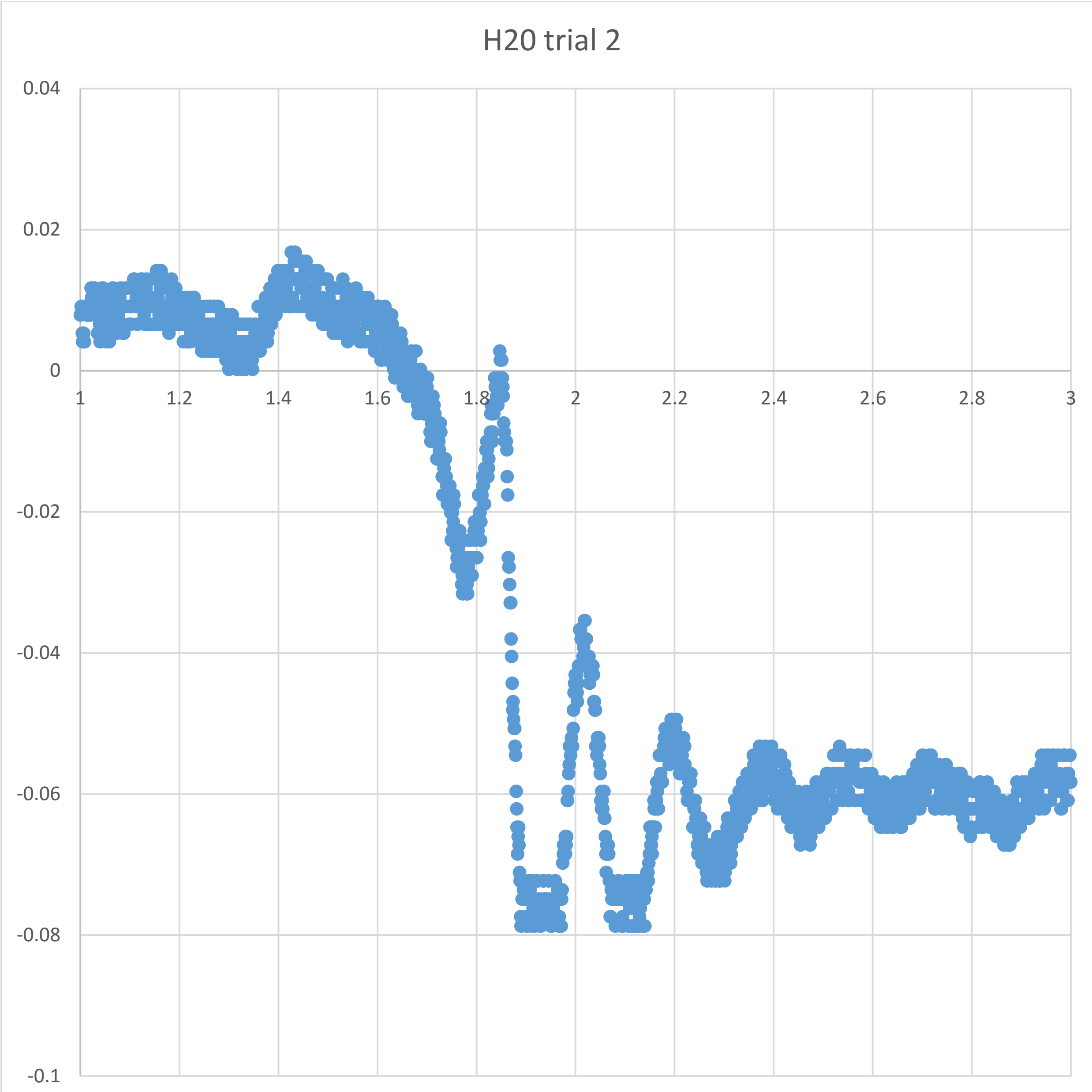


Figure 14. H20 trial 2

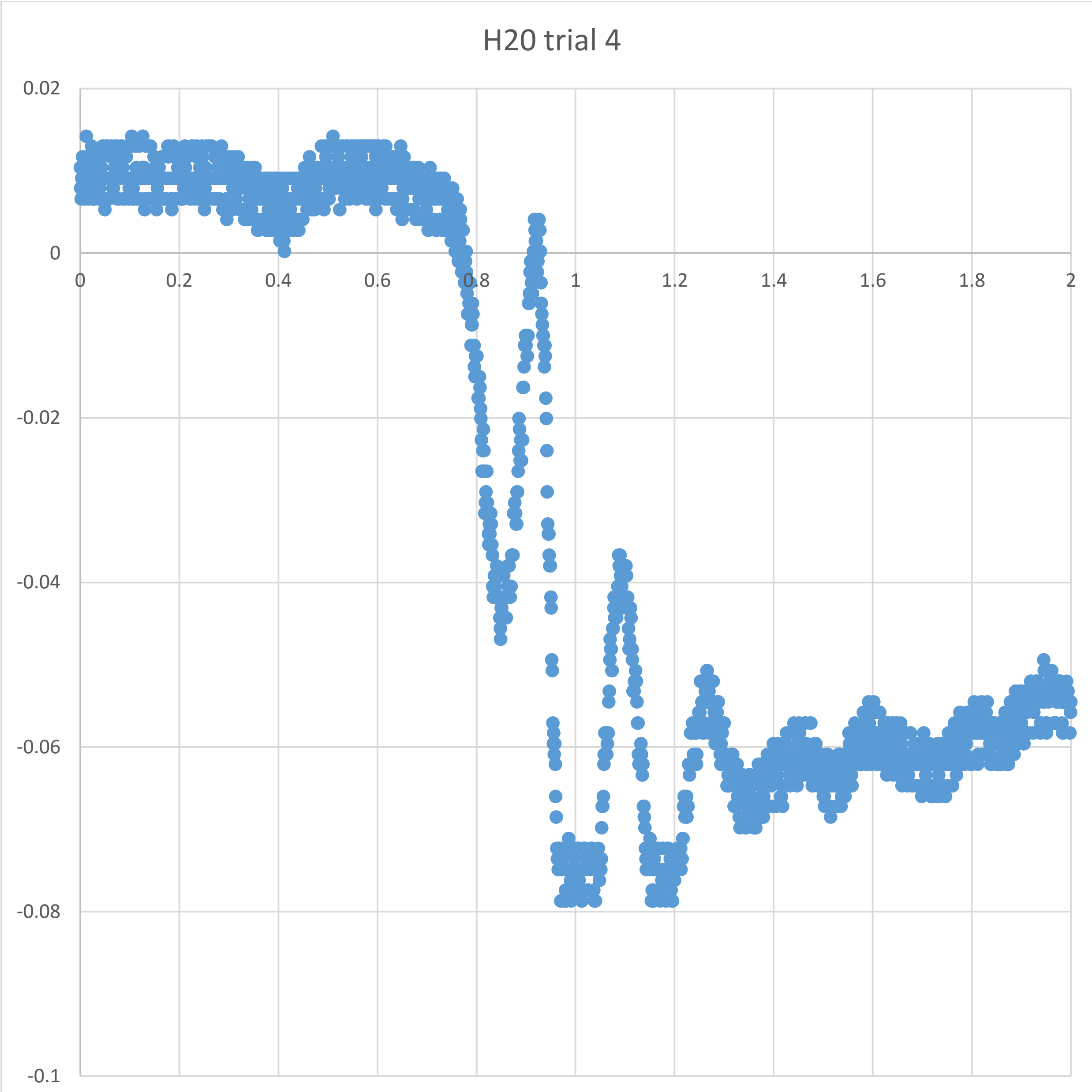


Figure 15. H20 trial 4

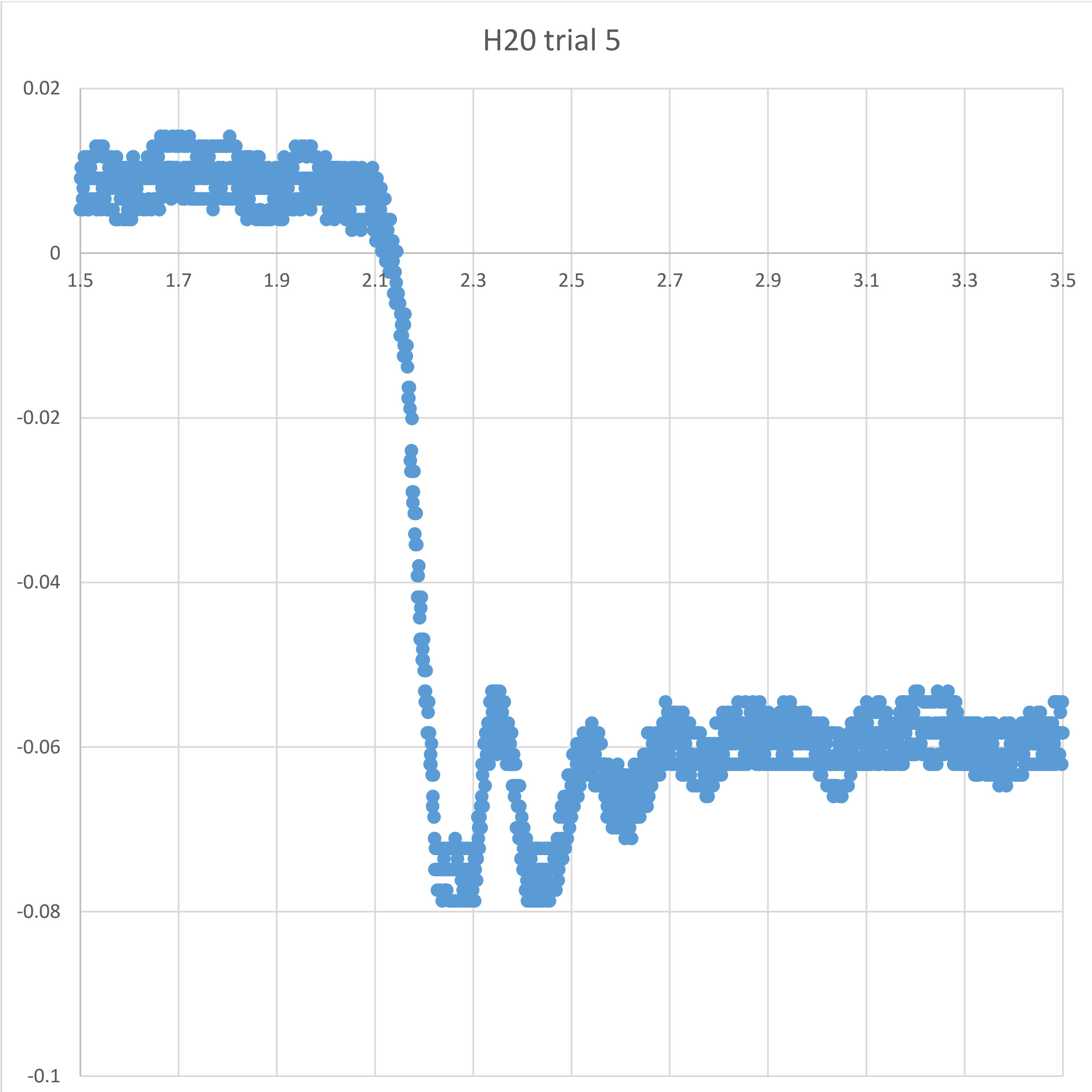


Figure 16. H20 trial 5

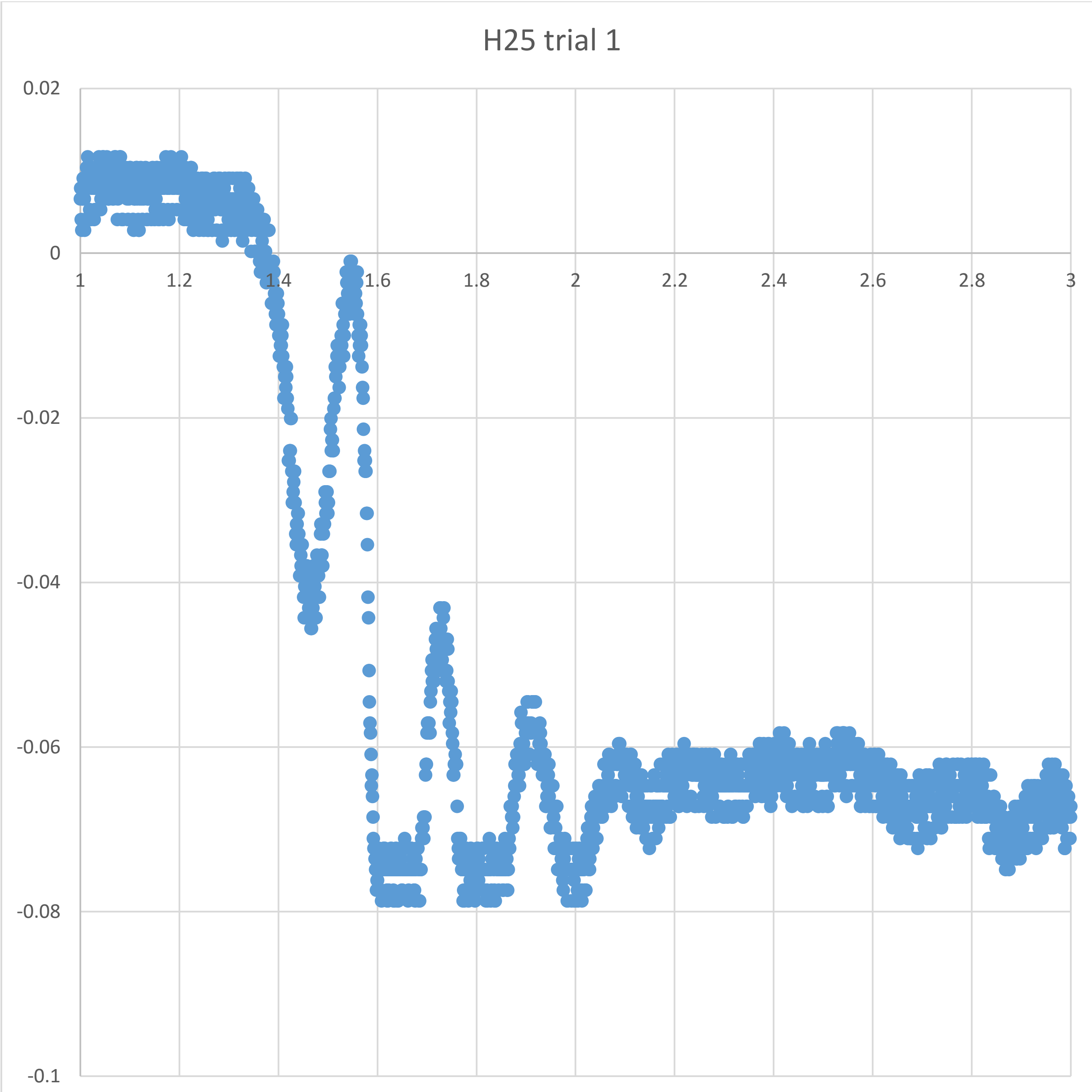


Figure 17. H25 trial 1

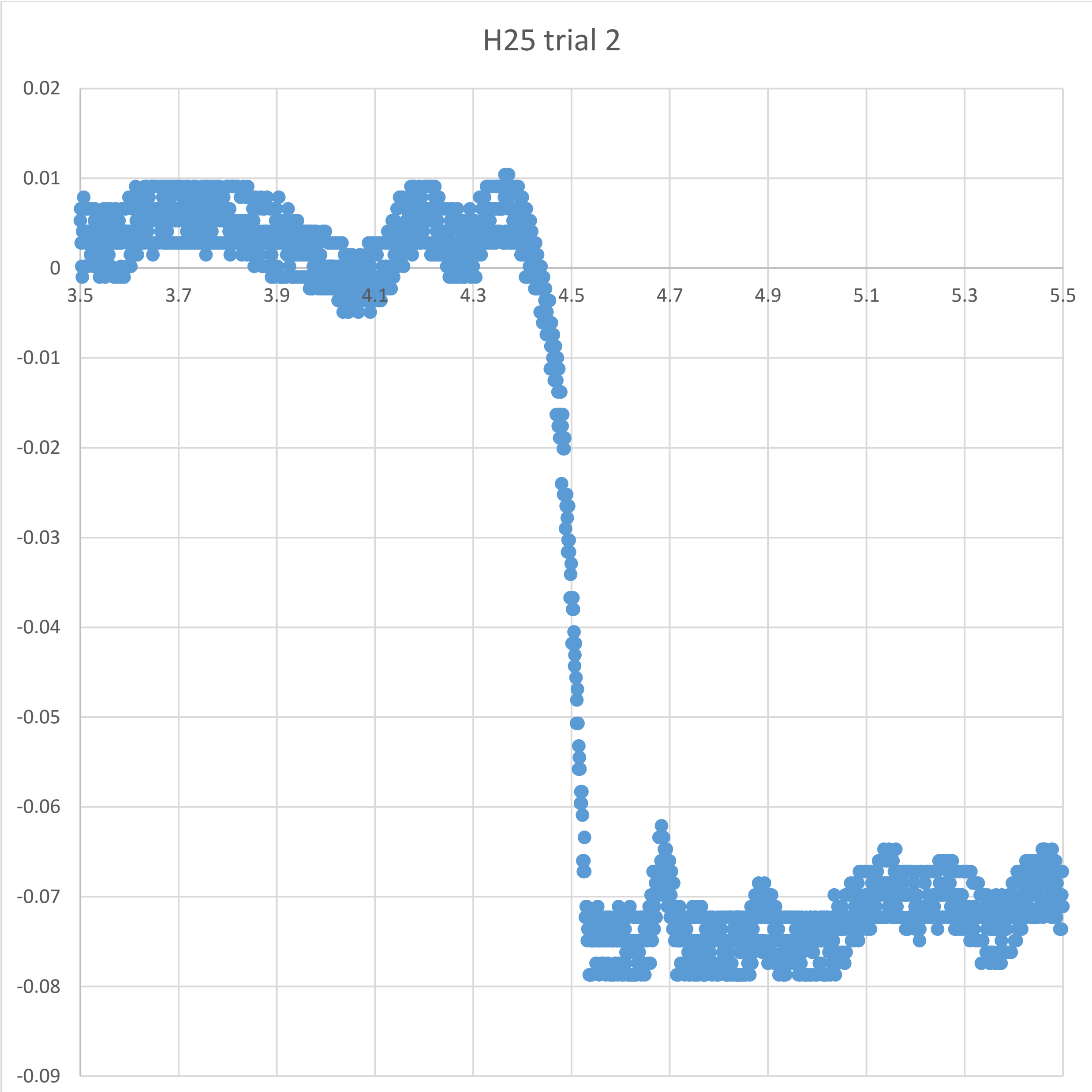


Figure 18. H25 trial 2

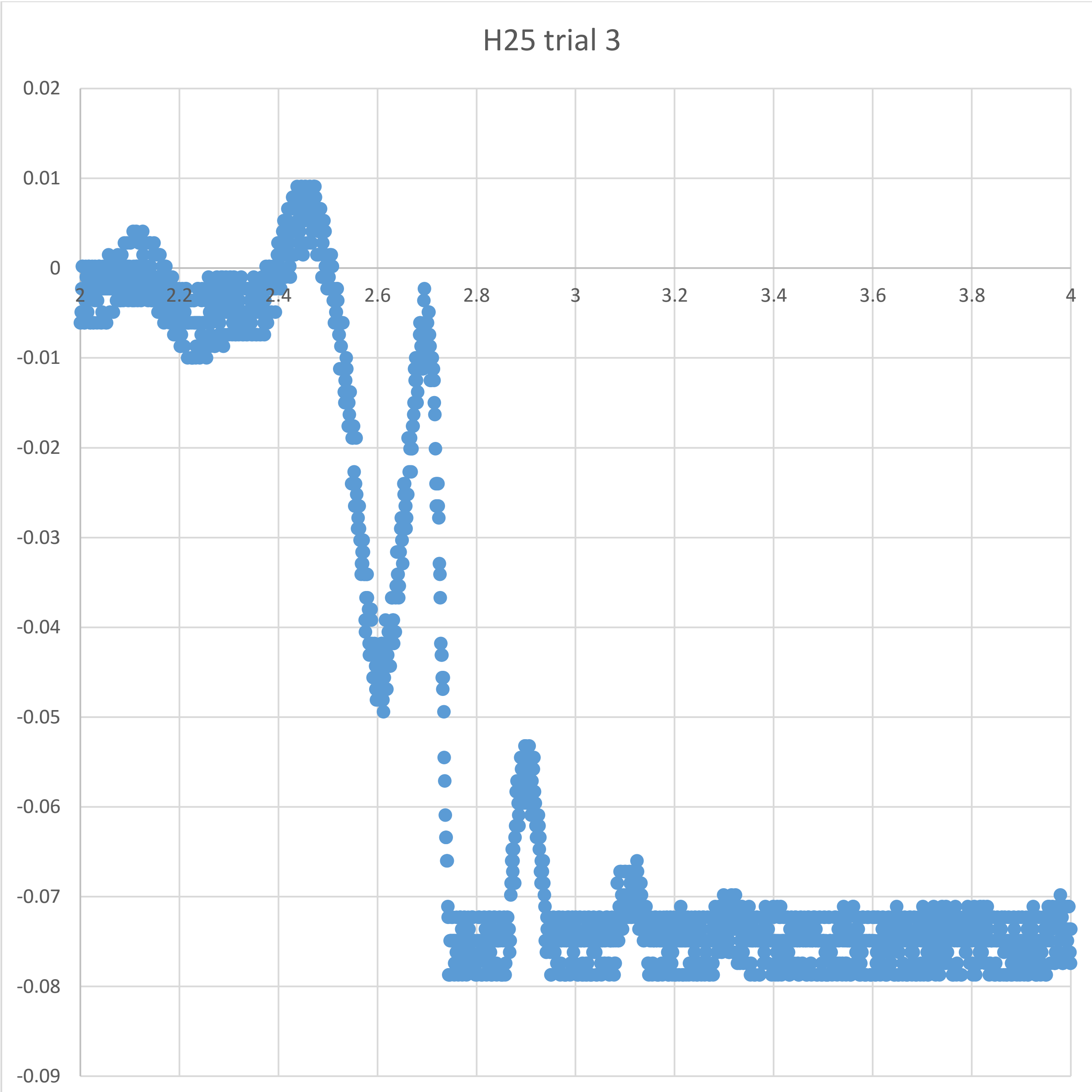


Figure 19. H25 trial 3

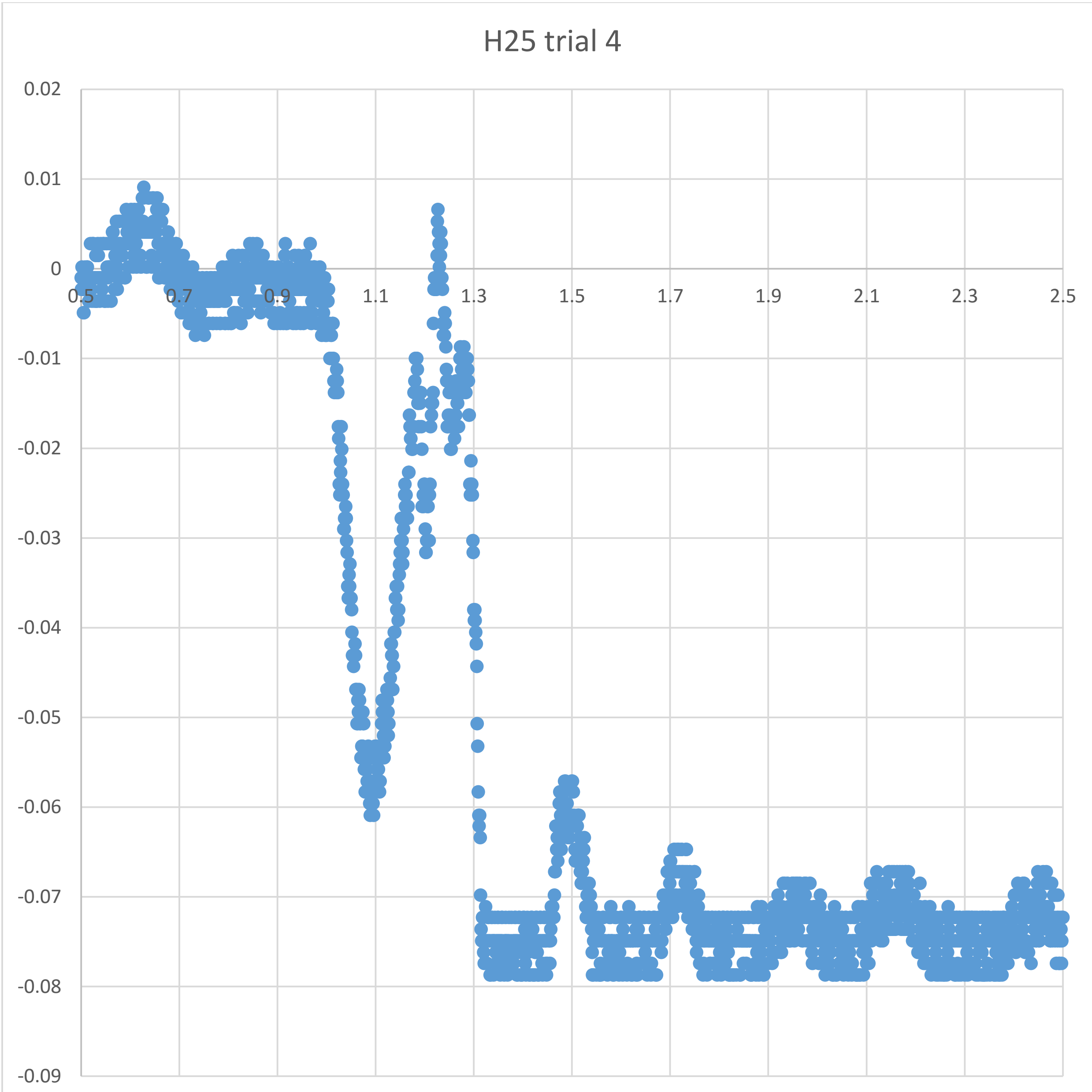


Figure 20. H25 trial 4

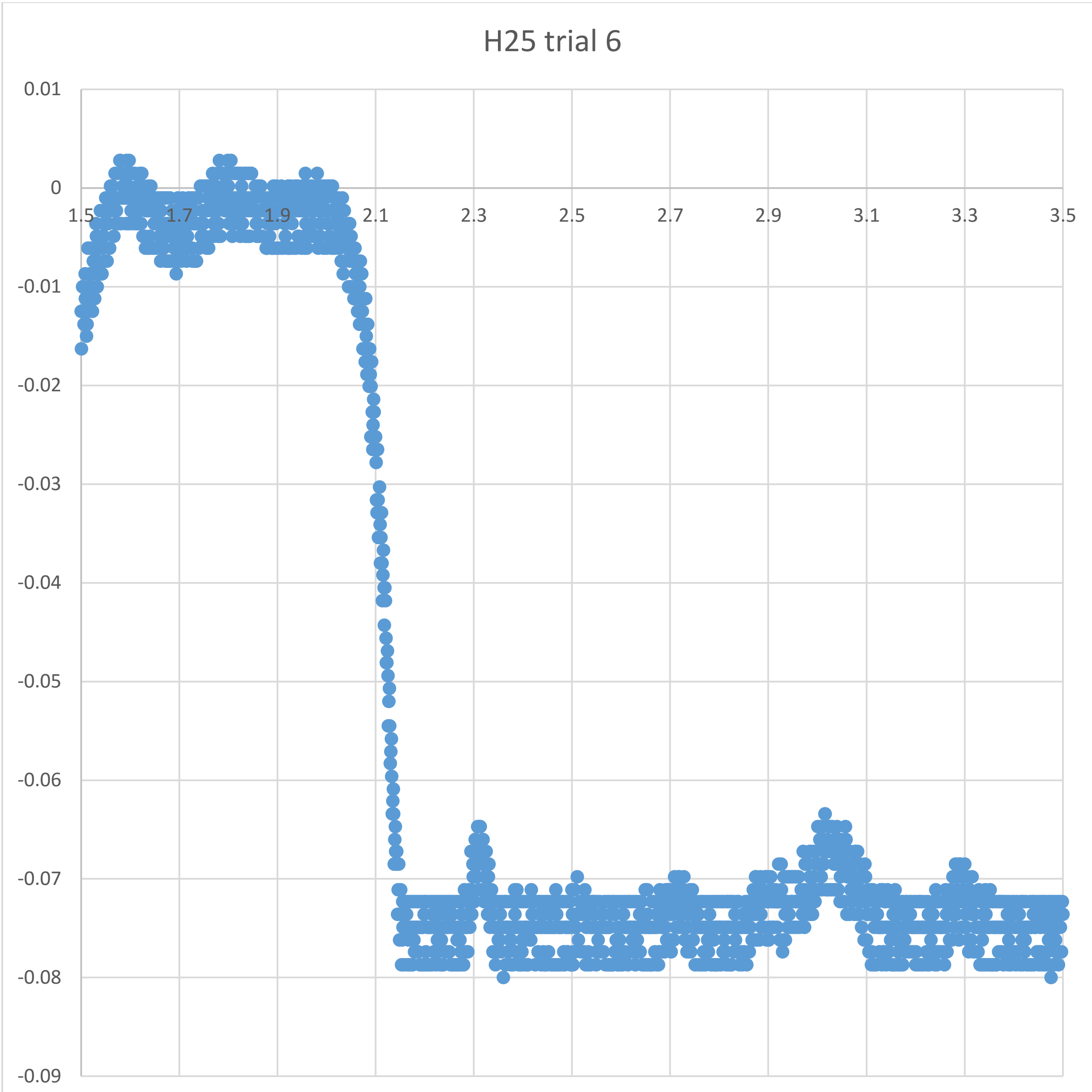


Figure 21. H25 trial 6

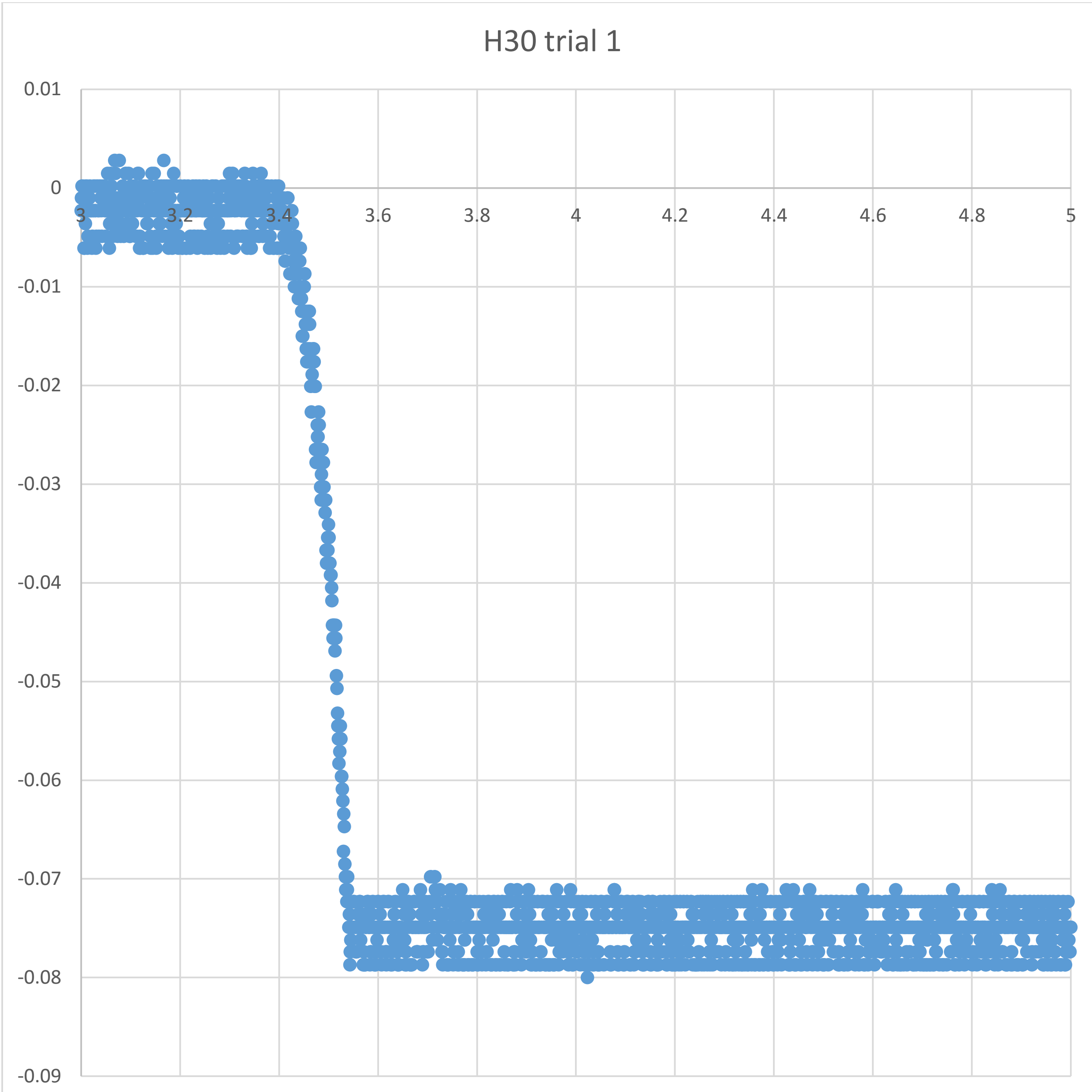


Figure 22. H30 trial 1

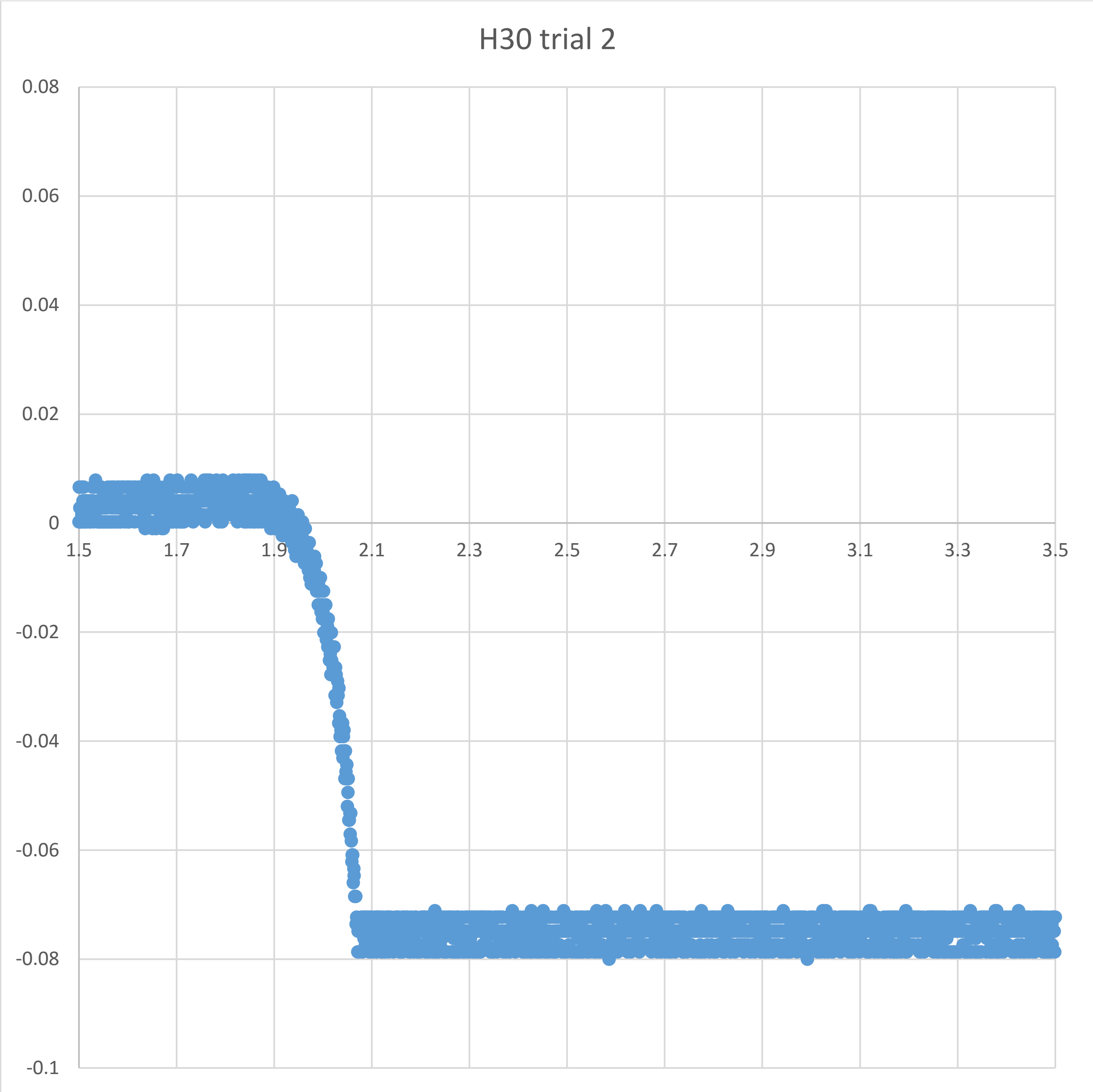


Figure 23. H30 trial 2

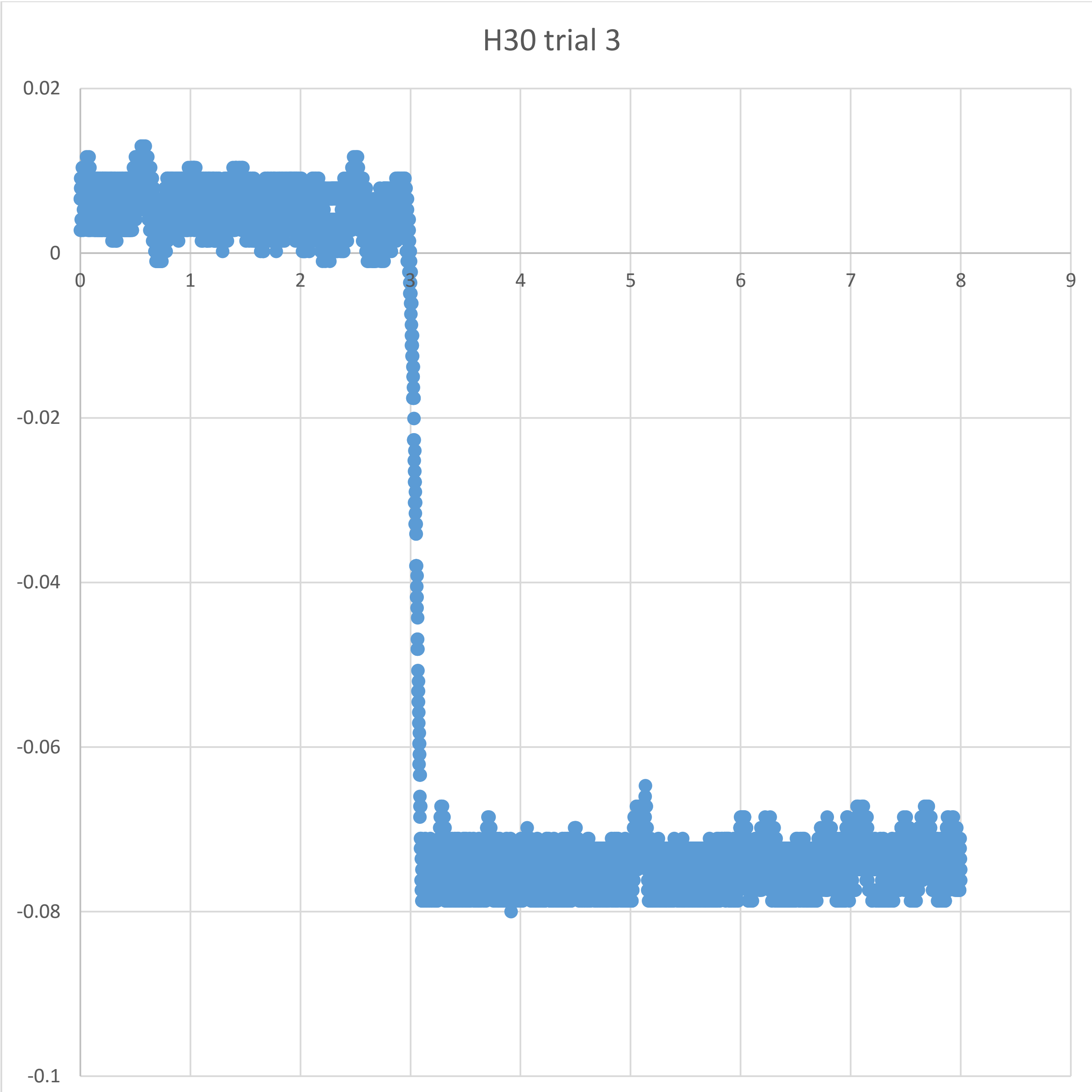


Figure 24. H30 trial 3

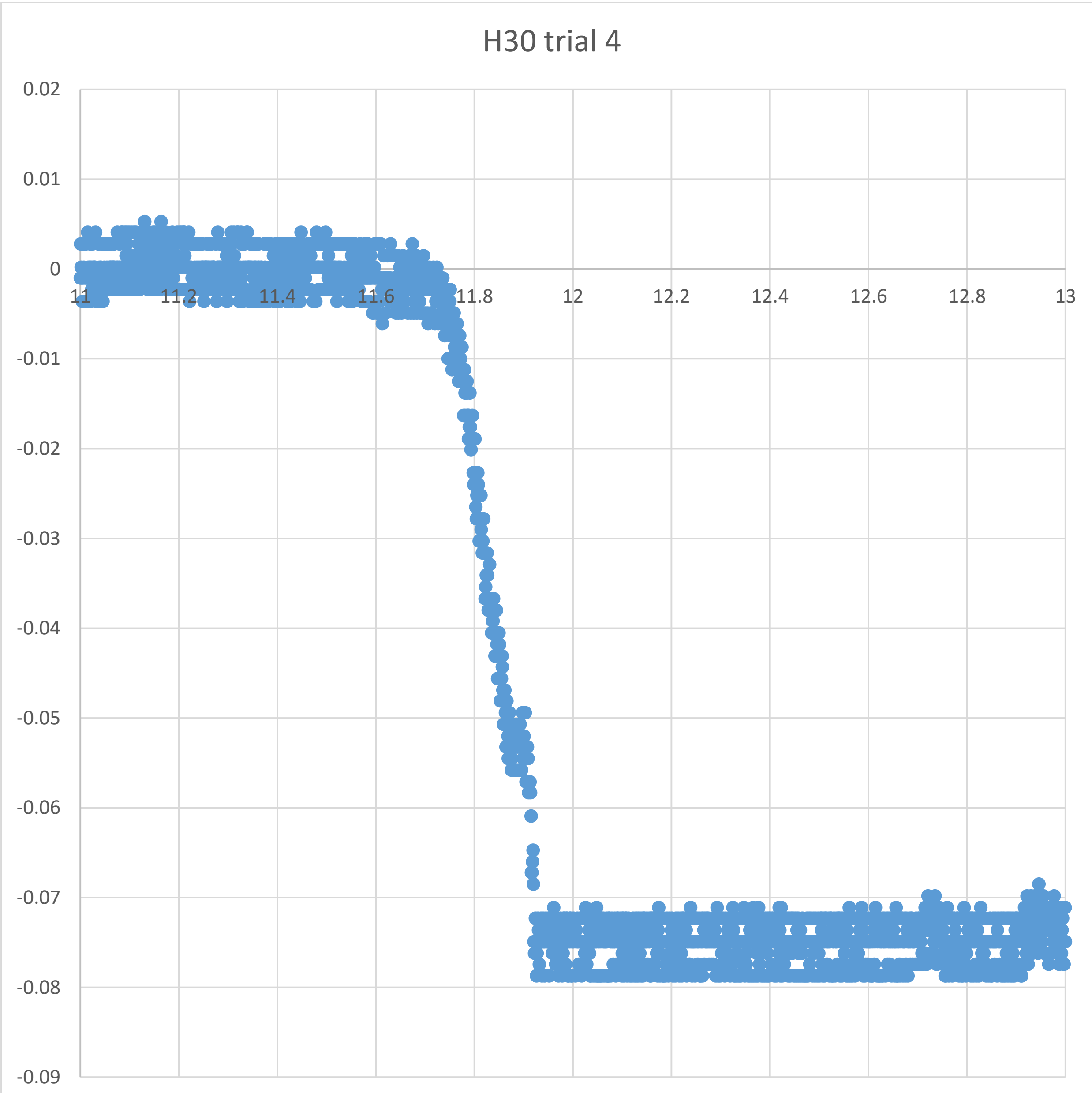


Figure 25. H30 trial 4

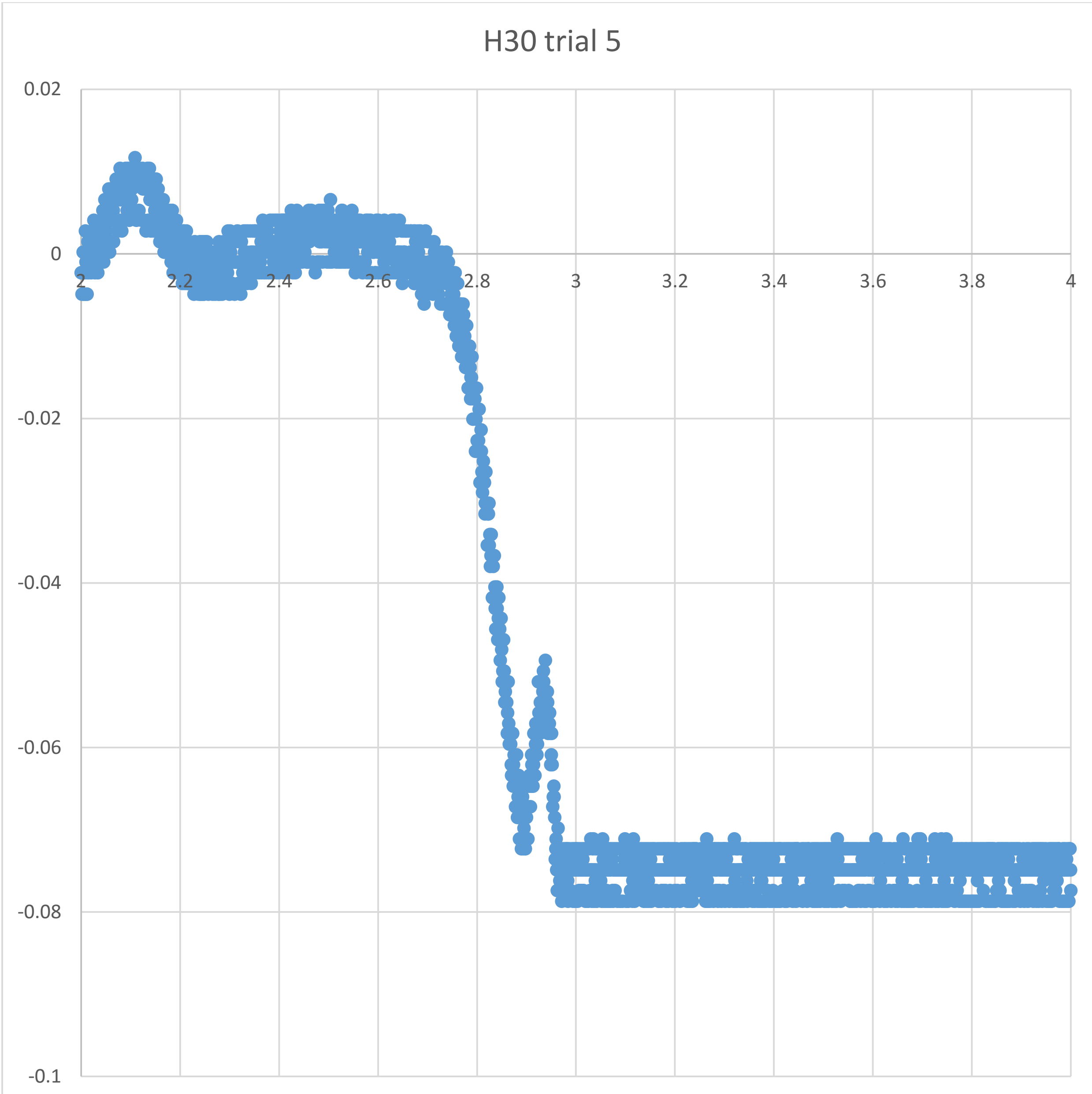


Figure 26. H30 trial 5

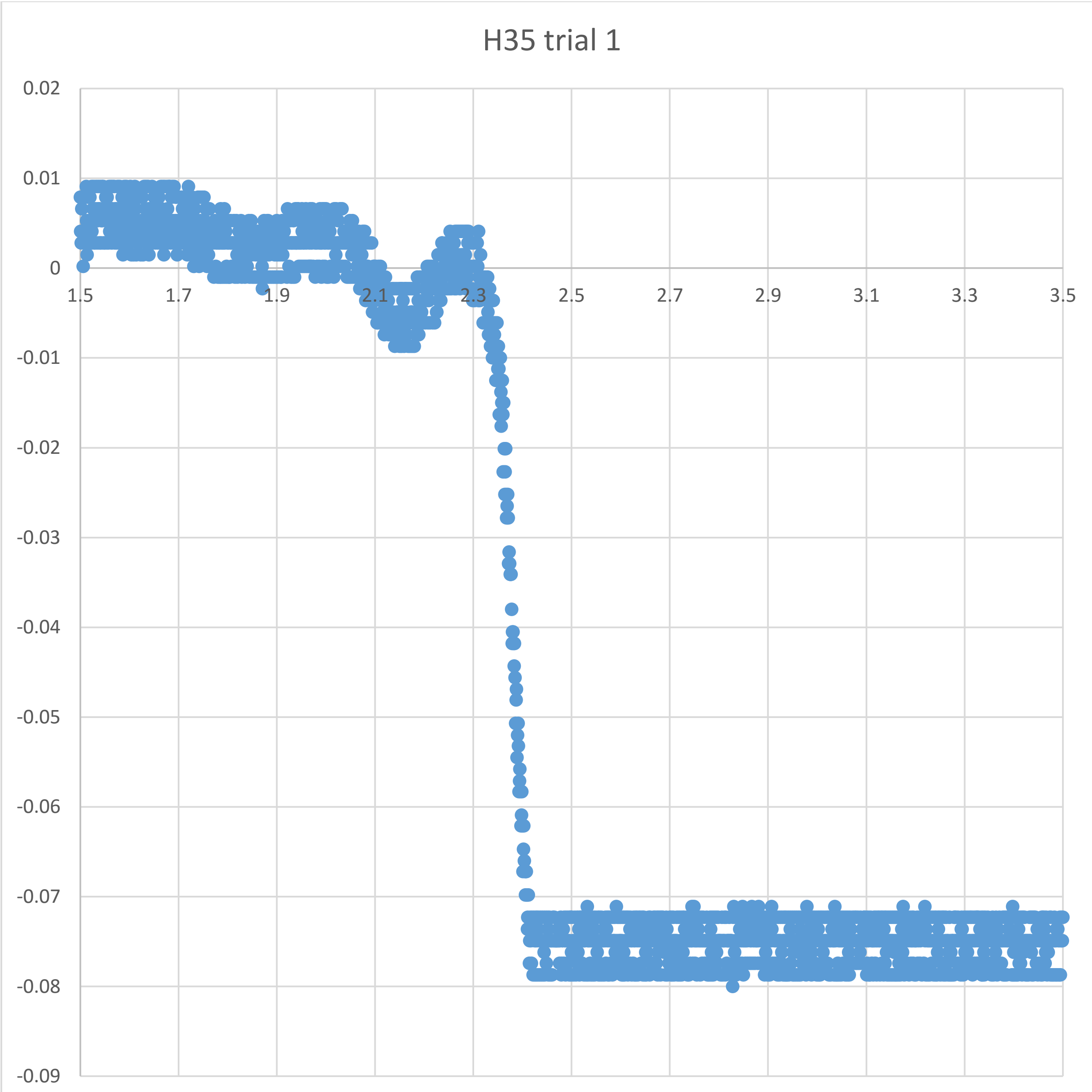


Figure 27. H35 trial 1

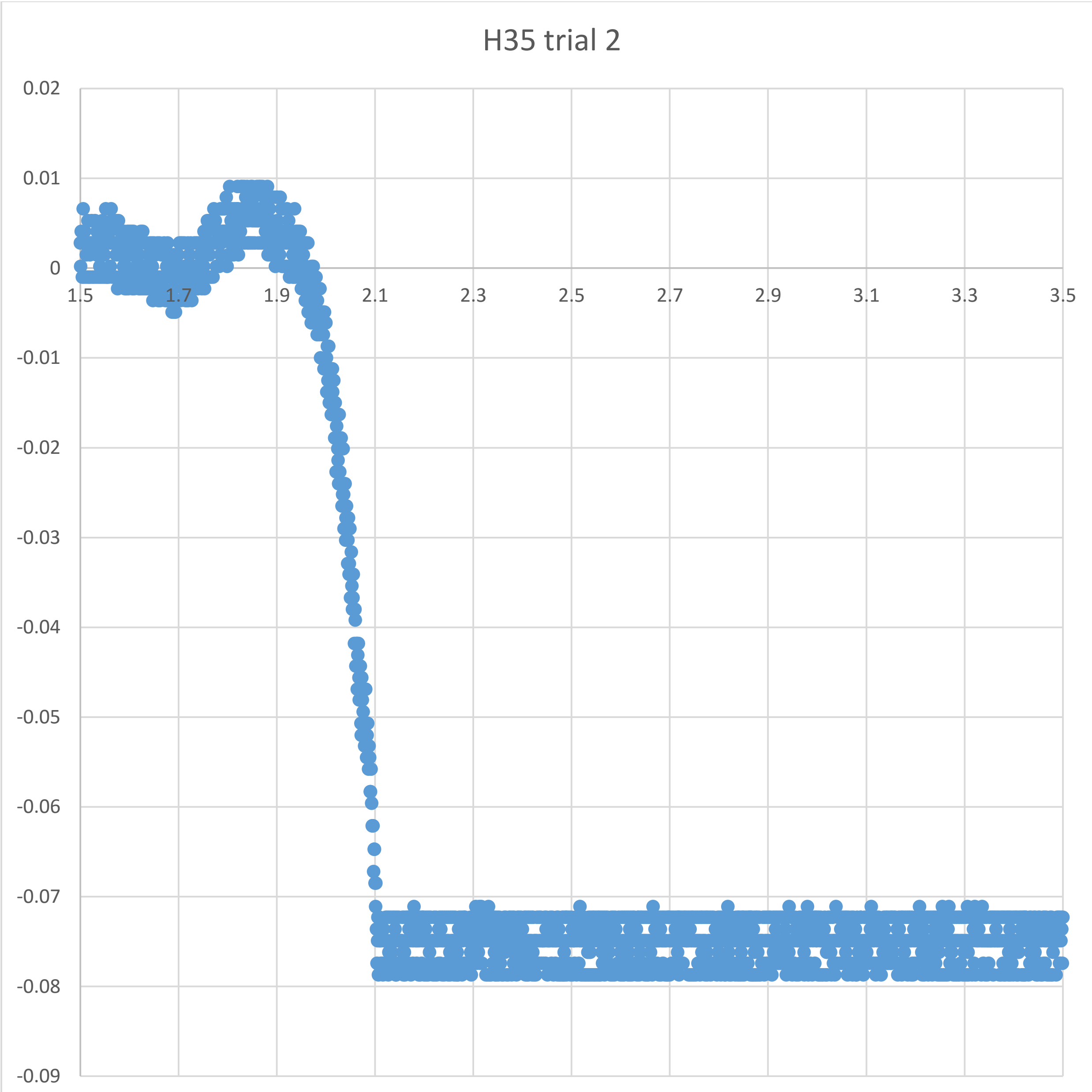


Figure 28. H35 trial 2

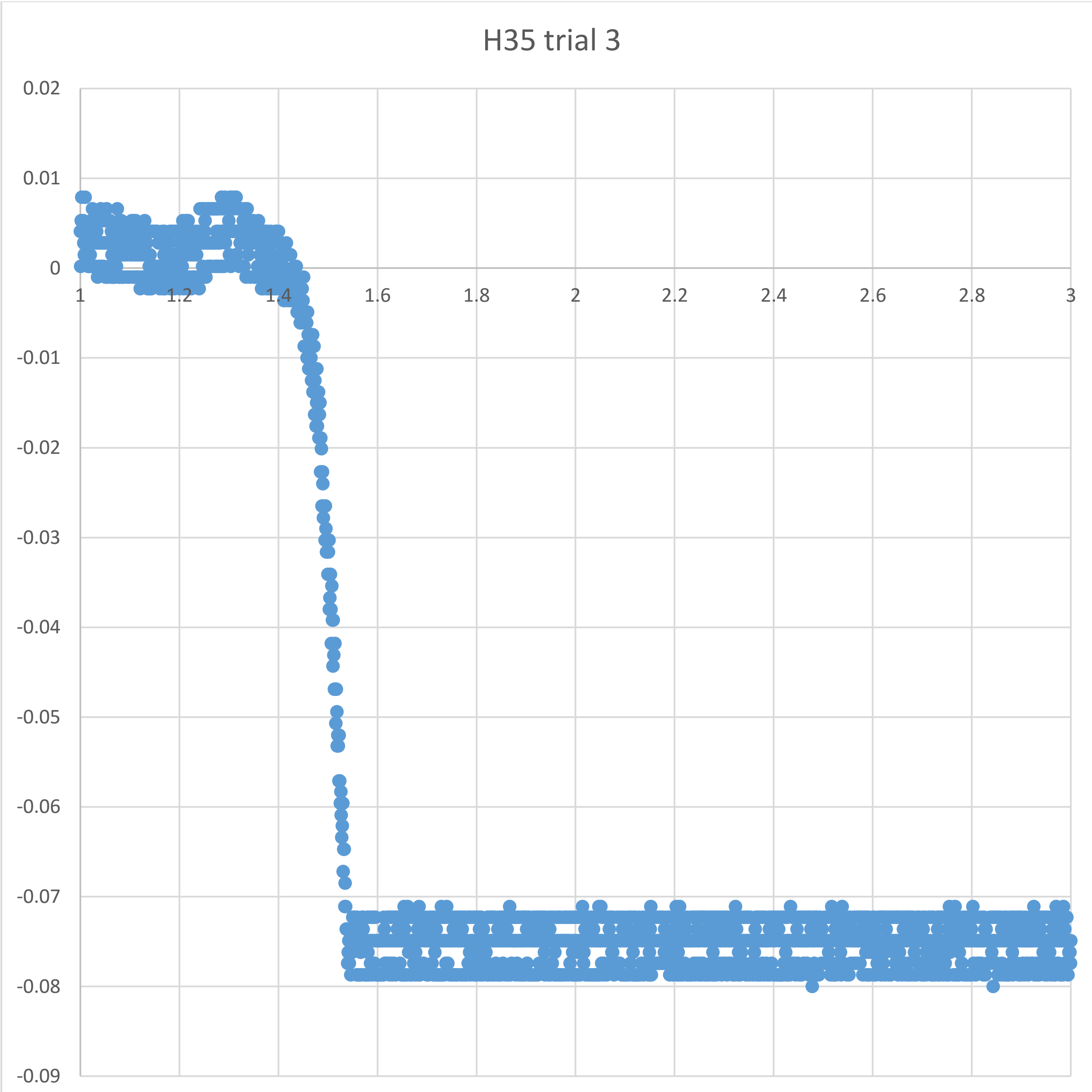


Figure 29. H35 trial 3

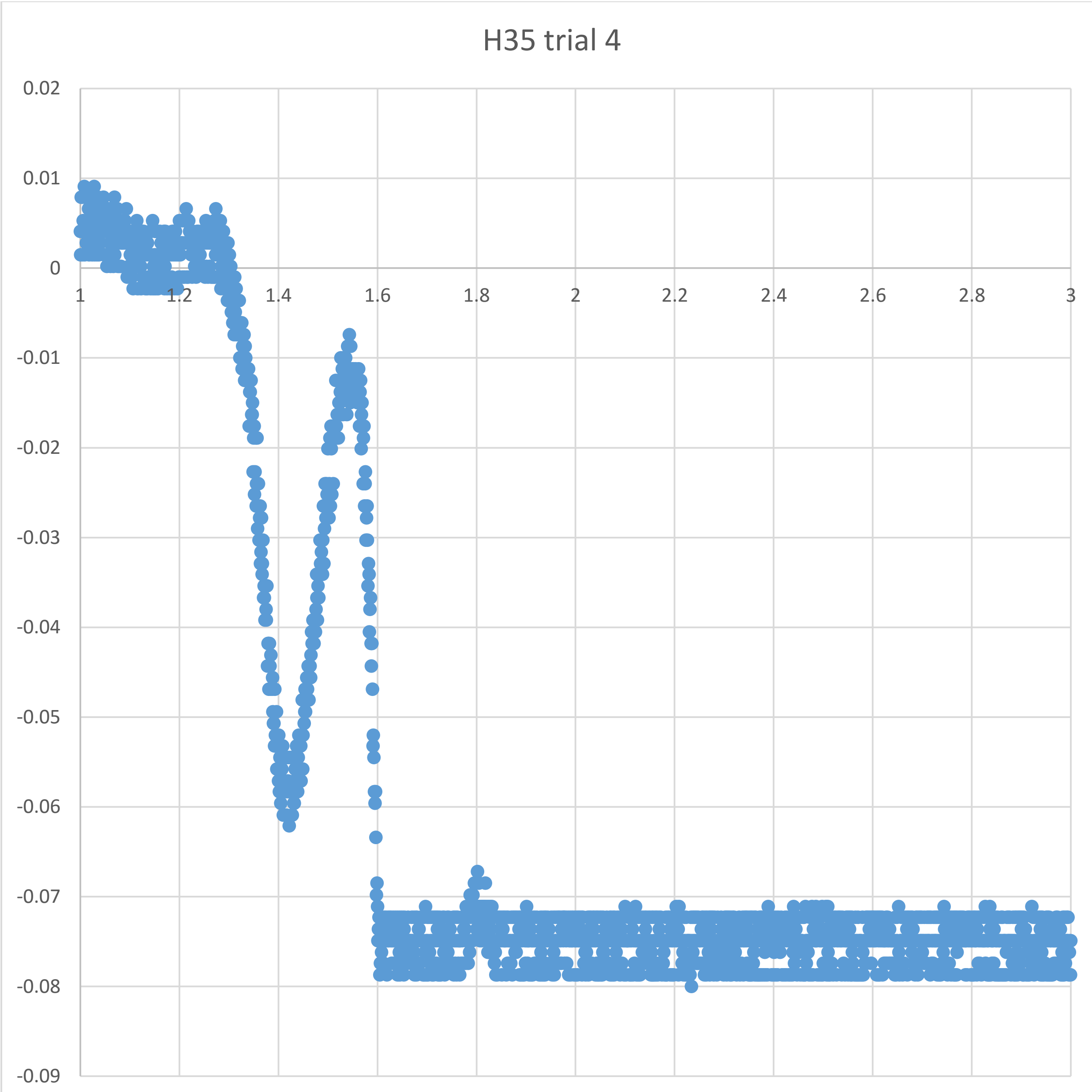


Figure 30. H35 trial 4

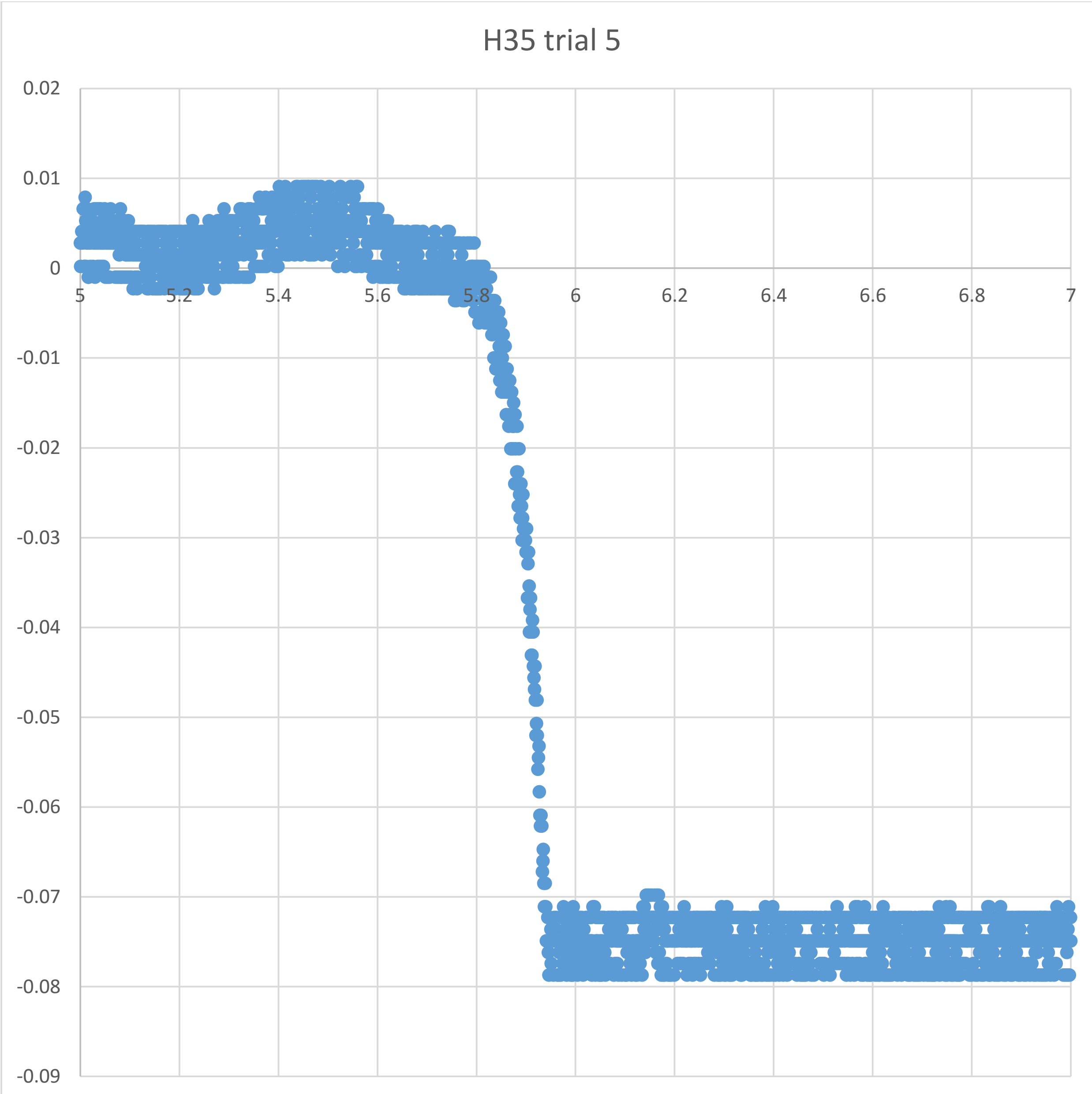


Figure 31. H35 trial 5

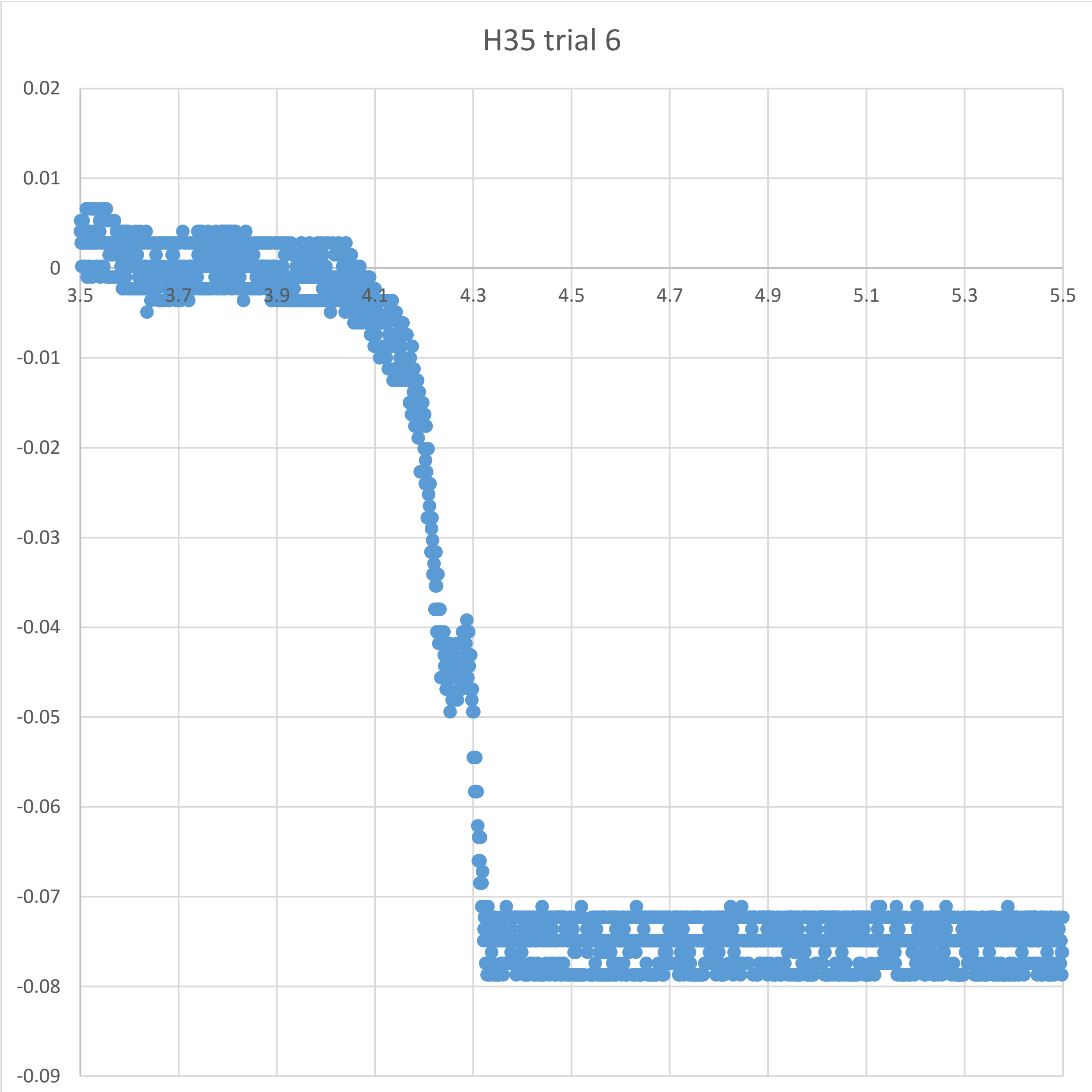


Figure 32. H35 trial 6

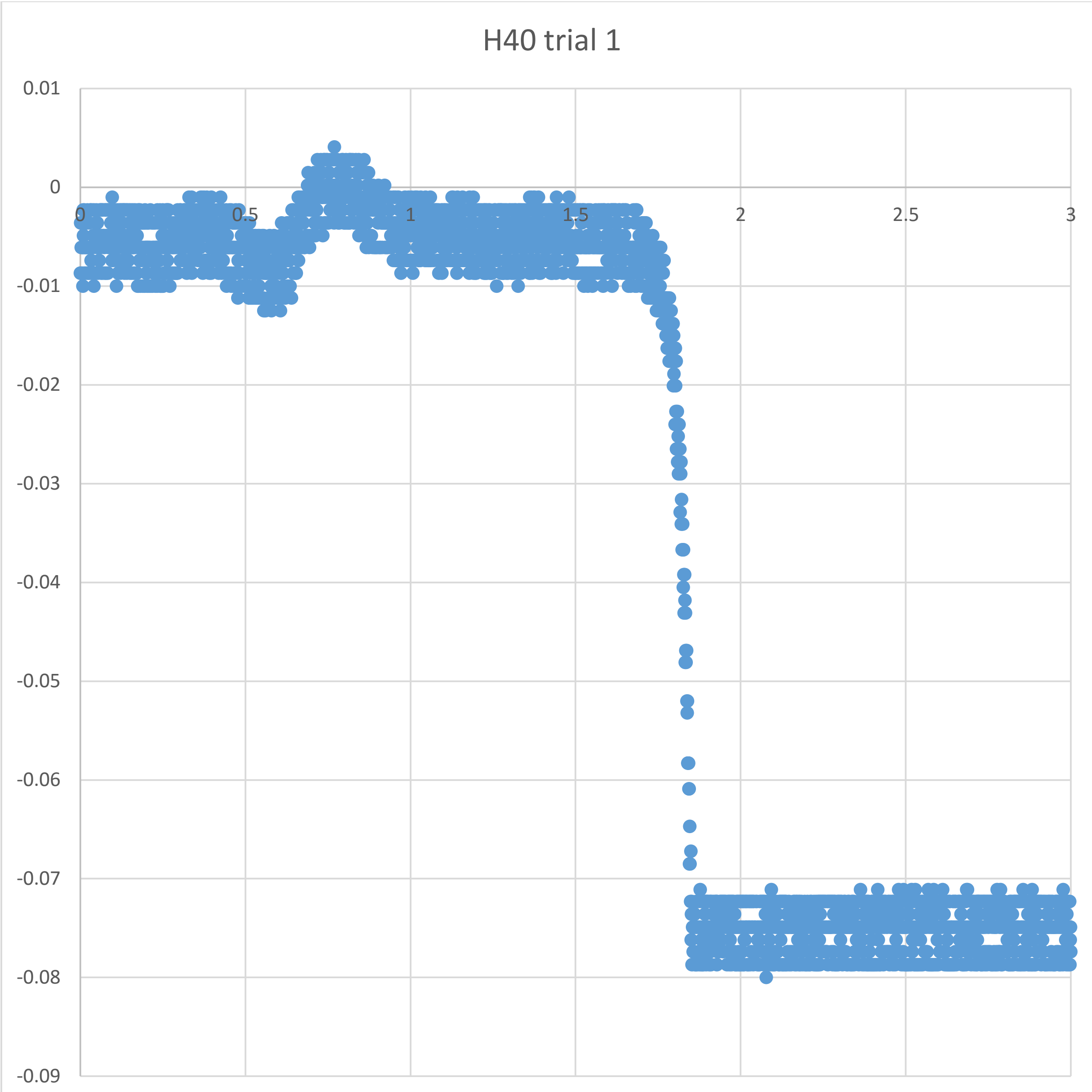


Figure 33. H40 trial 1

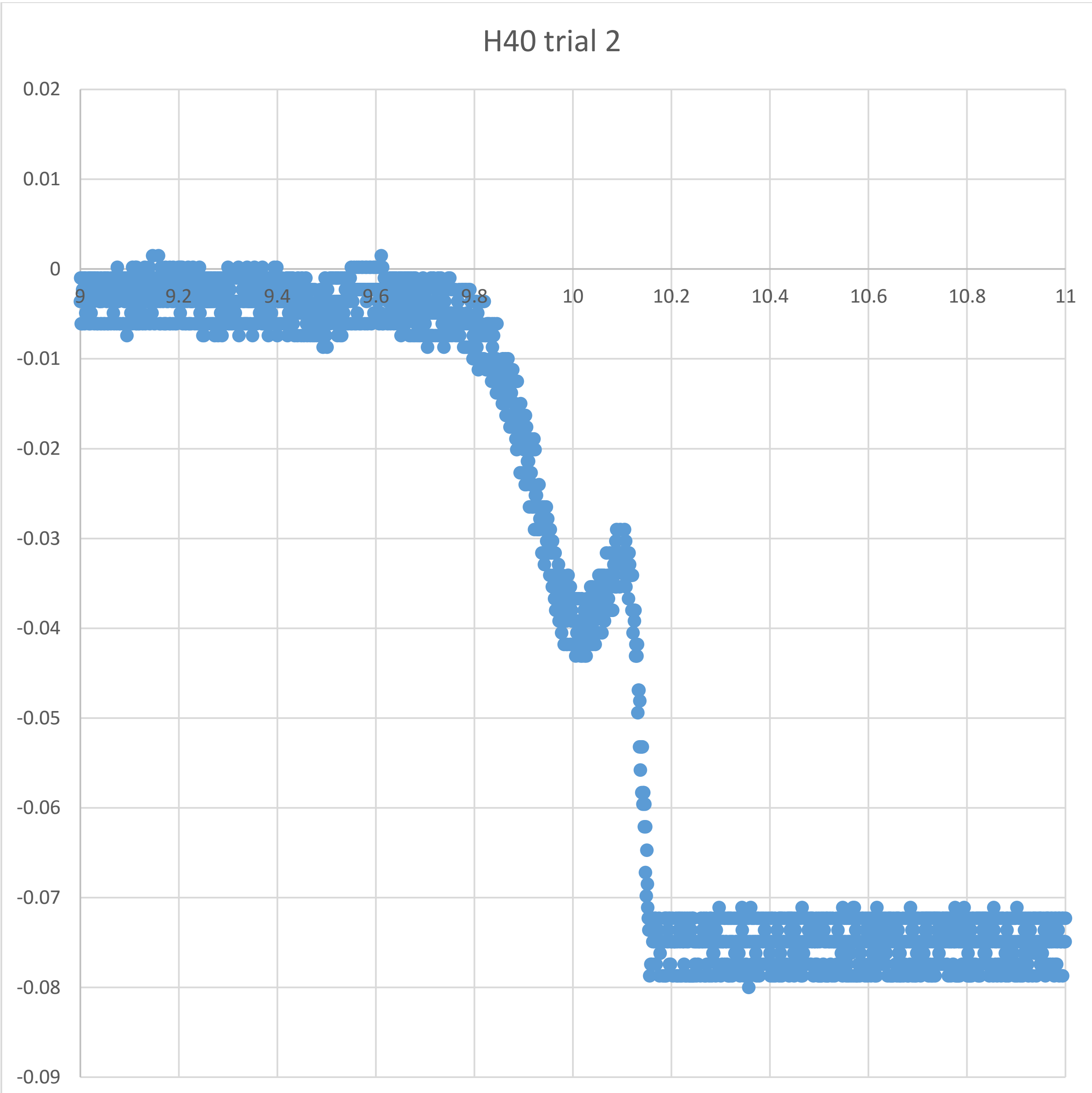


Figure 34. H40 trial 2

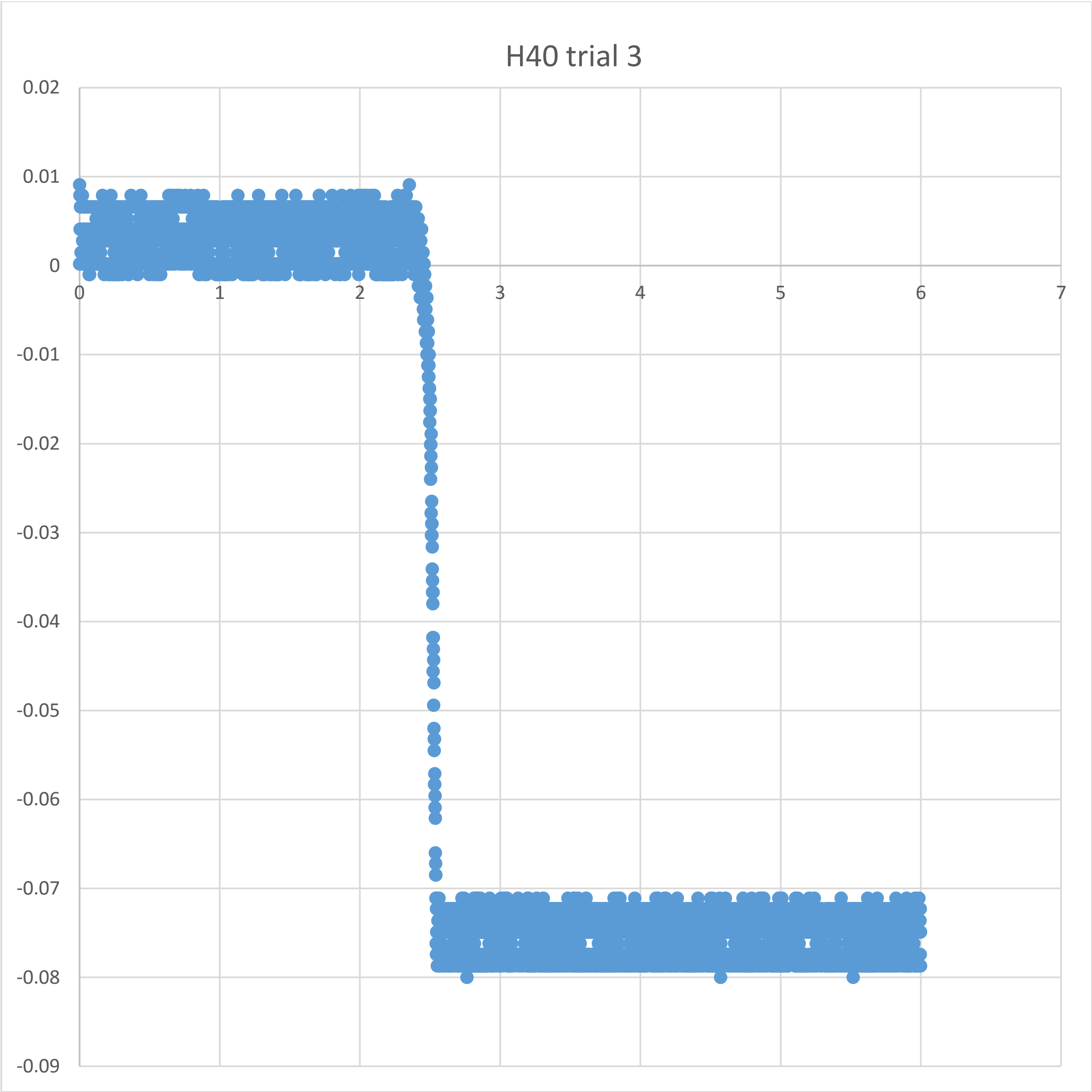


Figure 35. H40 trial 3

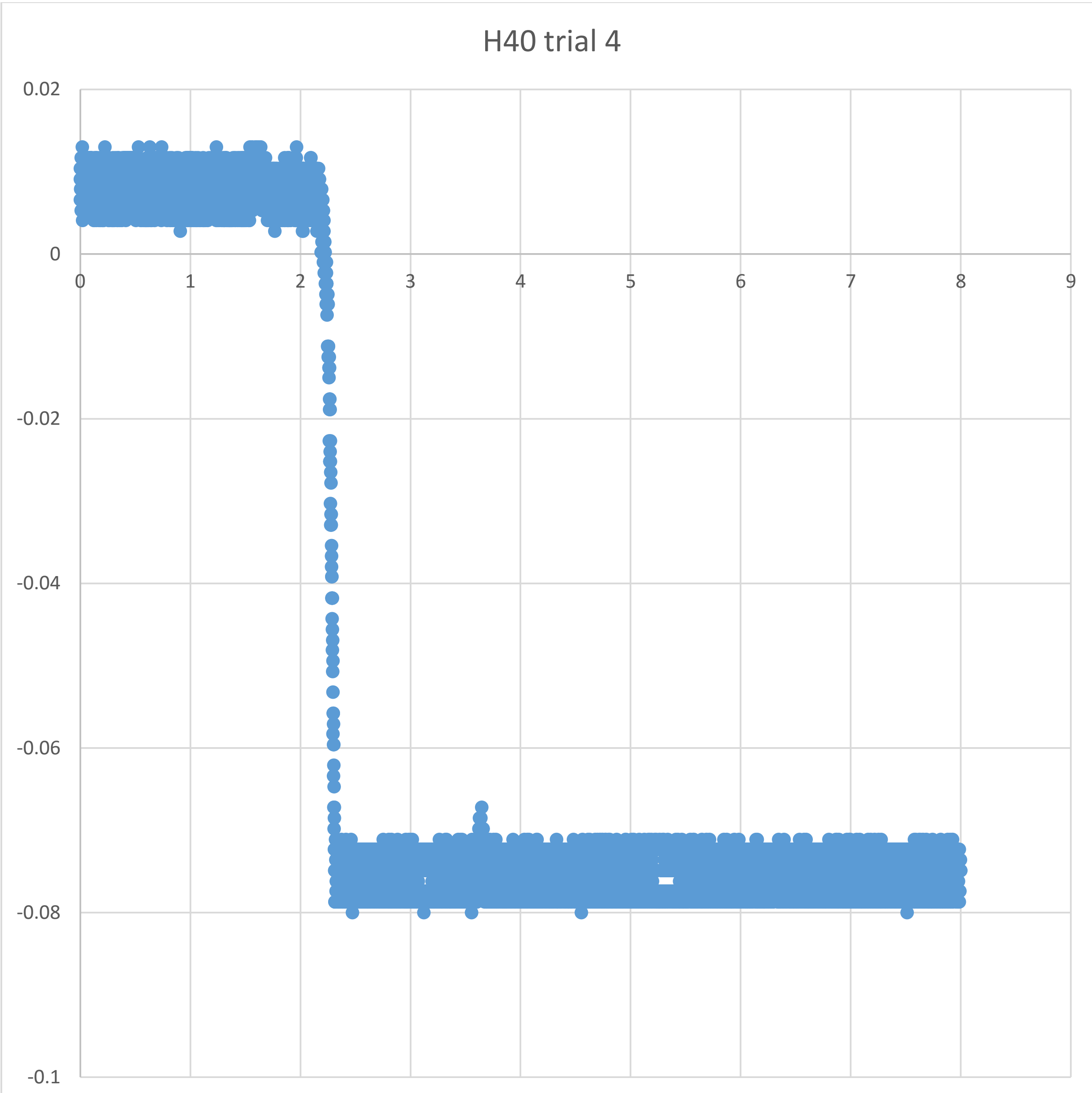


Figure 36. H40 trial 4