



PRIFYSGOL CYMRU

Y Drindod Dewi Sant

UNIVERSITY OF WALES

Trinity Saint David

Ducati Panigale 1199 S Dynamic Vehicle Response Measurement Platform

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

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1. Abstract

A highly sophisticated data acquisition setup is built and tested on a motorcycle by using inbuilt and aftermarket sensors in conjunction with an inertial measurement platform and a multi-antenna global positioning system, as well as a unique strategy for measuring physical rider input that is including the development of custom sensors and implementation of the theory behind mechanics of materials, for the purpose of analysing the dynamic response of single-track vehicles to steering inputs, quantifying the forces that are acting on the different components and dissecting the involved factors with regards to their overall contribution and effects on each other. This report covers an introduction to the project, which is followed by a detailed explanation of the approach that is taken, a description of the practical work that is carried out for the realisation of the project and the presentation of acquired results from testing, which are being evaluated and discussed, before a conclusion and an outlook for the project are provided.

2. Introduction and Objectives

For the final year project of the bachelor's degree in motorcycle engineering at the faculty of manufacturing and engineering in Swansea, the author has chosen to build a "Dynamic Vehicle Response Measurement Platform" on the basis of a 2012 Ducati Panigale 1199 S high-performance motorcycle. The aim of this project is to create and provide a data acquisition environment that is suitable for innovative research into motorcycle rider input in relation to the steering and stability behaviour of motorcycles via experimental and analytical investigations in the scientific field of motorcycle dynamics. Analysis of data that is recorded with a range of sensors which are fitted to motorcycles is common practise in motorcycle racing and, especially in world championships, the level of sophistication with regards to the technology that is used and the implementation of it is very advanced (Spalding, 2017). A great variety of analogue and digital sensors, like potentiometers or accelerometers, is not just used for the verification of rider feedback, monitoring component wear and operation or determining the best suspension setup for a certain race track under the given conditions, it is also supplying electronic control units, which are responsible for engine management and traction or wheelie control systems, with the data they require to continuously adjust the torque that is being produced by the engine and delivered to the rear wheel, for example by electronically controlling the throttle bodies or retarding the ignition when necessary, based on comparing the sensor readings to predefined limit and target values of parameters that are set by the engineers and defined via static and dynamic analytical motorcycle models

(Akitsu, 2012). However, it appears to the author that at present no data acquisition setup on any motorcycle is covering the physical force that is applied to the motorcycle by its rider, which is ultimately making it steer and behave from a stability mode point of view, as even the examination of recent datasets from MotoGP prototype motorcycles shows that the scope of measured and calculated channels may range from throttle opening that is demanded at the grip to possibly steering angle, however it is lacking the recording of essential and fundamental rider inputs, like the applied steering torque at the handlebars for example, which significantly contributes to the dynamic behaviour of a motorcycle. This steering torque is dependent on several dynamically changing forces and torques that are acting around the front assembly of a motorcycle and, with some involving gyroscopic moments, causing the measurement of steering angle alone to be inconclusive with regards to steering torque and overall rider input at the handlebars (Cossalter, et al., 2010). Furthermore, the trajectory or direction of travel of a motorcycle is also highly dependent on the attitude of the motorcycle, i.e. lean angle or roll, pitch and yaw, which, in addition to applying a steering torque, can be altered by the rider shifting their body weight forwards or backwards and onto either side of the motorcycle, as it can be observed in racing, where riders are “hanging off” the motorcycle to increase the highest achievable cornering speed for a given lean angle or putting their weight on the tank to prevent it from wheelieing under acceleration, thereby changing the weight distribution and overall location of the combined centre of gravity of the motorcycle and its rider, which the forces are acting on (Foale, 2002). Hence, the goal is to build and develop a highly sophisticated data logging environment that allows for most current and relevant channels to be used and interpreted in conjunction with novel sensors that are built and set up by the author to collect data of physical rider inputs at the handlebars, such as steering torque, so that, in addition to the usual and race focused data analysis, the interacting effects of applied steering inputs and changing vehicle attitude, as well as the results of different riding styles, in other words the highly complex vehicle stability and dynamic behaviour of motorcycles, can be quantified and studied, experimentally and analytically, on roads and at race tracks.

3. Timing Plan

After deciding on a suitable motorcycle that the project is supposed to be carried out and the platform set up on, a considerable amount of time is dedicated to research into motorcycle steering and stability modes in order to establish the requirements for measuring the forces that are involved and exerted by the rider at the handle bars, followed by research into the technology of existing sensors for measuring forces or torques and the assessment of the

applicability of different force and torque transducers currently available on the market. Once a solution has been found, the time is spent installing or building viable sensors for measuring the forces on the handlebars, before calibrating and testing the sensors, which is involving the derivation of mathematic formulae and determining the parameters that are required for this purpose. After successfully and reliably acquiring correct measurements of steering torque, an inertial measurement unit (IMU) with dual antenna GPS is fitted to the motorcycle and configured to provide highly accurate data of vehicle position and dynamic attitude. Before finally testing the full setup in the workshops and eventually under running conditions on public roads, all sensors need to be recalibrated and all data logging equipment, such as the wiring harness, main devices and the IMU, safely and securely accommodated on the motorcycle.

4. Research and Strategy

The motorcycle that is chosen for the project and considered as ideal for the creation of a dynamic vehicle response measurement platform is the university's 2012 Ducati Panigale 1199 S. It is powered by a 90° L-type longitudinal twin cylinder internal combustion engine with a total displacement of 1198 cm³ that provides a maximum crankshaft power output of 195 bhp at 10750 rpm and delivers a peak torque output of 132 Nm at 9000 rpm, whilst the dry weight of the motorcycle is stated at only 166,5 kg, which is making it one of the most powerful and fastest production motorcycles ever (Ducati Motor Holding S.p.A., 2002). Its chassis geometry, static weight distribution, adjustability of electronics, such as the anti-lock braking system and traction control, as well as nearly all major components, from almost the latest Öhlins front and rear suspension to very strong Brembo brakes and ultra-lightweight Marchesini forged magnesium wheels, are tailored towards best performance and handling characteristics. Moreover, Andrew Harrison, a member of staff and lecturer at the university, has already managed to hack into the controller area network (CAN bus) of the motorcycle and decipher the data streams of several inbuilt sensors, which allows for the recording of various and very important channels, like engine speed, wheel velocities or throttle body opening for example, whilst using reliable and robust sensors in a space and weight saving manner with the LG-μCAN09_engineer-000 external data logger from 2D Debus & Diebold Meßsysteme GmbH (2D Debus & Diebold Meßsysteme GmbH, 2009). Before a change of rules in the MotoGP forced every competing team to use a unified control system for their engine management strategies and Magneti Marelli software for data acquisition and analysis, which was instigated by the MotoGP organisers Dorna Sports as a reaction to the advantage that manufacturers like Honda or Yamaha had gained over their rivals with

respect to electronics in the recent years leading up to 2014, 2D was widely used at world championship level of motorcycle racing (Spalding, 2017). Apart from data logging devices and software packages for data analysis and post-processing, the company 2D offers a range of kits and sensors. Furthermore, its hardware is compatible with most analogue and digital sensors, like potentiometers from Penny & Giles, which had already been fitted to the Panigale and are responsible for measuring front and rear suspension travel, as well as steering damper movement. Thus, a very good basis for building a dynamic vehicle response measurement platform is found in the Panigale that is already owned and in use by the university, which allows for the primary focus to be on developing novel sensors capable of delivering measurements for channels of physical rider inputs. Research into motorcycle dynamics, especially on the topic of balance and steering, reveals that steering torque is the torque that is acting around the front assembly of a motorcycle and its steering head, where the magnitude of the torque that is applied by the rider is equal to the resultant of all moments that are generated by the forces which are acting on the front section with either misaligning or aligning influence on the steering (Cossalter, 2006). The centrifugal force of the front section, the lateral force on the front wheel and the gyroscopic effect of the front wheel are having an aligning influence for example, whilst the weight force of the front section, the normal load on the front wheel and the twisting torque of the front tire have a misaligning influence, as shown in *Figure 1* below (Cossalter, 2006).

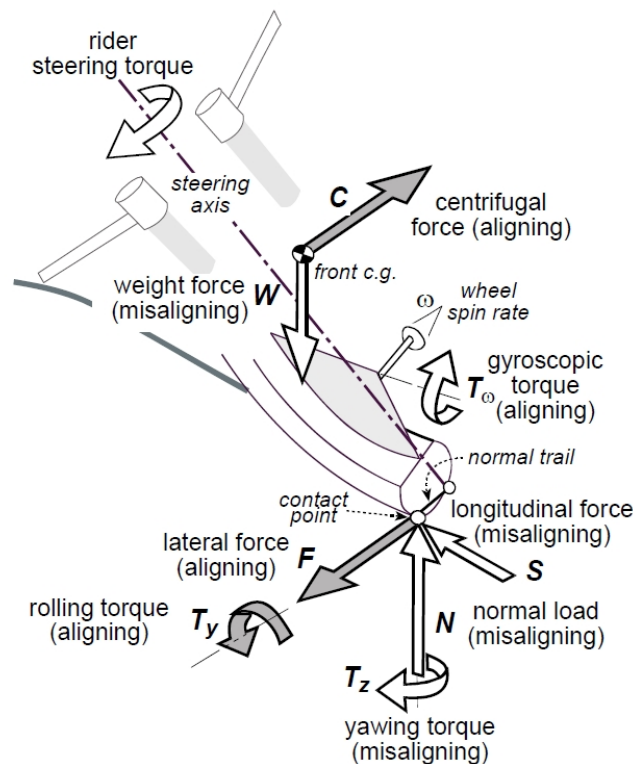


Figure 1 – Equilibrium of the front frame (Cossalter, et al., 2010)

Only very few journal papers on experimental investigations into steering torque based on physical measurements of the actual torque that is applied by the rider have been published, yet the recorded results of basic manoeuvring tests for a steady turn and lane change at moderate speed, which were conducted and presented by Roy S. Rice in 1979, are offering representative measurements of rider control inputs and motorcycle motion response (Rice, 1979). According to this SAE publication, the instrumentation that is used to measure the steering torque consists of torque transducers that are capable of measuring up to 27,12 Nm of torque and mounted between the control bar and the front assembly (Rice, 1979). However, research into the current technology of torque and force measuring devices suggests that most sensors, which is including even the latest multi-axis force torque sensors that are finding use in robotics, are unsuited for the application of measuring the torque at the steering head, as the majority of the devices are either static and reaction torque transducers, which means that they are measuring a torque that involves very little or no rotation of the object on which the torque is being measured, or rotary torque transducers that are designed to be fitted in-line with a shaft or around the outside of it to measure dynamic torque of fast and continuously rotating objects (Applied Measurements Ltd., 2004 - 2018). The screenshot of a computer aided design (CAD) model of an ATI multi-axis force torque sensor, which is shown in *Figure 2*, displays the inside of a transducer and shows the silicone strain gauges, highlighted in blue, from which measurements are taken on bridges that are connecting the outer wall of the transducer to an inner hub, so that mechanical loads can be converted into forces and torques by using the strain gauge readings (ATI Industrial Automation, Inc., 2018).

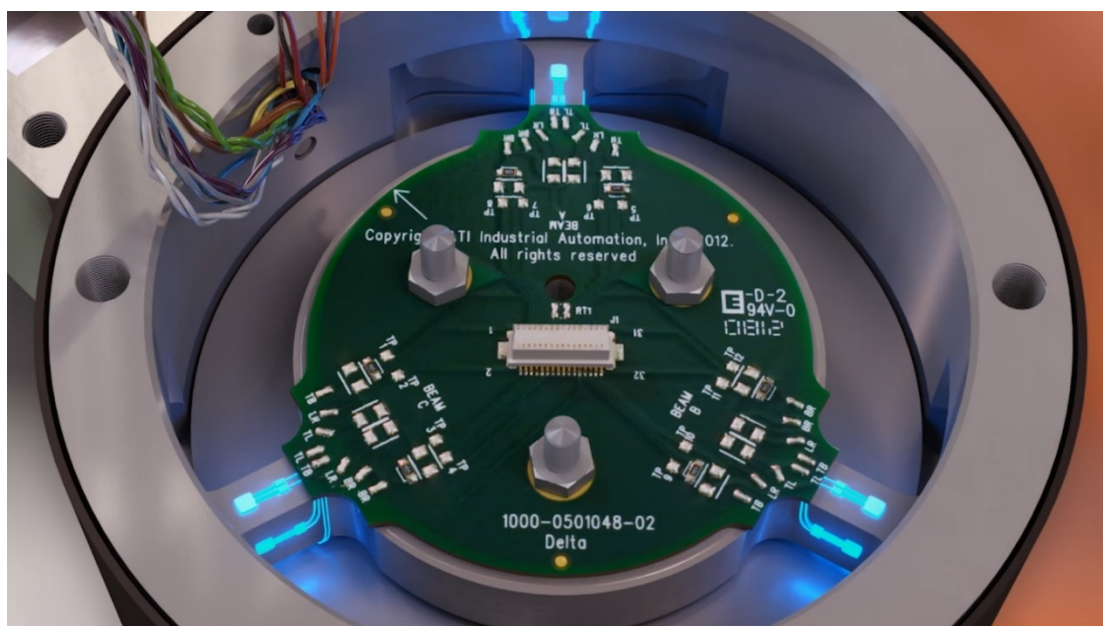


Figure 2 – CAD model of an ATI force torque sensor (ATI Industrial Automation, Inc., 2018)

Deciding against the use of torque transducers, due to their impracticality for measuring steering torque, results in the requirement of a different solution and, based on acquired knowledge through research and previous studies in the field of stress analysis as part of the course, the chosen approach is to install strain gauges directly on the handlebar tubes for measuring the strain inside the material which is resulting from the force that the rider is exerting at the grips of the handlebars. In an engineering context, if an external force is applied to a material, the internal resistance of the material to the deformation that is caused by the force is called stress and the formula for stress is given as (Twigg, 1996):

$$\text{Stress} = \frac{\text{Force}}{\text{Cross - Sectional Area}} = \sigma = \frac{F}{A}$$

Strain is the fractional change of dimension of the material under an applied force and can be calculated as follows (Bird, 2012):

$$\text{Strain} = \frac{\text{Change in Length}}{\text{Original Length of the Material}} = \varepsilon = \frac{\Delta l}{l}$$

According to Hooke's Law, the deformation of an elastic material under load is directly proportional to the load that is producing it and, since stress is directly proportional to the load and strain directly proportional to the deformation, stress is proportional to strain (Stephens, 1970). Hence, for any given material, the gradient of the linear relationship between stress and strain, i.e. the ratio of stress to strain, is a constant and it is called Young's Modulus of Elasticity, which has the formula (Stephens, 1970):

$$\text{Young's Modulus} = \frac{\text{Stress}}{\text{Strain}} = E = \frac{\sigma}{\varepsilon}$$

However, Hook's Law only applies below the limit of proportionality, beyond which a material behaves in a non-linear elastic manner until it reaches its elastic limit, from where it can no longer return to its original shape after the removal of external forces, which means that the elastic region is exceeded and the material has reached plastic deformation that will eventually result in failure (Bird, 2012). Therefore, by making use of strain gauges in conjunction with the theory of bending, the uniformly distributed load at each grip can be calculated and the component of the force that is acting as steering torque can be trigonometrically resolved, which is explained in more detail in the following chapters. With the university providing access to the BC-SG4-000 strain gauge amplifier from 2D that can be connected to the main 2D data logger via CAN input, the integration of the strain gauges is very direct and all calculations for the required and desired data channels can be done by code, using the calculation file manager post-processing tool within the 2D software package

(2D Debus & Diebold Meßsysteme GmbH, 2008). As the brackets for the clutch and brake levers are mounted right next to the clamps of the clip-on handlebars and therefore closer to the fixing clamps than the strain gauges can be positioned on the handlebar tubes, the strain gauges will pick up a reading that is resulting from the equal and opposite force which is applied to the handlebars when pulling in and releasing any of the levers. However, this force is not contributing to the steering torque, as a local and constant equilibrium of forces means that no component of this force is creating a global torque around the steering head. For the ability to quantify and subtract the measured strain which is introduced by operating the clutch, force-sensing linear potentiometers from Interlink Electronics, which are force sensitive resistor strips and capable of measuring location or magnitude of an applied force, can be wired up to the data logger (Pololu Corporation, 2001–2018). Due to their linear operating range and force sensitivity being limited to a maximum force of 20 N, regardless of the opportunity to change the sensitivity of the sensor by using a different resistor for the required circuitry, the force that is applied to the brake lever should be measured differently, as it will consistently exceed this limit (Interlink Electronics, Inc., n.d.). The final approach chosen to compare the full range of the force on the brake lever to the resulting strain measurements is similar to the method that is used for the handlebar tube that is carrying the clutch lever, however relating the CAN input channel for hydraulic pressure in the front brake lines to the channel of measured strain from a strain gauge pair that is set up in the same plane as the lever, hence in line with the opposing force, based on calibration tests that are conducted in the workshop. The dynamic attitude and position of the motorcycle is measured using the xNAV200 GNSS/INS from Oxford Technical Solutions Ltd., a highly accurate dual antenna GPS and inertial measurement unit, which is provided by the university. The package includes the main logger and accelerometer platform, which is 132 x 77 x 36 mm in dimension and weighing only 0,365 kg, two external GPS antennas that must be mounted with a separation of 1 to 5 m and along one of the vehicle axes, as well as software suites for configuration of the setup and post-processing of the acquired raw data (Oxford Technical Solutions Ltd., 2016). The collected data can also be exported from the OxTS software in a CSV file format and therefore be imported from Microsoft Excel to the 2D software for data analysis, where the channel of GPS time from a basic 2D antenna on the motorcycle allows for accurate synchronisation and alignment of the data that is previously recorded on the two separate devices. The IMU, along with the data logger and strain gauge amplifier, is accommodated just behind the seat inside the subframe of the motorcycle, however an enlarged seat unit cover is required to cater for the spacial needs of all the devices, with any available room on the Panigale being very restricted. Ideally, the IMU should be mounted as close as possible to the combined centre of gravity of the motorcycle and rider, which would statically be situated around the rear cylinder of the engine, yet the option of building a new

tank with a recess for the IMU appears unfeasible, given the timescale for completion of the project. Based on the author's previous experience of working with composite materials and the technology that is available at the university, the decision is made to design and create a new seat unit cover from carbon fibre instead, which offers enough room for the data logging equipment, as well as secure mounting points for the IMU and the rear GPS antenna, whilst the other one is fitted to the front of the motorcycle with an adjustable bracket by the dash. In addition, the new seat unit cover provides a convenient base for attaching an action camera that serves the purpose of monitoring rider movement on the motorcycle.

5. Building the Platform

5.1. Setup for Rider Input Measurement

To measure the strain inside the handlebars and calculate the force that is applied by the rider, bonded metallic strain gauges are installed on each handlebar tube. The strain gauges consist of metallic foil that is arranged in a grid pattern and bonded to a carrier, which is a thin backing that is directly attached to the test specimen, in this case the outer surface of the handlebar tubes, and the strain that is experienced by the material linearly changes the electrical resistance within the strain gauges, which is measured at two leads that are coming off each strain gauge, with the configuration of strain gauges being based on the concept of a Wheatstone bridge to measure the small changes in resistance (National Instruments, 2016). A Wheatstone bridge is the electrical equivalent of two voltage divider circuits that are in parallel, with four resistive arms and an exciting voltage that is applied across the bridge, where the output voltage is measured between the middle nodes of the two voltage dividers (National Instruments, 2016). The configuration that is used is a half-bridge, which means that the circuit has two active elements, with a pair of strain gauges opposite each other and two dummy resistors on both handlebar tubes, as shown in *Figure 3*.

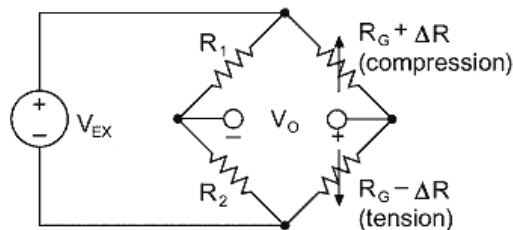


Figure 3 – Wheatstone half-bridge where R_1 and R_2 are dummy resistors (National Instruments, 2016)

Before the strain gauges can be glued to the handlebar tubes at the position that is chosen for best results and practicality, the material surface needs to be smoothened and polished with sandpaper. Wires are then soldered to the strain gauge leads and 120 Ω resistors to form the circuit that is displayed above, with four wires coming from the half-bridge and being soldered into a 4-pin binder connector to link the strain gauge amplifier to the circuit. The strain gauge amplifier uses 2 of the 4 pins for supplying voltage and grounding the half-bridge and the other 2 for the signal outputs, where an imbalance of the half-bridge from changing resistance within the strain gauges produces a nonzero output voltage that is a function of strain and converted to a reading of unitless digits within the 2D software, which can be adjusted, zeroed and amplified by a multiplying factor of 10 to 1000. With the implementation of the simple theory of elastic bending, a force that is applied anywhere between the strain gauges and the free end of the handlebars can ultimately be calculated from the resulting strain measurements. The bending equation states that (Hearn, 1997):

$$\frac{\text{Bending Moment}}{\text{Second Moment of Area}} = \frac{\text{Stress}}{\text{Distance to the Neutral Axis}} = \frac{\text{Young's Modulus}}{\text{Radius of Curvature}}$$

$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}$$

This formula can be rearranged for stress as follows:

$$\frac{M}{I} = \frac{\sigma}{y}$$

$$\sigma = \frac{M * y}{I}$$

Where (for a point load on a hollow shaft):

$$M = \text{Load} * \text{Distance to Point of Interest} = (-)W * x = m * g * x$$

$$y = \frac{\text{Outer Diameter}}{2} = \frac{D}{2}$$

$$I = \left(\frac{\pi}{64}\right) * (\text{Outer Diameter}^4 - \text{Inner Diameter}^4) = \left(\frac{\pi}{64}\right) * (D^4 - d^4)$$

This way, the stress within the material can be calculated for any known load, conversely, the applied load and therefore the force can be calculated, when the stress within the material at a particular point of interest is known. However, when combining the equation for Young's modulus with the bending equation and rearranging it for stress, the stress inside the handlebar tubes cannot be calculated from using strain measurements only, if the material property of Young's modulus is an unknown constant, as rearranging gives:

$$\text{Stress} = \text{Young's Modulus} * \text{Strain} = \sigma = E * \varepsilon$$

The Ducati handlebar tubes with part numbers 875P1731BA and 875P1741BA that are fitted to the Panigale appear to be made from aluminium, but the exact grade and material code that is required to establish their value of Young's modulus could not be determined, despite enquiring with Ducati engineers and contacting several dealerships. Thus, Young's modulus for the unique material of each handlebar tube is calculated by using the bending theory that is described above and recorded strain gauge readings from repeated experiments involving measured weights. For this purpose, different loads are hung from the free end of the handlebar tubes, with the other end being fixed inside the clip-on that is clamped in a vice, as shown in *Figure 4* below.

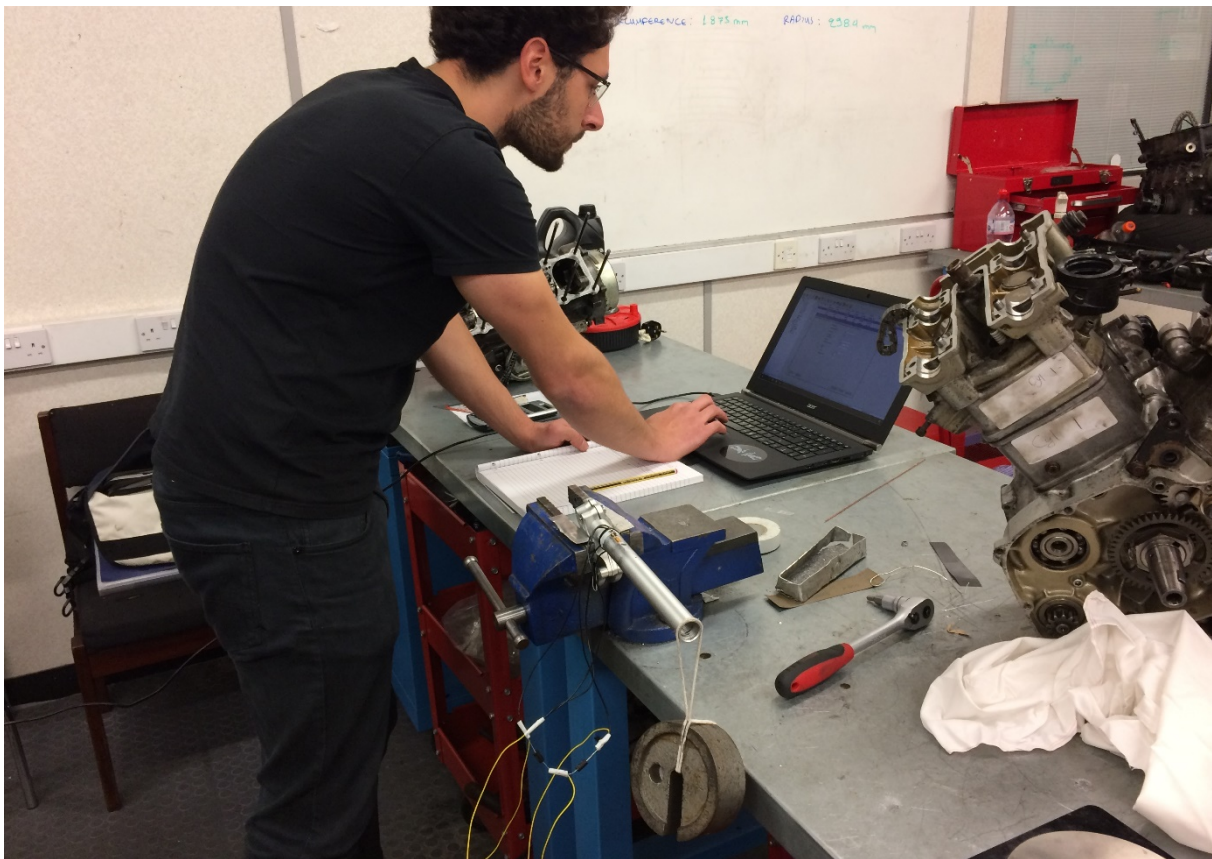


Figure 4 – Experiment setup with a weight of 3 kg hanging from the free end of the handlebar tube (Przibylla, 2017/2018)

From the known loads and dimensions of the handlebar tubes, the bending moments and stresses at the location of the strain gauges can easily be determined and compared to the strain that is measured in 2D. *Figure 5* shows a sketch of the loading conditions for the calculations with a point load (PL) at the free end of the tube.

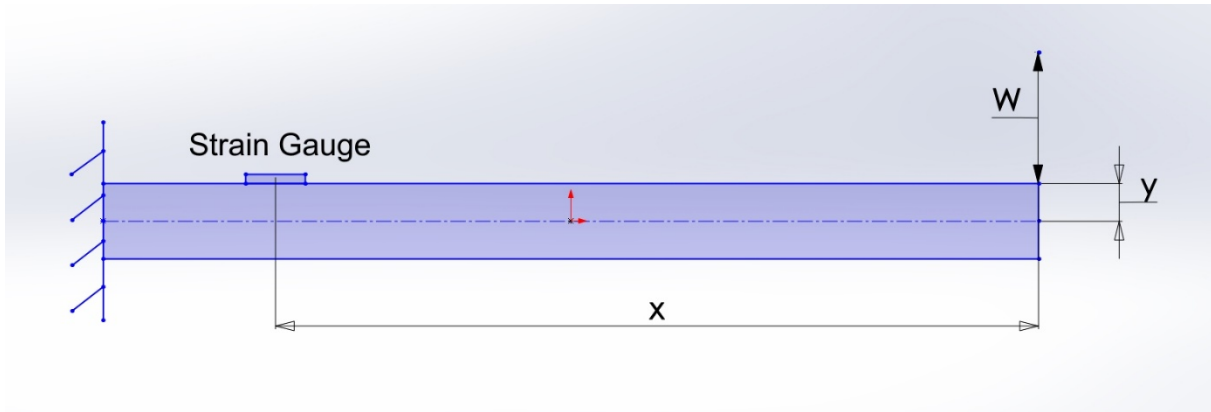


Figure 5 – Sketch of the loading conditions for the experiment with a point load at the free end (Przibylla, 2017/2018)

To achieve the highest possible accuracy of the measurements, the maximum amplification of 1000 is used for greatest sensitivity of the strain gauge bridges on both handlebar tubes, even though this results in more noise of the recorded channel. To counteract this effect, the 2D data is later exported to Excel and an average function used to filter out the noise. Figure 6 shows the data trace of a strain gauge measurement on the left handlebar tube.

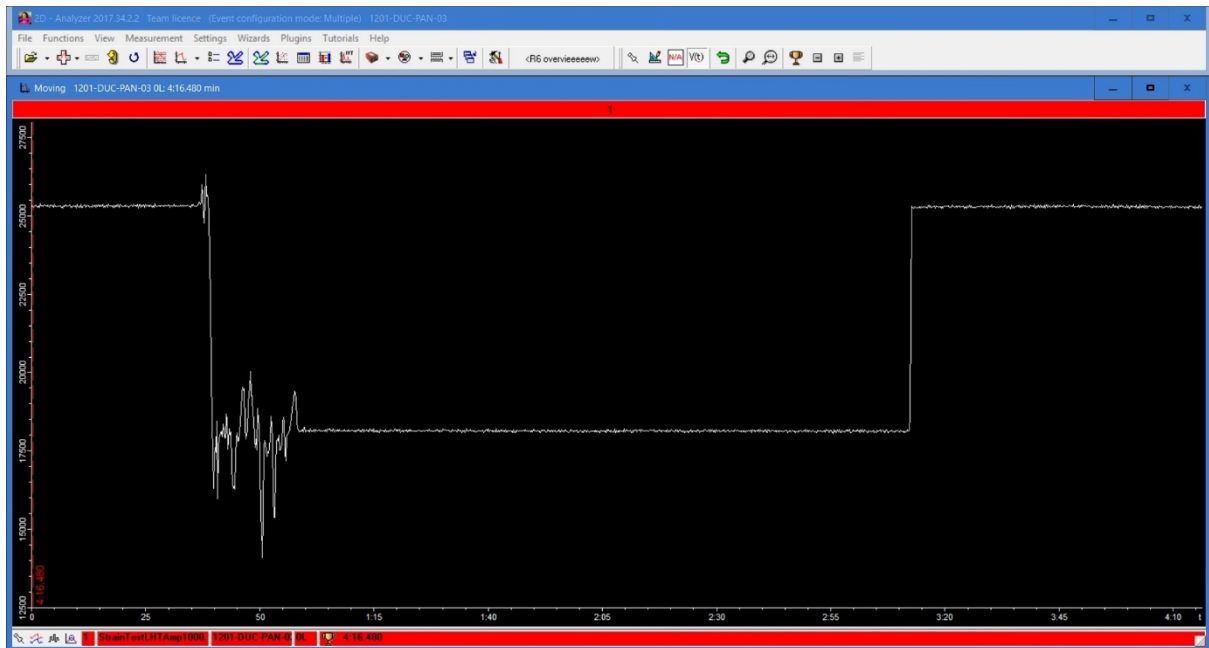


Figure 6 – Recording of strain measured during the experiments (Przibylla, 2017/2018)

From these experiments, the value of Young's modulus for each handlebar tube can be calculated using the following equations.

$$\sigma = \frac{M * y}{I}$$

$$\varepsilon = \frac{\Delta V (when stressed)}{V (unstressed)}$$

$$E = \frac{\sigma}{\varepsilon}$$

As 2D gives amplified and combined measurements from the strain gauge pair in digits instead of resistance or voltage, the equation of the ratio for strain becomes:

$$\varepsilon = \frac{1}{2} * \left\{ \frac{(digits_{stressed} - digits_{unstressed}) / Amplification}{digits_{unstressed}} \right\}$$

The values that are used for the following calculations are obtained by physical measurement of the handlebar tube dimensions and average distances from their free end to the centre of the two strain gauges, measuring the chosen weights with a mass of 3 kg on a scale and using Excel for evaluating the strain gauge readings.

For the left handlebar tube:

$$Weight = 3 \text{ kg}$$

$$Distance \text{ to the Strain Gauges} = x = 183 \text{ mm}$$

$$Outer \text{ Diameter} = D = 22 \text{ mm}$$

$$Inner \text{ Diameter} = d = 14,35 \text{ mm}$$

$$Average \text{ } digits_{unstressed} = 37246,958919$$

$$Average \text{ } digits_{stressed} = 30113,844894$$

$$M = 3 * 9.81 * 0.183 = 5,38569 \text{ Nm}$$

$$y = \frac{0,022}{2} = 0,011 \text{ m}$$

$$I = \left(\frac{\pi}{64} \right) * (0,022^4 - 0,01435^4) = 9,4175 * 10^{-9} \text{ m}^4$$

$$\sigma = \frac{5,38569 * 0,011}{9,4175 * 10^{-9}} = 6290685,587 \text{ N/m}^2$$

$$\varepsilon = \frac{1}{2} * \left\{ \frac{(30113,844894 - 37246,958919)/1000}{37246,958919} \right\} = 9,5754314333 * 10^{-5}$$

$$E = \frac{6290685,587}{9,5754314333 * 10^{-5}} = 65,69610603 * 10^9 \text{ N/m}^2 = \mathbf{65,7 \text{ GPa}}$$

For the right handlebar tube:

$$\text{Weight} = 3 \text{ kg}$$

$$\text{Distance to the Strain Gauges} = x = 177,22 \text{ mm}$$

$$\text{Outer Diameter} = D = 21,85 \text{ mm}$$

$$\text{Inner Diameter} = d = 14,03 \text{ mm}$$

$$\text{Average digits}_{\text{unstressed}} = 37246,645089$$

$$\text{Average digits}_{\text{stressed}} = 44153,962607$$

$$M = 3 * 9.81 * 0.17722 = 5,215585 \text{ Nm}$$

$$y = \frac{0,02185}{2} = 0,010925 \text{ m}$$

$$I = \left(\frac{\pi}{64} \right) * (0,02185^4 - 0,01403^4) = 9,28664 * 10^{-9} \text{ m}^4$$

$$\sigma = \frac{5,215585 * 0,010925}{9,28664 * 10^{-9}} = 6135723,320421 \text{ N/m}^2$$

$$\varepsilon = \frac{1}{2} * \left\{ \frac{(44153,962607 - 37246,645089)/1000}{37246,645089} \right\} = 9,2724022557 * 10^{-5}$$

$$E = \frac{6135723,320421}{9,2724022557 * 10^{-5}} = 66,1718846 * 10^9 \text{ N/m}^2 = \mathbf{66,17 \text{ GPa}}$$

The calculated values for Young's modulus of the left handlebar tube and the right handlebar tube are 65,7 GPa and 66,17 GPa respectively and differ slightly, which could be due to a

possible disparity in material composition of the ingredients that are used for the metal, variations in the process of making it or small differences in the geometry, with holes and dowels for the positioning and restriction of throttle grip and lever mounts in different places of the tubes. Nevertheless, the results seem realistic and sufficiently accurate, as the typical value for the modulus of elasticity of most common aluminium alloys is stated to be around 68,3 GPa (AZoNetwork UK Ltd., 2017). For further verification of the acquired results and calculations for the stress and strain that is experienced by the material in the experiment, a finite element analysis (FEA) is done for the handlebar tubes by using the CAD software package Solidworks, which is a linear solver and therefore appropriate for the static loading condition under consideration. *Figure 7* shows a CAD model and study mesh of the right handlebar that is built in Solidworks, where the clip-on is represented by a simple block that rigidly fixes the tube, whilst a point load with 3 kg is applied to the free end.

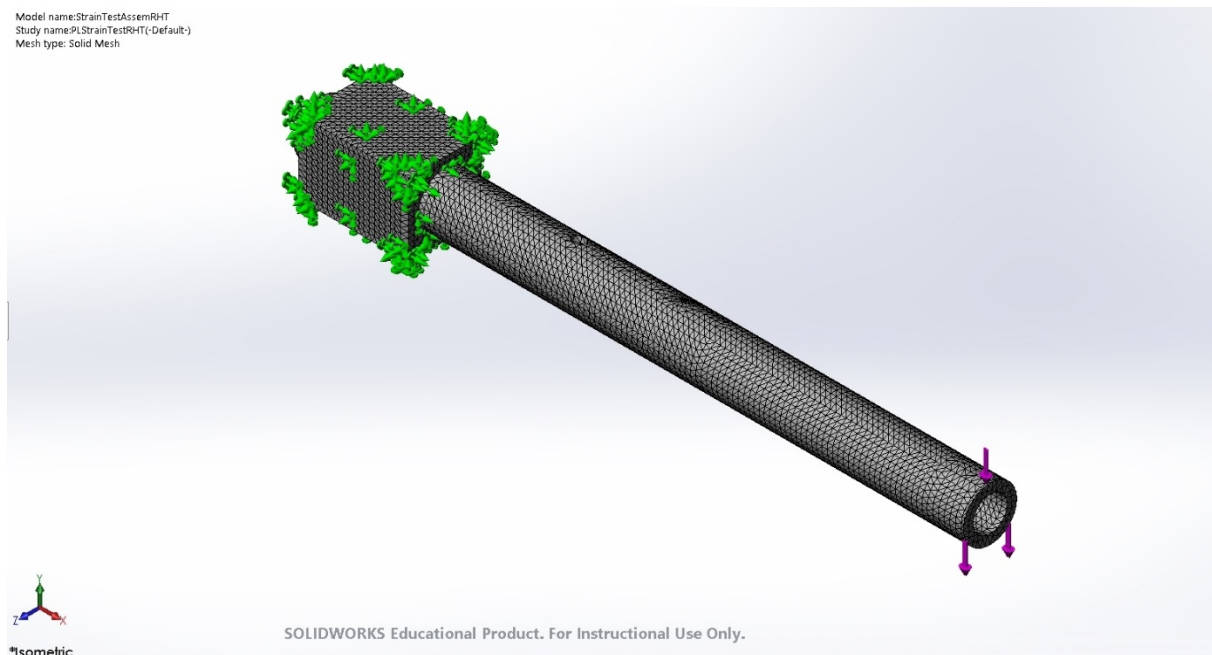


Figure 7 – CAD model and mesh of the load case study for the right handlebar tube in Solidworks (Przibylla, 2017/2018)

The results of the FEA study that is carried out for the same scenario and experiment that is conducted in the workshop match the numbers that are obtained via hand calculations, when assigning the material properties of a standard aluminium alloy to the part, and are displayed in *Figure 8* and *Figure 9* on the following page.

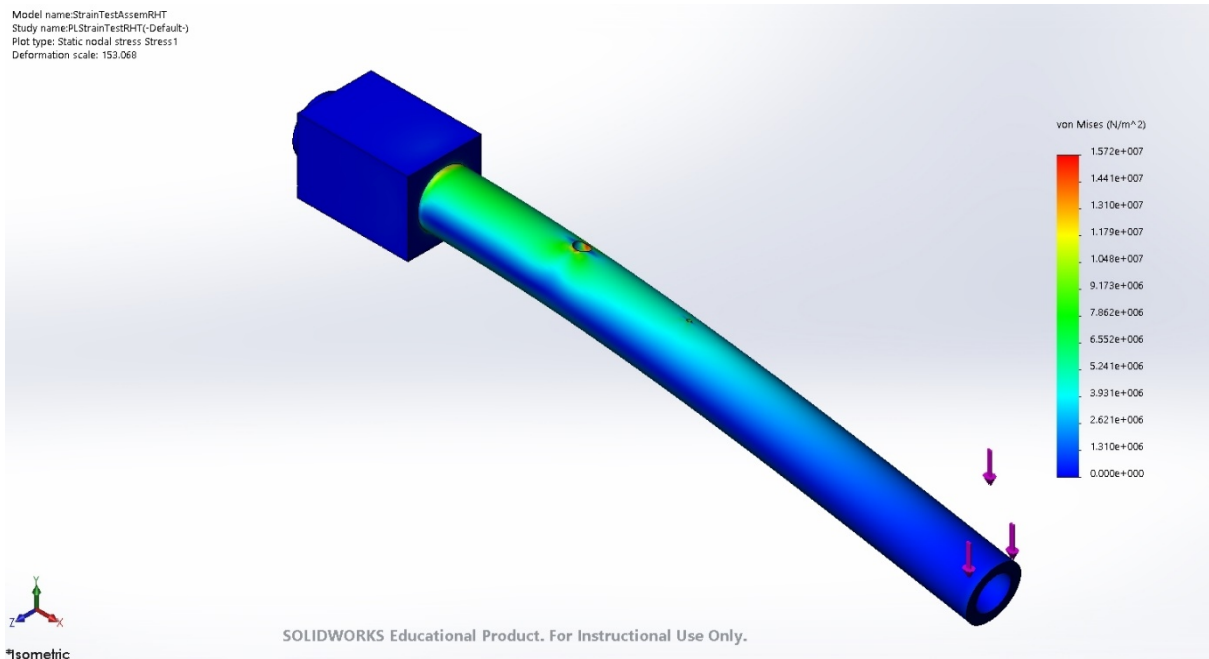


Figure 8 – FEA results for stress within the handlebar tube (Przibylla, 2017/2018).

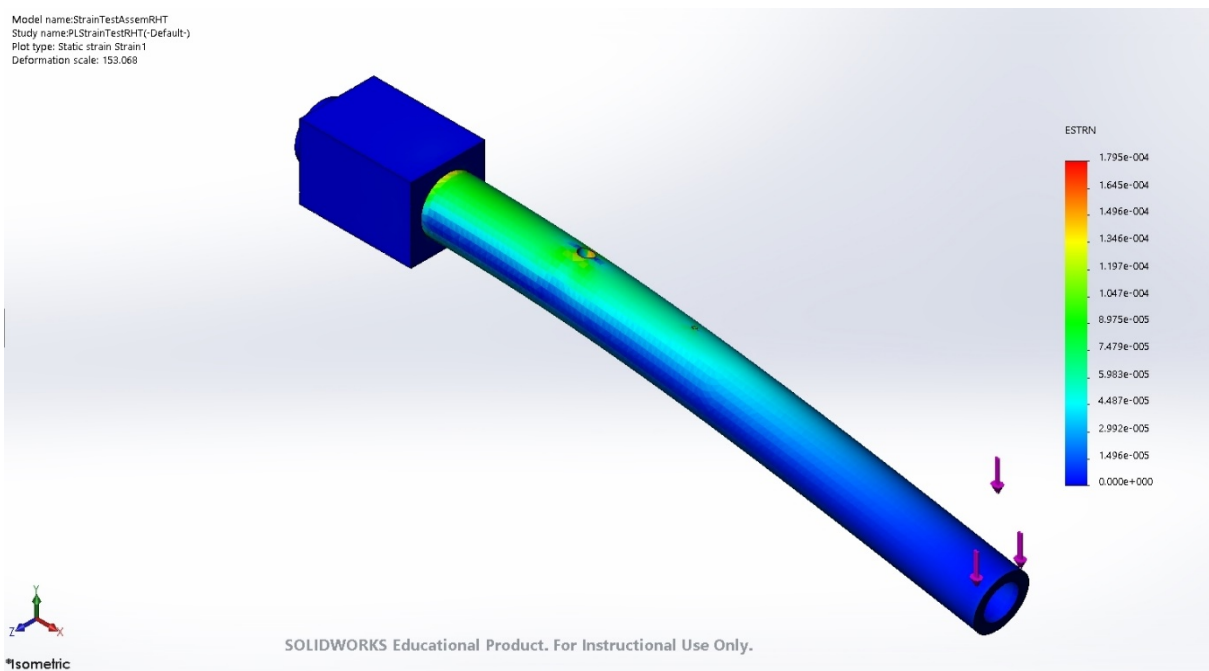


Figure 9 – FEA results for strain within the handlebar tube (Przibylla, 2017/2018).

The same basic relationships and formulae that are used for calculating the stress and bending moment can be applied to a load case with a uniformly distributed load (UDL) that acts across the handlebar grip, whilst representing the force that the rider is applying in reality, and, after having determined Young's modulus, the force that is exerted at the handlebars can be calculated from the strain that is measured with the strain gauges by replacing the distance to the free end with the distance to the centre of the grips in the equation for the bending moment, as the theory of bending states that the moment which is created by a UDL is equal to the moment of a PL with the same total magnitude that is assumed to be acting at the centre of the UDL (Hearn, 1997). To evaluate the chosen position of the strain gauges and visualise the difference in behaviour of the tubes under an applied force by the rider, another FEA study is carried out for a UDL that is acting across the span of the handlebar grip and creating the same bending moment. *Figure 10* shows the load case of the study.

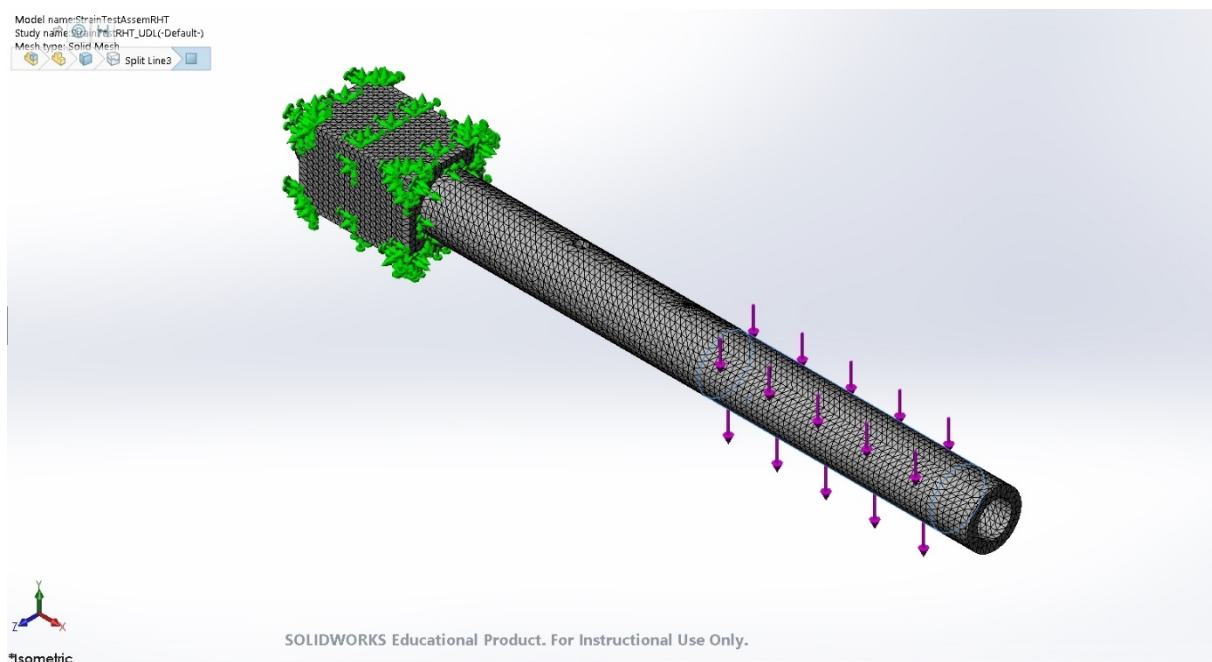


Figure 10 – Mesh of the load case study with a UDL on the right handlebar tube in Solidworks (Przibylla, 2017/2018)

The results of this study are displayed in *Figure 11* and *Figure 12* overleaf.

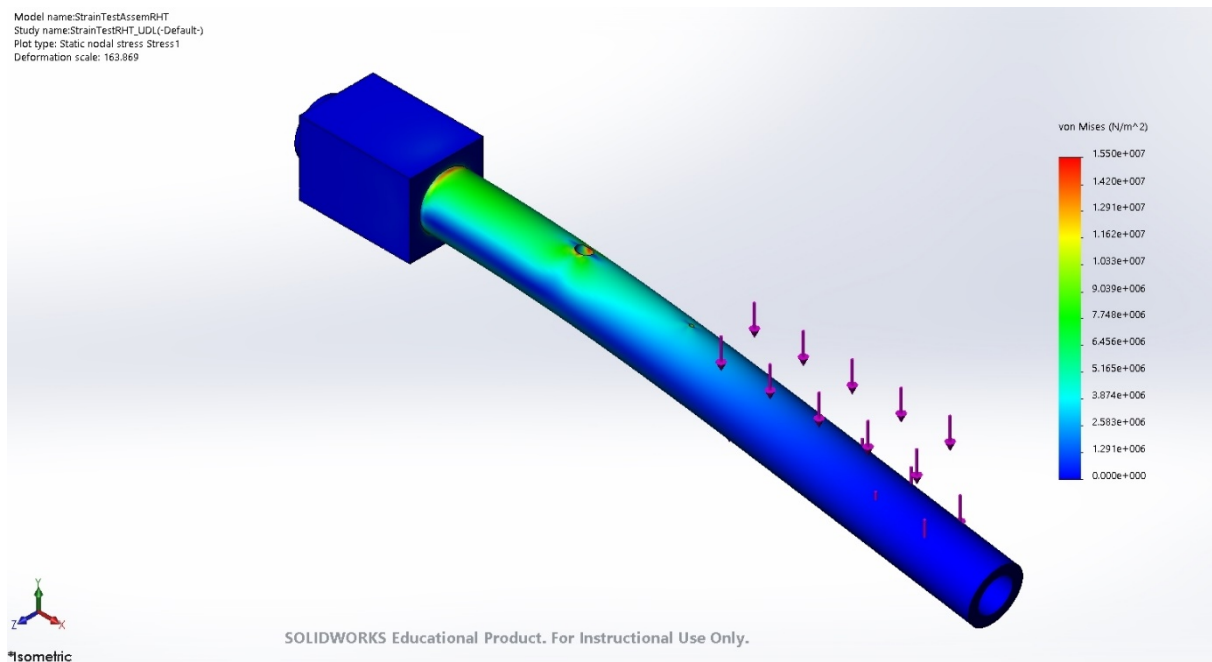


Figure 11 – FEA results for stress within the handlebar tube from a UDL (Przibylla, 2017/2018).

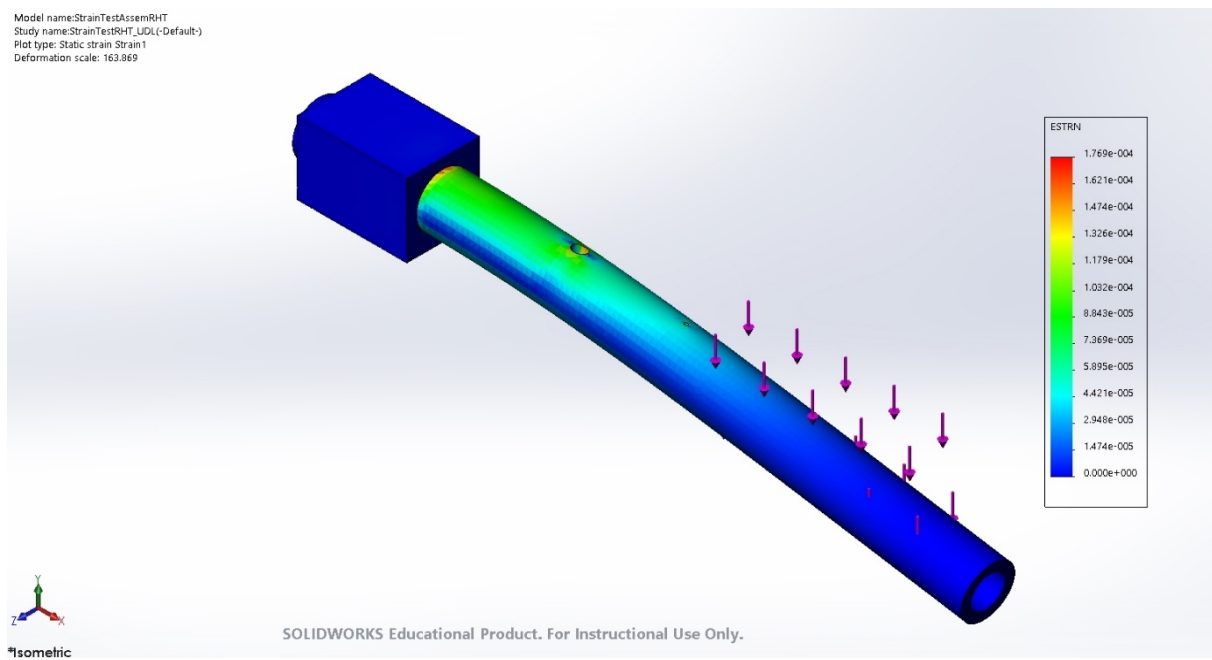


Figure 12 – FEA results for strain within the handlebar tube from a UDL (Przibylla, 2017/2018).

Judging by a visual assessment of the occurring stress and strain, the exact positioning of the strain gauges is appropriate and not requiring any alteration, so that two additional strain gauges can now be fitted to each handlebar tube and in a 90° offset to the strain gauge pairs that are already installed. The added strain gauges have the same half-bridge configuration and are wired up to the remaining two slots of the strain gauge amplifier. This final setup, shown in *Figure 13*, with two strain gauge pairs on each handlebar tube and orientated at 90° to each other, which is forming a perfect circle with a perpendicular intersection of the two measurement axes in its centroid, allows for the magnitude and direction of the resultant force on the handlebar tube that is calculated using the measurements of both strain gauge pairs to be determined anywhere in 360°, as it is further described in the next chapter.

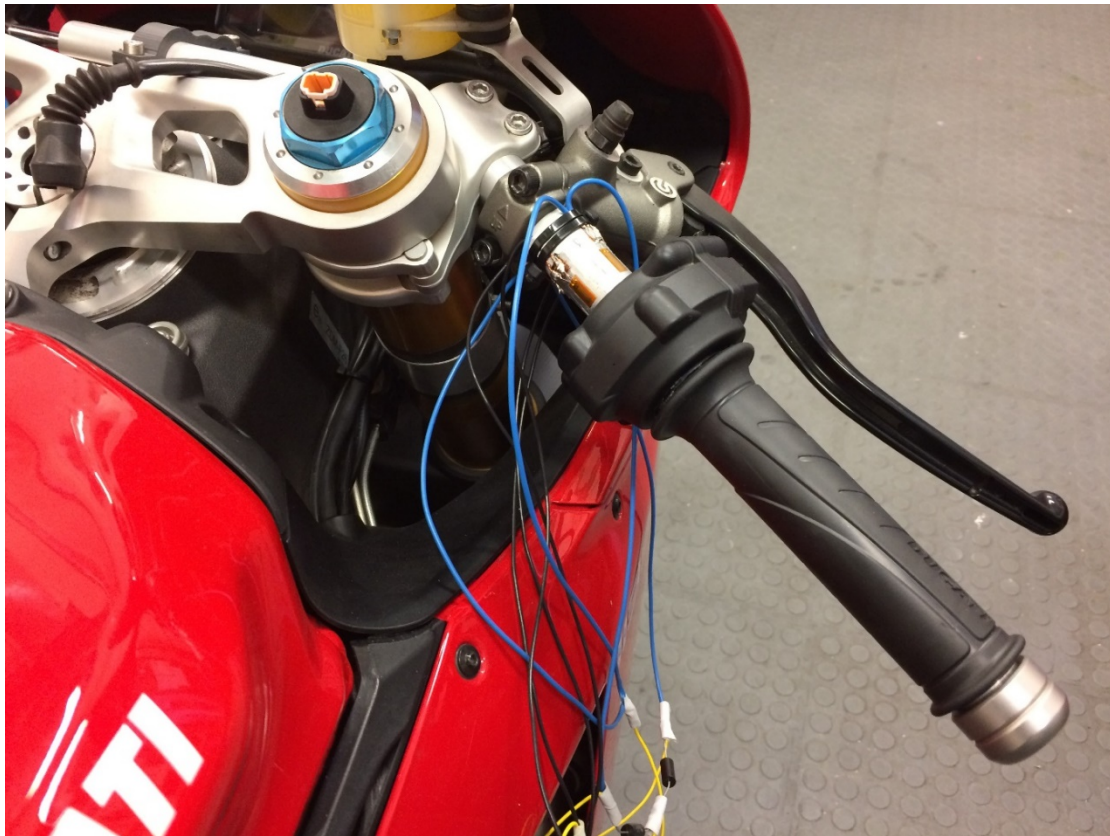


Figure 13 – Final strain gauge setup on the right handlebar tube of the Panigale with 4 strain gauges fitted at 90 degrees to each other (Przibylla, 2017/2018)

Due to the strain gauges being highly fragile and their leads prone to touching and braking, which immediately causes a short circuit, silicone is used on the soldered connections between the leads and the ends of the wires. In addition, plastic brackets that cover the strain gauges on the handlebars and further support the wires are designed in Solidworks and made by using a 3-D printer, also to protect the strain gauges against impact and from

the drag that exponentially increases with the velocity of the motorcycle. Finally, all the wires that are coming from the brackets, as shown in *Figure 14*, are packed in expandable cable sleeve and have to be routed to the strain gauge amplifier and data logger at the back of the seat unit along the inside of the motorcycle.

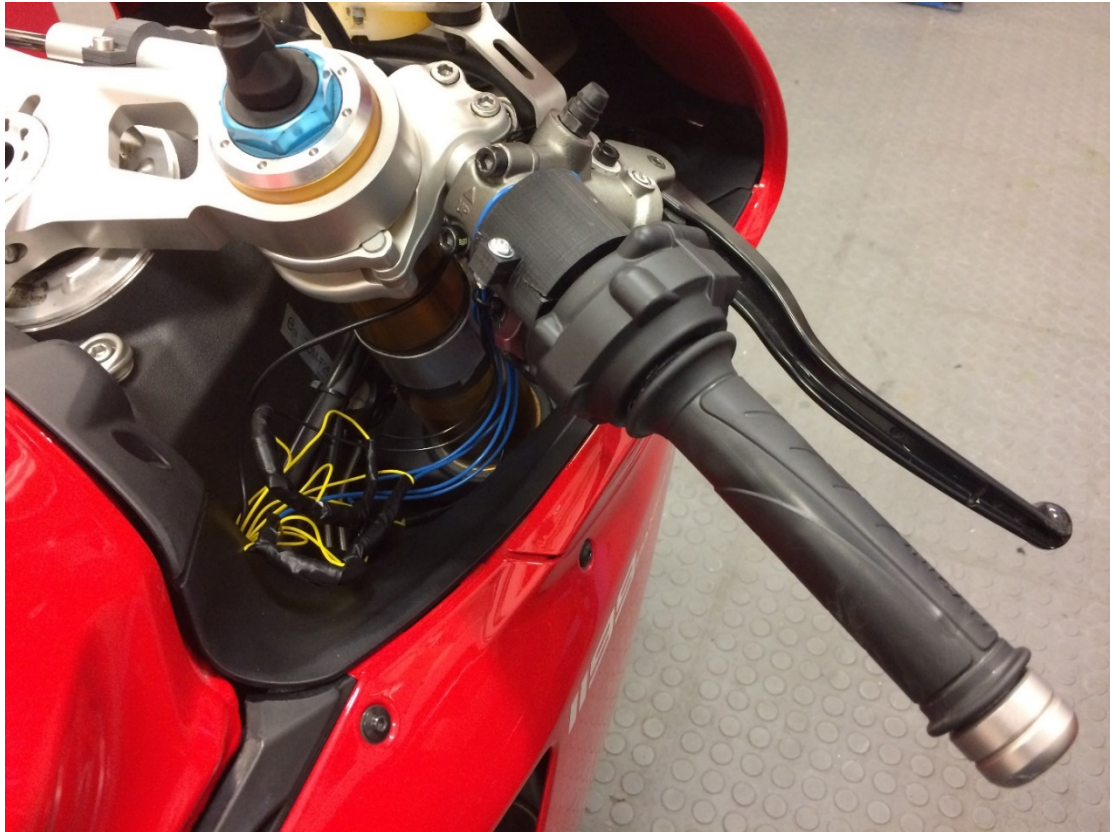


Figure 14 – Strain gauge protection and wiring to the main data logger (Przibylla, 2017/2018)

In order to relate and subtract the amount of strain that is introduced by operating the clutch from the total measurement of the strain gauge pair that is in line with the clutch lever on the left handlebar tube, as it is resulting from a force that is locally balanced and not contributing to the overall steering torque, a force-sensing linear potentiometer strip (FSLP) is used to record the magnitude of the force that is applied to the lever. The FSLP is a three-terminal device and its internal circuit is the equivalent of three resistors, which means that it is capable of measuring the relative position of an applied force, however a fourth and external resistor needs to be added to the circuit, if the magnitude of the force shall be recorded (Pololu Corporation, 2001–2018). The sensor is glued onto the clutch lever and directly connected to the 2D data logger by using the configuration that shown in *Figure 15* and described below, however without the implementation of a microcontroller.

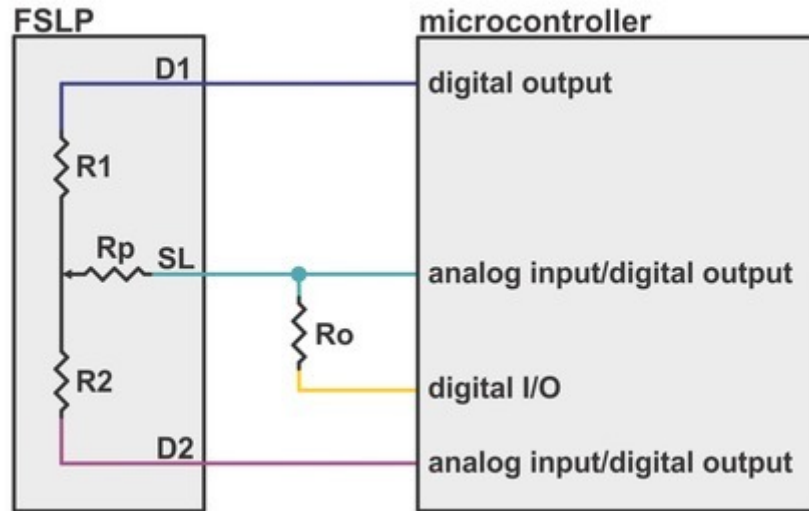


Figure 15 – Configuration and wiring diagram of the FSLP (Pololu Corporation, 2001–2018)

The resistance R_p is directly dependant on the magnitude of the force that is applied and, with D1 being used for a 5 V supply voltage and the bottom of R_o to ground the sensor, the sense line SL becomes the output of a voltage divider with R_p as the numerator and R_o as the denominator, which has an input voltage that is measured at D2, which is allowing for R_p to be calculated independently of R_1 and R_2 that change with the position of the applied force (Pololu Corporation, 2001–2018). Thus, the magnitude of the force that is applied to the strip is calculated as follows (Interlink Electronics, Inc., n.d.). The current that is flowing through R_o is known and the same current is flowing through R_p :

$$I = \frac{V_1}{R_o}$$

As no current flows through R_2 , the voltage drop across R_p equals $V_2 - V_1$ and R_p can be calculated from:

$$R_p = R_o * \frac{(V_2 - V_1)}{V_1}$$

The force on the sensor is given by the reciprocal of the above, where a convenient value can be used for the scaling factor R_o , as it is a constant:

$$F = 32 * \frac{V_1}{(V_2 - V_1)}$$

After cutting the sensor strip to the right length, wires are soldered to the FSLP, with a 4,7 kΩ resistor that is spliced into the sense line from the ground, and by using 2D connectors and

pins the circuit is integrated with the main data logger that supplies the FSLP with the exciting voltage, acts as a ground and creates two channels for the measured voltages via analogue inputs. Once the wires are packed and routed along the inside of the motorcycle, the sensor strip is protected with heat shrink to ensure that the sensor strip cannot accidentally be pulled off the lever by the gloves of the rider, as shown in *Figure 16*.



Figure 16 – FSLP fitted to the clutch lever on the left handlebar tube (Przibylla, 2017/2018)

To account for the strain that is caused by operation of the brake lever on the right handlebar tube, the brake pressure sensor of the Panigale that is already integrated in 2D is used to relate the locally balanced force on the lever, which is not contributing to steering torque, to the recorded strain measurements. The resulting strain can then be subtracted from the respective channel using the calculation file, which is written for post-processing of all the acquired data and explained in the following chapter.

5.2. Coding and Software Integration

The calculation file manager is a tool within the 2D software package that can be used to create and calculate new channels based on referencing already existing ones. For this purpose, a mathematical code that uses the default syntax which is defined by the software has to be written and saved as a calculation file, before it can be run for post-processing and analysis of acquired datasets. Therefore, with the four strain gauges on each handlebar tube and the force-sensing linear potentiometer strip on the clutch lever being directly connected to the 2D data logger, all necessary calculations to implement the sensors and create the required channels for computing steering torque in 2D can be carried out as part of a calculation file and in the 2D software environment. *Figure 17* and *Figure 18* on the following two pages show the first four sections of the code, in which the UDL at the grip of each handlebar tube is calculated by using the measurements from the strain gauges, where the even numbers 2 and 4 represent the two strain gauge pairs on the right handlebar tube, whilst the strain gauge pairs on the left handlebar tube are labelled with the uneven numbers 1 and 3.

```

1 ;last modified 20/04/2018 13:02:58 by aprzi
2
3 [UDL_RHT2]
4 @SGB2_RHTzero=EnterValue('Zero Digits Value for SGB2_RHT',32768.45)
5 c1=-(@SGB2_RHTzero,#SGB2_RHT)
6 c2=/(#c1,@SGB2_RHTzero)
7 @SGB_Amp=EnterValue('Multiplier for SGB Amplification',-0.01)
8 c3=*(@SGB_Amp,#c2)
9 Strain2=/(#c3,2)
10 @D_RHT=EnterValue('Outer Diameter of RHT',0.02185)
11 @d_RHT=EnterValue('Inner Diameter of RHT',0.01403)
12 @y_RHT=EnterValue('Distance to Neutral Axis of RHT',0.010925)
13 @x2=EnterValue('Distance to Strain Gauge SGB2',0.1146)
14 @YM_RHT=EnterValue('Youngs Modulus of RHT',66171884602)
15 Stress2=*(#Strain2,@YM_RHT)
16 Stress2=Set(Dim='N/m²')
17 @I_RHT=EnterValue('Second Moment of Area for RHT',0.0000000093)
18 c4=*(#Stress2,@I_RHT)
19 Moment2=/(#c4,@y_RHT)
20 Moment2=Set(Dim='Nm')
21 TotalUDL_RHT2=/(#Moment2,@x2)
22 TotalUDL_RHT2=Set(Dim='N')
23 BrakingUDL_RHT2=*(#F_Brake,0.90)
24 BrakingUDL_RHT2=Set(Dim='N')
25 UDL_RHT2=-(#TotalUDL_RHT2,#BrakingUDL_RHT2)
26 UDL_RHT2=Set(Dim='N')
27
28 [UDL_RHT4]
29 @SGB4_RHTzero=EnterValue('Zero Digits Value for SGB4_RHT',32776.966)
30 c5=-(@SGB4_RHTzero,#SGB4_RHT)
31 c6=/(#c5,@SGB4_RHTzero)
32 c7=*(@SGB_Amp,#c6)
33 Strain4=/(#c7,2)
34 @x4=EnterValue('Distance to Strain Gauge SGB4',0.11485)
35 Stress4=*(#Strain4,@YM_RHT)
36 Stress4=Set(Dim='N/m²')
37 c8=*(#Stress4,@I_RHT)
38 Moment4=/(#c8,@y_RHT)
39 Moment4=Set(Dim='Nm')
40 UDL_RHT4=/(#Moment4,@x4)
41 UDL_RHT4=Set(Dim='N')
42

```

Figure 17 – Calculation file code for computing the UDL from each strain gauge pair on the right handlebar tube (Przibylla, 2017/2018)

```

42
43 [UDL_LHT1]
44 @SGB1_LHTzero=EnterValue('Zero Digits Value for SGB1_LHT',32769.51)
45 c9=- (@SGB1_LHTzero,#SGB1_LHT)
46 c10=/(#c9,@SGB1_LHTzero)
47 c11=*(@SGB_Amp,#c10)
48 Strain1=/(#c11,2)
49 @D_LHT=EnterValue('Outer Diameter of LHT',0.022)
50 @d_LHT=EnterValue('Inner Diameter of LHT',0.01435)
51 @y_LHT=EnterValue('Distance to Neutral Axis of LHT',0.011)
52 @x1=EnterValue('Distance to Strain Gauge SGB1',0.1165)
53 @YM_LHT=EnterValue('Youngs Modulus of RHT',65696106029)
54 Stress1=*(#Strain1,@YM_LHT)
55 Stress1=Set(Dim='N/m²')
56 @I_LHT=EnterValue('Second Moment of Area for LHT',0.0000000094)
57 c12=*(#Stress1,@I_LHT)
58 Moment1=/(#c12,@y_LHT)
59 Moment1=Set(Dim='Nm')
60 TotalUDL_LHT1=/(#Moment1,@x1)
61 TotalUDL_LHT1=Set(Dim='N')
62 c1v=- (#V2,#V1)
63 c1V=/(#V1,#c1v)
64 Clf=*(32,#c1V)
65 ClF=+ (#clf,51.2)
66 ClutchUDL_LHT1=*(#ClF,0.165)
67 ClutchUDL_LHT1=Set(Dim='N')
68 UDL_LHT1=- (#TotalUDL_LHT1,#ClutchUDL_LHT1)
69 UDL_LHT1=Set(Dim='N')
70
71 [UDL_LHT3]
72 @SGB3_LHTzero=EnterValue('Zero Digits Value for SGB3_LHT',32763.6238)
73 c13=- (@SGB3_LHTzero,#SGB3_LHT)
74 c14=/(#c13,@SGB3_LHTzero)
75 c15=*(@SGB_Amp,#c14)
76 Strain3=/(#c15,2)
77 @x3=EnterValue('Distance to Strain Gauge SGB3',0.1174)
78 Stress3=*(#Strain3,@YM_LHT)
79 Stress3=Set(Dim='N/m²')
80 c16=*(#Stress3,@I_LHT)
81 Moment3=/(#c16,@y_LHT)
82 Moment3=Set(Dim='Nm')
83 UDL_LHT3=/(#Moment3,@x3)
84 UDL_LHT3=Set(Dim='N')

```

Figure 19 – Calculation file code for computing the UDL from each strain gauge pair on the left handlebar tube (Przibylla, 2017/2018)

The channel range of each strain gauge bridge reaches from 0 to 65535 digits and the supply voltage can be adjusted to zero the signal that is coming from each bridge or to introduce an offset, if required (2D Debus & Diebold Meßsysteme GmbH, 2014). As the strain gauges are measuring the strain in positive and negative direction, i.e. compressive and tensile strain, the supply voltage in millivolts is adjusted to cause each strain gauge pair to idle with a signal output of 32768 digits in the centre of the range before every recording. Thus, the code starts with the digit values that each strain gauge pair is zeroed to, before it calculates the strain, stress and bending moment from the same dimensions and equations that are used and described in the previous chapter. Line 23 of the code introduces a separate UDL to the total UDL that is calculated for the strain gauge bridge #2, based on the recorded channel of brake pressure, which is then subtracted from the total UDL. This channel represents the UDL that results from applying the front brakes of the motorcycle when using the brake lever and the calculated UDL from the strain that is measured during repeated tests and in the same plane with the lever is found to be closest to 95% of the value for the brake pressure that is measured in bar, if a strain gauge amplification of 100 is used. The tests are conducted using cable ties, G-clamps and physical force to pull in the brake lever, whilst avoiding the application of any other external force in a different direction as best as possible. *Figure 19* shows measured and calculated data from a test with a G-clamp and comparing the yellow graph of the total UDL to the orange graph of the calculated UDL from braking reveals that a sufficient compromise has to be found, as the strain gauge measurements are more sensitive and accurate than the readings from the brake pressure sensor, which is preventing the channels from cancelling fully at all times.

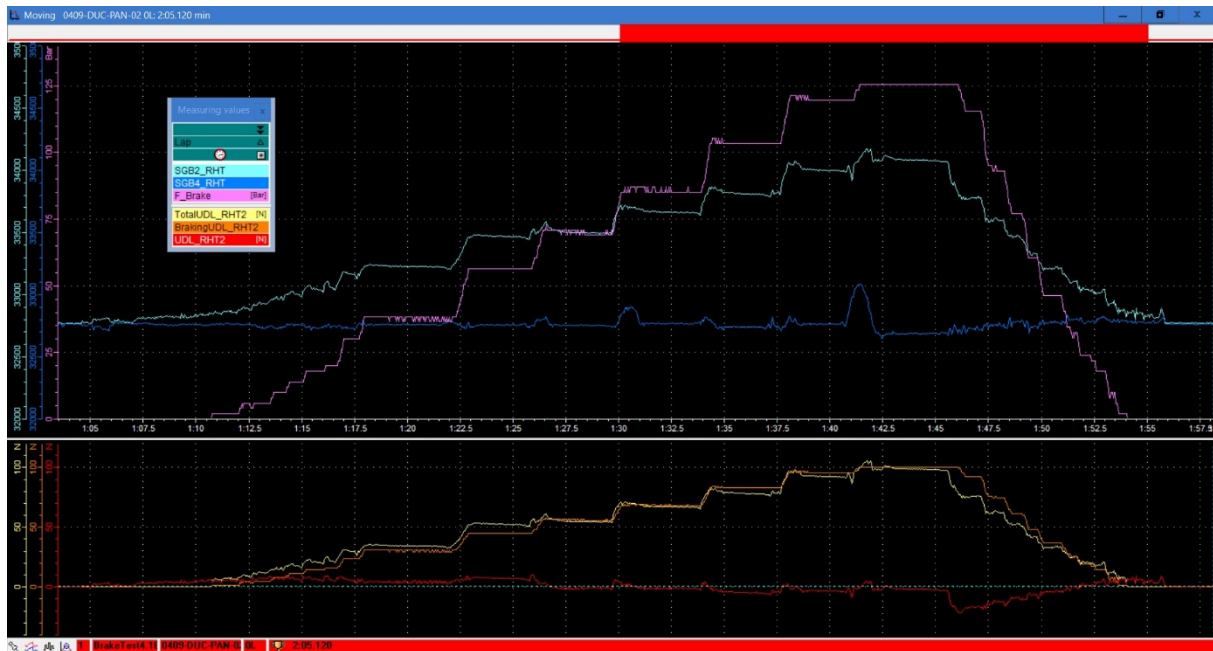


Figure 19 – 2D dataset for the calibration of the UDL that is resulting from braking (Przibylla, 2017/2018)

Similarly, the force which is measured with the FSLP on the clutch lever and calculated in lines 62 to 64 of the code, by using the electronics formula and two output voltages of the sensor that are derived and described in the previous chapter, is resulting in strain measurements from the strain gauge pair #1 on the left handlebar tube. Hence, the total UDL that is calculated from the strain which is measured with the strain gauge pair #1 is related to the channel of this force in line 66, based on the data that is recorded from tests by using the same approach as for the right handlebar tube. Line 65 is accounting for a constant signal offset from the FLSP, which is determined during zero reading, and the calculated component of the total UDL with no effect on steering torque is then subtracted from it.

Figure 20 shows measured and calculated data from a test in which physical force is used to pull in the clutch lever. The pink and light blue graphs of the voltage drop and force on the FSLP spike considerably when the lever is at the end of its travel, without a correlating or noticeable further increase in strain, which consequently causes the calculated UDL from operating the clutch lever to exceed the total UDL that is calculated from the measured strain and is ultimately resulting in a cancellation error. The reason for this error is that the clutch lever can come into contact with the grip of the handlebar, which is restricting its travel, and any additional force that is applied to the lever will be measured by the FSLP, however not causing an increase in the measurement of any strain, since the opposing force is no longer resulting in a bending moment due to it creating an equilibrium at the point of contact on the other side of the handlebar tube. Instructing the rider to account for this could be a solution to

the problem, yet the displayed dataset suggests that the calibration might still not be completely free of slight inaccuracies.

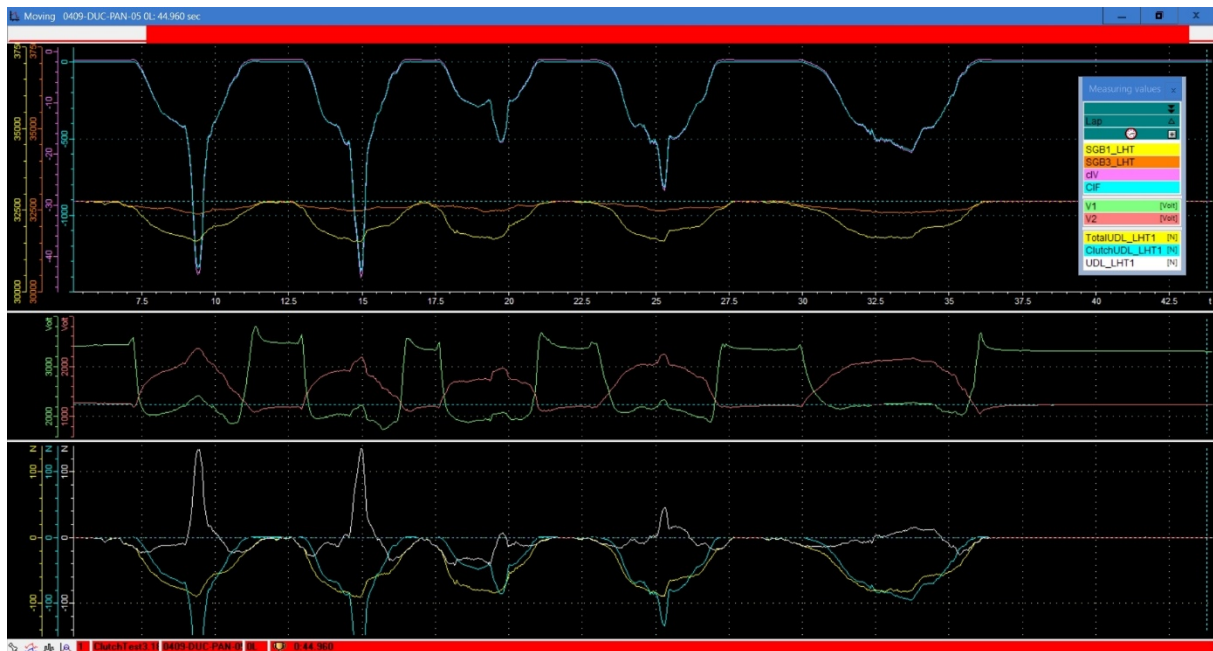


Figure 20 – 2D dataset for the calibration of the UDL that is resulting from using the clutch (Przibylla, 2017/2018)

Once the UDL is calculated from the measured strain of each strain gauge pair along their measurement axes, a resultant UDL can be determined anywhere in 360° and for every quarter that is formed by the perpendicularly intersecting measurement axes that resemble a two-dimensional coordinate system on each handlebar tube. For this purpose, trigonometry is used to calculate the direction and magnitude of any resultant UDL from the previously created UDL channels. *Figure 21* shows a schematic diagram of the coordinate system that is formed by the two strain gauge pairs and measurement axes, as well as its orientation to the horizontal plane and the relative position of the plane in which the steering force is acting, which are labelled with the letters H and S respectively, when looking at the right side of the motorcycle.

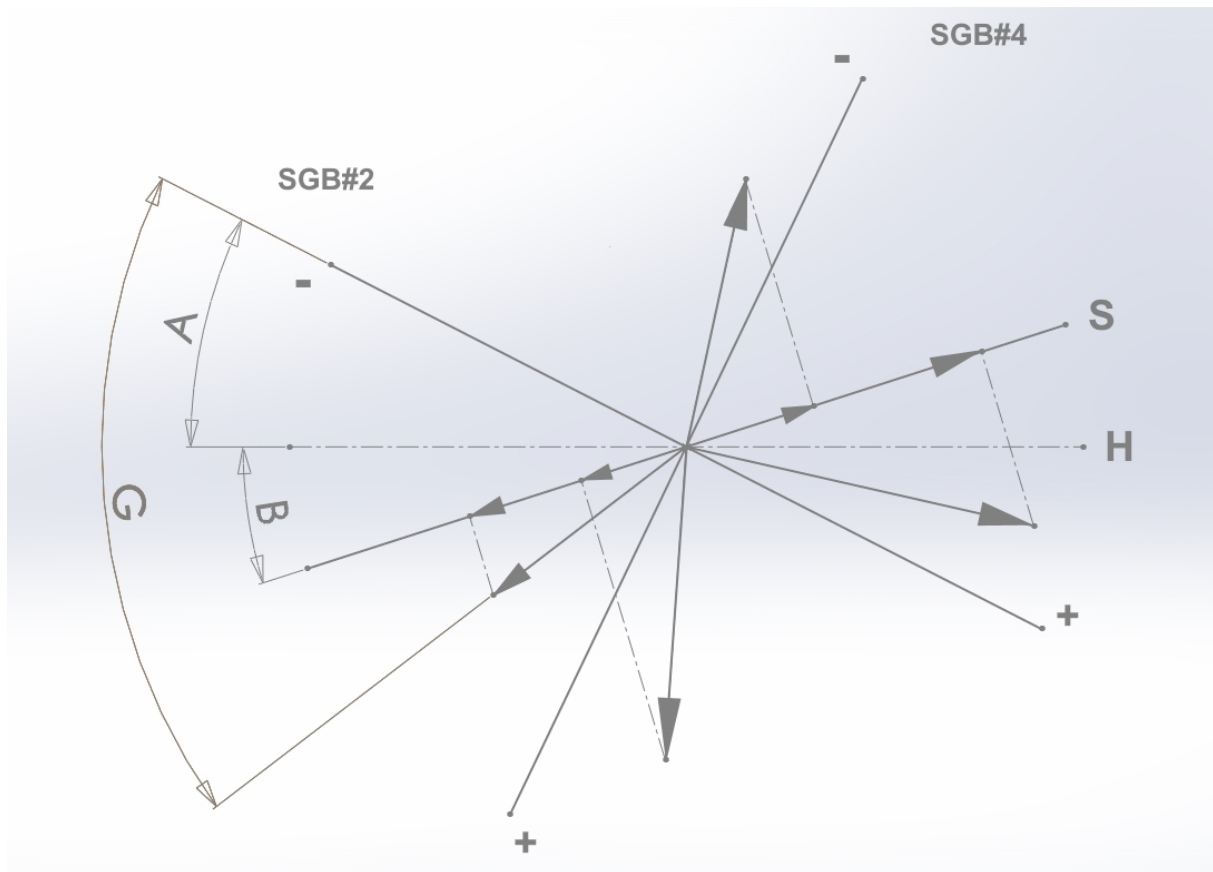


Figure 21 – Schematic diagram of the coordinate system formed by the strain gauges on the right handlebar tube and its orientation to the horizontal and steering plane (Przibylla, 2017/2018)

The steering plane can be understood as a plane that is perpendicular to the forks of the motorcycle and parallel to the steering head, around which the handlebars are being pushed and pulled to change the steering angle or torque. Whilst the angle G continuously changes with the direction of the applied and resultant load, the sum of the angles A and B will remain constant, even when the motorcycle is pitching, and their static values are determined by physically measuring the strain gauge positions and the steering head angle on the motorcycle. *Figure 22* shows the next four sections of the calculation file code, in which the resultant UDL and force on each handlebar tube is calculated by using trigonometric equations that are derived and explained as follows.

```

85
86 [ResUDL_RHT]
87 c17=/(#UDL_RHT4,#UDL_RHT2)
88 gamma_RHT=ArcTan(#c17)
89 gamma_RHT=Set(Dim='rad')
90 c18=Sin(#gamma_RHT)
91 ResUDL_RHT=/(#UDL_RHT4,#c18)
92 ResUDL_RHT=Set(Dim='N')
93
94 [ResUDL_LHT]
95 c19=/(#UDL_LHT3,#UDL_LHT1)
96 gamma_LHT=ArcTan(#c19)
97 gamma_LHT=Set(Dim='rad')
98 c20=Sin(#gamma_LHT)
99 ResUDL_LHT=/(#UDL_LHT3,#c20)
100 ResUDL_LHT=Set(Dim='N')
101
102 [F_RHT]
103 @Alpha_SGB=EnterValue('Angle of SGB to Horizontal',20)
104 @Beta_SH=EnterValue('Angle of SH to Horizontal',23.5)
105 Gamma_RHT=*(57.2958,#gamma_RHT)
106 Gamma_RHT=Set(Dim='°')
107 c21=+ (#Gamma_RHT,@Alpha_SGB)
108 ABG_RHT=+ (#c21,@Beta_SH)
109 ABG_RHT=Set(Dim='°')
110 c22=DCos(#ABG_RHT)
111 F_RHT=*(#ResUDL_RHT,#c22)
112 F_RHT=Set(Dim='N')
113
114 [F_LHT]
115 Gamma_LHT=*(57.2958,#gamma_LHT)
116 Gamma_LHT=Set(Dim='°')
117 c23=+ (#Gamma_LHT,@Alpha_SGB)
118 ABG_LHT=+ (#c23,@Beta_SH)
119 ABG_LHT=Set(Dim='°')
120 c24=DCos(#ABG_LHT)
121 F_LHT=*(#ResUDL_LHT,#c24)
122 F_LHT=Set(Dim='N')
123

```

Figure 22 – Calculation file code for computing the resultant UDL and force on each handlebar tube (Przibylla, 2017/2018)

In order to understand the derivations and equations that are used for the sections of the code which are displayed in Figure 22, it is important to note that the strain gauge configuration of the right handlebar tube differs to the configuration of the strain gauge half-bridges on the left handlebar tube, with the strain gauge pairs #2 and #4 giving a positive reading when the right handlebar is being pushed forwards or downwards and a negative reading in the opposite direction, whilst the strain gauge pairs #1 and #2 are giving a negative reading when the left handlebar is being pushed forwards or downwards and a positive reading in the opposite direction. This is done deliberately and achieved by wiring up the strain gauge circuits in the opposite way, to account for the fact that a push on the right

handlebar is being helped by a pull on the left handlebar and vice versa, hence the pushing and pulling adds up to a steering torque in the same direction. With that being the case, the equations that are derived have to ensure that a resultant force in the frontal quarters of the coordinate system on the right handlebar tube is always positive and a resultant force in the other two quarters negative, whilst a resultant force in the frontal quarters of the coordinate system on the left handlebar tube has to be negative and a resultant force in the other two quarters positive. The following equations satisfy this condition together and are used for determining the direction and magnitude of the resultant UDL.

For the right handlebar tube:

$$G = \tan^{-1} \left(\frac{UDL\#4}{UDL\#2} \right)$$

$$UDL_{Res} = \frac{UDL\#4}{\sin(G)}$$

For the left handlebar tube:

$$G = \tan^{-1} \left(\frac{UDL\#3}{UDL\#1} \right)$$

$$UDL_{Res} = \frac{UDL\#3}{\sin(G)}$$

Following that, the UDL is resolved for the steering plane and converted to the force which is a component of the total force that is applied by the rider and acting in the same plane as the steering torque. The basic condition for the following trigonometric formula is that a force which lies behind or in front of a perpendicular to the steering plane that intersects the origin of the coordinate system has to be resolved in the correct direction along the steering plane, regardless of the quarter of the coordinate system that it is situated in, as shown by the arrows that are pointing directly upwards and downwards in *Figure 21*. This is the case for any resultant with a combined angle that is greater than 90°, hence the following equation is used to ensure that the sign changes accordingly.

For both handlebar tubes:

$$UDL_{Steering\ Plane} = UDL_{Res} * \cos(A + B + G)$$

$$Force_{Steering\ Plane} = UDL_{Steering\ Plane}$$

Before the steering torque can be calculated from the force that is creating a torque around the steering head, the previously determined force that is acting in the steering plane has to be resolved once more, however in a third dimension to the two-dimensional coordinate system that is referred to so far. As the strain gauge pairs are measuring the strain that is occurring at their position and from a load that is acting along their measurement axes, the force that is calculated from the UDL has a vector which is perpendicular to the handlebar tubes. The handlebar tubes on the Panigale are mounted diagonally and not square to the motorcycle, which results in the calculated force pointing further outwards from the arc of rotation around the steering head than the force that is directly creating a torque around its centre, as shown in *Figure 23*.

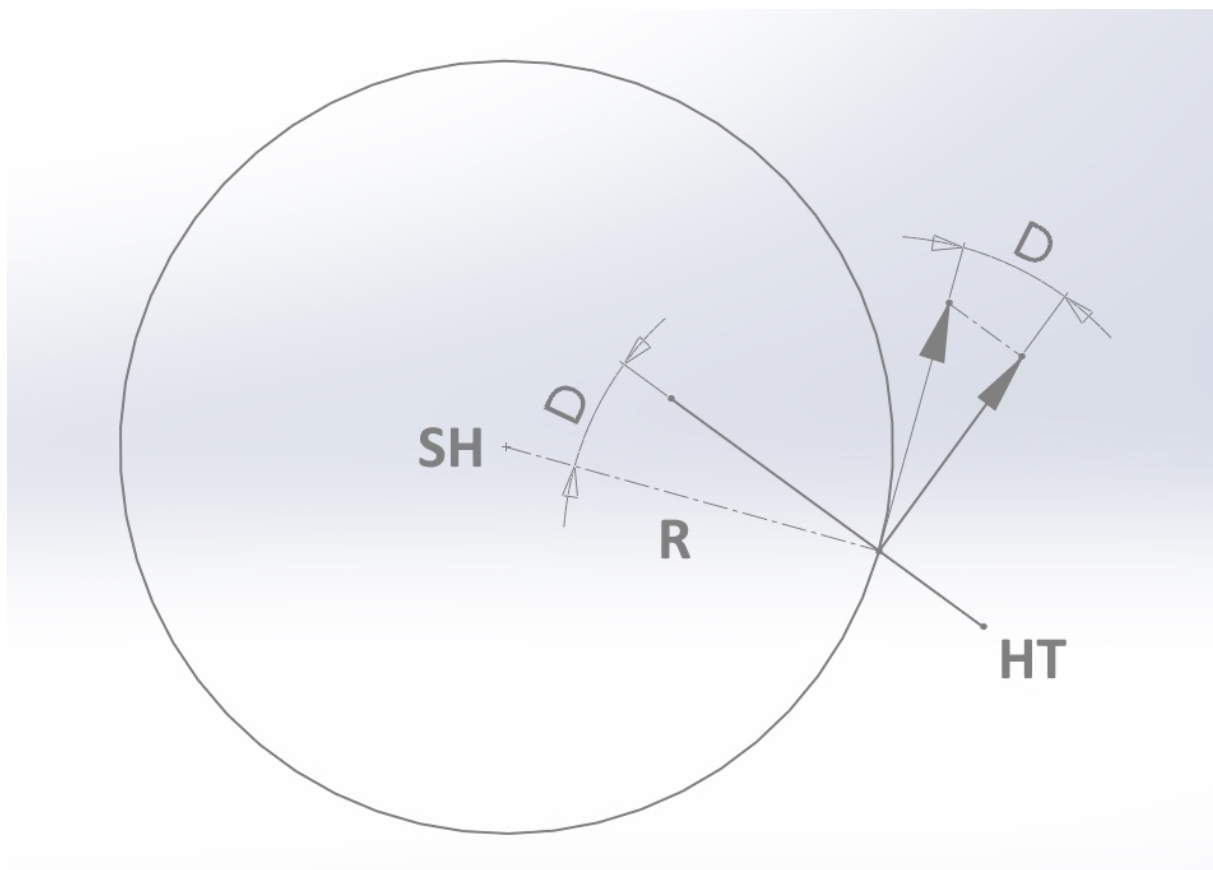


Figure 23 – Sketch of the forces on the right handlebar tube and its orientation to the circle that it describes around the centre of the steering head (Przibylla, 2017/2018)

Torque is the turning moment of a force-couple and it is defined as the magnitude of either force multiplied by the perpendicular distance between the two forces, which means that the steering torque results from a force that is acting at 90 degrees to the distance between it and the centre of the steering head (Bird, 2012). In this case, the steering torque is

calculated from the force which is acting at the centre of each handlebar grip, therefore the forces on each handlebar are resolved for the component that is acting at 90 degrees to the turning radius, i.e. the distance to the centre of the steering head. *Figure 23* shows that the angle with which the previously calculated force is offset from the desired force component is equal to the angle that the handlebars are tilted by and it can physically be measured on the motorcycle, together with the distances from the centre of the steering head to the centre of each grip. Based on the assumption that a rider pushes or pulls the handlebars directly forwards or backwards, rather than pushing out or pulling in on the handlebars, the wanted force component represents the hypotenuse of the triangle under consideration and is therefore of greater magnitude than the force that is originally measured and calculated. Thus, the equations for both handlebars are given by:

$$Force_{Steering} = \frac{Force_{Steering\ Plane}}{\cos(D)}$$

$$Torque_{Steering} = Force_{Steering} * Distance\ to\ Centre\ of\ Steering\ Head$$

$$Steering\ Torque = Torque_{Steering\ right\ Handlebar} + Torque_{Steering\ left\ Handlebar}$$

Figure 24 shows the final sections of the code, which are calculating the steering force and steering torque by using the equations that are described above.

```

123
124 [StF_RHT]
125 @Delta_HT=EnterValue('Cosine for Angle of HT to SH Radius',0.866)
126 StF_RHT=/(#F_RHT,@Delta_HT)
127 StF_RHT=Set(Dim='N')
128
129 [StF_LHT]
130 StF_LHT=/(#F_LHT,@Delta_HT)
131 StF_LHT=Set(Dim='N')
132
133 [StT_RHT]
134 @x6=EnterValue('Distance to Centre of SH from RHT',0.3)
135 StT_RHT=*(#StF_RHT,@x6)
136 StT_RHT=Set(Dim='Nm')
137
138 [StT_LHT]
139 @x5=EnterValue('Distance to Centre of SH from LHT',0.3)
140 StT_LHT=*(#StF_LHT,@x5)
141 StT_LHT=Set(Dim='Nm')
142
143 [StTorque]
144 StTorque=+ (#StT_RHT,#StT_LHT)
145 StTorque=Set(Dim='Nm')
146

```

Figure 24 – Calculation file code for computing the steering force and torque on each handlebar tube, as well as the overall steering torque (Przibylla, 2017/2018)

5.3. Carbon Fibre Seat Unit Cover

The original seat unit cover of the Panigale, which is shown in *Figure 25*, does not offer enough space inside the seat unit for the storage of the main data logger, the strain gauge amplifier and the IMU that has to be fixed in place. Therefore, a custom-made seat unit cover that caters for the needs of the entire data logging equipment and provides mounting points for the IMU, the rear antenna and an action camera is made from carbon fibre.



Figure 25 – Original Ducati seat unit cover of the Panigale (Przibylla, 2017/2018)

A CAD model for the new seat unit cover is designed in Solidworks and prints of engineering drawings with a scaling ratio of 1:1 are used to verify the chosen dimensions of the new cover and ensure a perfect fit of the outside edges. *Figure 26* shows the final CAD model for the new seat unit, from which a mould file is created within the software. The file is used to write the program for a CNC milling machine that is machining the mould out of model board. Before the mould can be used for laying up the carbon fibre, any tooling marks and imperfections need to be removed with sanding paper and the mould is coated with 10 layers of mould release wax to prevent the carbon fibre part from bonding to it, as shown in *Figure 27*.

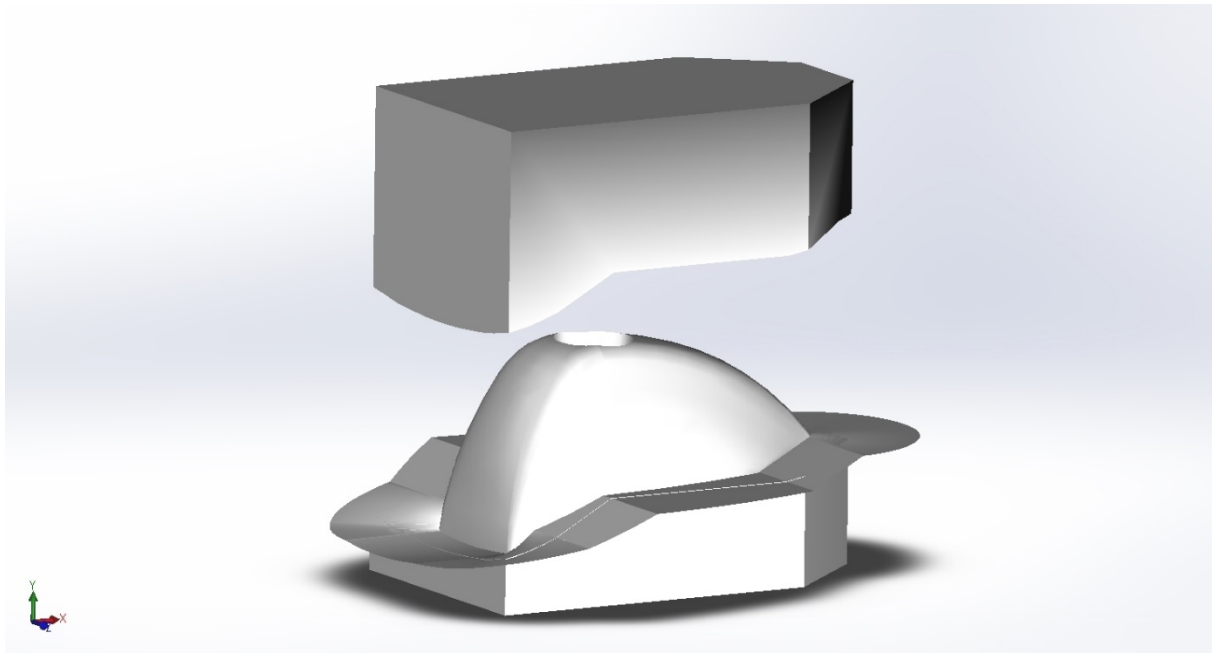


Figure 26 –CAD model of the new seat unit cover and the mould for machining (Przibylla, 2017/2018)

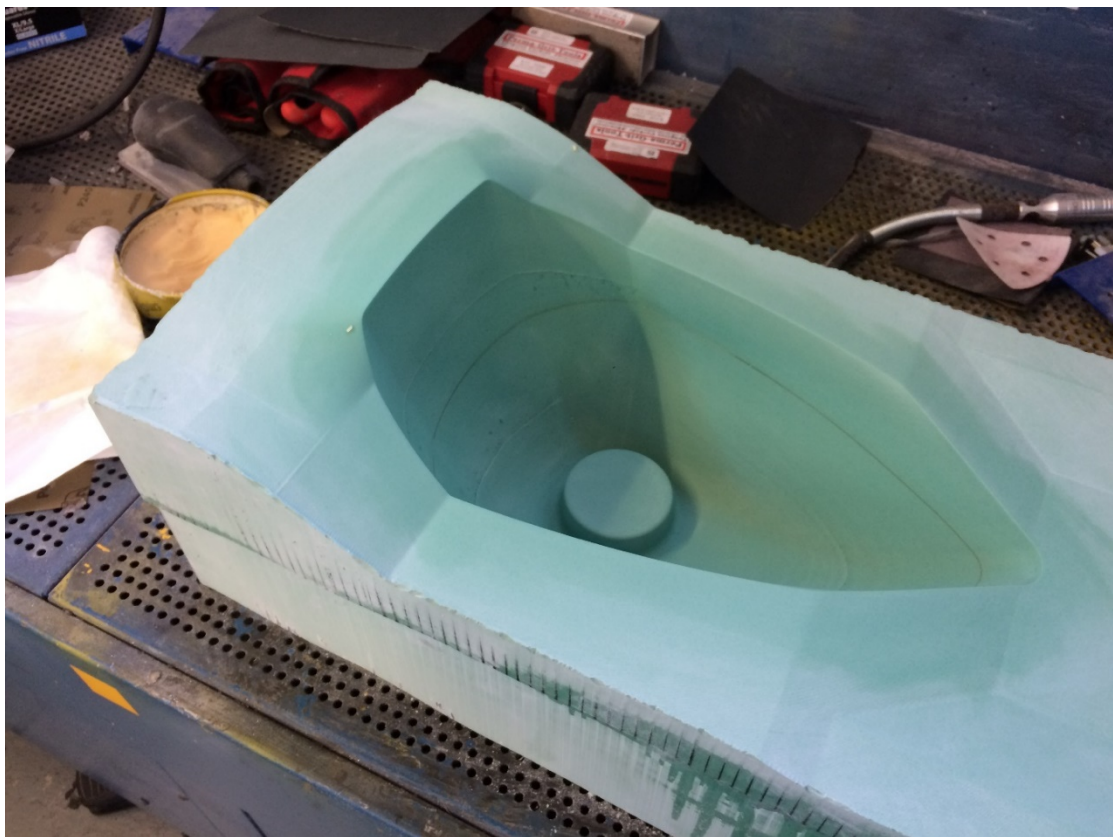


Figure 27 – Fully prepared model board mould for the new cover (Przibylla, 2017/2018)

The process that is chosen for making the part is a dry lay-up of carbon fibre which is not pre-impregnated with resin and, after four layers of carbon fibre are laid up and bonded together by using adhesive spray, any excess material is trimmed off at the edge of the mould. As shown in *Figure 28*, the part is then laid out with different sheets of special cloth and a honey combe plastic to encourage the flow of a resin and hardener mixture that follows the bagging and vacuuming of the part and is distributed through a plastic hose, which is routed around the outside of the part and supplied by the mixture via a pump.

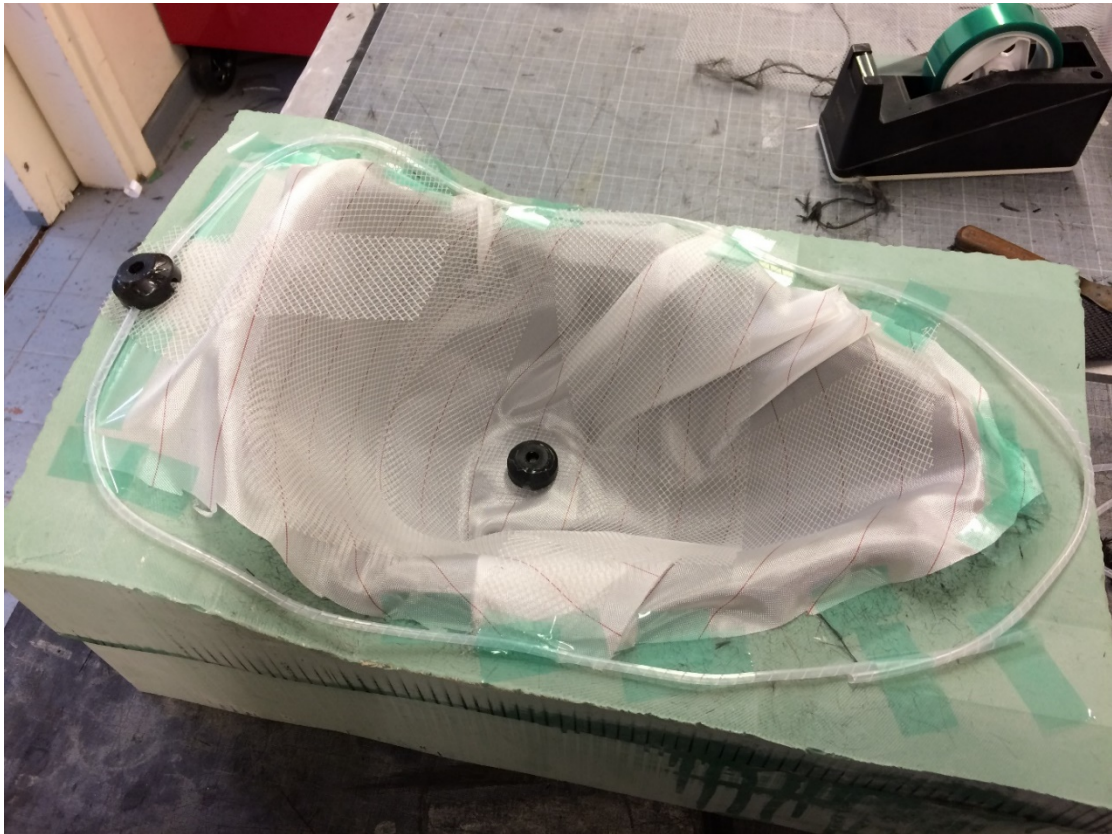


Figure 28 – Setup to encourage the flow of resin and hardener through the layers of carbon fibre (Przibylla, 2017/2018)

The vacuumed and sealed part, which as the hose that is supplying it with resin and hardener connected to it, is shown in *Figure 29* on the next page.



Figure 29 – Vacuumed and sealed mould with the carbon fibre part (Przibylla, 2017/2018)

This process for making parts out of carbon fibre is not requiring any application of varying pressure or temperature, as the mixture of resin and hardener should make the part self-curing. Unfortunately, the part did not cure well enough and, as a repeat of the procedure in a second attempt did not prove to be successful either, the decision is made to create the new seat unit cover by using the alternative method of laying up pre-impregnated carbon fibre and curing the part in an autoclave. For this purpose and after the mould is prepared again, four layers of pre-impregnated carbon fibre are laid up and formed into the mould with the help of a heat gun. *Figure 30* shows the part during the lay-up process and before the entire mould is wrapped in layers of plastic foil, soft cloth and bagged again. Once the part is vacuumed, as shown in *Figure 31*, it is cured under control inside the autoclave.



Figure 30 – Pre-impregnated carbon fibre layers inside the mould (Przibylla, 2017/2018)



Figure 31 – Bagging and vacuuming as preparation for the autoclave (Przibylla, 2017/2018)

Figure 32 shows the cured seat unit cover and, once it is released from the mould, a disc grinder is used to trim off the edges and ensure that the cover fits neatly onto the seat unit.



Figure 32 – The carbon fibre seat unit cover after curing in the autoclave (Przibylla, 2017/2018)

To make use of the designated lock for the seat unit cover on the Panigale and to stop the cover from moving up and down by allowing for it to hook in at the back, brackets are bonded to the inside of the new seat unit cover by using fibreglass and resin, as shown in *Figure 33*. Finally, the outside of the cover is sanded and lacquered to give the part a decent finish. *Figure 34* shows the new seat unit cover after sanding.



Figure 33 – Bonding of brackets with fibreglass and resin (Przibylla, 2017/2018)



Figure 34 – Polished carbon fibre seat unit cover for the Panigale (Przibylla, 2017/2018)

5.4. Device Installation and Configuration

On top of providing enough space for the data logging equipment, the new seat unit cover is designed to act as a mounting point for the primary GPS antenna at the rear end of the motorcycle and, as the antenna is magnetic and requiring a metal base for best multipath rejection, as well as clear view of the sky, a circular steel plate is cut and ground to fit inside the recess in the top of the cover, to which it is bonded with resin (Oxford Technical Solutions Ltd., 2016). The two GPS antennas have to be mounted along an axis of the vehicle and in line with each other, hence the secondary antenna is also mounted in the centre of the motorcycle, however in front of the headstock to make sure that the required antenna spacing of at least 1 meter is achieved (Oxford Technical Solutions Ltd., 2016). The GPS antenna that is located at the front end of the motorcycle sits on another circular steel plate that is bonded to an aluminium bracket, which is mounted in front of the dash and can be adjusted to ensure that the exact angle of both antennas is the same, as shown in *Figure 35*.



Figure 35 – GPS antenna on a custom-made bracket that is mounted to the front of the chassis (Przibylla, 2017/2018)

Whilst the main data logger and the strain gauge amplifier can be loosely accommodated inside the seat unit, the IMU needs to be securely fixed in position and the underside of the

recess in the seat unit cover acts as its mounting base, which is ensuring that the IMU and both antennas are parallel. For easy accessibility and secure fixation of the IMU, it is fitted to the inside of the cover with heavy-duty dual lock tape pads and an aluminium bracket is made for the IMU to provide a smooth surface for the glue of the pads, as shown in *Figure 36*.

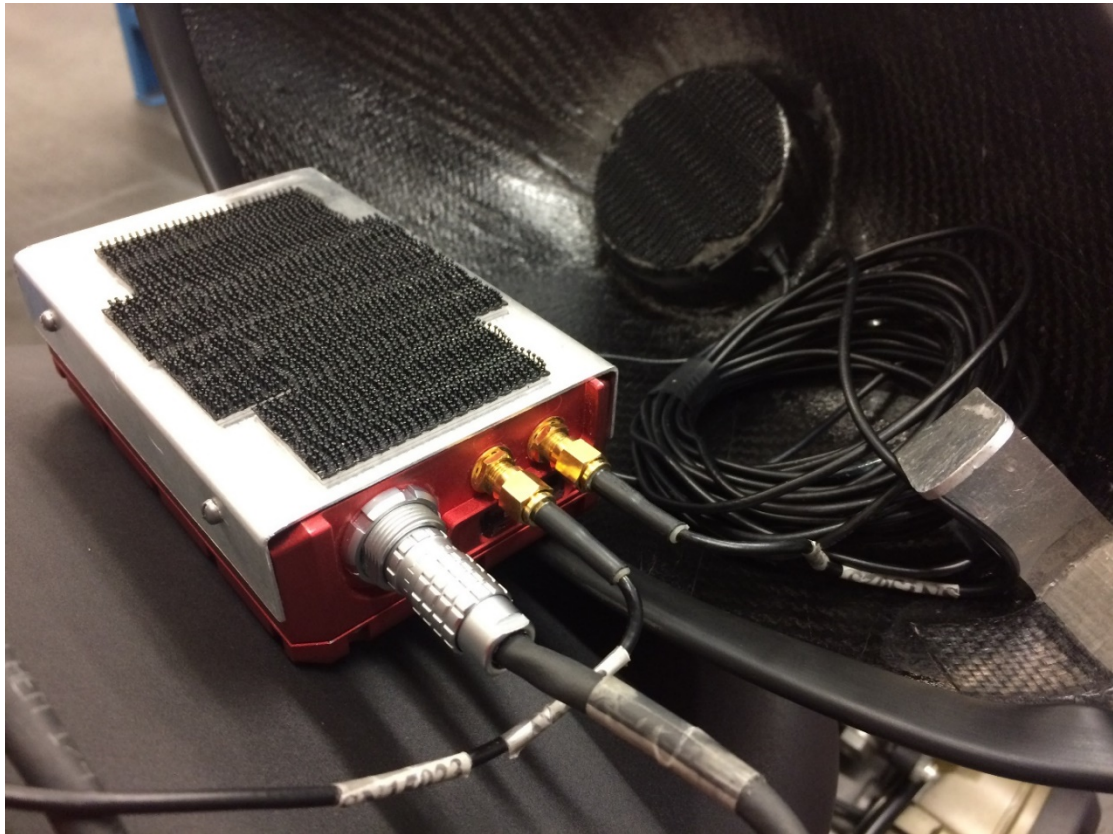


Figure 36 – xNAV200 with a bracket for the dual lock tape pads with which it sticks to the recess in the seat unit cover (Przibylla, 2017/2018)

Figure 37 shows the data logging equipment once it is fitted to the motorcycle and it becomes obvious that it is taking up most of the space that is created with the new seat unit cover.

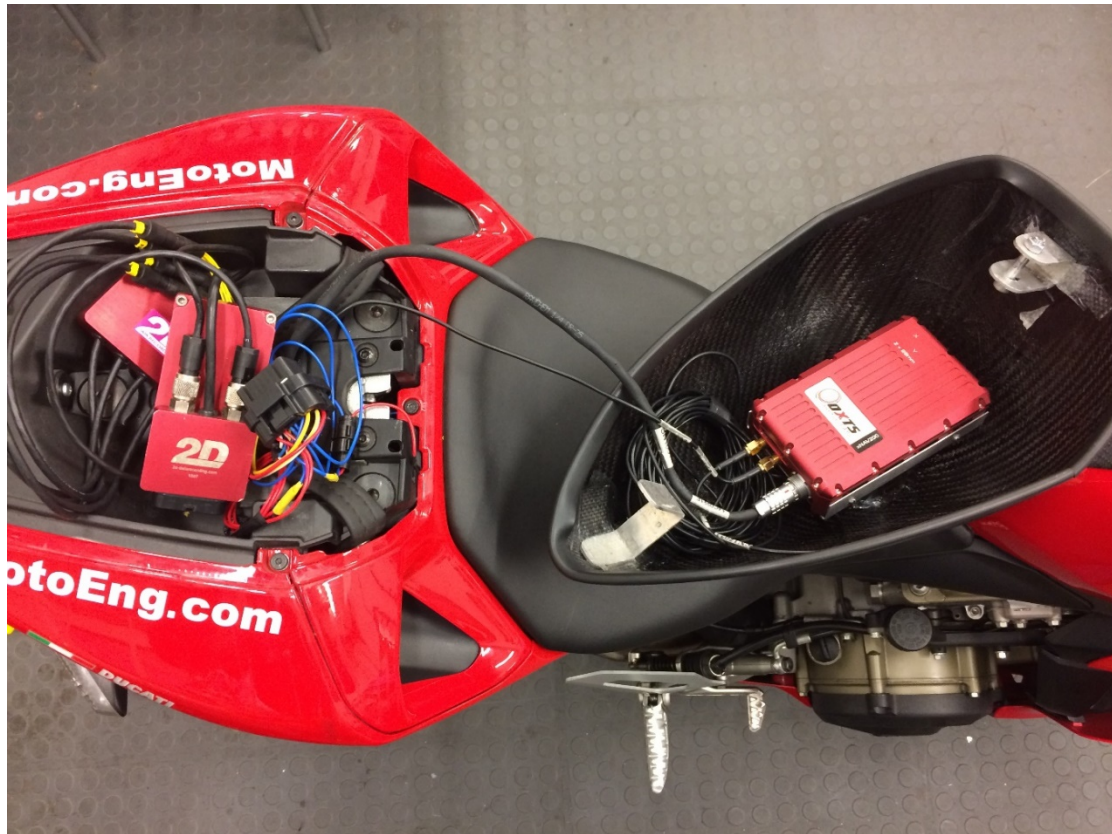


Figure 37 – The main data logger, strain gauge amplifier and IMU on the Panigale (Przibylla, 2017/2018)

The rubber trim that is used along the edges of the new seat unit cover serves the purpose of sealing the bottom of the cover to the seat unit and restricting possible movement that could be caused by vibration and result in noisy attitude measurements from the IMU or reduced quality of the videos that are recorded with an action camera, which mounts to the bracket on top of the cover, as shown in *Figure 38*.



Figure 38 – Finished seat unit cover and data acquisition setup (Przibylla, 2017/2018)

As the exact and permanent positions of the IMU and GPS antennas on the motorcycle are defined, the configuration of the inertial and GNSS measurement system can now be calibrated by using the OxTS software suite NAVconfig. An ethernet connection is set up between a laptop and the IMU, to load the existing configuration settings from the device and commit an updated version to it with the configuration wizard. First of all, the orientation of the xNAV must be defined in relation to the coordinate frame of the host vehicle, which means that the directions of the three measurement axes, x , y and z , need to be established and referenced. The distances from the measurement origin of the xNAV to the centre of the primary antenna is then measured and its relative position to the xNAV is input with an overall accuracy of 5 mm, before the distance and height offset from the primary antenna to the secondary antenna is measured and defined with an accuracy of 5 and 10 mm in the next step. This accuracy is more than sufficient for the xNAV, as it refines itself to the specification during every warm-up period and overstating the accuracy could cause it to look in the wrong place, which would increase the time it takes the xNAV to find the correct solution (Oxford Technical Solutions Ltd., 2016). With the primary antenna sitting on a level steel plate in the recess of the seat unit cover and the IMU being fitted to the underside of this recess, the rear antenna and the xNAV are in the same plane, whilst an angle meter is

used to ensure that the bracket for the secondary antenna is giving it a parallel base and the same orientation. The configuration wizard offers for further parameter to be set, which are aimed at improving the heading accuracy and lateral drift performance when GNSS is unavailable, by specifying the position of a non-steered axle for example, however these features are not suitable for a motorcycle, as it is a single-track vehicle that can have a significant lateral velocity and perform wheelies (Oxford Technical Solutions Ltd., 2016). In the last step of the configuration procedure various recording settings can be adjusted, for example to change vibration modes that the IMU will be exposed to, initialisation speed and trigger pulses or the IMU output rate, which is set to 100 Hz but can be increased up to 250 Hz, before the custom configuration is saved on the laptop and committed to the device. To calibrate and configure the sensors that are used with 2D, the signal channels from the CAN inputs, potentiometers, strain gauges and FSLP can be adjusted by using the communication suite of the 2D software package with the main data logger, when it is connected to a laptop via USB. The finished dynamic vehicle response measurement platform is shown in *Figure 39*.



Figure 39 – Fully prepared Ducati Panigale 1199 S (Przibylla, 2017/2018)

6. Testing and Discussion of Results

Regarding the setup for measuring the physical rider input at the handlebars, repeated tests are conducted in the workshop to verify the calculation file and optimise the code. In order to ensure that the calculated steering torque is correct, the trigonometry that is used to resolve the direction and magnitude of the UDL on each handlebar tube must be true. This is tested by hanging a weight of 1 kg from the free ends of both handlebars on the motorcycle and comparing the resultant UDL, after changing the referenced distance to the strain gauges back to an approximate distance to the free ends within the code. *Figure 40* shows the graphs of measurements from each strain gauge pair, the calculated magnitude of the resultant UDL on each handlebar tube and the combined angle relative to the steering plane, where the window on the left displays the results at the highlighted data point from the measurements on the right handlebar tube and the window on the right displays results of an exemplary data point from the measurements on the left handlebar tube.

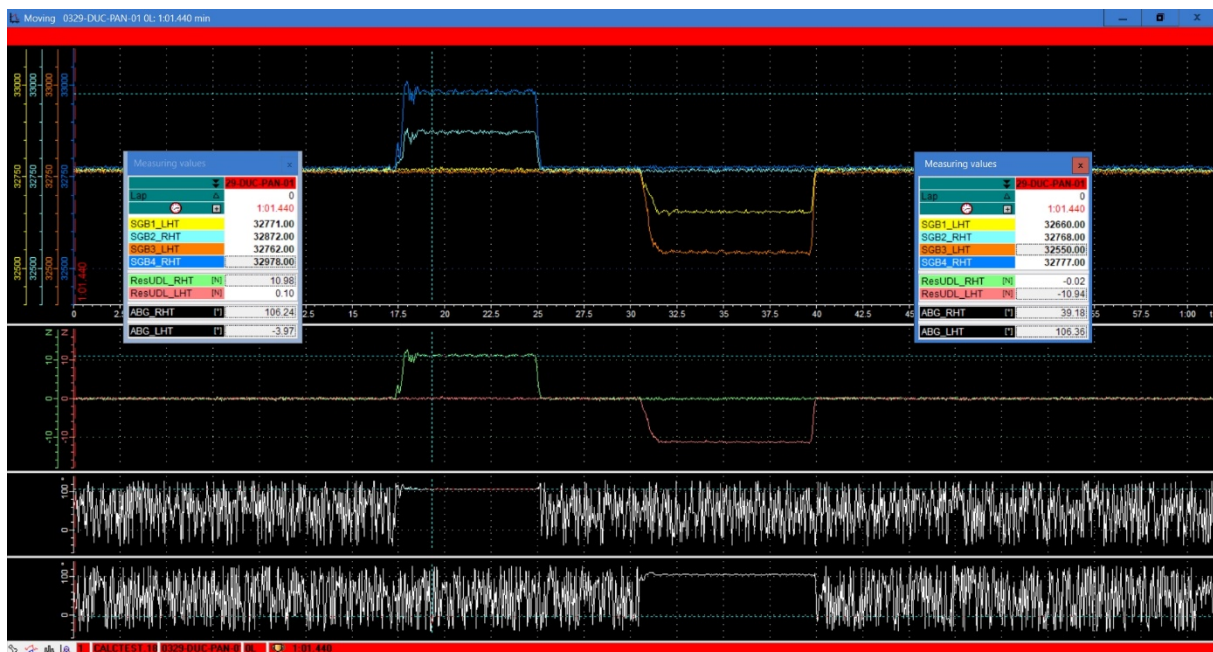


Figure 40 – 2D dataset of a test with weights to validate the calculated direction and magnitude of a resultant UDL (Przibylla, 2017/2018)

Comparing the combined angle of the load that is pointing directly downwards due to gravity proves that the orientation of both strain gauge coordinate systems is perfectly symmetrical and that the previously measured angle of the strain gauge pairs #1 and #2 is indeed very close to 20° relative to the horizontal, as the sum of the angles A, B and G is 106° in each case. With the weight pulling downwards at 90° to the horizontal and the angle of the

steering head being $23,5^\circ$, the definitive angle of the strain gauges is out by $7,5^\circ$, however the test is done with the motorcycle being on a stand and lifted at its rear end. Therefore, the exact angle of the strain gauges can be determined via calculation when the test is repeated without the use of a motorcycle stand. Nevertheless, the resultant UDL from the weight on the right handlebar tube and the resultant UDL from the same weight on the left handlebar tube are matching and dividing the two loads by the value of gravitational acceleration gives a calculated mass of 1,12 kg, which is sufficiently close the actual weight that is used and hung from the handlebars with a string. Hence, the formulae for resolving the loads that are applied to the handlebars are correct. As the resultant UDL is situated in the frontal and bottom quarter of each strain gauge coordinate system, the signs of the UDL suggests a push on each handlebar, yet the weights are pulling the handlebars downwards behind the fork legs. The code must ensure that the steering force is resolved with an opposite sign, which is resulting in a steering torque in a clockwise direction at the right handlebar and in an anti-clockwise direction at the left handlebar, and *Figure 41* proves that this is successfully achieved by using the cosine of the combined angle that is greater than 90° in the code.

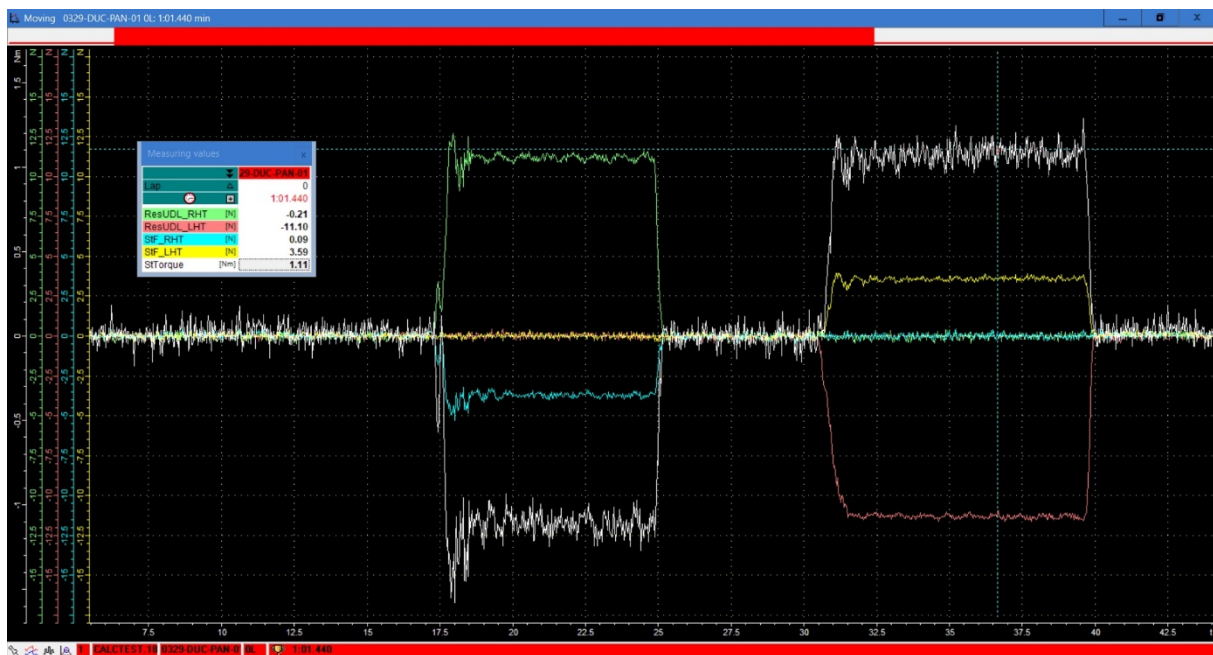


Figure 41 – 2D dataset of the test with weights to validate the calculated steering force and steering torque (Przibylla, 2017/2018)

The results for steering torque from a stationary test are displayed in *Figure 42* on the next page. Note that a steering damper is activated to exaggerate the steering torque from pushing and pulling on the handlebars during this test.

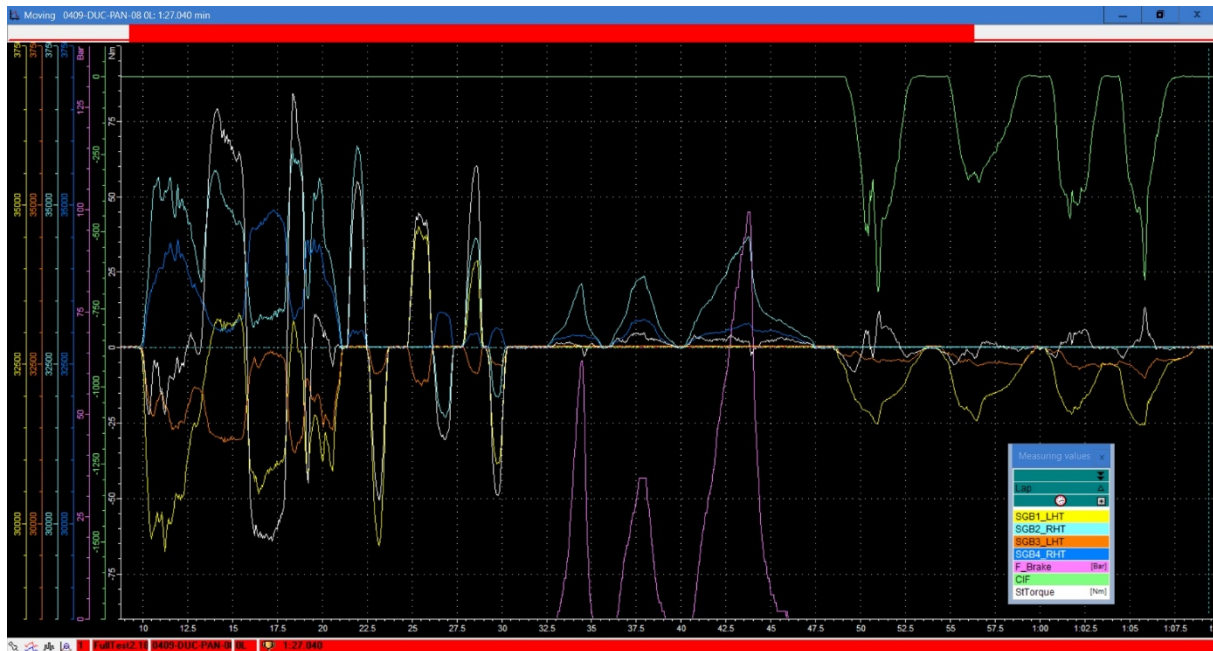


Figure 42 – 2D dataset of a stationary test for validation of the calculated steering torque (Przibylla, 2017/2018)

The first section of the dataset that is displayed in *Figure 42* shows the strain gauge measurements and calculated steering torque from simply turning the front assembly with the handlebars, whilst the middle section shows the effects of applying the front brakes and the final section shows the effects of operating the clutch. As the only force that is applied to the handlebars in the last two sections is the force that is required to pull in the brake and clutch levers, the steering torque should be zero and the load that is calculated from the pink channel for brake pressure cancels out the total load that is calculated from the strain gauge measurements sufficiently, with the data trace of the calculated steering torque only picking up marginally in the middle section. The final section shows that the cancellation of the loads that are calculated based on the measurements from the FSLP and the strain gauges is not working as effectively, which is due to the arising contact between the clutch lever and the handlebar itself, as it is explained in chapter 5.2., yet it seems acceptable when the force on the FSLP correlates with the measured strain, like it is the case during the second and third pull of the lever, during which the data trace of the calculated steering torque is almost negligible. For verification of the entire data acquisition setup of the dynamic vehicle response measurement platform and testing of the stableness and reliability of the novel sensors on the motorcycle, the Panigale is taken for a ride on public roads. *Figure 43* shows a dataset of this test run with compiled graphs of measurements from a range of sensors, as well as graphs of calculated channels, and the section that is displayed includes a turning manoeuvre at a large roundabout in between two lane changing manoeuvres, with a gentle

one in the beginning of the section and a second and more aggressive one after the exit onto an A road at the very end.

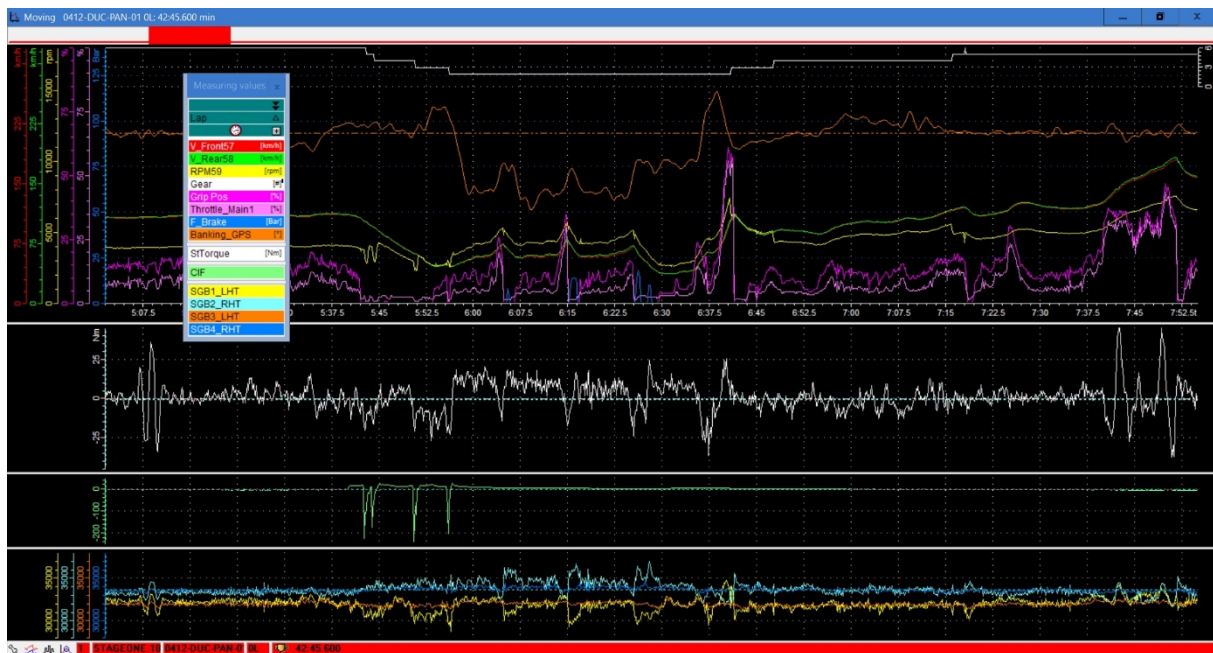


Figure 43 – 2D dataset section of a ride on public roads for verification of the data acquisition setup (Przibylla, 2017/2018)

The acquired data from the test ride proves that the sensor setup is working consistently well and suggests that an increased strain gauge amplification could be used to further improve the accuracy of the calculated channels, although the calculated channel for steering torque seems representative and the results are of high authenticity, based on the expectations and comparisons with existing publications. *Figure 44* shows the view of a GoPro action camera that is monitoring the movement of the rider throughout the test.



Figure 44 – Perspective of an action camera that is mounted onto the seat unit cover (Przibylla, 2017/2018)

The raw data of IMU and GPS measurements from the test ride can be processed and exported by using the OxTS software NAVsolve, which is shown in Figure 45.

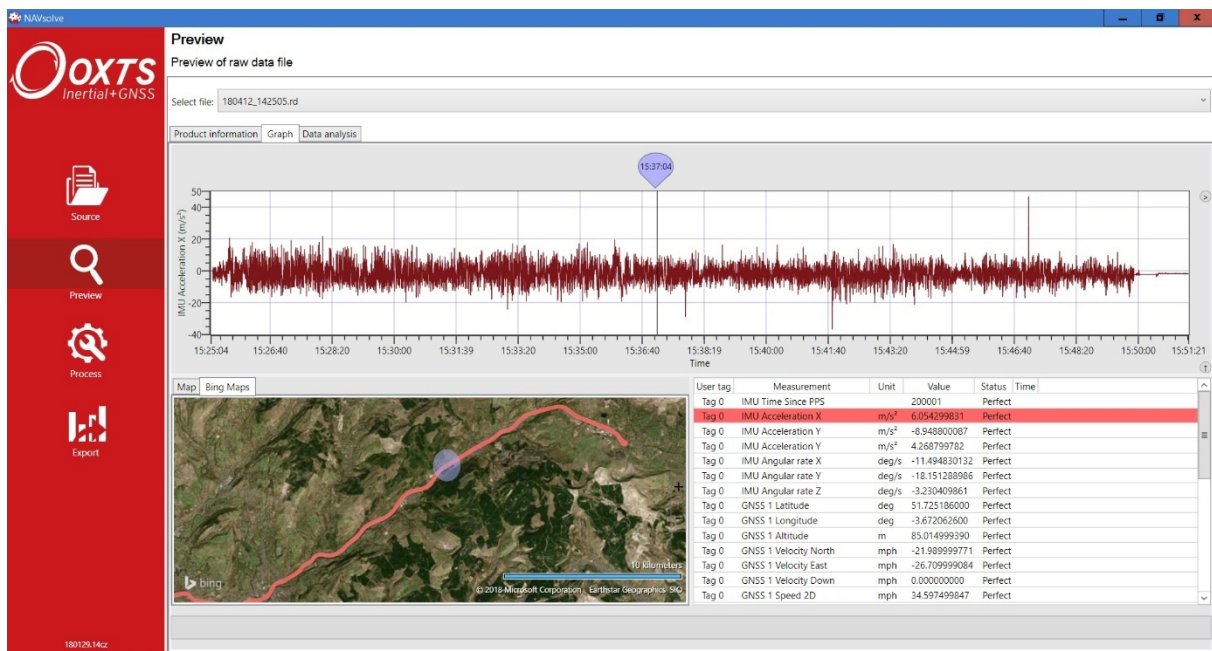


Figure 45 – IMU and GPS raw data for processing and exporting in NAVsolve (Przibylla, 2017/2018)

Furthermore, it is plotted and analysed in more detail within the software suite NAVgraph, as shown in *Figure 46* below. The red data trace of roll angle reveals that, despite the correct configuration of the xNAV measurement axes inside the coordinate frame of the vehicle, the recorded measurements are jumping from positive values below 180° to negative values above -180° , which is due to the IMU being mounted upside down underneath the seat unit cover of the motorcycle.

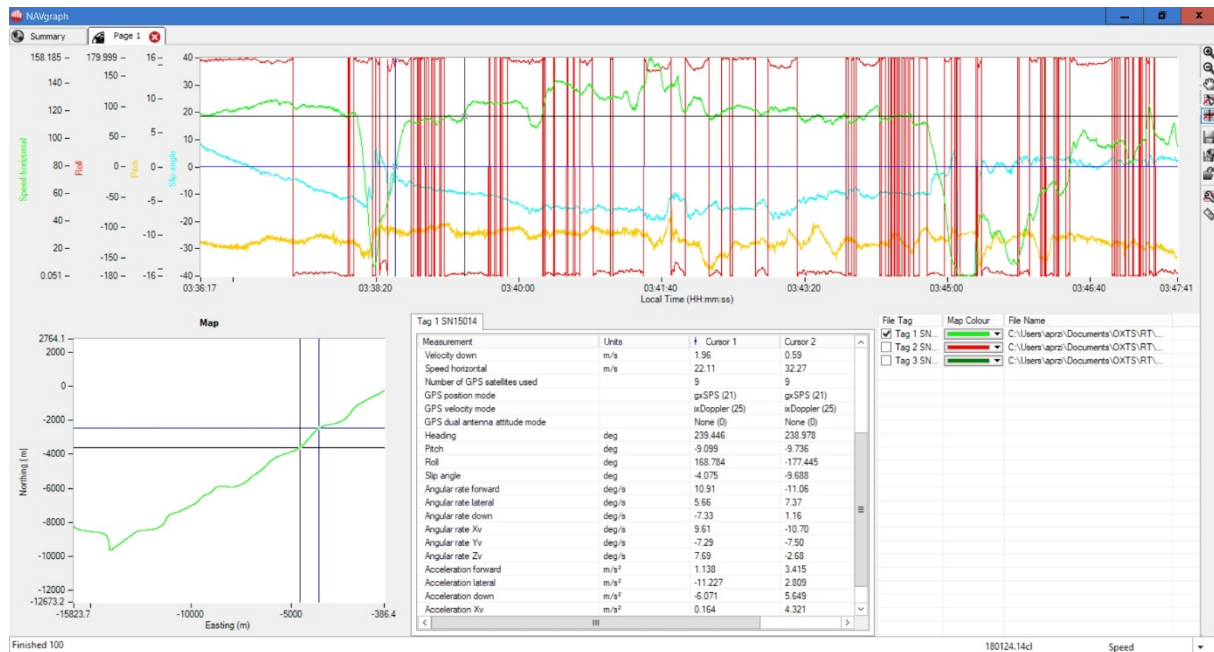


Figure 46 – IMU and GPS dataset of the test run in NAVgraph (Przibylla, 2017/2018)

As the entire dataset with all the recorded channels can be exported in a CSV file format, a new column for the data of roll angle is created in Excel and the issue that is stated above is resolved by either adding 180 to the measured values or subtracting it from them with an IF-function, before the Excel file is imported to the 2D software for improved ease of data analysis and post-processing. This allows for direct comparison of the xNAV data in conjunction with the data channels that are acquired and calculated with 2D, once the two separate datasets are synchronised by aligning the channels of GPS time and date from the 2D antenna with one of the corresponding channels from the GNSS of the xNAV, as shown in *Figure 47*.

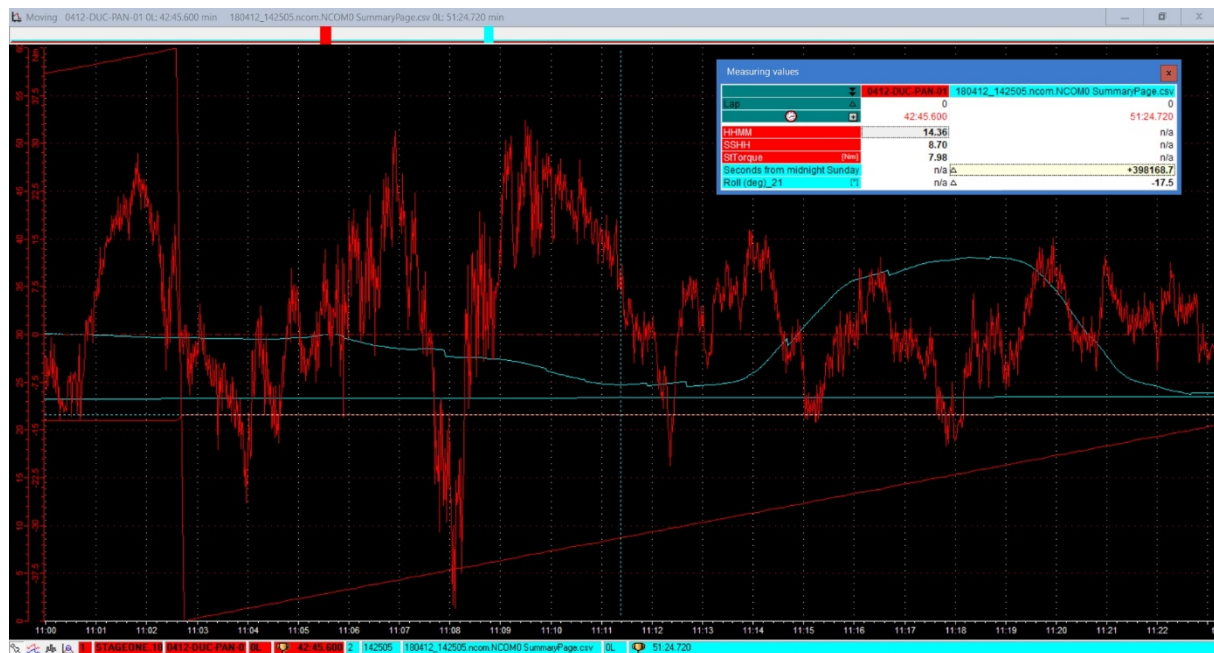


Figure 47 – Synchronisation of the datasets from 2D and the xNAV in 2D by using GPS time and date (Przibylla, 2017/2018)

The test ride proves that the data acquisition setup is fully functioning and reliably recording during running conditions. In addition, the data from the measured and calculated channels is realistic and of satisfying quality. Additional and more in-depth data analysis will be carried out and presented during the oral examination of the final viva voce.

7. Conclusion

The relevance and purpose of the creation of a dynamic vehicle response measurement platform are described and the realisation of it is explained in detail. Furthermore, the validity of the collected information from the finished platform is assessed, together with convincing results from a test ride on public roads that are acquired with measurements from standard and novel sensors, the data logging equipment on the motorcycle and software tools for post-processing and data analysis. The outcome of the tests is demonstrating a high functionality and promising viability of the newly created platform, which is suggesting that it can be tested used under even harsher and more demanding conditions.

8. Further Work

To use the dynamic vehicle response measurement platform for experimental studies and analytical investigations in the field of motorcycle dynamics, the plan is to take the Panigale to different race tracks and fine-tune the data acquisition setup for the provision of conclusive measurements at the highest level of performance, where the dynamic behaviour of motorcycles reaches its limits and reveals its extremes. Furthermore, the author has a personal interest in examining the forces that are occurring at very high speeds and during quick changes of direction of travel and attitude of the motorcycle, as the effort that is required from the rider to control a motorcycle appears to be heavily intensified during racing and the potential benefits from the realisation of certain ideas of engineering solutions, which are aimed at improving the agility of motorcycles and ultimately enabling racers to go faster, could possibly be evaluated and assessed this way.

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