BACHELOR THESIS

Mechanical Engineering

PASSIVE IMPEDANCE OF A BICYCLE RIDER

TUDELFT

Memory and Annexes

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http://bicycle.tudelft.nl/schwab/

Abstract

The aim of this project is to identify the biomechanical properties of the human body from laboratory test, realized in a controlled environment. The response of the vehicle together with the response of the cyclist wants to be studied. The participant will not only act as an active rider (trying to control his response to the different stimuli), but he will also act as a passive rider (responding unconsciously to the stimuli), during the different behaviour modes of the vehicle (wobble, weave and capsize).

For this reason, we will be focusing on designing, building and instrumenting a mock-up bicycle that will be mounted on top of a Stewart platform to determine the forces the rider applies to the interaction interfaces (handlebars, foot pegs and seat), the velocities and accelerations of the trunk of the participant. In addition, the relative position of the upper body of the rider to the platform. This way, we will be able to identify the transfer function of the rider in two different postures (one with straight arms and the other with flexed arms).

The response of the rider's body will be represented in the frequency domain by means of frequency response functions (FRF). The FRF will describe the motion of the rider's trunk and upper torso relative to the platform, and the mechanical impedance of the rider body. All of this will be described by non-parametric system identification methods.

The force frequency response functions can be further used from other researchers to identify the parameters of lumped mass biomechanical models, suited to integration with the multi-body model of the bicycle.

The motions proposed for the experimentation process are to excite the 6 degrees of freedom present in the bike. The test subjects will be divided by age groups (young adult, adult, middle aged). The excitation will be produced using a pseudo-random multi-sinusoidal signal, going from 0.1 Hz to 10 Hz.

The maximum forces expected are of 200 N for the handlebars, 400 N for the foot pegs and 500 N of lateral force and 1000 N of vertical force for the seat.

Acknowledgments

I would like to thank the people that made this project possible, beginning with Riender Happe and Arend Schwab for accepting me and giving me the opportunity of working on this project. Also thank Jos van Driel for the help provided with the strain gauges and software development.

In addition, especial thanks to George Dialynas (PhD researcher for the motorist project) for the guidance during the project, as without his experience and knowledge this project would not be finished.

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Chapter 1: Introduction

Nowadays, the dynamic behaviour of the bicycle has been studied in the past and it is well known. However, the rider has been less studied and the knowledge regarding his behaviour is not as deep as the vehicle. Besides an active rider control model, there is also a need to describe the behaviour of a passive rider. In the past, some studies of the impedance on single-track vehicle riders have been done, but they never specialized in bicycles. This is why a study with an adequate motion and range of frequencies that would include shimmy, typically this happens around 7 Hz, thus a range of 0.5 to 10 Hz should be studied. In addition, it is important to include the effective rider mass and compliance in this study.

This way, in the future we will be able to generate a passive control model, that together with the active control model would help understand what the rider does and how he interacts with the bicycle.

1.1. Objectives

The aim of this project is not only to identify the transfer functions of the rider in the different interfaces of the bike (handlebar, pedals and seat), but it also is to identify the frequency response function (FRF) of the rider's trunk in response to motion of the saddle.

1.2. Scope

In this project, we will proceed to the design, construction and instrumentation of a metallic frame. The frame will meet the requested specifications. The electronic and software part necessary for the realization of this project will not be part of this project, as they will come from third parties or available solutions in the market.

Chapter 2: Structure

2.1. Requirements

For the measured forces to be considered valid and consistent, the frame needs to be rigid enough. Moreover, due to the nature of the experiments, where a group of participants is needed, it needs to comply with the safety standards provided from the ethical committee of TUDelft.

Another important aspect of the structure, is that in the interfaces a small deformation is needed in order for the strain gauges to work properly.

Lastly, the frame needs to have a variable geometry while maintaining its rigidity. The variable geometry is needed in order to experiment with different styles of bicycle, this will be achieved changing the stack and reach of the frame.

2.2. Design

In the beginning, a normal frame of an existent bicycle was going to be used, but the idea was quickly discarded, due to the difficulty of achieving a variable geometry and the impossibility of using certain types of sensors. In addition, an additional base was needed in order to connect the bicycle with the Steward platform that would be able to resist the force and strain applied during the experiments.

Therefore, the following step was to design from scratch a frame that would allow for variable geometry. This way the placing of the sensors would have been considered from the beginning of the design process.

Figure 1.1. First frame (Source: Toni Prats)

However, this solution also presented the same base problem as the previous idea. In addition, as the time was rather limited for the realization of this project was rather limited and knowing that the manufacturing of a custom bicycle frame could take up to 5 or 7 months the design was discarded.

Following the advice of more experienced members of the laboratory that were working in other projects, a different solution was adopted. For the design of the frame, a metallic structure that would combine the frame and a base would be the best solution. For this reason we would use steel tubes with an exterior diameter of 25 mm and claps made of aluminium from Rose+Krieger, because in previous constructions this solution had given good results.

Figure 1.2. Second design (Source: Toni Prats)

The design continuously evolved following the advice provided by the different supervisors in the arranged meetings. The first structure was discarded as a result of its complexity and apparent lack of stability and rigidity. The following designs would add more stability and rigidity but they would also increase their level of complexity.

Figur3 1.3. Third structure (Source: Toni Prats)

Finally, it was decided to make a few changes in the last model that would allow to simplify the assembly and distribute better the loads along the frame.

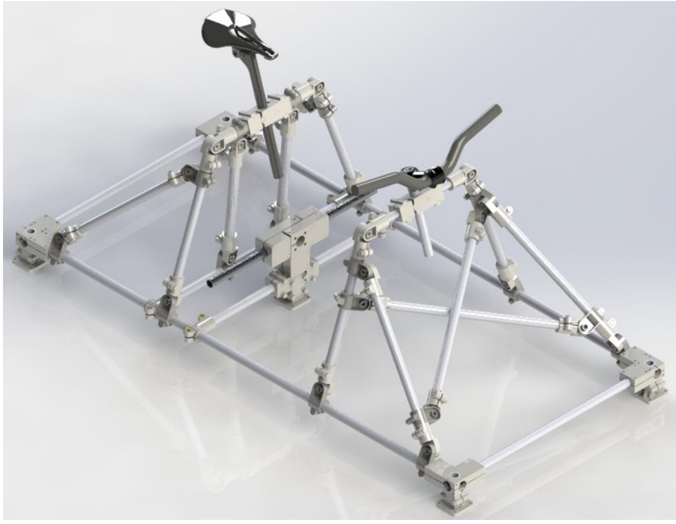

Figure 1.4. Final design (Source: Toni Prats)

Nevertheless, this last design was not exempted of changes and improvements during its assembly in order to increase the overall rigidity and solve some issues that in the design process were not noticed. Nonetheless, this increase in rigidity diminished the ability to perform a quick change in the geometry of the frame. In the actual structure the possibility of changing the geometry is still available.

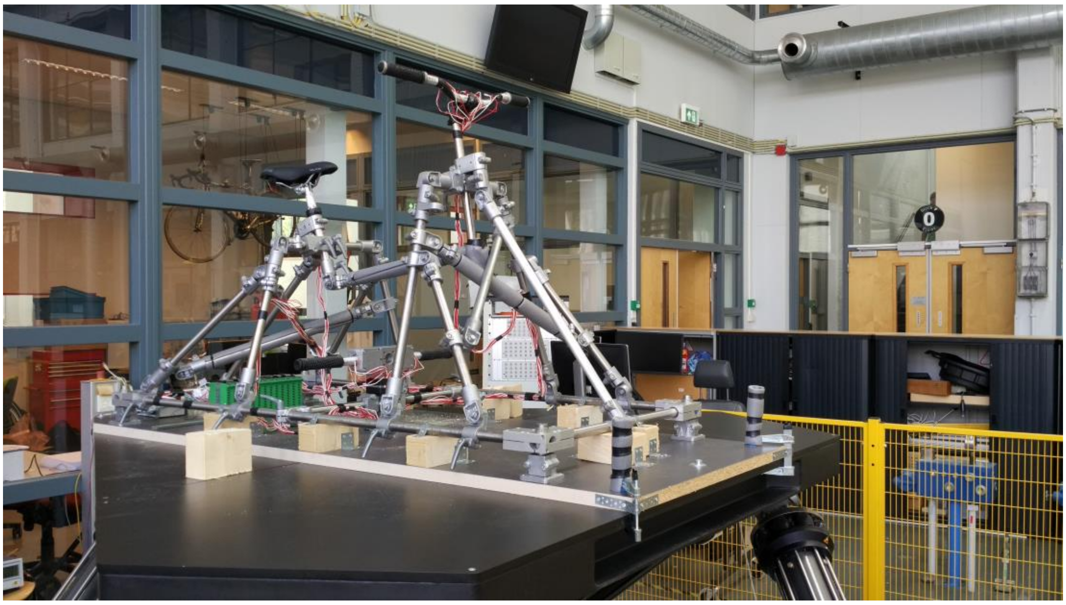

Figure 1.5. Final Mock-up (Source: Toni Prats)

Figure 1.6. Rear view of the Mock-up (Source: Toni Prats)

The dimensions and geometry used in this project have been based on different bicycle models available in the current market and have been checked with rattleCAD.

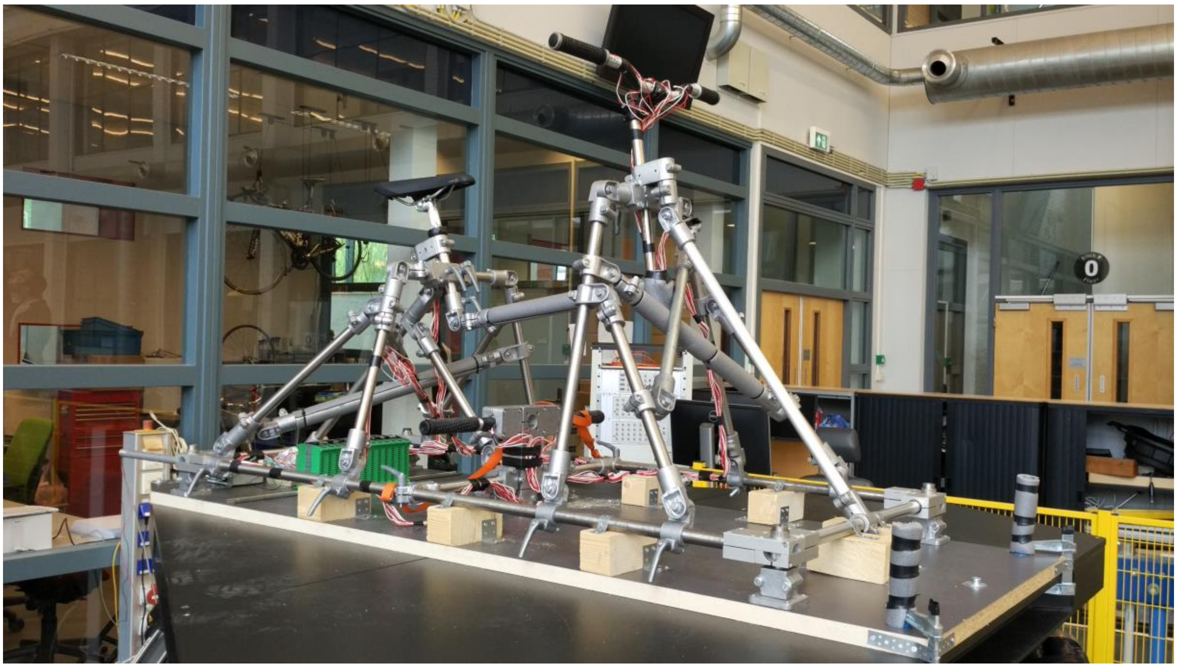

Figure 1.7. Side view of the Mock-up (Source: Toni Prats)

The structure consists of 4 subassemblies. The frontal subassembly consists of a structure that will holds the handlebar and will distribute the load applied in the handlebar to the base. The rear subassembly will distribute the load exerted from the seat to the base. This two subassemblies are connected in order to prevent the respective subassemblies to flex. The third subassembly consist in a simplification of the pedals of a bicycle, this way the transfer of the load is not affected by the position of the feet. The final subassembly is the base.

2.3. Base

One important issue was how to connect the structure with the hexapod in a safe way. The taken solution was to use a secondary base, made of wood. This way we could secure the whole metallic structure to the wood base using the pertinent screws. Additional supports made of soft wood were used in order to damp out any possible vibration that the system could have, moreover, this supports would also prevent the base tubes from flexing.

The wood base was secured to the Steward platform using three M9 and two M6 screws, in addition two clamps were used in the front as a safety measure.

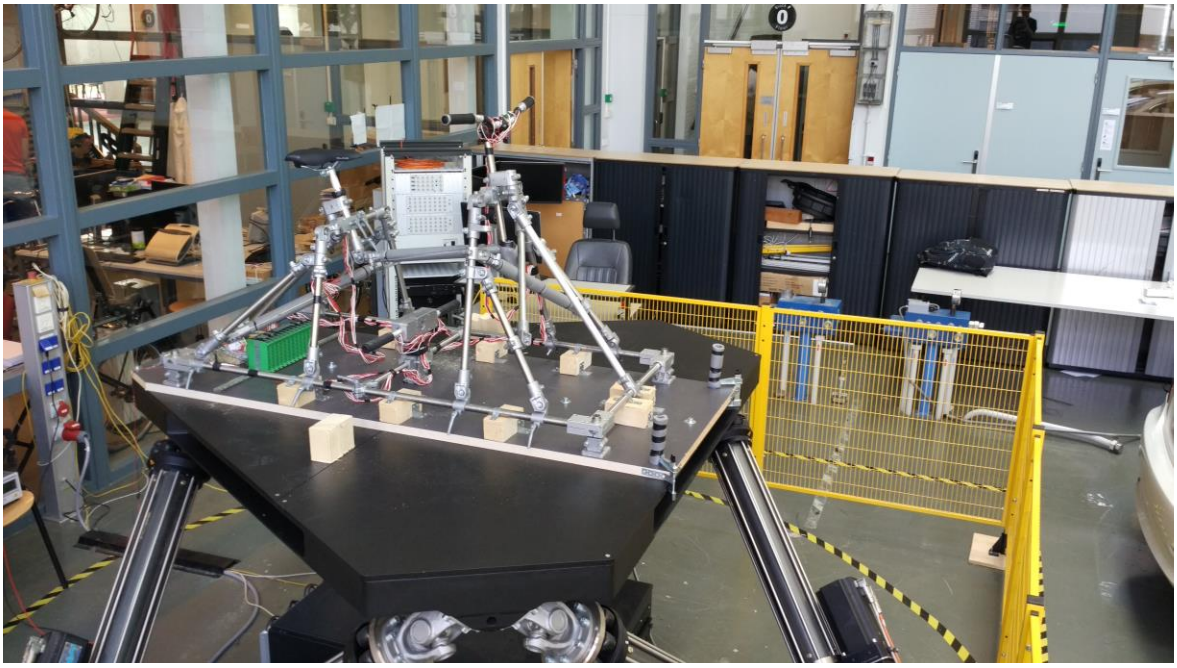

Figure 1.8. View of the whole structure (Source: Toni Prats)

Figure 1.9. Detail of the front (Source: Toni Prats)

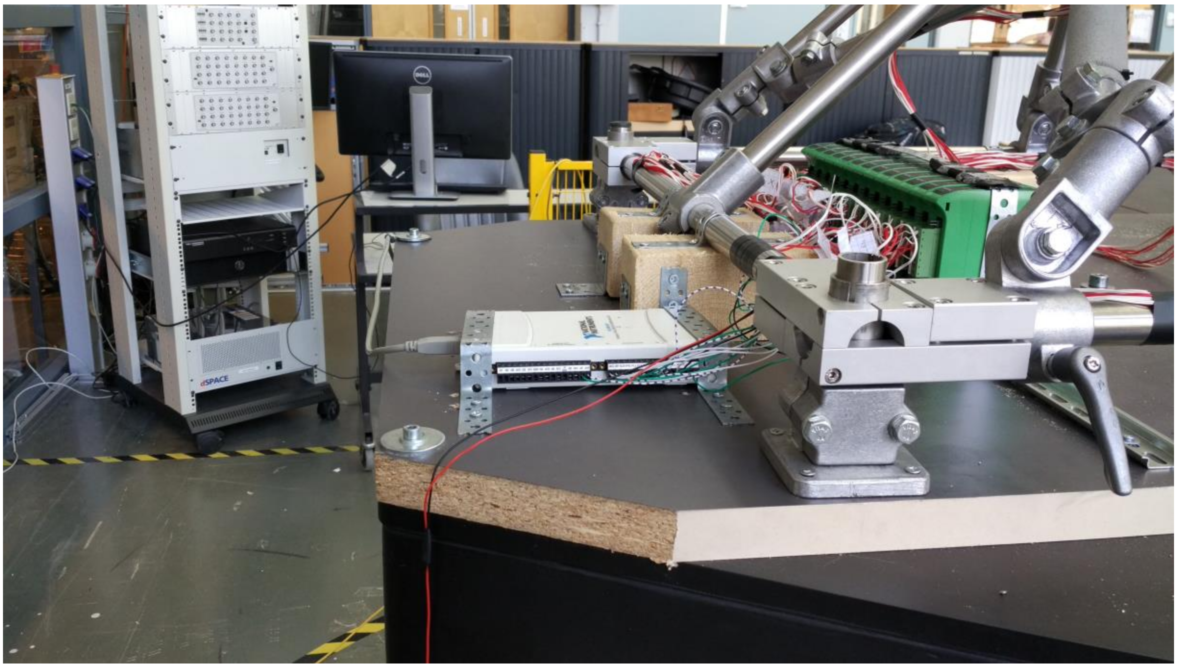

Figure 1.10. Detail of the rear (Source: Toni Prats)

Figure 1.11. Detail of the screws used (Source: Toni Prats)

2.4. Instrumentation

For the data acquisition some options were compared, the use of load cells in addition to torque sensors, load cells and sensing bearings, strain gauges. The solution that was chosen was the one with strain gauges, because it was easier to implement and cheaper. If the strain gauges are correctly placed they allow to measure 3D forces in every axis.

We will obtain data from the interaction interfaces between human and bicycle (handlebar, pedals and seat). In the seat and handlebar we will be able to measure the forces in every axis, however in the foot-pegs we opted for only measuring two axis, as we did not expected traction or compression in this interface.

The configuration used for the strain gauges is to form Wheatstone bridges consisting of 4 actives gauges, and putting one bridge in every axis we want to measure. A total of 13 Wheatstone bridges are used in this mock-up, with their corresponding amplifier. See annex A for the deformation and strain calculus for the strain gauge selection.

The strain gauges have been calibrated in a test environment, where weights were placed in the direction of the expected force to act, and then a linear correlation between the voltage measured and the weight applied was done. See annex D for the strain gauges calibration.

Moreover, the inertial data of the rider's trunk will also be controlled and measured respectively from the frame. To achieve this two IMU units from Xsense will be used. One will be placed in the rider's chest and the other near the seat, in a position where it will not be affected by any magnetic field.

Figure 1.12. Detail of the strain gauges used in the seat post (source: Toni Prats)

Figure 1.13. View of the amplifiers and data acquisition system (Source: Toni Prats)

Figure 1.14. Used IMU units, MTw Awinda (Source: Toni Prats)

Figure 1.15. Detail of the IMU placed in the neoprene strip (Source: Toni Prats)

Chapter 3: Experimentation

3.1. Description

The realization of the experiments will be done to 3 different groups of participants divided in age groups. A table with the characteristics of the participants will be filled, see annex B. The experimental process will consist of 6 parts, where in each different part a different motion of the platform will be exited with a multi-sinusoidal signal.

The data from the strain gauges will be obtained through the data acquisition system and it will be sampled at a frequency of 20 Hz. The IMU will also record data from the participant's chest and from the frame, using their own specific software.

With this experiments the 6 degrees of freedom (DOF) will be studied, in addition two different cases will be studied. In the first case, the rider will be relaxed and will act in a passive way. In the second case, the participant will be asked to co-contract. With this we pretend to see if there is any subconscious stiffening of the body.

The whole experimental procedure will be first tested with a test subject, who forms part of the developing team. This way we will check the correct functionality of the whole system and the data obtain will be processed and used as a reference for the following experiments.

In this report only the co-contracted data from the roll experiments using the signals B1 and B3 from the test subject will be analysed, marking the path to follow for the other experiments, due to the lack of time.

The axle of rotation has been placed below the seat of the mock-up and in the imaginary point of intersection between the tyres and the ground.

3.1.1. Roll

The main reason to excite this motion is to evaluate the transfer function of the rider's trunk while he tries to stabilize the system in a scenery with cross wind or weave. The intention is to represent the FRF of the respective angular rates, and also of the torque applied in the handlebar and angular rate of the platform.

3.1.2. Pitch

To know what happens to the rider while he is cycling in an irregular terrain we need to study this motion. This could also prove useful in the future to know what frequencies are dampened by the human and what frequencies need to be absorbed by the frame or by a suspension system. The objective is to obtain the FRF of the angular rates, and seeing how the rider transfers the load.

3.1.3. Yaw

This motion is important to study because it is the main reason that the bicycle is able to change directions. The FRF that need to be obtain are the FRF of the angular rates and the torque applied in the handlebar with the angular velocity of the platform.

3.1.4. Heave

This motion will be studied for the same reasons as the pitch motion. Moreover, with this motion we can determine how the load and accelerations are transmitted through the trunk of the participant. The FRF that are going to be obtain are from the linear accelerations. In addition, we will be able to study the apparent mass, to evaluate the comfort level.

3.1.5. Sway

This motion is related to the roll motion due to the modes of behaviour of the bicycle. In this motion the FRF will also be from the linear accelerations.

3.1.6. Surge

This motion will provide information about the accelerations and decelerations that can occur while riding a bicycle. The aim is to obtain the FRF of the linear accelerations, see the load distribution in the handlebar and seat and study the apparent mass.

3.2. Signal

The signals used for the experimental process are multi-sinusoidal randomly generated between a range of 0.1 to 10 hertz, this way the signal will seem totally random to the participant and he will not be able to get used to it and affect the data. Three signals will be used for each motion, the bandwidth will change between them but the power spectrum will remain linear (Table 1).

Signal	Bandwidth (Hz)	Max. Displacement**	Max. velocity**	Max. acceleration**
B1	0.15 – 0.75	0.8 / 0.05	0.15 / 0.15	0.4 / 0.4
B3	0.15 – 2.85	0.9 / 0.035	0.25 / 0.09	2 / 0.5
B10	0.15 – 9.95	0.01 / 0.01	0.04 / 0.03	0.9 / 0.5

Table 1. Different bandwidth of the signals (Source: Toni Prats)

** Translation [m] [m/s] [m/s^2] / Rotation [rad] [rad/s] [rad/s^2]

The separation in different bandwidth is done because the human reaction is affected by the frequencies of the stimulus. If the experiment only had low frequencies, we would only see one type of behaviour in the response. However, if we also add high frequencies the way the human responds will be affected even in the low frequencies.

To simplify the experimental process, it has been decided to use the same signal in similar motions. This means that all the rotation signals will have the same set of signals, and so will the translation motions have, but the set of signals will be different between rotation and translation.

The main signal is composes of 3 sub-signals, containing displacement, velocity and acceleration. The signal has a duration of 2000 samples and it will be repeated 3 times. The signal will also have a fade in and fade out in order to evade the transitional behaviour in the data recollection. This means that the final signal will have a total duration of 8000 samples that with a sample frequency of 100 Hz the total duration of the signal will be of 80 seconds.

See annex C, to see the signals.

In this report, it has been chosen to work with the signals B1 and B3, because during the test experimental process the signal B10 did not show satisfactory results and needs to be redesign. Because, as we increase the bandwidth we are decreasing the power and the amplitude of the movement was insufficient, meaning that the signal to noise ratio worsens. Next, the coherence of the two signals used will be shown.

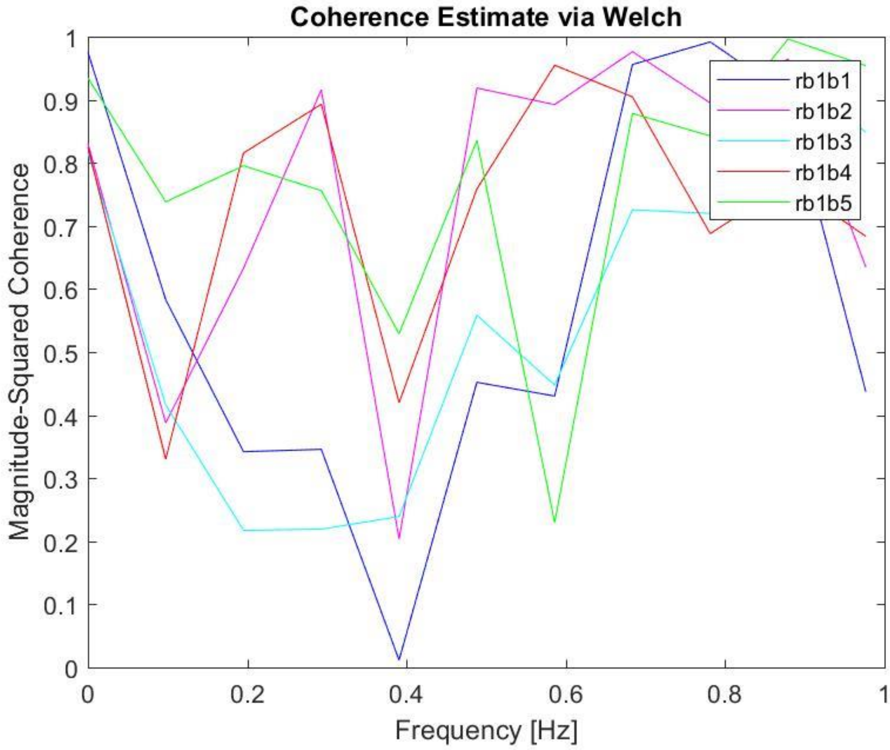

Figure 2.1. Coherence of all B1 experiments (Source: Toni Prats)

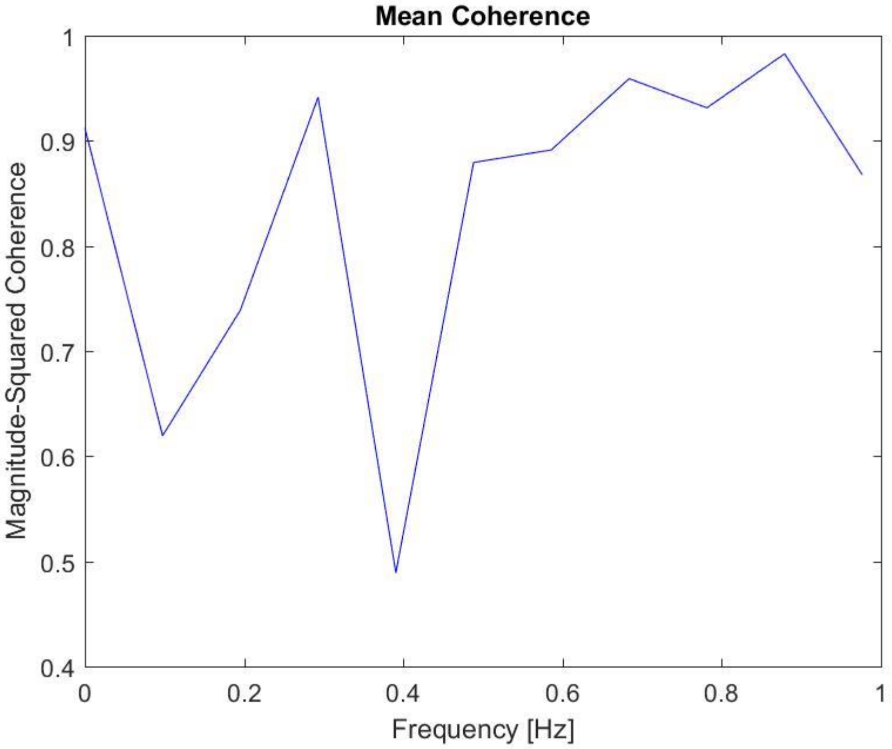

Figure 2.2. Mean coherence of B1 (Source: Toni Prats)

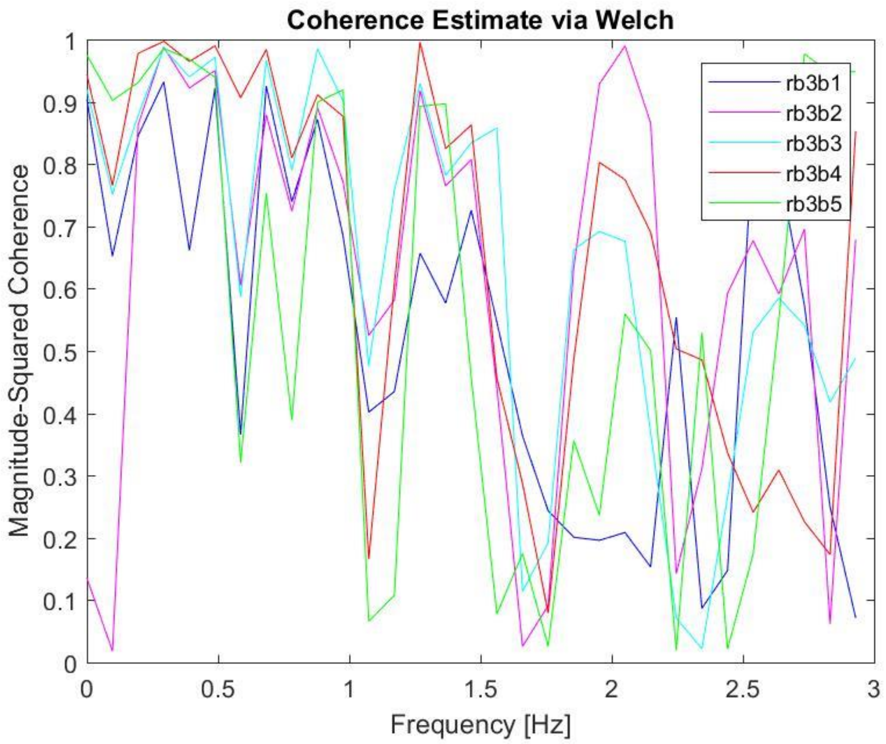

Figure 2.3. Coherence of all B1 experiments (Source: Toni Prats)

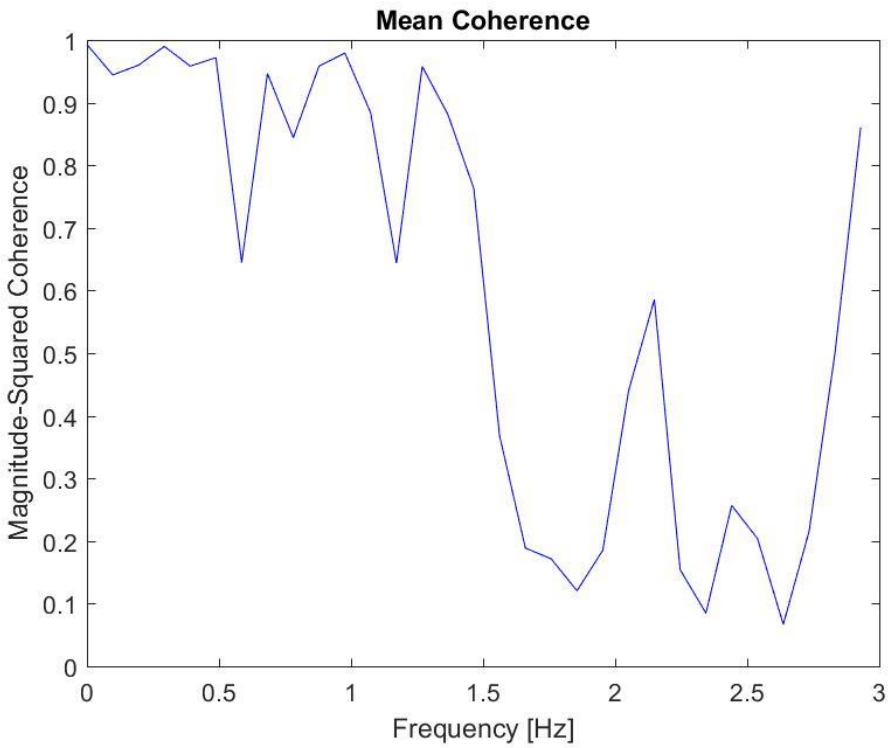

Figure 2.4. Mean coherence of B3 (Source: Toni Prats)

These plots show the relation between the input signal and the output signal, they describe the predictability of the model. The closest the signals are to one, the more linear the relation is. In the plots of the signal B1 we can see how the tendency is to have a good average coherence, where at the lowest frequency of 0.15 Hz we have the lowest coherence between our signals, as the following lowest point is at 0.4 Hz which is not part of our input signal. Then for the other frequencies (0.25, 0.35 0.45, 0.65, 0.75 Hz) we see that the coherence goes up and starting from 0.45 Hz we are at a coherence of approximately 0.9 which indicates a good linearity of the system.

For the mean coherence of B3, we can see how the coherence for the low frequencies is very high, nearly one at some points, indicating a good linearity of the system in low frequencies, but then when going above 1.45 Hz the coherence quickly decreases, it even goes down the threshold of 0.2 which would indicate a system with very high non-linearity behaviour. This is a result of the interactions between the rider and the system created by the higher frequencies in this signal, because the human response changes when it is excited by high frequencies. Then we see one peak in coherence, at 2.05 Hz, following this peak we see a sudden increase in coherence in the las two highest frequencies of our signal (2.75 and 2.85 Hz).

3.3. Safety

Due to the nature of this project and the necessity to involve groups of people in the experiments, the change of injuring a participant must be erased or highly reduced. As the platform can achieve very high accelerations and amplitudes, the participant will be secured with a military grade harness to the celling crane, this way the participant will not be thrown away in case of failure. Moreover, there is also a safety strap on the foot-pegs that will make sure that in case the participant let the handlebar go, that he will be kept in place. In addition, the Stewart platform has an emergency stop button that will be near the platform operator in case of an emergency.

Figure 2.5. Emergency stop button (Source: Toni Prats)

Figure 2.6. Celling crane (Source: Toni Prats)

Figure 2.7. View of the whole system (Source: Toni Prats)

Figure 2.8. Detail of the military grade harness (Source: Toni Prats)

Figure 2.9. View of the whole security system (Source: Toni Prats)

3.4. Expected Forces

For the correct calibration of the strain gauges we need to know approximately what will be magnitude of the forces acting in the different interface points of the mock-up. To calculate this forces, we will base our calculi with the roll motion, and this motion will be considered as a simple harmonic movement. This will be the equations used:

$$\omega = 2\pi \cdot f \qquad \textbf{(Eq. 0.1)}$$

$$a = -(2\pi \cdot f)^2 \cdot x \qquad \textbf{(Eq. 0.2)}$$

$$a = -\omega^2 \cdot x \qquad \textbf{(Eq. 0.3)}$$

$$F = m \cdot a \qquad \textbf{(Eq. 0.4)}$$

Knowing that the maximum frequency we are going to use is 10 Hz and the maximum amplitude will be approximately of 0.01 m, we can obtain the maximum acceleration our mock-up will have and from there we can obtain the force. However, this way the acceleration is not appropriate and will be reduced to ½ g. Next, assuming a maximum mass of 100 Kg we can calculate said forces.

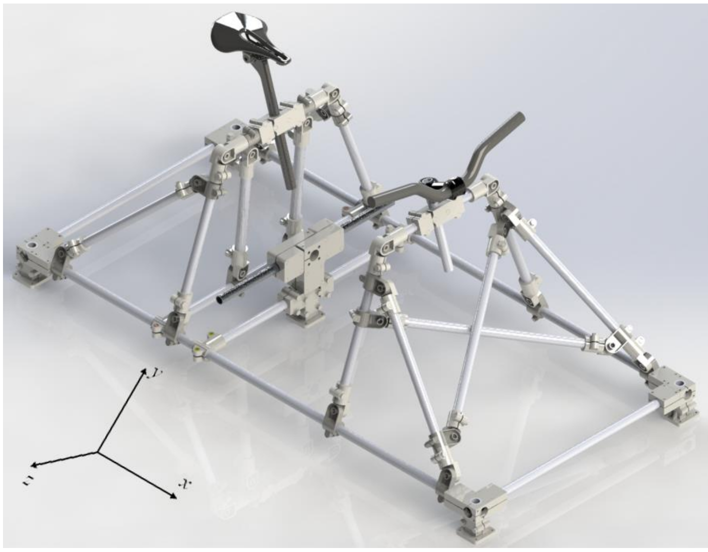

Figure 2.10. Main axis (Source: Toni Prats)

	F_x (N)	F_y (N)	F_z (N)
Handlebars	200	200	200
Foot-pegs	400	400	-
Seat	500	1000	500

3.5. Data Analysis

To analyse the data obtain the transfer function of the rider will be obtained. This transfer function will describe the angular rates of the Stewart platform as an input and the trunk of the rider as an output. This will be done for the B1 and B3 signals.

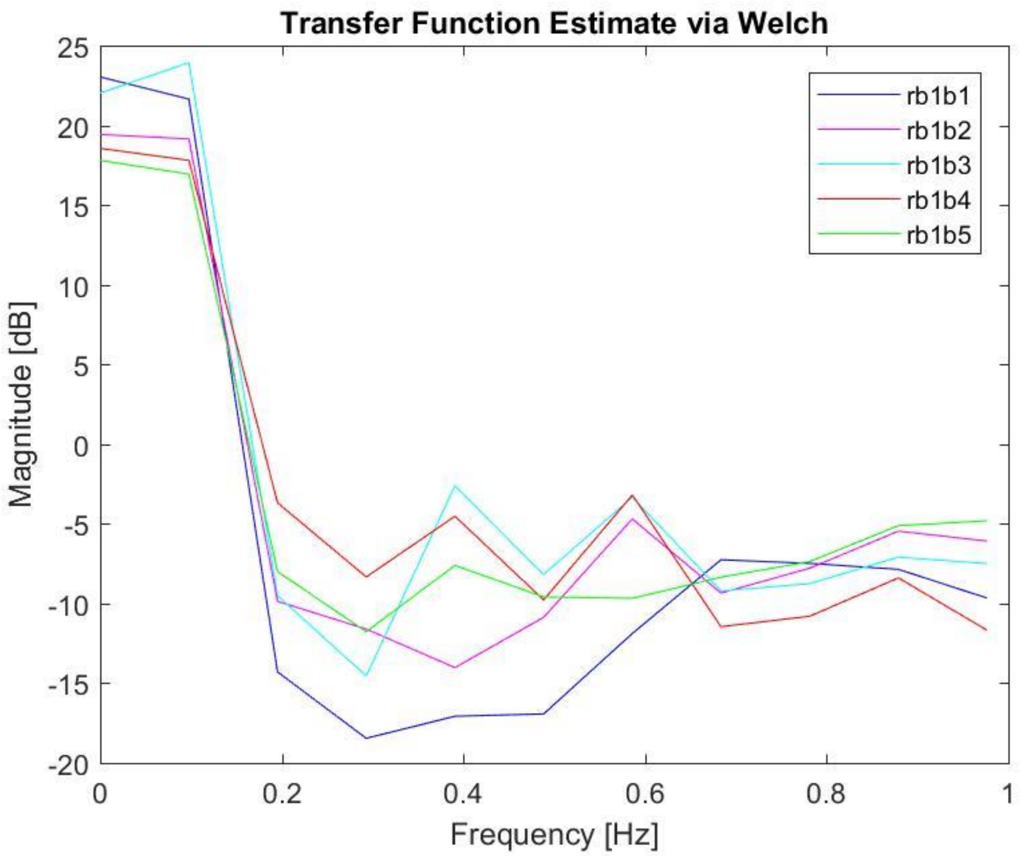

Figure 2.11. TF of the different B1 experiments (Source: Toni Prats)

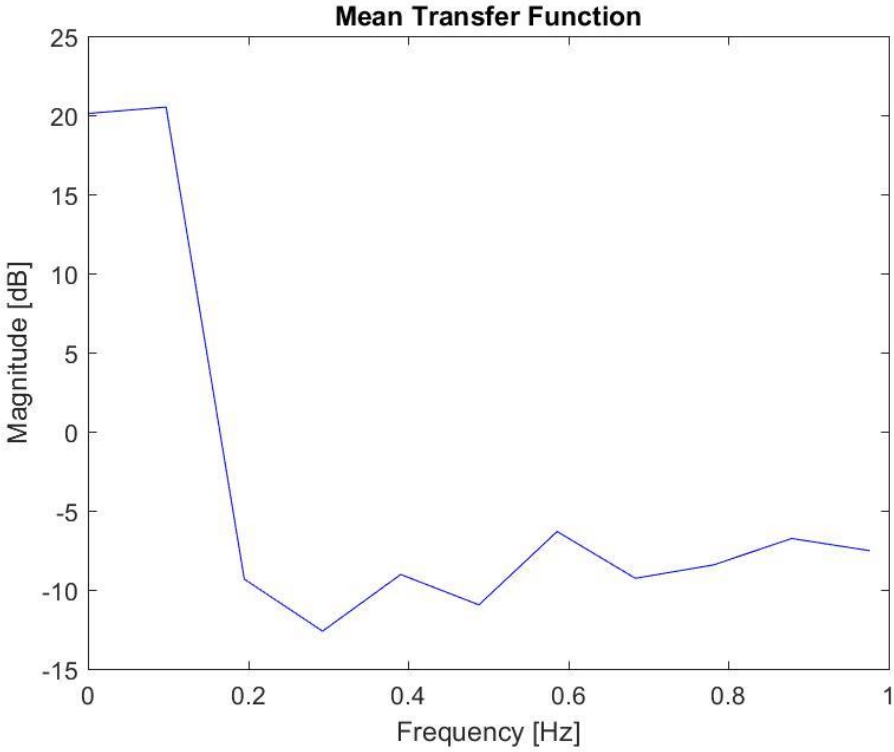

Figure 2.12. Mean TF of B1 (Source: Toni Prats)

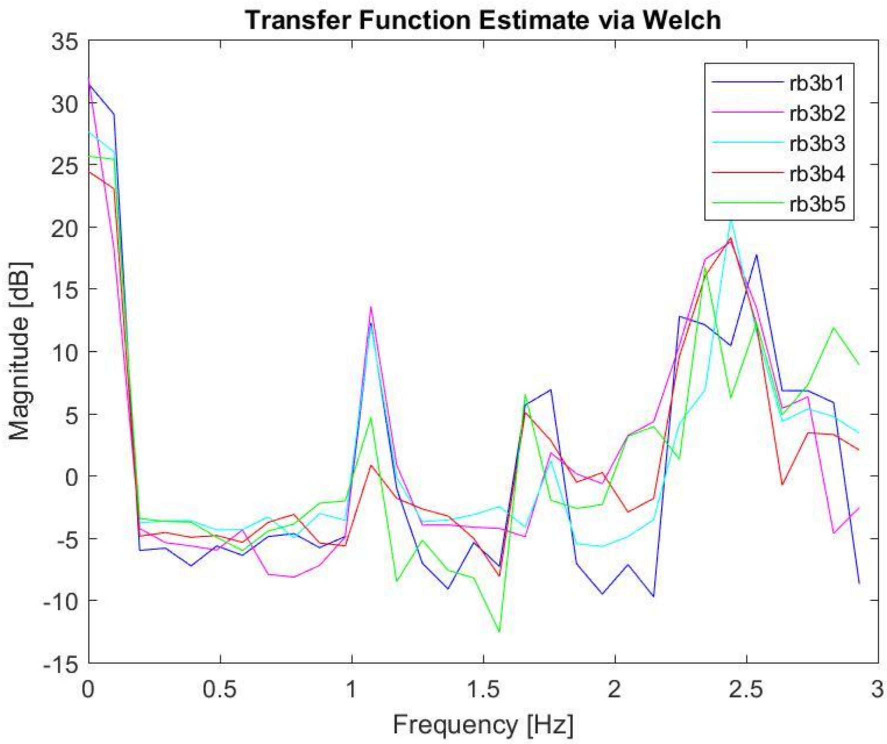

Figure 2.13. TF of the different B3 experiments (Source: Toni Prats)

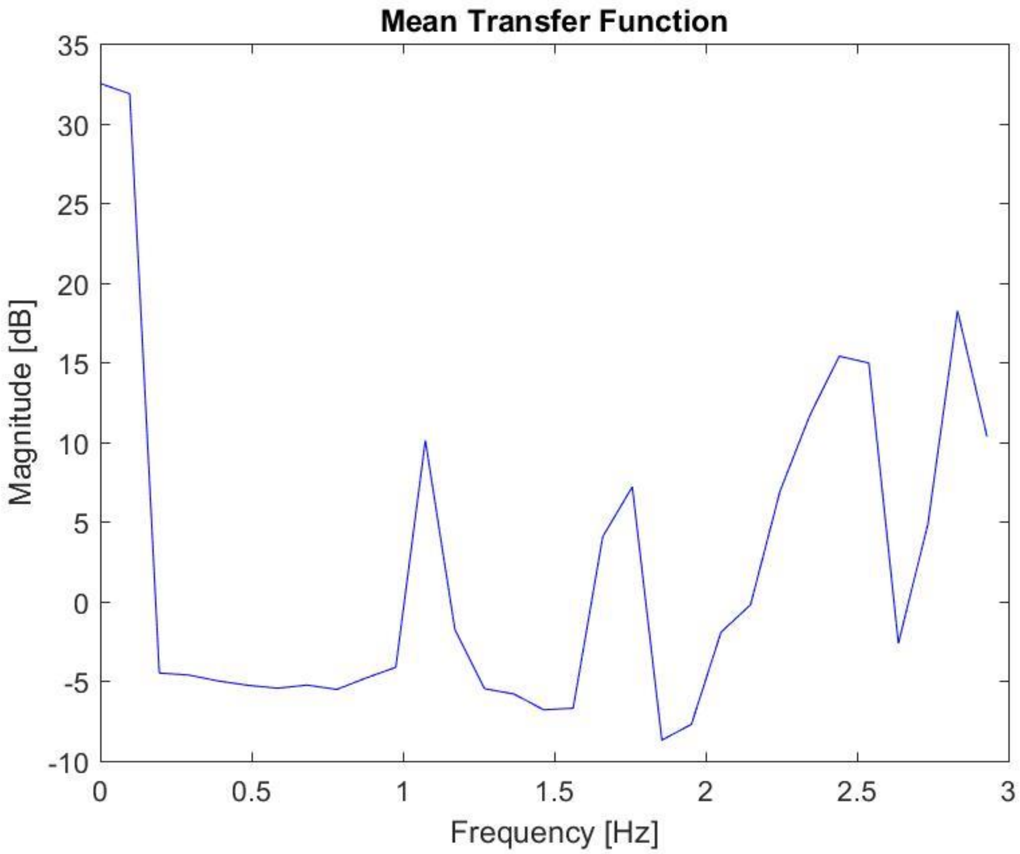

Figure 2.14. Mean TF of B3 (Source: Toni Prats)

In figure 2.11 we can see a first peak around 0.1 Hz, then it quickly decreases. In the majority of trials there are two peaks more around 0.4 and 0.6 Hz. This is also shown in figure 2.12 where the mean of this trials is plotted. We can also see in both figures a last peak at around 0.9 Hz, but this one is not as big as the others.

In figure 2.13 we can see a tendency similar to the previous signal, however, this time there are more peaks and are placed on the higher frequencies. This is also shown in the figure 2.14 where the mean is plotted. In general, with this signal we get the same starting peak and same decreasing behaviour as before, but the first peak appears at around 1.1 Hz. The following peaks are around 1.7, 2.5 and 2.8 Hz.

These graphics show that at very low frequencies the rider moves almost in face with the platform, having a bigger rotation of the trunk due to the effect of gravity. Then the peaks appear, these peaks can be two things, it can be a peak due to resonance or it also can be that the rider is not capable of responding accordingly to the stimuli.

Nonetheless, this plots of the various transfer functions are improbable because the magnitude goes too high, 20-30 dB which normally means a 100 or 200% gain. Moreover, it also goes down to -5 to -

20 dB which should not happen. This may be because of the inverse pendulum effect produced by the placement of the IMUs.

Conclusions

In the design and assembly phase a compromise between rigidity and adaptability to different riders had to be done. In the final mock-up this compromise did not eliminate the possibility to adapt the system to different riders while maintaining a good structural rigidity. Nevertheless, to adapt the system to a different set up will require some work and time.

While analysing the processed data, we can see how the participant tries to stabilize himself during the experiments and how he resonates with the system. This stabilization can come from different methods. The first method is using the inner ear, this will provide information about relative movements thus helping in maintaining the position, nevertheless, once you are already rotated this method will not help you return to your initial position. Another method, is the use of the velocity and acceleration sensors in the muscles, this way the human can involuntarily stiffen up his lateral and back muscles to go in face with the motion, however, this muscles are does not have an infinite rigidity, so the trunk of the participant will have more motion than the platform because he will act as a spring being pushed by gravity. The last method is using the visual sense, this provides absolute information and when used the participant damps out the motion of the platform, rolling less than the platform.

With this said, the two most effective methods to maintain the equilibrium and position are the use of the velocity and acceleration sensors in the muscles and the eyes. This two methods can also be used in combination to improve the efficiency.

Recommendations

In the future, the FRF of the trunk acceleration in front of the forces exerted in the seat for the roll experiment should be studied in order to see if the signal used is valid in our set up. Because, as we test it comparing the roll rates and the rotation point is in the contact patch of the wheels, the IMU placed in the chest of the rider may cause an inverse pendulum effect, countering the movement and making the coherence strike down and making the transfer function improbable.

Another aspect to improve, is the synchronization of the data acquisition. We are using three different programs to realize the experiment (one to operate the platform, one to measure from the strain gauges and another to measure from the IMUs). So, in order to facilitate the processing of the data in the future, the data recollection should be synchronized. This should be done writing a script that would be able to start all the data acquisition systems when the start button in the platform programme is pressed.

Budget

Name	Description	Quantity	Price (€/unit)	Cost (€)
W 25	Union element (clamp)	6	15.19	91.14
WRT 25	Union element (clamp)	3	42.77	128.31
WER 30	Union element (clamp)	4	93.78	375.12
WERT 32	Union element (clamp)	1	95.17	95.17
FRR 25	Union element (clamp)	5	35.60	178.00
GW 25	Union element (clamp)	20	39.20	784.00
GP 25	Union element (clamp)	6	39.20	235.20
P 25	Union element (clamp)	2	46.75	93.50
Stainless steel tube	3m; Ø25X2 mm	6	37.04	222.24
Handle HV M8x35	Handle to quickly release a clamp	10	5.92	59.20
Handle HV M8x45	Handle to quickly release a clamp	5	7.92	39.60
Handle HV M8x60	Handle to quickly release a clamp	5	8.92	44.60

Strain gauges	Pack of 10 units	3	200.00	600.00
Amplifier	Signal amplifier	13	100.00	100.00
Power source	-	1	250.00	250.00
USB-6211	Data acquisition system of 16 channels	1	1030.00	1030.00
Harness	Military grade security harness	1	300	300
MTw Awinda Development Kit Lite MTw2-DK-LITE	IMU system with two trackers	1	1140.00	1140.00
Strap set	Strap set to place the trackers	2	115.00	230.00
Wood base	3x0.8x0.25 m	1	85.00	85.00
Wood beam	5x0.8x0.8 m	1	60.00	60.00
Screws	Pack of 100 units	2	6.50	13.00
Squadron	Assembly squadron, pack of 4 units	5	5.50	27.50
Metal plate	Assembly metal plate, 10 m	1	8.50	8.50
Tube protection	Ø28 mm, 1 m	2	2.00	4.00
Renthal FatBar Riser Bar	Handlebar	1	56.99	56.99
Selle San Marco Milano Glamour Saddle	Seat	1	10.99	10.99

Thomson Elite InLine Seatpost	Seatpost	1	62.99	62.99
Lizard Skins Northshore Lock-On Bonus Pack	Grips	1	26.49	26.49
Cult x Vans Waffle Sole Flangeless Grips	Grips	1	12.99	12.99
Ritchey Comp 30 Deg Stem	Steam	1	32.49	32.49
Engineering hours	-	400	25	10000.00
Labour	-	250	20	5000
			Total	21397.02

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7775782%5Cnhttp://www.sciencedirect.com/science/article/pii/S2351978915000165%5Cnhttp://dx.doi.org/10.1016/j.trf.2013.12.010%5Cnhttp://ezproxy.usq.edu.au/login?url=http://.

Annex A: Calculus

To realize the calculus to select the strain gauges, it was decided that the interfaces where the strain gauges will be place would be made of aluminium 70xx. This means that the Young moduli used will be of 72 GPa. Moreover, the maximum mass will be of 100 Kg and gravity will be approximated to 10 m/s^2, in order to simplify the process.

B.1. Seat

Knowing that exterior diameter of the tube is 25 mm and the inner diameter is 23 mm and the length of the tube being of 410 mm. We can calculate the strain and deformation that this interface will suffer using the following equations:

$$P = m \cdot g \qquad \text{(Eq. B.1)}$$

$$A = \frac{\pi}{4} \cdot \left(d_e^2 - d_i^2 \right) \qquad \text{(Eq. B.2)}$$

$$\sigma = \frac{F}{A} \qquad \text{(Eq. B.3)}$$

$$\varepsilon = \frac{\sigma}{E} \qquad \text{(Eq. B.4)}$$

$$P = 100 \cdot 10 = 1000N \qquad \text{(Eq. B.2)}$$

$$A = \frac{\pi}{4} \cdot \left(25^2 - 23^2 \right) = 75.39mm^2 \qquad \text{(Eq. B.2)}$$

$$\sigma = \frac{1000}{75.39} = 13.26 \frac{N}{mm^2} \qquad \text{(Eq. B.3)}$$

$$\varepsilon = \frac{13.26}{72000} = 1.84 \cdot 10^{-4} \qquad \text{(Eq. B.4)}$$

B.2. Handlebars

The handlebar dimensions are as following: the length until the point of the force application is 292 mm, the exterior radius is 11.4 mm and the inner radius is 10 mm. The maximum expected force in the handlebars is 400 N.

$$S = \frac{\pi \cdot (r_e^4 - r_i^4)}{4 \cdot r_e} \quad \text{(Eq. B.5)}$$

$$\sigma = \frac{F \cdot L_p}{S} \quad \text{(Eq. B.6)}$$

$$\varepsilon = \frac{\sigma}{E} \quad \text{(Eq. B.7)}$$

$$S = \frac{\pi \cdot (11.4^4 - 10^4)}{4 \cdot 11.4} = 474.66 mm^3 \quad \text{(Eq. B.5)}$$

$$\sigma = \frac{400 \cdot 292}{474.66} = 246.07 \frac{N}{mm^2} \quad \text{(Eq. B.6)}$$

$$\varepsilon = \frac{246.07}{72000} = 3.41 \cdot 10^{-3} \quad \text{(Eq. B.7)}$$

B.3. Foot-pegs

The equations used will be the same as in the handlebars case. The dimensions used in the calculus are the following: the length until the point of the force application is 160 mm, inner radius of 10.5 mm, exterior radius of 12.5 mm and maximum expected force of 400 N.

$$S = \frac{\pi \cdot (12.5^4 - 10.5^4)}{4 \cdot 12.5} = 770.25 mm^3 \quad \text{(Eq. B.5)}$$

$$\sigma = \frac{400 \cdot 160}{770.25} = 83.09 \frac{N}{mm^2} \quad \text{(Eq. B.6)}$$

$$\varepsilon = \frac{83.09}{72000} = 1.15 \cdot 10^{-3} \quad \text{(Eq. B.7)}$$

Annex B: Table of Participants

EXPERIMENT:...

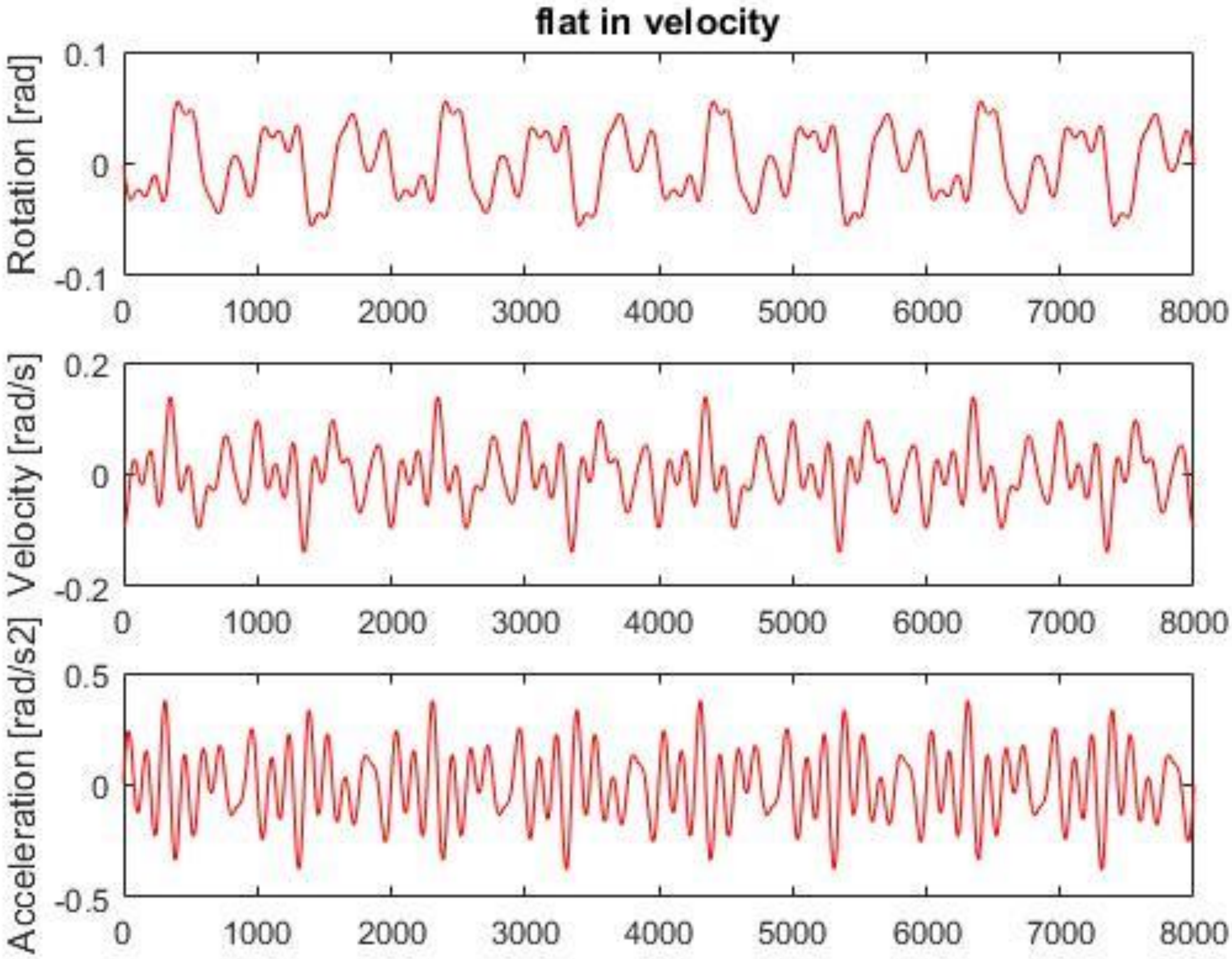
Category of participants: light / average / heavy

Date: ...../......./.......

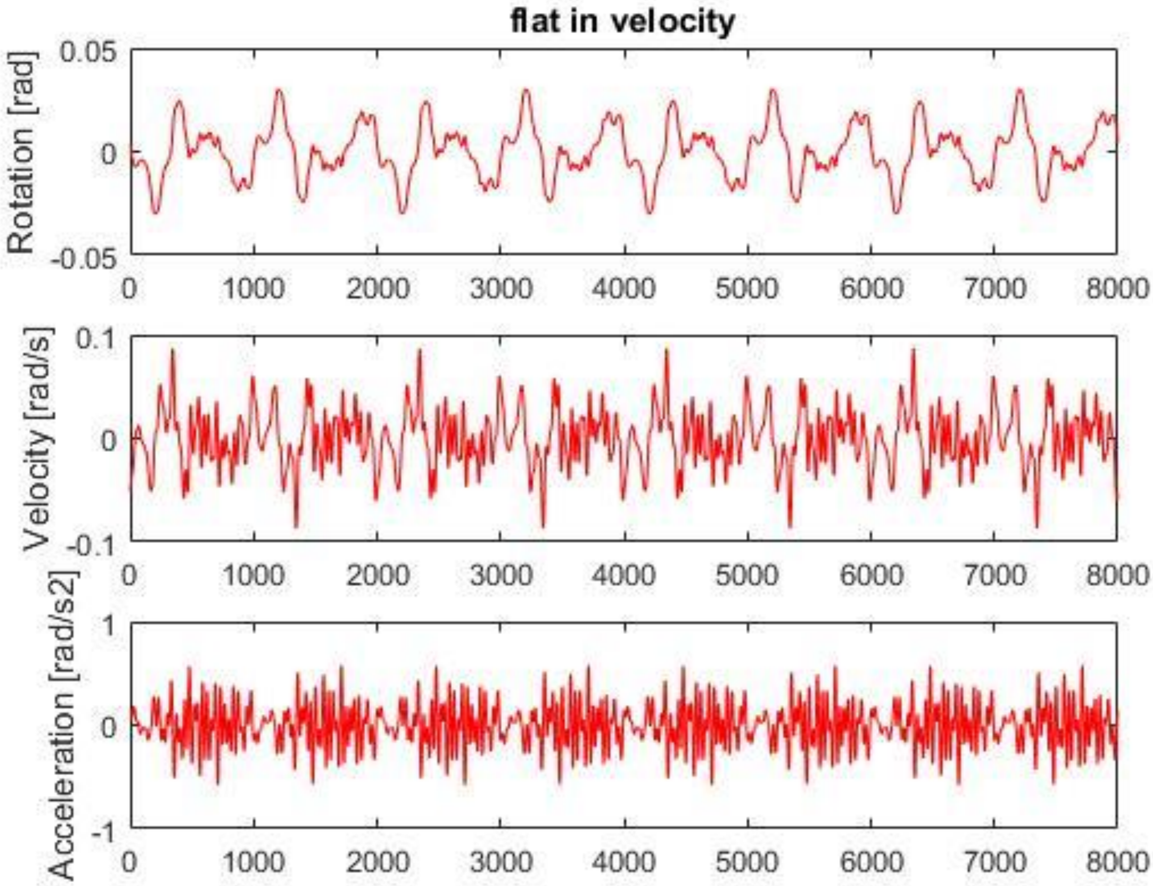
Nº of Participant	Name	Age (years)	Height (cm)	Mass (Kg)	Torso Inclination (deg)	Knee Position (deg)
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						

Annex C: Experimental Signals

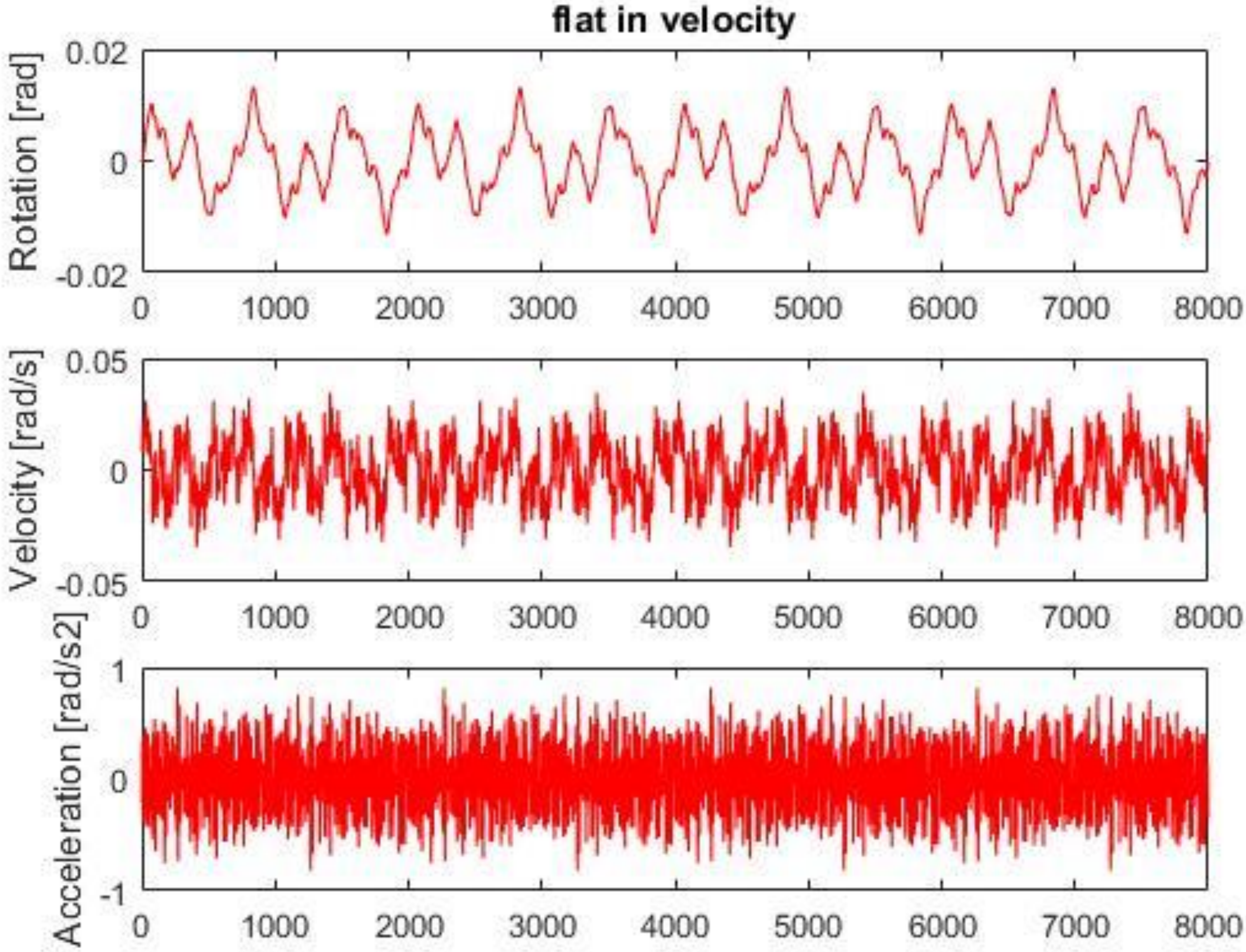
C.1. Rotation B1 signal



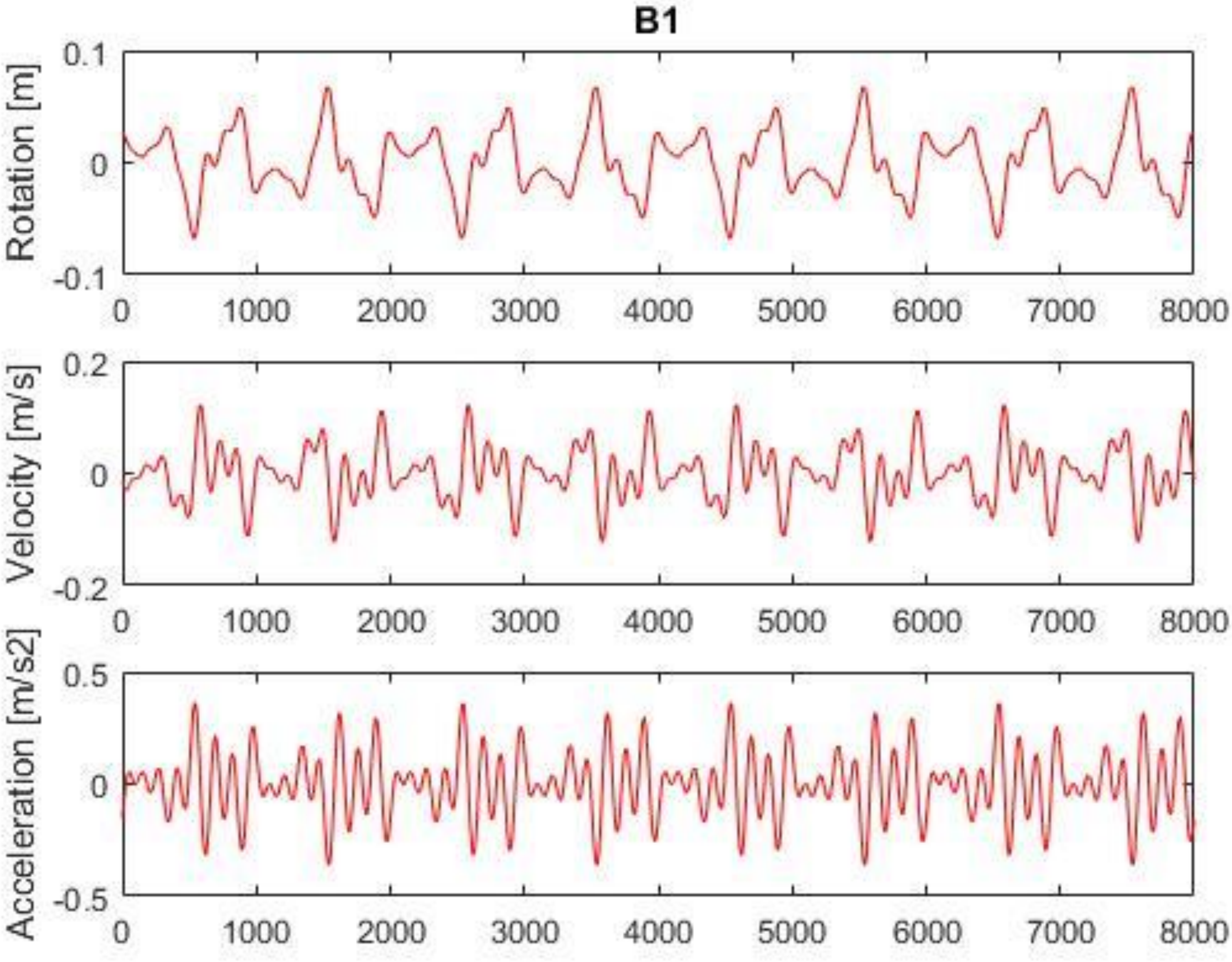
C.2. Rotation B3 signal



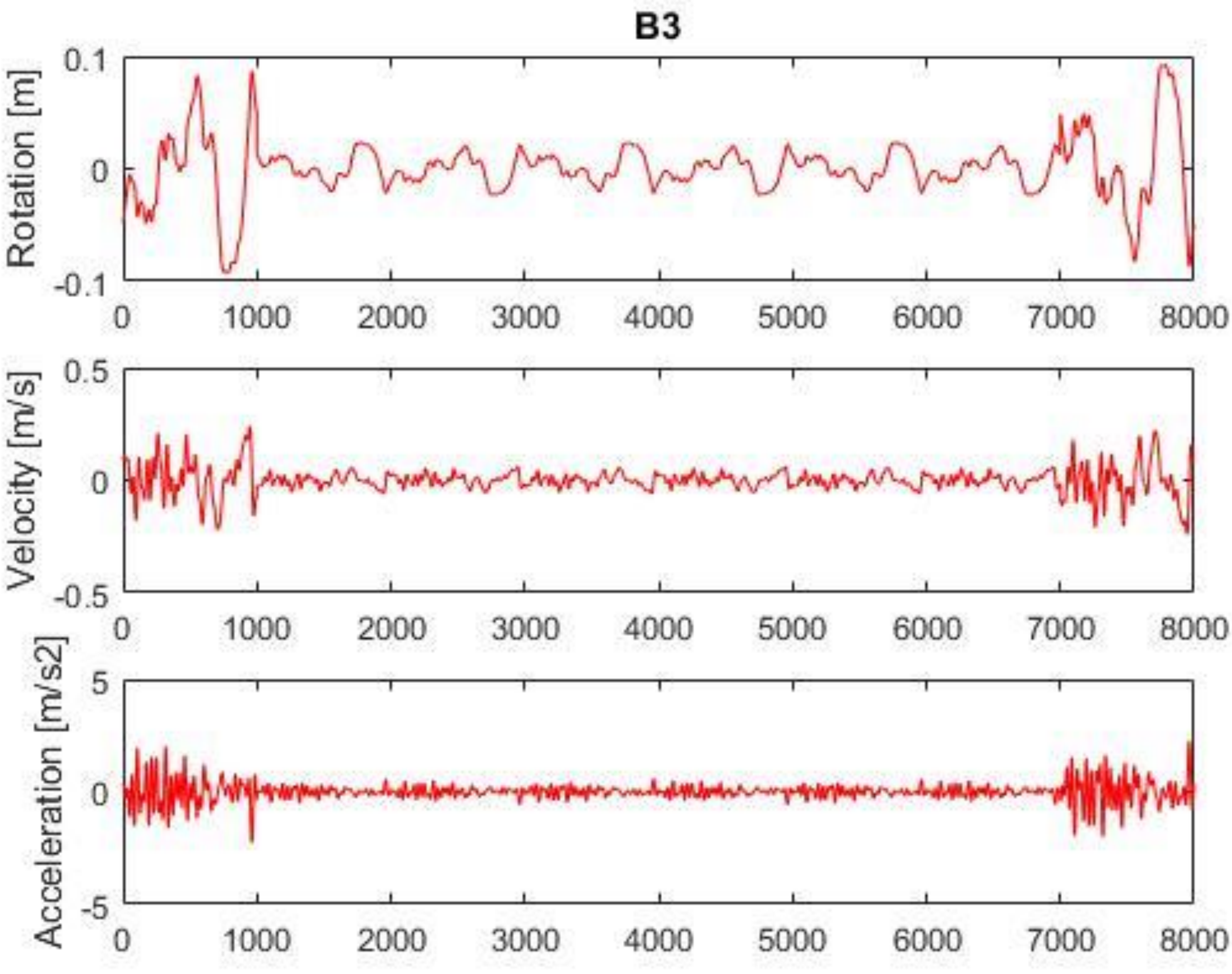
C.3. Rotation B10 signal



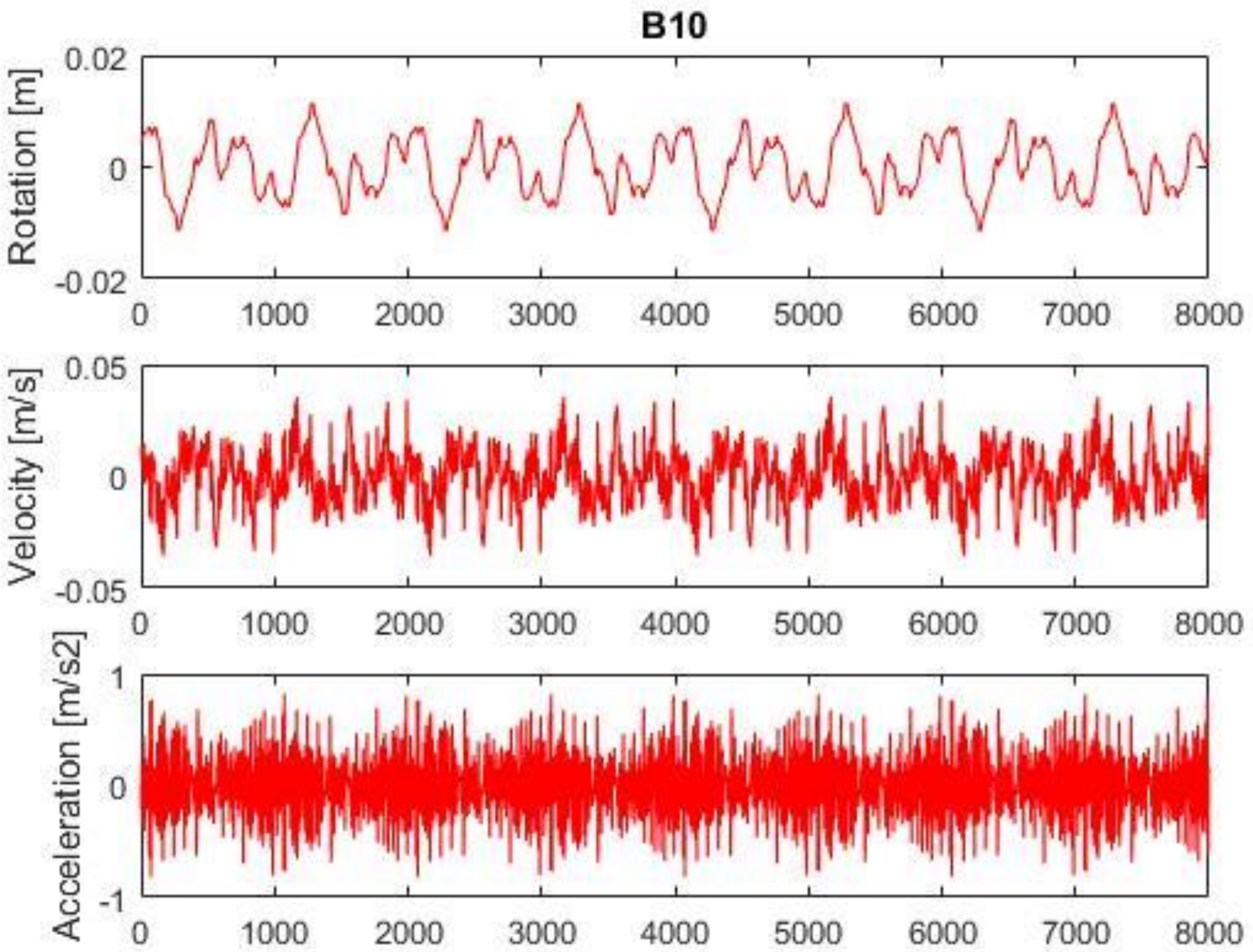
C.4. Translation B1 signal



C.5. Translation B3 signal



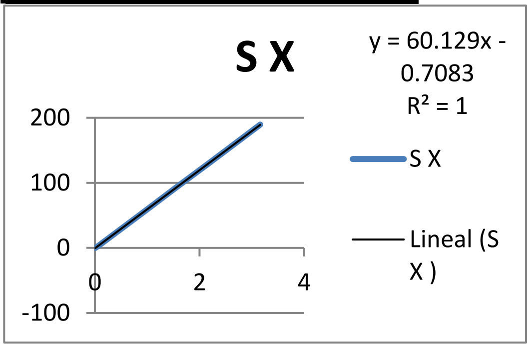
C.6. Translation B10 signal



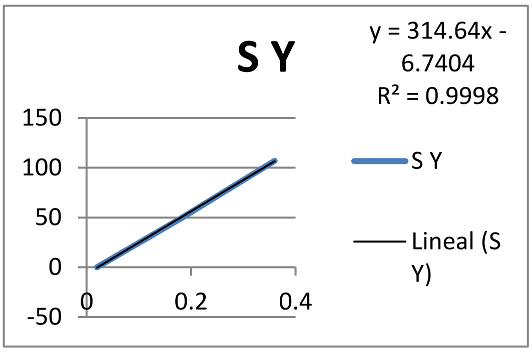
Annex D: Strain Gauges Calibration

In this annex, the tables, plots and equations for the calibration of the strain gauges will be shown. This way we can convert the volts read to newton.

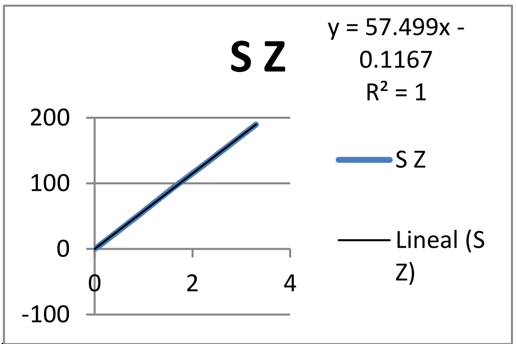
volt	S X	kg
0.01	0	0
0.08	4.2183	0.43
0.9	53.2683	5.43
1.55	92.5083	9.43
2.21	131.7483	13.43
3.16	189.6273	19.33



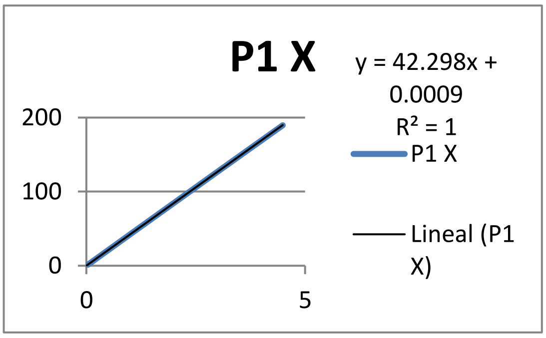
volt	S Y	kg
0.02	0	0
0.18	49.05	5
0.36	106.929	10.9



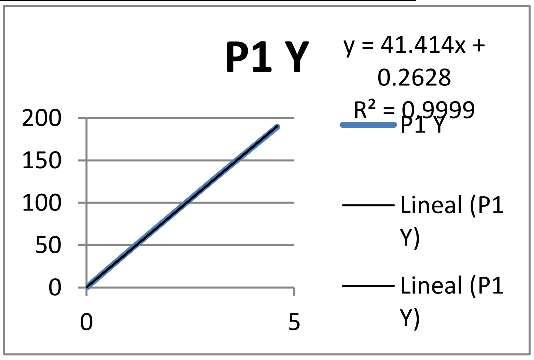
volt	S Z	kg
0	0	0
0.08	4.2183	0.43
0.93	53.2683	5.43
1.6	92.5083	9.43
2.3	131.7483	13.43
3.3	189.6273	19.33



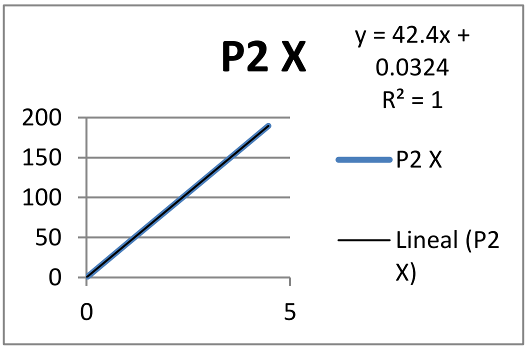
volt	P1 X	kg
0	0	0
0.11	4.2183	0.43
1.02	43.4583	4.43
1.95	82.6983	8.43
3.11	131.7483	13.43
4.49	189.6273	19.33



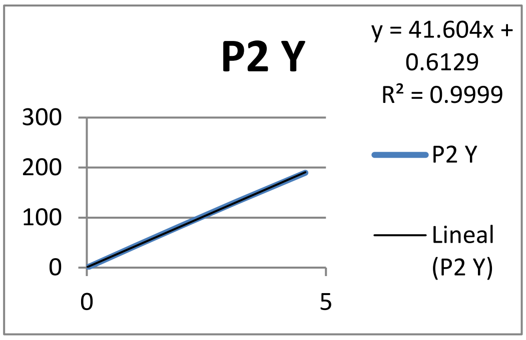
volt	P1 Y	kg
0.01	0	0
0.1	4.2183	0.43
1.03	43.4583	4.43
1.98	82.6983	8.43
3.16	131.7483	13.43
4.59	189.6273	19.33



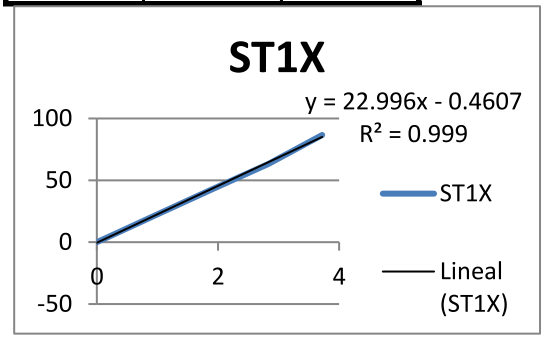
volt	P2 X	kg
0	0	0
0.1	4.2183	0.43
1.02	43.4583	4.43
1.95	82.6983	8.43
3.11	131.7483	13.43
4.47	189.6273	19.33



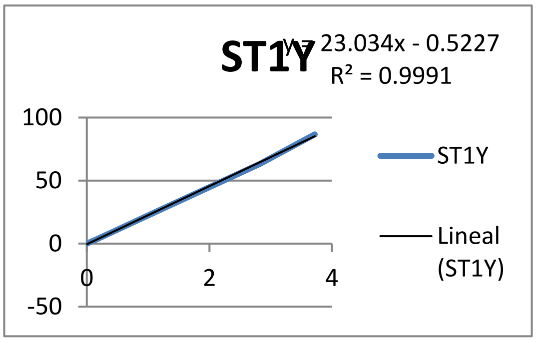
volt	P2 Y	kg
0	0	0
0.1	4.2183	0.43
1.02	43.4583	4.43
1.95	82.6983	8.43
3.13	131.7483	13.43
4.57	189.6273	19.33



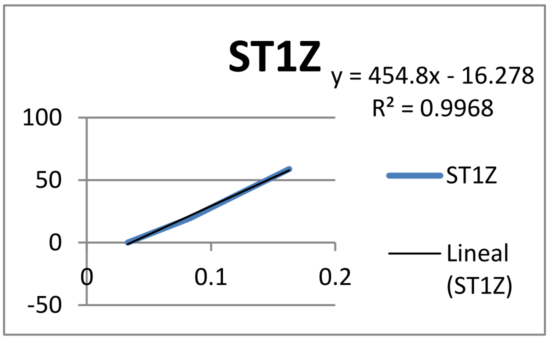
volt	ST1X	kg
0	0	0
0.19	4.2183	0.43
1.06	23.8383	2.43
1.94	43.4583	4.43
2.83	63.0783	6.43
3.72	86.6223	8.83



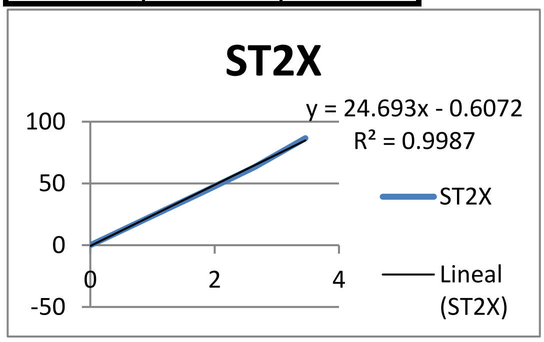
volt	ST1Y	kg
0	0	0
0.19	4.2183	0.43
1.07	23.8383	2.43
1.94	43.4583	4.43
2.82	63.0783	6.43
3.72	86.6223	8.83



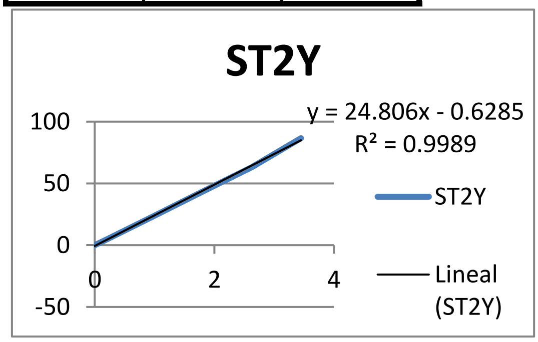
volt	ST1Z	kg
0.033	0	0
0.083	19.62	2
0.123	39.24	4
0.163	58.86	6



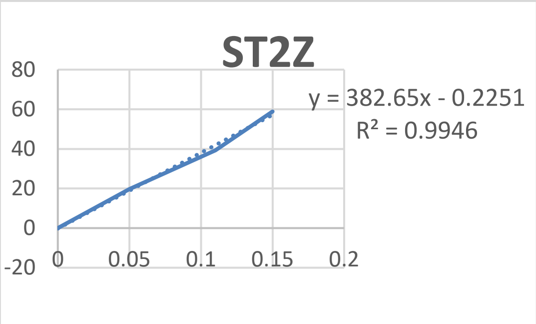
volt	ST2X	kg
0	0	0
0.176	4.2183	0.43
1	23.8383	2.43
1.83	43.4583	4.43
2.64	63.0783	6.43
3.46	86.6223	8.83



volt	ST2Y	kg
0	0	0
0.18	4.2183	0.43
1	23.8383	2.43
1.81	43.4583	4.43
2.63	63.0783	6.43
3.45	86.6223	8.83



volt	ST2Z	kg
0	0	0
0.05	19.62	2
0.11	39.24	4
0.15	58.86	6



Annex E: Matlab Code

E.1. Reading data from the IMU

```
clear all
clc

%% Read xls files

%{
filename = 'myExample.xlsx';
sheet = 1;
xlRange = 'B2:C3';

subsetA = xlsread(filename,sheet,xlRange)
%}
%% Loading Roll Rate Data

filename = 'rb1b1.xlsx';
sheet = 1;
xlRange = 'I4500:I6499';

%%{
rb1b1 = xlsread(filename,sheet,xlRange);

filename = 'rb1c1.xlsx';
rb1c1 = xlsread(filename,sheet,xlRange);

filename = 'rb1b2.xlsx';
rb1b2 = xlsread(filename,sheet,xlRange);

filename = 'rb1c2.xlsx';
rb1c2 = xlsread(filename,sheet,xlRange);

filename = 'rb1b3.xlsx';
rb1b3 = xlsread(filename,sheet,xlRange);

filename = 'rb1c3.xlsx';
rb1c3 = xlsread(filename,sheet,xlRange);

filename = 'rb1b4.xlsx';
rb1b4 = xlsread(filename,sheet,xlRange);

filename = 'rb1c4.xlsx';
rb1c4 = xlsread(filename,sheet,xlRange);

filename = 'rb1b5.xlsx';
rb1b5 = xlsread(filename,sheet,xlRange);

filename = 'rb1c5.xlsx';
rb1c5 = xlsread(filename,sheet,xlRange);
%}
```

```
%%
%{
filename = 'rb3b1.xlsx';
rb3b1 = xlsread(filename,sheet,xlRange);

filename = 'rb3c1.xlsx';
rb3c1 = xlsread(filename,sheet,xlRange);

filename = 'rb3b2.xlsx';
rb3b2 = xlsread(filename,sheet,xlRange);

filename = 'rb3c2.xlsx';
rb3c2 = xlsread(filename,sheet,xlRange);

filename = 'rb3b3.xlsx';
rb3b3 = xlsread(filename,sheet,xlRange);

filename = 'rb3c3.xlsx';
rb3c3 = xlsread(filename,sheet,xlRange);

filename = 'rb3b4.xlsx';
rb3b4 = xlsread(filename,sheet,xlRange);

filename = 'rb3c4.xlsx';
rb3c4 = xlsread(filename,sheet,xlRange);

filename = 'rb3b5.xlsx';
rb3b5 = xlsread(filename,sheet,'I2666:I6665');

filename = 'rb3c5.xlsx';
rb3c5 = xlsread(filename,sheet,'I2666:I6665');
%}
%% Ploting input signal
%{
plot(rb1b1)
hold on
plot(rb1b2)
hold on
plot(rb1b3)
hold on
plot(rb1b4)
hold on
plot(rb1b5)
legend('rb1b1','rb1b2','rb1b3','rb1b4','rb1b5')
%}
%{
plot(rb3b1)
hold on
plot(rb3b2)
hold on
plot(rb3b3)
hold on
plot(rb3b4)
hold on
plot(rb3b5)
hold on
```

```
legend('rb3b1','rb3b2','rb3b3','rb3b4','rb3b5')
%}
%{
plot(rb1c1)
hold on
%%}
%%{
plot(rb1c2)
%%{
hold on
plot(rb1c3)
hold on
plot(rb1c4)
hold on
plot(rb1c5)
%%}
legend('rb1c1','rb1c2','rb1c3','rb1c4','rb1c5') %
'rb1c1',,'rb1c3','rb1c4','rb1c5'
%}
%{
plot(rb3c1)
hold on
plot(rb3c2)
hold on
plot(rb3c3)
hold on
plot(rb3c4)
hold on
plot(rb3c5)
hold on
legend('rb3c1','rb3c2','rb3c3','rb3c4','rb3c5')
%}

%% Save data

%{
save('pqfile.mat','p','q')
%}
%%{
save('D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\2ARateB1.mat','rb1b1','rb1b2','rb1b3','rb1b4','rb1b5','
rb1c1','rb1c2','rb1c3','rb1c4','rb1c5')
%save('D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\ARateB3.mat','rb3b1','rb3b2','rb3b3','rb3b4','rb3b5','r
b3c1','rb3c2','rb3c3','rb3c4','rb3c5')
%}
```

E.2. Calculating the coherence of the signals

```
clear all
clc

%% Load Signals
load('ARateB1');
load('ARateB3');

%% Calculing the mean of the signals
%B1
%{
i=1;
while i<=4000
    rb1b(i)=(rb1b1(i)+rb1b2(i)+rb1b3(i)+rb1b4(i)+rb1b5(i))/5;
    rb1c(i)=(rb1c1(i)+rb1c2(i)+rb1c3(i)+rb1c4(i)+rb1c5(i))/5;
    i=i+1;
end

rb1b=rb1b(:);
rb1c=-rb1c(:);
%{
plot(rb1b)
hold on
plot(rb1c)
legend('rb1b','rb1c')
%}
% B3
i=1;
while i<=4000
    rb3b(i)=(rb3b1(i)+rb3b2(i)+rb3b3(i)+rb3b4(i)+rb3b5(i))/5;
    rb3c(i)=(rb3c1(i)+rb3c2(i)+rb3c3(i)+rb3c4(i)+rb3c5(i))/5;
    i=i+1;
end

rb3b=rb3b(:);
rb3c=-rb3c(:);
%{
plot(rb3b)
hold on
plot(rb3c)
legend('rb3b','rb3c')
%}
%saving the mean signals
save('D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\B1mean.mat','rb1b','rb1c')
save('D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\B3mean.mat','rb3b','rb3c')
%}

%% Load Mean signals
load('B1mean');
load('B3mean');

%% Coherence
% B1
```

```
% cxy = mscohere(x,y)
%%{
figure(1)
mscohere(rb1b1,rb1c1,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
l=length(x);
xr=100*x;

while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a(i)=xr(i);
        b(i)=y(i);
    end
    i=i+1;
end

figure(2)
mscohere(rb1b2,rb1c2,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a2(i)=xr(i);
        b2(i)=y(i);
    end
    i=i+1;
end

figure(3)
mscohere(rb1b3,rb1c3,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a3(i)=xr(i);
        b3(i)=y(i);
    end
    i=i+1;
end

figure(4)
mscohere(rb1b4,rb1c4,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');
```

```
i=1;
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a4(i)=xr(i);
        b4(i)=y(i);
    end
    i=i+1;
end

figure(5)
mscohere(rb1b5,rb1c5,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a5(i)=xr(i);
        b5(i)=y(i);
    end
    i=i+1;
end

figure(6)
mscohere(rb1b,rb1c,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a6(i)=xr(i);
        b6(i)=y(i);
    end
    i=i+1;
end

figure(7)
plot(a,b,'b')
hold on
plot(a2,b2,'m')
hold on
plot(a3,b3,'c')
hold on
plot(a4,b4,'r')
hold on
plot(a5,b5,'g')
xlabel('Frequency [Hz]');
ylabel('Magnitude-Squared Coherence');
title('Coherence Estimate via Welch')
legend('rb1b1','rb1b2','rb1b3','rb1b4','rb1b5')
%saveas(figure(7),'D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\Coherence B1.jpg')
```

```
figure(8)
plot(a6,b6,'b')
xlabel('Frequency [Hz]');
ylabel('Magnitude-Squared Coherence');
title('Mean Coherence')
%saveas(figure(8),'D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\Mean Coherence B1.jpg')
%}

% B3
%{
figure(1)
mscohere(rb3b1,rb3c1,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
l=length(x);
xr=100*x;

while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a(i)=xr(i);
        b(i)=y(i);
    end
    i=i+1;
end

figure(2)
mscohere(rb3b2,rb3c2,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a2(i)=xr(i);
        b2(i)=y(i);
    end
    i=i+1;
end

figure(3)
mscohere(rb3b3,rb3c3,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a3(i)=xr(i);
        b3(i)=y(i);
    end
```

```
    i=i+1;
end

figure(4)
mscohere(rb3b4,rb3c4,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a4(i)=xr(i);
        b4(i)=y(i);
    end
    i=i+1;
end

figure(5)
mscohere(rb3b5,rb3c5,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a5(i)=xr(i);
        b5(i)=y(i);
    end
    i=i+1;
end

figure(6)
mscohere(rb3b,rb3c,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a6(i)=xr(i);
        b6(i)=y(i);
    end
    i=i+1;
end

figure(7)
plot(a,b,'b')
hold on
plot(a2,b2,'m')
hold on
plot(a3,b3,'c')
hold on
plot(a4,b4,'r')
```

```
hold on
plot(a5,b5,'g')
xlabel('Frequency [Hz]');
ylabel('Magnitude-Squared Coherence');
title('Coherence Estimate via Welch')
legend('rb3b1','rb3b2','rb3b3','rb3b4','rb3b5')
saveas(figure(7),'D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\Coherence B3.jpg')

figure(8)
plot(a6,b6,'b')
xlabel('Frequency [Hz]');
ylabel('Magnitude-Squared Coherence');
title('Mean Coherence')
saveas(figure(8),'D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\Mean Coherence B3.jpg')
%}
```

E.3. Calculating the transfer function of the signals

```
clear all
clc

%% Load Signals
load('ARateB1');
load('B1mean');
load('ARateB3');
load('B3mean');

%% FRF
% B1
% tfestimate(x,y,window,noverlap,f,fs)
%{
figure(1)
tfestimate(rb1b1,rb1c1,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
l=length(x);
xr=100*x;

while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a(i)=xr(i);
        b(i)=y(i);
    end
    i=i+1;
end

figure(2)
tfestimate(rb1b2,rb1c2,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a2(i)=xr(i);
        b2(i)=y(i);
    end
    i=i+1;
end

figure(3)
tfestimate(rb1b3,rb1c3,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
```

```
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a3(i)=xr(i);
        b3(i)=y(i);
    end
    i=i+1;
end

figure(4)
tfestimate(rb1b4,rb1c4,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a4(i)=xr(i);
        b4(i)=y(i);
    end
    i=i+1;
end

figure(5)
tfestimate(rb1b5,rb1c5,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a5(i)=xr(i);
        b5(i)=y(i);
    end
    i=i+1;
end

figure(6)
tfestimate(rb1b,rb1c,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 1 Hz in normalized frequency
    if xr(i)<=1
        a6(i)=xr(i);
        b6(i)=y(i);
    end
    i=i+1;
end

figure(7)
plot(a,b,'b')
hold on
```

```
plot(a2,b2,'m')
hold on
plot(a3,b3,'c')
hold on
plot(a4,b4,'r')
hold on
plot(a5,b5,'g')
xlabel('Frequency [Hz]');
ylabel('Magnitude [dB]');
title('Transfer Function Estimate via Welch')
legend('rb1b1','rb1b2','rb1b3','rb1b4','rb1b5')
saveas(figure(7),'D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\TF B1.jpg')

figure(8)
plot(a6,b6,'b')
xlabel('Frequency [Hz]');
ylabel('Magnitude [dB]');
title('Mean Transfer Function')
saveas(figure(8),'D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\Mean TF B1.jpg')
%}

% B3
%%{
figure(1)
tfestimate(rb3b1,rb3c1,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
l=length(x);
xr=100*x;

while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a(i)=xr(i);
        b(i)=y(i);
    end
    i=i+1;
end

figure(2)
tfestimate(rb3b2,rb3c2,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a2(i)=xr(i);
        b2(i)=y(i);
    end
    i=i+1;
```

```
end

figure(3)
tfestimate(rb3b3,rb3c3,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a3(i)=xr(i);
        b3(i)=y(i);
    end
    i=i+1;
end

figure(4)
tfestimate(rb3b4,rb3c4,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a4(i)=xr(i);
        b4(i)=y(i);
    end
    i=i+1;
end

figure(5)
tfestimate(rb3b5,rb3c5,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
        a5(i)=xr(i);
        b5(i)=y(i);
    end
    i=i+1;
end

figure(6)
tfestimate(rb3b,rb3c,2000)
h = findobj(gca,'Type','line');
x=get(h,'Xdata');
y=get(h,'Ydata');

i=1;
while i<=l  %getting the range of 0 to 3 Hz in normalized frequency
    if xr(i)<=3
```

```
        a6(i)=xr(i);
        b6(i)=y(i);
    end
    i=i+1;
end

figure(7)
plot(a,b,'b')
hold on
plot(a2,b2,'m')
hold on
plot(a3,b3,'c')
hold on
plot(a4,b4,'r')
hold on
plot(a5,b5,'g')
xlabel('Frequency [Hz]');
ylabel('Magnitude [dB]');
title('Transfer Function Estimate via Welch')
legend('rb3b1','rb3b2','rb3b3','rb3b4','rb3b5')
saveas(figure(7),'D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\TF B3.jpg')

figure(8)
plot(a6,b6,'b')
xlabel('Frequency [Hz]');
ylabel('Magnitude [dB]');
title('Mean Transfer Function')
saveas(figure(8),'D:\Mis Documentos\Uni\TFG\matlab\Data
Processing\Report\Mean TF B3.jpg')
%}
```

E.4. Calculating FFT

```
clear all
clc

%load('R_B2'); %load signal
load('ARateB1');

%%
%{

Fs = 1000;                % Sampling frequency
T = 1/Fs;                 % Sampling period
L = 1500;                 % Length of signal
t = (0:L-1)*T;            % Time vector

Y = fft(X);

P2 = abs(Y/L);
P1 = P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);

f = Fs*(0:(L/2))/L;
plot(f,P1)
title('Single-Sided Amplitude Spectrum of X(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')

Y = fft(S);
P2 = abs(Y/L);
P1 = P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);

plot(f,P1)
title('Single-Sided Amplitude Spectrum of S(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')

%}

Fs = 100;                % Sampling frequency
T = 1/Fs;                 % Sampling period
L = 4000;                 % Length of signal
t = (0:L-1)*T;            % Time vector

Y = fft(rb1b1);

P2 = abs(Y/L);
P1 = P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);

f = Fs*(0:(L/2))/L;
figure(1)
plot(f,P1)
```

```
axis([0 3 0 0.1])
title('Single-Sided Amplitude Spectrum of X(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')

Y2 = fft(rb1c1);

P22 = abs(Y2/L);
P12 = P22(1:L/2+1);
P12(2:end-1) = 2*P12(2:end-1);
figure(2)
plot(f,P12)
axis([0 3 0 0.1])
title('Single-Sided Amplitude Spectrum of X(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')
%{
Y3 = fft(rb2v);

P23 = abs(Y3/L);
P13 = P23(1:L/2+1);
P13(2:end-1) = 2*P1(2:end-1);
figure(3)
plot(f,P13)
axis([0 3 0 0.1])
title('Single-Sided Amplitude Spectrum of X(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')
%}
```