Part IIA Project - **SC2** Bicycle Design

Data-driven quantification and modelling of optimal suspension configurations for cross country (XC) mountain bike racing

Final Report

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(abstract overleaf)

Contents

Abstract

This project focuses on the experimental exploration of mountain bike suspension deisgn for cross-country (XC) racing, and aims to quantify the ideal configuration of a suspension system for a given trail or course that incorporates a wide range of terrain types. To do this, a number of experimental runs were carried out on an offroad circuit using an accelerometer, and the *rebound* setting of a shock adjusted across these to quantify the performance effect of altering suspension parameters. Analysis of this data yielded a number of results; that the magnitude of acceleration for a given trail section correlated well with the roughness perceived by the rider, that the power spectral density was strongly influenced by the *rebound*, and that the results were consistent in both shape and magnitude across a number of repeats. Finally, it was found that detection methods could be employed to characterise trail features successfully, and that this methodology motivated further developments in suspension control systems, including an upcoming automatic suspension adjustment system (SR Suntour).

1 Introduction

1.1 Suspension in Cross Country Mountain Biking

Cross country (or XC) is a type of mountain bike racing that lies somewhere in the middle of the traditional scale of cycling disciplines, blending physical prowess required for road racing with the technical handling ability needed for *downhill* racing. XC racing is concerned with going fast over rough terrain that includes uphill and downhill sections alongside technical features like jumps, drops, *berms*, roots, and rocks (as seen in Figure 1).

In the last few decades, XC courses have become increasingly technical, including rougher *singletrack* and steeper climbs than ever before, partly fuelled by professional racing (XC is currently the only offroad cycling discipline in the Olympic Games). This variety in courses means that good bicycle setup is essential, especially when it comes to suspension; an optimally configured machine will allow a rider to glide over rougher features whilst limiting the amount of fatigue they feel due to impacts, in turn helping them to race faster.

Figure 1: Tom Pidcock racing through a rough *rock garden* section on his way to victory at the first round of the XC World Cup 2023 [1]

Figure 2: A 2018 Cannondale Scalpel Si Carbon, the *full suspension* mountain bike used for testing throughout this project.

Most modern courses suit a *full suspension* MTB, where the main frame (and therefore the rider) is isolated from the front wheel input by a suspension fork, and the rear wheel (triangle) by a *shock*. However, the resulting trade-off is increased weight and a small but noticeable reduction in pedalling efficiency (whereby the rider's input power is also dissipated in the suspension). Therefore, *lockout* systems are employed to reduce unwanted energy dissipation, or a *hardtail* bicycle (front suspension only set up) is used instead on less technical courses.

Currently available suspension components incorporate an array of adjustability for the rider to fine-tune their setup for the course and for the conditions. Alongside the *lockout* (which essentially adjusts the shock's stiffness by reducing the aperture through which the fluid is forced), there is often *rebound* (which changes how quickly the shock re-extends after an input, typically adjusted to suit the scale of the bumps encountered), and the pressure (which is tuned to rider weight as a guide and then to preference). Tokens and dampers can also be used to finely adjust the characteristics of the hydraulic fork, often to eliminate 'wallow' (the physically felt result of overdamping), but are typically a specialist addition.

This poses the question: what suspension settings could be considered optimal for a given scenario, and how might they be quantified? That in turn motivates the exploration of the relationship between the optimal settings and the course type; for example, how does a course with a rocky surface and steep inclines compare to a flatter, softer surfaced one in terms of suspension set-up?

Simplistically, the aim of suspension is to reduce the vibrations and acceleration experienced by the rider whilst retaining traction, and consequently minimise the vibrational energy dissipated in the rider's muscles. This should in turn yield the 'fastest' possible suspension configuration for a given course. However, there are many variables here that are very difficult to characterise, and so any modelling will need to make generalisations and simplifications.

1.2 Literature Review

A literature review [2] was conducted during the project, focusing on studies into the characterisation and quantification of the performance of mountain bike suspension systems, both for *hardtail* (front *fork* only) and *full suspension* (front *for* and rear *shock*) configurations. The main focus of most studies into XC suspension systems is the physiological impact on the rider, typically trialling different configurations over a range of terrains with a sample of riders. From this, performance is often measured by using metrics such as VO_2, *cycling economy*, and heart rate as proxies for the physiological performance of riders. Three major studies also incorporated measures of acceleration as way of quantifying rider performance as a function of suspension across different terrains.

- Faiss et al. (2007) [3] conducted a study into "The effect of mountain bike suspensions on vibrations and off-road uphill performance", comparing the pedalling efficiency of hardtail and full suspension bicycles on an uphill test section to determine the net efficiency of each system from a physiological standpoint.
- Macdermid et al. (2017) [4] sought to combine uphill and downhill performance measurement by using a test lap with uphill and downhill sections, analysing VO_2 and heart rate to determine the effect of the terrain type on both the accelerations felt by and overall performance of a sample of eight national level athletes.
- Titlestad et al. (2003) [5] used a stationary rig with the surface roughness varied by the height of bumps on a rolling road, quantifying the power transmitted through the pedals and into the rider for a range of suspension configurations (rigid, hardtail, full suspension), alongside physiological parameters.

Additionally, these papers aided the experimental process of the project significantly, especially regarding acceleration measurements and their subsequent analysis. A number of stationary and field tests provided valid acceleration data that was then analysed in a number of ways. Firstly, in using simple magnitude and statisical characterisation. Secondly, using spectral analysis to model the bicycle as a linear system, with a power spectral density of the input acceleration (via the wheel) and output (via the saddle). Finally, rolling road tests illustrated the impulse responses of different systems, which would be mirrored by rocks and roots on a typical trail.

Although the findings from previous studies are more completely explored in the full literature review [2], a definitive takeaway was the conclusion that **a reduction in the accelerations felt by the rider results in an increase in physiological performance**. This therefore suggests that the measurement of the rider's acceleration throughout a test run is an appropriate analogy for overall physiological performance, and therefore limiting the vibrational energy transfer using suspension will result in the objectively fastest set-up. Adjusting suspension parameters between repeats of the same course will also provide insight into the optimal suspension configuration for a given terrain, and assist in the development of a model for suspension set-up for variable courses.

2 Experimental Testing

2.1 Test Loop

The major portion of experimental testing for the project centred around a main test loop; a five kilometre section of the *Red 'Lime Burner' Trail* at Thetford Forest, Suffolk, was chosen as it incorporated a range of trail types and was of sufficient length to collect an appropriate amount of data for further analysis.

As shown in Figure 3, the loop was dividied into eight distinct trail sections:

1. Stating with 'Cannock's Chase', the terrain is relatively smooth, with a large number of banked turns (or *berms*) and then a section with a small drop.
2. Following this, 'Root Chute' has an uneven, rooty surface, but is still reasonably fast.
3. 'Shockwave' has a smooth surface with a gradual 180-degree flat turn.
4. 'Rock n' Roller' is a twistier trail decorated with humps (or *rollers*) and narrow *singletrack*.
5. 'Quarry Line' begins with a fast hardpack surface, before transitioning to a rougher *rock garden* with increasingly large drops.
6. 'The Omen' heads back into the forest, with larger berms and rollers.
7. 'Centurion' is a more technical section with successively larger drops and *rock gardens*, before opening out into a sandier, flowier section.
8. 'Round the Pit' is a faster section with a few roots that gently weaves up a slight incline.

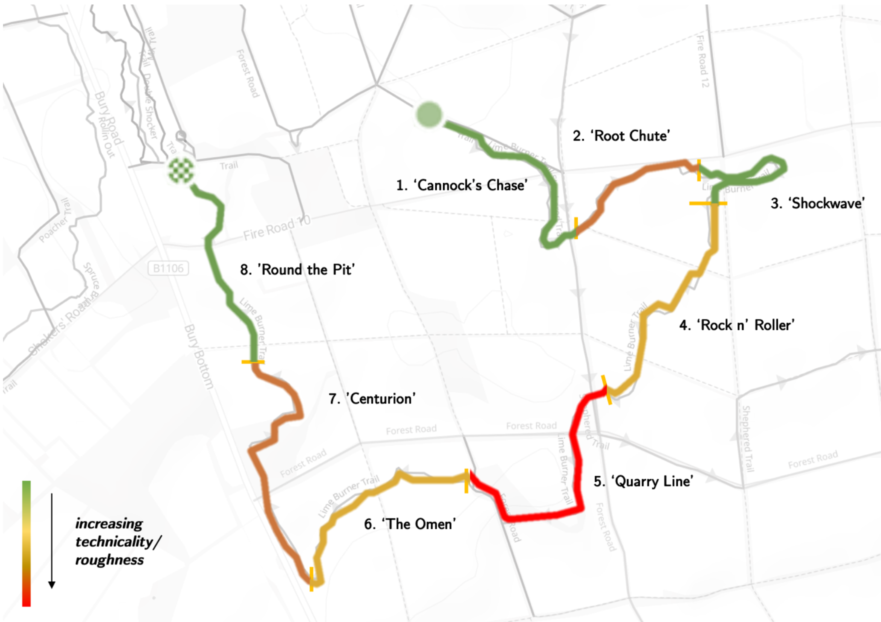

Figure 3: Map showing the main 5km test loop used, with a colour map showing the qualitative roughness of each of eight named sections of the trail. [6]

Figure 3 shows the sectioning of the loop according to the eight trail segments, with a qualitative colour mapping based on the rider's perspective of how 'technical' the trail section was. Generally, mountain bikers characterise trails qualitatively in terms of their 'tech' and 'flow':

'Tech' is the measure of how technical a trail feels, and this usually correlates with the *perceived roughness* of a section. For example, a fast downhill where the surface is broken up by rocks and tree roots would be considered 'techy', as a good level of rider skill and bike handling is required to navigate it successfully. Equally, a climb or uphill section where the surface is stepped might also be described as 'techy'. A 'tech' trail is not necessarily a slow trail, but the perceived speed may be lower, and there is a perception that the bicycle's suspension system is employed to a greater extent during a technical section.

'Flow' is the measure of how smooth a trail is, and is usually mirrors the *perceived speed* of a section well. For example, a smoothly surfaced downhill trail, with *berms* to help the rider conserve speed through the corners, would be considered a 'flowy' trail. A 'flow' trail also requires a high level of rider skill to best utilise the speed-conserving features, and the feeling of 'flow' itself is one of transitioning smoothly between features.

Therefore, 'tech' and 'flow' can be considered two independent qualitative metrics for a trail section, and each utilises the suspension system in a different way. 'Tech' will usually require a *fast rebound* or overdamping to isolate the rider from the high surface roughness at the tyre, and 'flow' will require *slower rebound* in order to transition smoothly between sections without a suspension reaction that the rider might consider jarring.

To that extent, a trail can be qualitatively characterised in terms of its *perceived 'tech' and 'flow'*, and this can be expressed visually on a two-dimensional plot as per Figure 5. The expected 'tech' of the trail section (from the experience of the rider) should correlate with the acceleration profile measured during the experiment.

The loop was also recorded using a head-mounted video camera (GoPro Hero 7) for later analysis and reference for characterising the loop used; a still from this footage is shown in Figure 4.

Figure 4: Video still from a head-mounted camera used during a test run, illustrating the *rock garden* in the middle of 5. 'Quarry Line'.

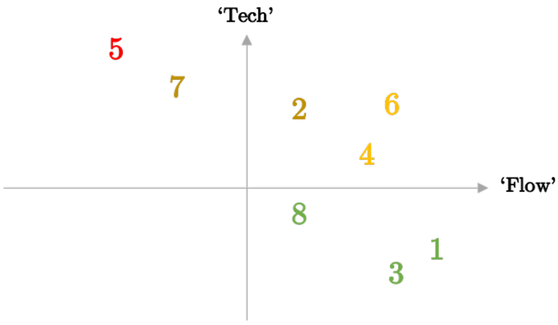

Figure 5: Qualitative characterisation of the eight trail sections used, comparing their perceived 'tech' and 'flow', with the colour map relating to the *percieved roughness*.

2.2 Rebound Adjustment

The independent variable for testing was the variation of the *rebound* of the rear suspension shock on the test bicycle (Figure 2). Colloquially, the *rebound* adjustment of a suspension component (whether that be a front suspension *fork* or rear suspension *shock*) controls how fast the return after an impact is. For example, a *fast rebound* shock would return to it's unloaded position far quicker than a *slow rebound* shock after an impact like a root on the trail. Alternatively, mountain bikers who focus more on jumps (*downhill* or *freeride* riders) would perceive this as the rate of 'bounce-back' or 'reset speed' after landing a jump and compressing the suspension.

Therefore, the ideal *rebound* setting is highly dependent on the application. The aforementioned *freerider* tends to prefer a long-travel set-up with a *slow rebound* to make landing more comfortable and stable. Whereas an XC rider might prefer a *fast rebound* to manage a rooty section with a higher frequency input better, and retain grip over comfort, which might otherwise leave the bike feeling 'wallowy' (the perceived result of overdamping).

Whilst this terminology is colloquial, it does mirror the field of *mechanical vibrations* perfectly; the measure of *rebound* is equivalent to the *damping ratio* of a suspension component, and also its time constant (as seen in 'fast' and 'slow' rebound). A *slow rebound* configuration is overdamped, and a *fast rebound* is underdamped. However, this raises the question as to what is critically or ideally damped in this situation?

Cross country courses in particular are highly variable in their terrain, so the input to the suspension system is very dependent on the specific circuit. Therefore in taking experimental measurements, a set-up that is close to the ideal case given the course should be characterisable. Extending this to a feature by feature basis would allow the construction of a model that maps terrain type to ideal suspension parameters, and aid successful adjustment of suspension significantly.

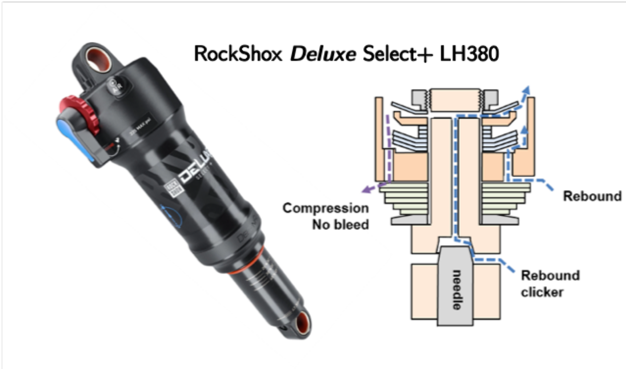

Figure 6: An image and diagram of a *Rockshox Deluxe* shock, similar in construction to the *Monarch* used, highlighting the red rebound adjustment wheel, and the mechanism which adjusts this internally. [7]

2.3 Rebound Measurements

The test loop described in Section 2.1 was carried out five times for increasing *rebound*, recording the entirety of the lap using the triaxial accelerometer in a Google Pixel 6A via the *phyphox* app [8]. The *rebound* dial on the *Rockshox Monarch* rear shock is indexed from 1 (slowest) to 10 (fastest), and so tests were carried out for rebounds 1, 3, 5, 7, and 9. This resulted in approximately one hour of accelerometer data recorded at 56Hz. The accelerometer is triaxial, but only the absolute data was used in analysis as the placement of the phone in a back jersey pocket means that the axes were not aligned, and so x, y, z data is meaningless.

GPS data recorded by a *Garmin Edge 830* cycling computer was analysed using the *Strava* website [9], and time stamps were taken for the start of the individual trail sections for each recording. This allowed for accurate segmentation of the files so that the difference between *rebound* settings per trail section could be ascertained.

2.4 Repeatability Measurements

In order to understand the repeatability of the test method and equipment used, a shorter section of trail was repeated a number of times with the same *rebound* setting to show that the same results were achieved. The *Strava* segment for 'The Downhill' at Thetford is shown in Figure 7, highlighting the consistency of the time taken for each repeat. The trail is gently downhill, beginning with a fast rooty section into 15 successive *berms*, some separated by *rollers*, before ending in a final, large 180-degree *berm* into a stepped *rock garden* to finish.

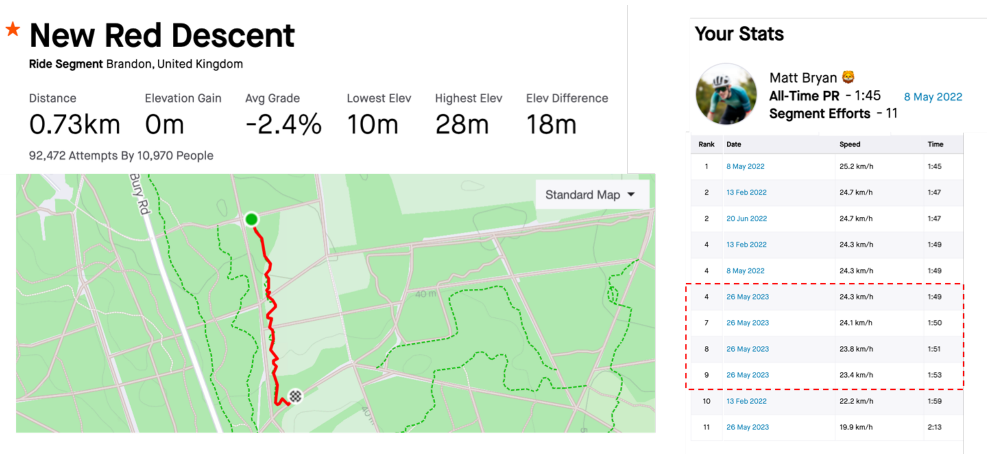

Figure 7: Annotated screencapture from *Strava* [9], showing the repeated downhill section 'segment', and the times per repeat captured by the GPS recording.

From the GPS data, it can be seen that the timing of the sections was consistent, and so if the experimental method is indeed repeatable, then the acceleration measurements should be roughly comparable. There will be some deviation due to the rider taking slightly different lines, braking later, or any other permutation during the trail, but the major features, namely the *berms* and *rollers*, should be recognisable. These features should be consistent in shape and magnitude, and will show some small drift in time between runs. Verifying this should give reasonable confidence in the consistency and accuracy of the testing methodology used for the main loop testing for varying *rebound*.

3 Data Analysis

3.1 Validity of Measurements

Figure 8 shows the smoothed acceleration data over time for three of the five validation runs on 'The Downhill' section (as set out in Section 2.4), showing the final portion of the trail in each case. Although there is a slight timing offset between the repeats, there are a number of distinct features that match between the data sets following smoothing. The first of these is a characteristic peak due to a group of roots, followed by a section of lower amplitude that corresponds to a smooth section between two *berms*. The shape of these peaks is highly similar, with a more gradual initial slope, followed by a tail that drops sharply after the final root.

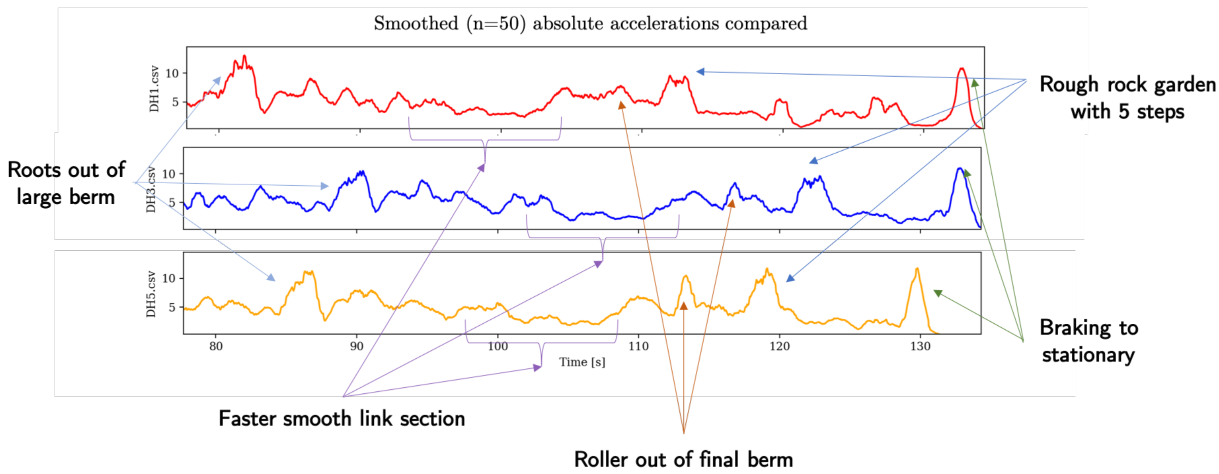

Figure 8: Aligned comparison of the end of three repeats of the same downhill trail section, labelled with common features that are distinguishable from the acceleration profile.

Following this, another characteristic shape can be found, corresponding to a small *roller* out of the final *berm*, followed by a *rock garden* with five steps that correspond to five small individual peaks on a major peak in the acceleration profile. From this, it can be determined with a high degree of confidence that the test methodology and equipment are self consistent, and that applying this same process to a loop whilst varying suspension settings will give data that only varies according to the effect of this adjustment (rather than significant error from the method or equipment).

3.2 Magnitude Analysis

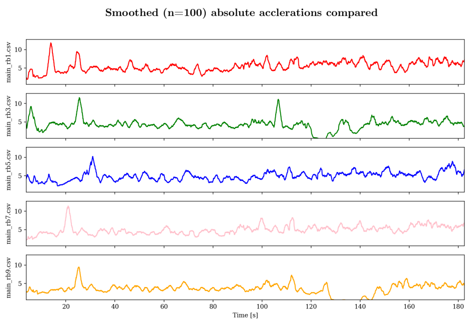

Figure 9: Plots showing the smoothed (flat window of 100 samples, c. two seconds) acceleration against time for the five separate runs of the main test loop (outlined in Section 2.1), for increasing rebound rate (from top to bottom).

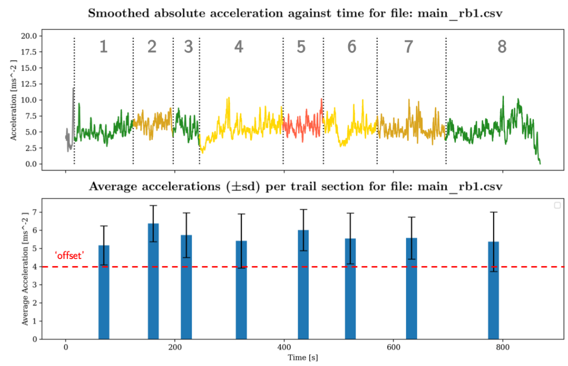

Figure 10: Plot showing the smoothed acceleration profile split into the eight trail sections outlined in Section 2.1, with bar plots of the average acceleration and an error bar of one standard deviation ($\pm\sigma$) for each section shown below.

One method of quantifying the effect that suspension has on the accelerations felt by the rider is magnitude analysis. Different forms of magnitude analysis were employed to help build an understanding on the *rebound* setting's effect for different terrain types. This information can then be employed in the development of a model between suspension settings and trail types.

Figure 9 shows a comparison of all five *rebound* settings for the first section of trail. This data has been smoothed, as the initial acceleration data at 56Hz has a large amount of measurement noise, which makes it difficult to acertain the true shape of the profile. Therefore, a moving average smoothing method with a variable window size was used to aid data analysis and subsequent calculation. This is implemented by convolving the original data with a rectangular window of length n, which is mathematical equivalent to a moving average scheme.

Figure 10 uses the segmented data (via the GPS timing data discussed in Section 2.3), and calculates the average acceleration for each trail section, plotting this as a bar chart, with the standard deviation ($\pm\sigma$) plotted as the error bar. There is an acceleration offset of around $4ms^{-2}$ due to the poor calibration of the sensor, as well as taking the absolute acceleration. Neglecting this shows that there is some positive correlation between the *perceived roughness* and the magnitude of the acceleration felt by the rider.

However, the statistical metrics of mean and variance are not necessarily the most applicable when it comes to describing sections of a signal such as the acceleration. Analysis of the peak and average powers of the signal, as well as the peak-to-average ratio, would be useful in this case to quanitify the energy dissipated in the suspension system, but accurate comparison of these metrics would require calibration that is beyond the capabilities of the hardware used. But rough calculation shows that there is more power transmitted to the rider in the perceivedly rougher sections (comparing segments 1 and 5 for example), and this will be further explored in the frequency domain in Section 3.3.

3.3 Spectral Analysis

Analysis in the time domain provides good information on the accelerations felt by the rider, but analysis in the frequency domain yields information on the performance of the suspension as a function of the input frequency. If the input spectrum of the trail is known, and the output spectrum of the rider measured (or at another point in the human-bicycle system), then the suspension's frequency response can determined by treating it as a linear system. The hardware constraints of the project prevented additional instrumentation of the bicycle wheel to find the input spectrum, but analysis of the output spectrum proves useful for determining the effect of *rebound* on the composition of the acceleration felt at the rider level, and whether this adjustment might be beneficial.

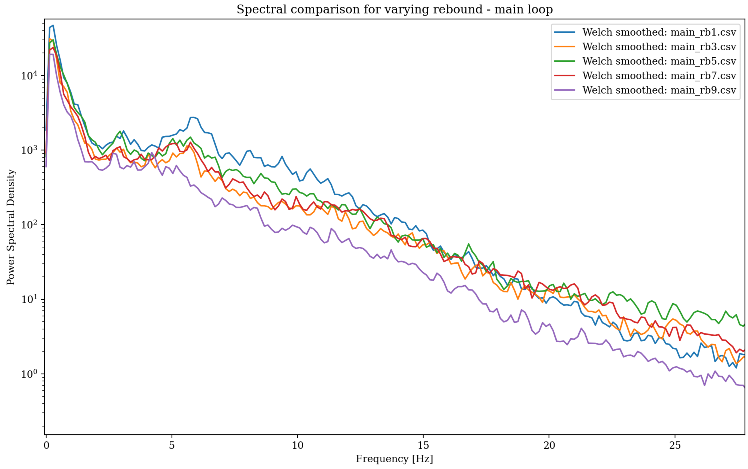

Figure 11: Plot showing the uncalibrated power spectral density (PSD) for each of the main loop tests, on a logarithmic y-axis and linear x-axis, which is limited to 0-26Hz due to the *Nyquist-Shannon sampling theorem*.

Figure 11 shows the power spectral density (PSD, smoothed using *Welch's Method*) of the vibrations felt by the rider for varying *rebound*, showing a large peak for lower frequencies, which might be associated with pedalling or general whole body movement, and a secondary smaller peak around 6Hz that is evident in every plot. This higher frequency peak is more likely to be associated with trail-induced motion, as it is far in excess of a typical pedalling cadence of 90rpm (which would equate to a frequency of 1.5Hz), and so is more indicative of the performance of the suspension system.

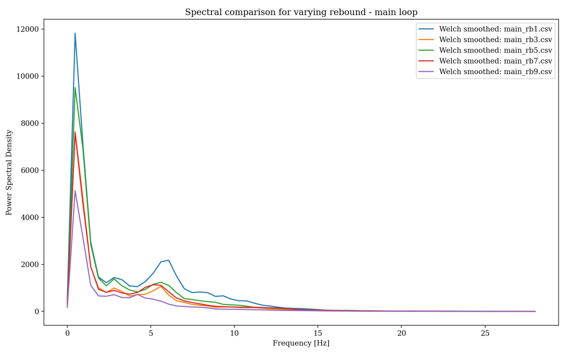

Figure 12: Plot showing the uncalibrated PSD for the same tests, now with a linear y-axis.

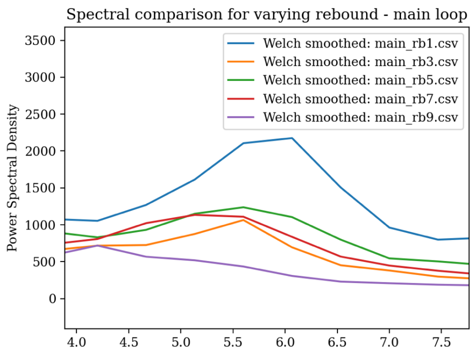

Figure 13: Plot showing a magnified section of the linear PSD around the secondary 6Hz peak.

The plot in Figure 12 is identical to that of Figure 11, but instead uses a linear power scale, presented here firstly to show the characteristic 6Hz peak more clearly, but also for comparison with results discussed by Faiss et al. [3]. The study instrumented a *hardtail* and a *full suspension* bicycle at the wheel and saddle, and plotted PSDs for both. Figure 12 accurately matches their findings (see Appendix A.2), with a lower frequency 'rider' peak, and higher frequency peak due to the trail input.

Figure 13 shows an enlarged section of the same plot, centred on the characteristic 6Hz peak. From this, it can be seen that increasing the *rebound* or damping rate reduces the power in this peak, with the slowest *rebound* trace at the top, and subsequent traces decreasing in power for increasing damping. Therefore, the widely known fact that an increase in the damping ratio increases the energy dissipated in the suspension system can be shown convincingly in the experimental data.

Whilst the input power spectrum was not measured experimentally, an approximate function can be assumed to be one with decreasing power for increasing frequency, but the rate of this decrease is dependent on the surface in question. In the case of an offroad track with variable surface, this might be assumed to be a linear decrease in power, as the power is a result in the scale of the bumps on the surface, and the speed at which the vehicle travels. An offroad track has larger scale bumps than a tarmac surface, and so would likely have greater power at the low frequency level than a road. Applying this approximate input spectrum would yield a frequency response for the bicycle that exhibits the same aforementioned peaks, albeit at a slightly reduced amplitude.

3.4 Trail Feature Classification

A particularly valuable analysis technique is the classification of different trail features using a range of mathematical rules; this is because if a trail feature can be identified using acceleration data, then the suspension set-up can be altered accordingly to the optimal value. Although adjusting this in real time would be a significant electromechanical challenge, XC races usually take place over many laps of the same circuit, so being able to anticipate the trail features from lap to lap would be extremely valuable. For example, if a course includes a climb every lap that transitioned into a downhill section, a control system could 'learn' the lap via its acceleration profile, locking the suspension out for the climb, before automatically unlocking it before the technical downhill section.

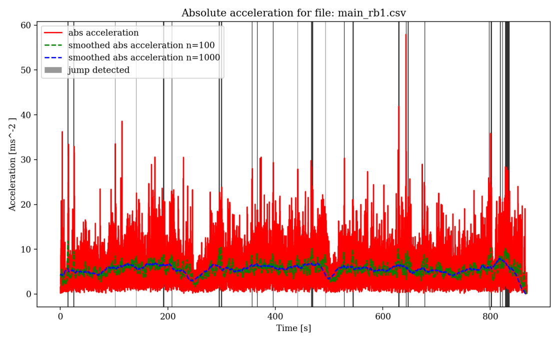

Figure 14: Plot showing the acceleration against time for one of the test loops, with smoothing of order 100 and 1000, and a trial implementation of the threshold 'jump detection' (vertical shading).

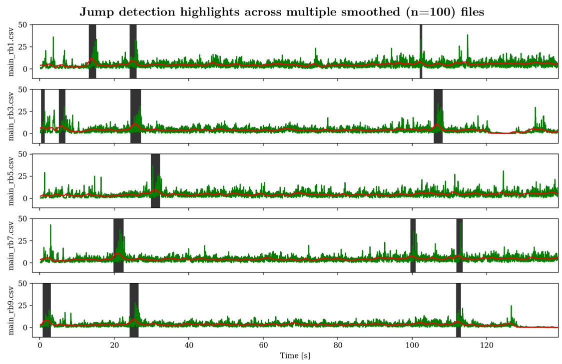

Figure 15: Plot showing the jump detection algorithm applied across all five test files, to illustrate the behaviour of common acceleration features and their repeatability.

Figure 14 shows a plot with a trial of a simple 'jump detection' algorithm that first smoothes the acceleration data, and then applies a threshold which triggers an output signal when the acceleration exceeds this value. The length of the smoothing window (n) is an important parameter here, and would need to be chosen with knowledge of the sampling rate of the sensor used and the speed of the electromechanical system in altering parameters.

Figure 15 (shown enlarged in the Appendix A.2) shows this same algorithm applied to a section of all five runs, showing similarity in its classification of jumps, although this is not perfect. This approach is simplistic, and may benefit from a more complex recognition system, for example a *Bayesian inference* method. Data from additional sensors could also prove useful, as measures like yaw rate or fixed lateral acceleration would be able to differentiate jumps from berms (which would otherwise appear identical). These different trail features would require different set-ups as a jump would benefit from a *slower rebound* upon landing, whereas a *berm* requires a *fast rebound* on exit to enable maximum acceleration out of the corner.

Such a system may have been implemented recently in SR Suntour's TACT system [10]. At the time of this project, techncial details of the product have not been made available except that the system uses an array of sensors to measure a trail section and feed information to electronic actuators that adjust the suspension settings automatically at approximately 0.3Hz whilst riding.

4 Conclusions

Over this project into *data-driven quantification and modelling of optimal suspension configurations for cross country (XC) mountain bike racing*, a number of conclusions regarding suspension design, experimental testing using accelerometers, and optimisation of suspension parameters have been made, alongside methodologies for developing a model for automatic suspension systems. Therefore, it can be concluded that:

- Acceleration measurements can be used to quantify the roughness of a trail section with a reasonable degree of accuracy, as well as draw comparisons between quantative data and qualitative judgements of perceived 'tech' and 'flow'. This is achievable experimentally with consumer products equipped with accelerometers as opposed to industry or research grade equipment.
- Varying the *rebound* for a suspension system results in a change of the damping ratio, and that this can be verified by analysing experimental data in the frequency domain. Such analysis can be used to model the bicycle suspension as a system, and influence design of suspension parameters for varying courses and terrains.
- Acceleration data can be used to anticipate trail features and suggest the optimal suspension set-up for a given section. Such a model could be implemented in a control unit alongside electromechanical actuators to adjust the suspension during the trail without any input from the rider, which would lead to theoretically better performance and faster lap times.
- Suspension is essential to the performance of mountain bikes, especially in XC racing, and that perceived feel from the rider is still a major factor when it comes to good design.

4.1 Further Work

Over the course of the project, a number of additional subjects arose that would have been explored in the absence of time constraints. Chief amongst these was the modelling of suspension linkage geometry. The linkage is the mechanical mechanism by which the isolation of the rear wheel is converted to the linear actuation of the telescopic shock, and a number of designs with varying complexity and performance are commonplace. Different linkage designs provide different travel ratios at the shock as the instantaneous centre of rotation evolves during the stroke, resulting in different suspension behaviour. XC bikes have largely adopted a *virtual pivot point* design, which has reduced weight, but there are a number of unanswered questions as to whether this is better for the expected input. Therefore, further work would seek to model this and quantify the benefits.

Additonally, a final model for suggested suspension set-up for a given trail type that incorporates the findings of the project was proposed but not completed. For this, additional data would be required across a wider range of bicycles and trails. But from the data collected, it would appear possible to construct and build upon such a model that would provide a guide to XC racers with limited information on a given course.

5 References

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A Appendix

A.1 Cycling Terminology

All *italicised* terms are described below in alphabetical order:

- *Berm* - A banked turn, typically made by building up earth, designed to allow a rider to carry more speed through a turn.
- *Cycling economy* - The measure of the efficiency of a rider-bicycle system in converting food energy through the body and machine to mechanical energy for motion.
- *Downhill* - A form of mountain bike racing concerned with getting to the bottom of a hill as quickly as possible, tackling large jumps and drops. Downhill bicycles typically exhibit 200mm or more of front and rear suspension.
- *Fork* - A suspension fork for a bicycle, typically a pair of moving telescopic stanchions within a fixed lower tube, damped hydraulically.
- *Freeride* - A style of mountain biking concerned with jumps and tricks, typically at a purpose built bike park on *full suspension* bicycles with 180mm or more of suspension travel.
- *Full suspension* - A bicycle with a front suspension fork and rear suspension shock that isolates the main triangle (and rider) entriely from the ground. Often heavier and more complex than other bicycle suspension configurations.
- *Hardtail* - A bicycle with a front suspension fork and rigid rear end, whereby the rear wheel is not isolated from the rider via a suspension system. Often lighter and less expensive than *full suspension* bicycles.
- *Lockout* - A suspension parameter that hydraulically adjusts the stiffness of a component. A fully locked out fork or shock should theoretically behave like a rigid component.
- *Perceived roughness* - How rough a rider perceives a trail section to be based on their experience riding it, often correlates to the 'tech' of a trail.
- *Rebound* - The suspension parameter that changes the damping ratio of a component, with a slow rebound being overdamped and a faster rebound being underdamped.
- *Rock garden* - A section of trail with a rocky surface, often incorporating drops, that serves as a technical challenge to riders.
- *Roller* - An intentional hump on the trail, either to slow the rider down, or for the rider to 'pump' (force their body weight into the downslope of) in order to gain speed.
- *Shock* - The hydraulic damper that forms the rear suspension of a *full suspension* bicycle. They typically feature a number of adjustable parameters and are available in different sizes and suspension travels.
- *Singletrack* - Narrow portions of offroad trail, typically cut through woodland, that are only a single track wide. Such sections are a traditional mountain bike trail style and loved by many riders.
- *Strava* - An application for analysing ride statistics (like speed, power etc.) and sharing rides with other cyclists. Extremely popular with both road and offroad cyclists, especially for competing on segments via GPS or recording mileages.
- *XC* - Cross country mountain biking, a discipline characterised by both uphill and downhill sections with a focus on both rider fitness and skill.

Video footage to illustrate a 'techy' then 'flowy' trail section:
https://drive.google.com/file/d/1kliQ2owA6j9yl8tCfybS7KSpurCTM5ux/view?usp=sharing

A.2 Additional Graphs

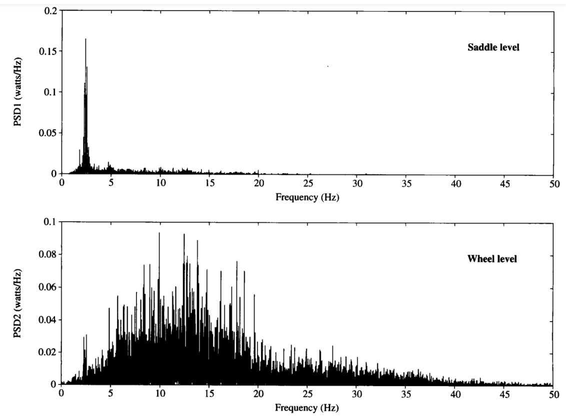

Figure 16: Plot of the PSD at the saddle (rider) level and wheel (trail) level for a *full suspension* bicycle on an offroad test loop as measured by Faiss et al. [3].

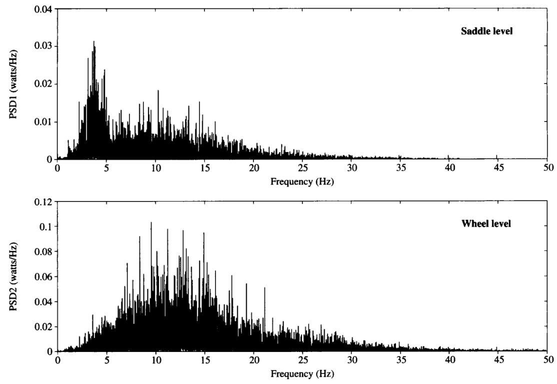

Figure 17: Equivalent plot compared to Figure 16 for a *hardtail* bicycle on the same loop, showing an overall greater power transferred into the rider, and at a broader band of frequencies compared to the *full suspension*.

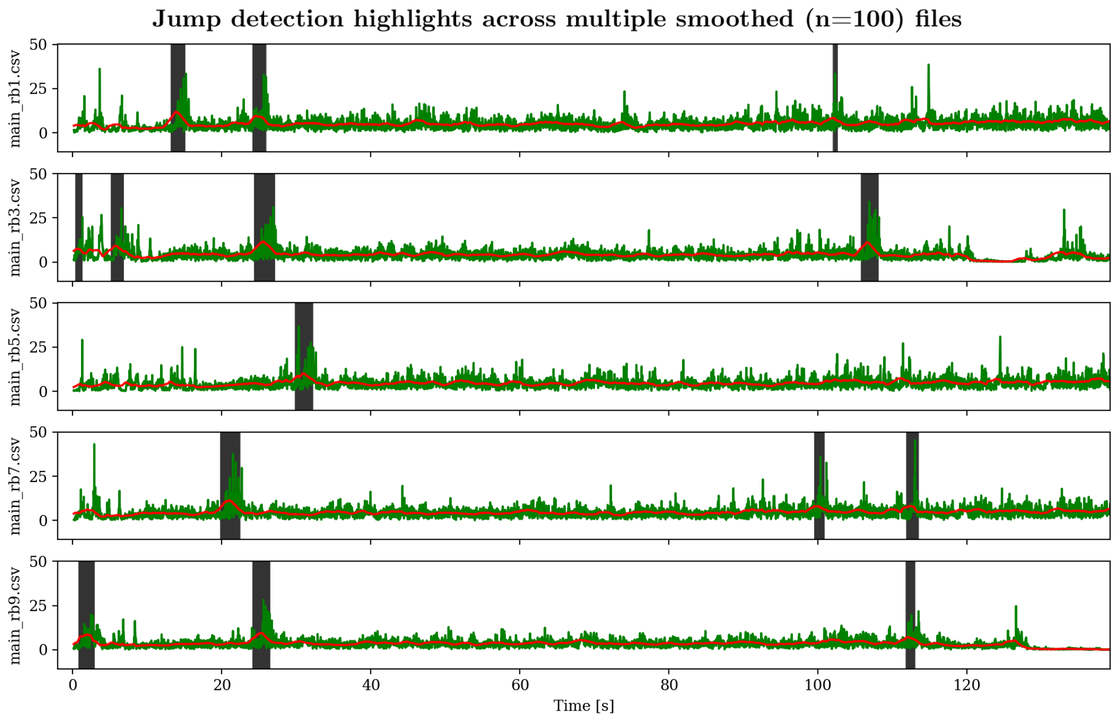

Figure 18: Enlarged version of Figure 15 presented for easier comparison.

A.3 Group Discussion 1 Notes

10:00-10:45am, Friday 19th May 2023, JDB 2nd Floor Meeting Room, CUED

Present:

Charlotte Brass (CB), Anna Griffiths (AG), Payal Shah (PS), Chris Newton, (CN), Matt Bryan (MB)

Project overviews:

CB begun the meeting by asking attendees to briefly outline their problems, and for others to ask questions:

- AG - Saddle heights vs. seat height and ancillaries affecting comfort. Ergonomic analysis of bikes, adapting cars and chairs to the same extent. Finding a criteria for this. Effect on speed versus comfort?
- MB - Shock design. Data-driven analysis of optimal suspension settings for XC racing. Modelling of the suspension and the effect of the geometry. Experimental data taken using accelerometer and used to 'detect' trail type and give best settings accordingly. Hopefully result in model that give a good idea of the best set-up for a given course.
- PS - Vibrating handlebar grips for navigation. Deliveroo riders are encouraged to go faster, audio and visual cues may not be as strong. Off-axis mass on a motor controlled by PCB. Directions give distractions?
- CN - How can the built environment encourage bike use over car use and reduce carbon emissions? Studies into road networks are numerous, but fewer look into anything else. Perception based data and surveys available.

Discussion:

CN - On the topic of the built environment, encouraging cyclists vs. discouraging drivers. All contributed to general discussion about driving vs. cycling in Cambridge, and groups to be surveyed. MB suggested CN get in touch with a CUCC member who completed her dissertation on cycling infrastructure a few weeks ago.

Possible problems:

CB asked attendees to indentify any possible issues with each of the projects:

- AG - Applications of manufacturing, might be better to do ergonomic data taking. Masses on bikes might influence handling to the worse. Surveying for data reasons; why did you choose this bike?
- PS - Source a tandem for navigation? Eye-tracking for distraction measurement probably not feasible? Vibration-based turn by turn navigation. Stationary rig for reaction time to steering vs. audio prompts and visual prompts. How does touch compare?
- CN - Not much chance to collect data personally, so heavily reliant on data already taken - need to be careful with sources and apply corrections. Looking at other cycle schemes in the UK. Survey of project group will give 23 or so. Public transport is very variable per city. Opinion of keen cyclists and non-cyclists.
- MB - Pictures of course to describe, numbering system. AG suggested to make it visual as not everyone is aware of the intricacies of MTB course design. MB planning to video and characterise different trail sections qualitatively.

A.4 Group Discussion 2 Notes

10:00-10:40am, Friday 26th May 2023, JDB 2nd Floor Meeting Room, CUED

Present:

Charlotte Brass (CB), Anna Griffiths (AG), Payal Shah (PS), Chris Newton, (CN), Matt Bryan (MB)

PS' Interview Questions:

PS begun the meeting by surveying attendees for her project:

Do you use directions whilst cycling and what do you use to get them? Do you make any mistakes? Do you use your phone otherwise (text/call)? Do notifications get in the way? Have you had any accidents/close calls as a result of phone use? Do you use your phone in a holder whilst driving?

Answers:

- AG: Earbuds with audio cues (phone in pocket), or phone resting on handlebars. More likely to take a wrong turn, doesn't use directions often. Crashed once on Magdalene Street.
- MB: Uses Garmin navigation, doesn't use phone otherwise really. No accidents as doesn't ever feel impaired by it, but is a very experienced cyclist.
- CN: Doesn't really use directions whilst cycling. Will look at route beforehand if going somewhere new - not really confident to use navigation whilst cycling, so will stop if necessary. Concerned about navigation impairing senses of where cars are.

Additionally on the topic of using e-bikes/scooters - MB only when needed for one way journeys, avoiding leaving bike locked up for longer periods of time. CN concerned that vibrational handlebar prompts might be too short notice, PS suggests it might be supplementary to knowing the route.

Project Updates

CB asked attendees to provide short updates on their project, and invited other to assist with any issues:

- AG: Planning to see how comfortable bikes are for her versus their owner, gather data on whether the bike is generally considered uncomfortable, or just hers (qualitative research methods). MB suggests duration until discomfort, CB suggests sorting by contact points eg. saddle, handlebars, pedals. Discussion of racing bike set-ups versus standard bike setups. MB discussed sensitivity to saddle height in experienced cyclists.
- CN: Has completed a relatively big literature review, no questions to ask at the moment, except for people to fill in the incoming survey for his project.
- MB: Has carried out some experimental testing, preliminary results look good. Small incident resulting in broken handlebars necessitates another trip. Spectral analysis completed, hoping to compare between different suspension types.