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Bicycle Drivetrain Noise and Vibration Test Development

Submitted in Partial Fulfilment of the Requirements for the Degree of Master in Mechanical Engineering in the speciality of Production and Project

Desenvolvimento de um teste de vibração e ruído numa transmissão de bicicleta

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“Life is like riding a bicycle. To keep your balance you must keep moving.”

Albert Einstein, on a letter to his son Eduard, 1930.

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Abstract

The bicycle market gets ever more competitive, as bicycle utilization is growing, from commuting to competition, and every detail is important. The noise originated by the bicycle's drivetrain won't reach levels that can cause physiological effects, but can cause psychological effects on the rider, such as annoyance or focus loss, thus being a determinant factor for the client. Being able to test bicycle drivetrain noise would allow to compare different drivetrains and attest product improvements. The objective of this investigation is to develop a test that quantifies the noise for any bicycle drivetrain.

Two hypotheses were investigated, vibration measurement and audio recording. Both hypotheses recorded the variation of an amplitude signal over time, that was then analyzed in frequency domain using FFT filters and quantified by RMS. A bicycle was equipped with a power meter and a cycling computer to display values of cadence and power, and fitted to a stationary trainer. Movement and load were generated by riding and braking the rear wheel. The accelerometer fixation and the vibration and audio data filtering were decided based on results of initial tests. A rattling noise characteristic of a bicycle's drivetrain is audible on audio tests filtered between 3000 Hz and 14000 Hz. Noise levels increased at the chain engagement frequency, it's double and at frequencies above.

The results demonstrated that power, polygonal effect and cross chaining cause a small but noticeable increase in noise level, whereas cadence, chainring teeth number and component design significantly raise the levels of noise. Vibration and audio tests results had a good correlation and both achieved results consistent with what was expected when applied to different drivetrains.

Vibration measurement might enable obtaining drivetrain noise results on real world riding, using portable vibration measurement and recording equipment.

Keywords Bicycle, Drivetrain, Noise, Vibration, Test Development, Frequency.

Resumo

O Mercado das bicicletas torna-se cada vez mais competitivo, à medida que a utilização da bicicleta cresce, desde a utilização quotidiana à competição, e cada detalhe importa. O ruído originado pela transmissão de bicicleta não alcança níveis que causem efeitos fisiológicos, mas podem causar ao ciclista efeitos psicológicos, como incómodo ou perda de concentração, sendo por isso um fator importante para o cliente. Poder testar o ruído de uma transmissão de bicicleta permitiria comparar diferentes transmissões e comprovar melhorias nos produtos. O objetivo desta investigação é desenvolver um teste que quantifique o ruído para qualquer transmissão de bicicleta.

Duas hipóteses foram investigadas, medição da vibração e gravação de áudio. Ambas as hipóteses registaram a variação de um sinal de amplitude com o tempo, que foi depois analisada em domínio de frequência através de filtros FFT e quantificada por RMS. Uma bicicleta foi equipada com medidor de potência e ciclo computador para mostrar valores de cadencia e potência e montada nuns rolos de treino estacionários. O movimento e a carga foram gerados a pedalar e a travar o travão de trás. A fixação do acelerómetro e a filtragem dos dados de ruído e vibração foram baseados em resultados de testes iniciais. Um ruído característico de uma transmissão de bicicleta é audível em testes de áudio filtrados entre 3000 Hz e 14000 Hz. Os níveis de ruído aumentaram na frequência do engrenamento da corrente, no seu dobro e em frequências superiores.

Os resultados demonstraram que potência, efeito poligonal e cruzamento da corrente causam um pequeno mas percetível aumento no nível de ruído, enquanto que cadencia, número de dentes do prato e *design* dos componentes aumentam significativamente os níveis de ruído. Os resultados dos testes de vibração e ruído tiveram uma boa corelação e ambos obtiveram resultados consistentes com o espectável quando aplicados a diferentes transmissões.

A medição da vibração pode permitir a obtenção resultados de ruído da transmissão em condições reais, utilizando equipamento de medição de vibração portátil.

Palavras-chave: Bicicleta, Transmissão, Ruído, Vibração, Desenvolvimento de Testes, Frequência.

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SYMBOLOGY AND ACRONYMS

Symbology

L_p– Sound Pressure Level

p – Sound Pressure

p_0 – Reference sound Pressure

f_c – Central frequency

f_{min} – Lower limit frequency

f_{max} – Upper limit frequency

ω_n – First natural frequency

f – Frequency

K – Stiffness

m – Mass

a – Acceleration

t – Time

C – Cadence

T – Number of teeth

R^2 – Coefficient of determination

Acronyms

DEM – Departamento de Engenharia Mecânica

FCTUC – Faculdade de Ciências e Tecnologia da Universidade de Coimbra

MEMS – Micro Electro-Mechanical Systems

SPL – Sound Pressure Level

FFT – Fast Fourier Transform

RMS – Root Mean Square

UCI – Union Cycliste Internationale

OEM – Original Equipment Manufacturer

RSD – Relative Standard Deviation

SD – Standard Deviation

1. INTRODUCTION

The bicycle has been a popular mean of transport since some inventions like the pneumatic tires, the drive chain or the freewheel have been made in late XIX and early XX centuries, allowing this vehicle to be more comfortable, safe, efficient and practical for people to travel small distances in a short period of time with a very low cost. Nowadays, the use of the bicycle is noticeably growing, not only for commuting, but also for professional, leisure or sport activities and so, there are several dozen different types of bicycles that fit any particular utilization that anyone anywhere in the world can demand.

Commuting by bicycle brings some advantages to the cyclist, like financial saving, healthier lifestyle and predictable travel times, and if adopted in a large scale it brings even more advantages to the society, like reducing congestion on the roads, which brings more space available, reducing atmospheric and noise pollution, which brings a health and quality of life improvement to the population, reducing oil-based fuel dependency and making urban areas safer and more appellative to pedestrian circulation. Those vantages motivate many cities through the world to elaborate plans to ban private car use in the next few years, forcing the population to rely on public transportation, walking or cycling in private owned or shared bicycles for moving around. In developing countries, the bicycle is also an important help to mobility and subsistence.

When pedaling a chain driven bicycle, the cyclist can hear a particular rattling noise originated in the bicycle’s drivetrain. That rattling noise can be a factor of disturb and discomfort to the rider, as well as affect his perception of the drivetrain’s quality and efficiency. A silent drivetrain is then a decision factor for the final client, that can be just as important for him as other factors like performance, weight, price or aesthetics. Being able to compare the performance of different drivetrains regarding the noise they emit while riding is then a matter of high importance, in order to compare the performance of the drivetrains along the product range, as well as with the competitor’s offerings and attest product improvements.

The objectives of this investigation are to develop a data acquisition test procedure for noise and vibration on a bicycle drivetrain, develop a data analysis procedure that translates the drivetrain noise phenomena, develop a quantification method that evaluates different drivetrains and perform the test on different types of drivetrains.

The hypotheses at which the test will be based are vibration recording and audio recording. Filter by frequency and quadratic mean will be used to manipulate data. A bicycle mounted on a stationary trainer will be used in the investigation and the possibility of mobile testing on road will be considered. The method to be used to generate movement, to generate load, the pedaling cadence and power are some of the variables to take in consideration.

2. LITERATURE REVIEW

2.1. Previous Investigations

Previous studies were made at SRAM to evaluate and improve specific situations, but no generic test was developed. These studies had the movement generated by hand and their sound measurements suggest that there is no significant difference between with and without load, that the chain engagement into the cassette is dominant and that in most sound measurement signals a frequency of twice the one of chain engagement is dominant.

There are numerous published articles related to bicycle dynamic comfort using vibration measuring. Lépine et al. (2013b) investigated the effect of cyclist-related and excitation-related test conditions, with excitation loads generated at the wheels using shakers or using a treadmill with a dowel, acceleration and load measurements at the seatpost and at the stem, testing different hand positions and wrist angles, stem static force levels, cyclist's mass and excitation load conditions. Lépine et al. (2013a), on another study, also investigated the characterization of road surface vibration excitation for future laboratory simulations, using an accelerometer on the rear wheel axle of a bicycle riden by a cyclist while being towed by a car on-road. Olieman et al. (2012) investigated comfort in cycling, testing on-road using wireless MEMS (Micro Electro-Mechanical Systems) accelerometers on the axles of the front and rear wheels, the stem and the seatpost, testing varied road surfaces, speeds, tire pressures and wheels. There are also some published articles characterizing bicycle brake noise and vibration, as is example the investigation by Redfield (2014).

However, there aren't in the literature studies investigating the noise or the vibration of bicycle drivetrains, or that consider the input vibration it brings to the bicycle-cyclist system. This investigation aims to characterize the noise of bicycle drivetrains alone, by audio and vibration testing.

2.2. Noise

Noise is a sound that, unlike music or an alarm, is not wanted by the people who are exposed to it, causing discomfort. It is a subjective appreciation, as it will depend on that sound being considered unpleasant, distracting, loud or interfering with hearing by those who perceive it.

2.2.1. Human Hearing

The human hearing converts sound pressure waves into electric signals that travel to the brain through the nervous system. The human perception of the sound pressure, however, doesn't respond equally to every sound frequency. The range of audible frequencies goes from 20 Hz to 20,000 Hz for a healthy adult, while frequencies below that range are considered infrasounds and frequencies above that range are considered ultrasounds.

Even inside the human audible frequency range, the perception of the sound pressure isn't linear over the frequency range. The human hearing is less sensitive to frequencies near the upper and lower limits of that range and more sensitive to frequencies between 400 Hz and 4,000 Hz, coinciding with the range of frequencies at which human speech occurs. Hearing loss, by aging or excessive noise exposure, also affects first the higher frequencies of the audible frequency range.

2.2.2. Effects

The effects of noise on the population's health and quality of life have been a matter of concern since the industrial revolution. Nowadays, traffic noise is the most pointed out source of noise to cause discomfort.

Some factors that are relevant to the effects of noise on health are the noise's sound pressure and frequency, the exposure time or the individual susceptibility to discomfort. Even if the excessive noise isn't enough to affect the hearing system, there are other serious health risks to concern about.

According with Instituto do Ambiente (2004), the effects of noise on human health can be divided in three categories:

- Psychological effects: When behavioral changes occur, for example: annoyance, discomfort, irritability, stress, fatigue, communication disturbance, focus loss, productivity loss, sleep disturbance. These effects depend more on the noise being irregular than its sound pressure.
- Auditory physiological effects: When physical changes in the hearing system occur, for example: transitory hearing loss, permanent hearing loss, deafness.
- Non-auditory physiological effects: When physical changes in the human body occur, for example: muscle tension, arterial hypertension, vibroacoustic disease and other cardiovascular problems and alterations.

2.3. Sound

When vibration spreads through a transmission medium, being that medium a gas, a liquid or a solid, it originates sound. A sound source, usually a vibrating solid such as the diaphragm of a speaker, transmits that vibration to the particles of the surrounding medium, most commonly air, which will then successively propagate that oscillating movement to the next adjacent particles of the transmission medium, thus forming longitudinal waves that travel away from the sound source. Those sound waves are created by a variation in the atmospheric pressure, as demonstrated in Figure 2.1, that can be detected by hearing and by microphones.

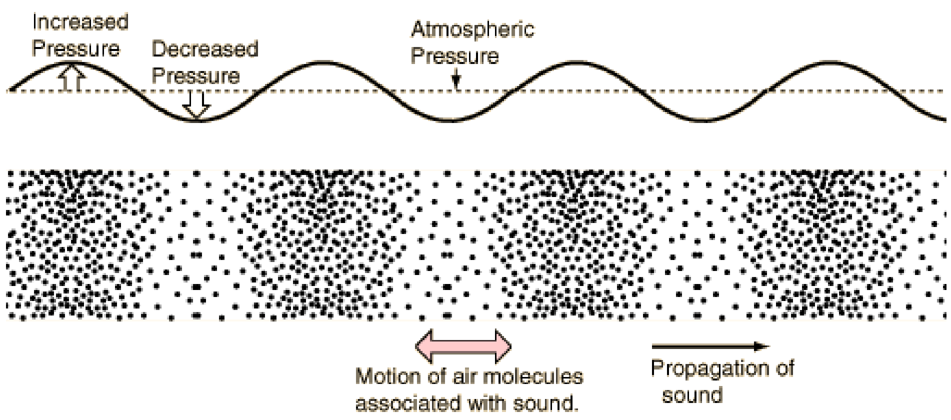

Figure 2.1. Propagation of a sound wave.

2.3.1. Sound Pressure

Sound Pressure is the amplitude of the variation in pressure due to the sound wave relatively to the atmospheric pressure, measured in the SI unit Pascal (Pa).

The human hearing has a hearing threshold of 20 µPa and a pain threshold that, depending on the literature, is considered to be between 20 Pa and 100 Pa. As the relation between these lower and upper limits is on the order of one million, a linear scale of sound pressure isn't practical to use, and so it is commonly used a logarithmic scale of SPL (Sound Pressure Level), denoted L_p and measured in Decibel (dB). SPL can be calculated using the following equation:

$$L_p = 10 \times log_{10}\left(\frac{p}{p_0}\right)^2 = 20 \times log_{10}\frac{p}{p_0}, \tag{2.1}$$

were p is the sound pressure and p_0 is a reference sound pressure, commonly the same as the hearing threshold, 20 µPa.

As explained before, the human hearing sensibility varies along the audible frequency range, so, in order to the sound pressure measurement to describe the human perception of loudness, the SPL should be weighted with a coefficient that depends on the sound frequency. The most commonly used weighting curve is A, ending up with A-weighted Sound Pressure Level, expressed in dB(A).

2.3.2. Frequency

Frequency is the number of occurrences of an event per unit of time. In the case of sound frequency, it's the number of cycles per second, expressed in Hertz (Hz). It is the inverse of the period, which is the duration of each cycle. Figure 2.2 demonstrates the different characteristics of waves with different frequencies.

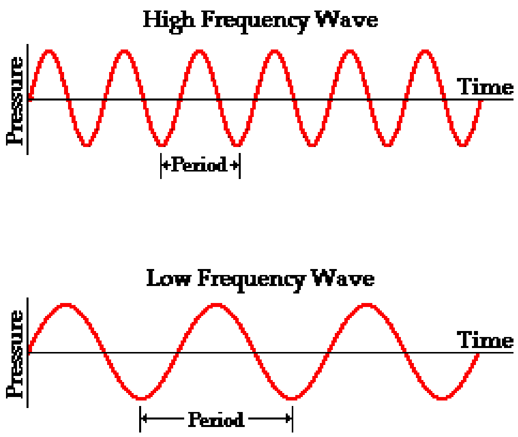

Figure 2.2. Waves with different frequencies.

Sounds with lower frequency generate bass and sounds with higher frequency generate treble. Generally, longer lasting impacts generate lower frequency noises and shorter impacts generate higher frequency noises.

Except for pure sounds, like those that can be obtained with a tuning fork, sounds are composed by the overlapping of multiple frequencies. Obtaining the values of sound pressure in frequency domain from the values in time domain is usually done using a FFT (Fast Fourier Transform) to analyze complex sounds.

2.3.3. Frequency Filters

A sound in frequency domain usually has a continuous spectrum that is complex to analyze, as so it can be decomposed in various frequency bands, filtering the sound in blocks that represent the mean of the sound level between the upper and lower limits of each frequency band. The most used frequency filters are octave bands and third octave bands.

A frequency band is characterized by a central frequency, f_c, a lower limit, f_{min}, and an upper limit, f_{max}. The central frequency is the mean of the lower and upper limits:

$$f_c = \frac{f_{min} + f_{max}}{2} \tag{2.2}$$

Octave bands are characterized for having an upper limit of twice the frequency value of the lower limit:

$$f_{max} = 2 \times f_{min} \tag{2.3}$$

Third octave bands have, as its name indicates, one-third the wideness of octave bands. These narrower bands allow a more detailed analysis of the sound or vibration in the frequency domain. The relation between the upper and lower frequency limits of each third octave band is as follow:

$$f_{max} = \sqrt[3]{2} \times f_{min} \tag{2.4}$$

2.4. Vibration

Vibration is a mechanical phenomenon whereby particles oscillate over their equilibrium point. It can be desirable, for example, when a musical instrument is played, or undesirable, for example, when driving over a rough road. The parameter used to describe the vibration levels is acceleration, in m/s^2.

Sound is just vibration spread through a transmission medium and, as such, the mechanical proprieties of sound, like frequency, also apply to define vibration. Frequency filter can be applied to analyze vibration as well.

2.4.1. Vibration Types

Vibration can be classified as free vibration or forced vibration.

In free vibration, there’s only one initial input, for example, a single impact or a release from a position other than at the equilibrium point, and then the system vibrates at it’s natural frequencies until it’s damping slows it down to a stop at the equilibrium point.

In forced vibration, the external force varies over time. Depending on that varying solicitation, forced vibrations can be classified as:

- Periodic:
  - Harmonic, for example a sinusoidal load.
  - Non-harmonic, for example a set of gears running.
- Non periodic:
  - Transient, for example a train stopping and leaving on the stations.
  - Random, for example when exposed to the wind.

2.4.2. Resonance

When the solicitation of a forced vibration has a frequency near one of the natural frequencies of the system, the amplitude of the vibration will rise abruptly, a phenomenon called resonance, and the solicitation frequency is said to be at a resonant frequency. If there is no damping in the system, the amplitude will theoretically tend to infinity.

Resonance can make it possible to generate large amplitudes with little effort, which may be desired, for example when pushing a child on a swing, but most of the time is undesirable and can even originate mechanical failure, so it’s very important to make sure that the solicitation frequency is different from the main natural frequencies of the system.

The expression to calculate the first natural frequency, in rad/s is the following:

$$\omega_n = 2\pi f = \sqrt{\frac{K}{m}}, \tag{2.5}$$

were K is the material stiffness, in N/m, and m is the mass, in kg. From the previous expression it can be deducted that raising the system stiffness, the natural frequency will be higher, and rising the system weight, the natural frequency will be lower.

2.4.3. Quantifying

According to Brüel & Kjær (1982), there are several ways to describe the vibration amplitude, illustrated in Figure 2.3:

- Peak-to-peak: Indicates the maximum displacement of the wave, a quantity that can be critical to maximum stress and clearance of a mechanical component.
- Peak: A value that can give an indication of the level of the maximum impact occurred.
- Average: Takes into account the history of the wave, but gives no indication about the oscillation as it averages both positive and negative values, so it has limited practical interest.
- RMS (Root Mean Square): The average of the absolute values of the wave, takes into account the history of the wave and gives an amplitude value that is related to its energy, it is therefore the most relevant

parameter for vibration quantification. The expression to calculate the RMS value is the following:

$$RMS = \sqrt{\frac{1}{T}\int_0^T [a(t)]^2\, dt}, \tag{2.6}$$

were $a(t)$ is the acceleration amplitude in function of time and $0 \leq t \leq T$.

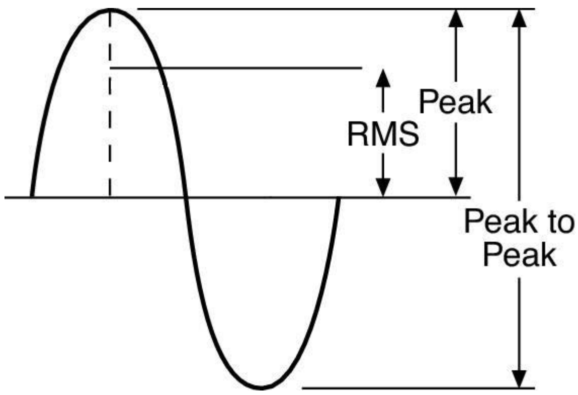

Figure 2.3. Vibration quantifying methods.

2.5. Cycling Performance

The propulsion of a bicycle is achieved by the pedaling motion of the rider, rotating the crankset. The faster and harder the rider pedals, the more power he generates and the faster he will move.

The values of power output and cadence in cycling vary greatly depending on rider fitness, rider preference, and road gradient.

2.5.1. Power

Power output is calculated by multiplying the torque, generated by the tangential force applied to the pedals, by the pedaling cadence. Power meters allow to measure power output on the fly, giving the rider a value that is related to the intensity of his effort. The unit of reference is the Watt (W).

A study realized by Ebert et al. (2006) concluded that, on professional men road racing, the mean power was 262 ± 30 W for short circuit races, 188 ± 30 W for flat stages races and 203 ± 32 W for hilly stages races, with peak powers of 1209 ± 173 W, 1119 ± 187 and 1108 ± 184 W, respectively. The power output necessary to the recreational use of a bicycle by an average person is considerably lower.

2.5.2. Cadence

Cadence is, in cycling, the number of revolutions per minute (rpm) of the crankset. The cyclist feels more comfortable or has a greater efficiency when pedaling within a certain cadence range, thus the advantage of a drivetrain with many gears, so he can maintain a preferred cadence at a wide range of speeds. Experienced cyclists tent to pedal with a higher cadence than untrained people.

A study realized by Lucía et al. (2000) concluded that, on three week long professional men road races, the mean cadence was around 70 rpm for high mountain stages and around 90 rpm for flat stages and time trials.

2.6. Bicycle

A bicycle is a human powered two-wheel vehicle. The general design of bicycles hasn't changed much since the introduction of the chain allowed for the appearance of the safety bicycle as an alternative to the penny-farthing in late IX century, both illustrated in Figure 2.4, but each component of a bicycle has evolved greatly in terms of materials used, design, stiffness, performance, weight and standards utilized, making for modern bicycles much more efficient and comfortable than just a few decades ago.

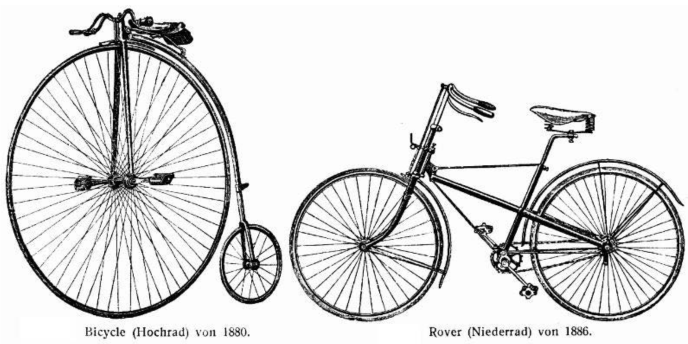

Figure 2.4. Penny-farthing bicycle (left) and a safety bicycle (right).

2.6.1. Types of Bicycles

There are different types of bicycles to achieve the best results in different types of bicycle utilizations or sports.

Some of the utility bicycles types are the following:

- Urban: Simple, durable, not very expensive bicycles for utility traveling within cities. Many times they have an internal gear hub, or single-speed or even fixed gear with no brakes.
- Folding: Bicycles that can be folded to occupy a small amount of space and so can easily be carried in public transports and stored at work place.
- Freight: Designed to transport bigger, larger loads.

Some of the recreational bicycle types are the following:

- Trekking (Figure 2.5): Hybrid bikes between a road and a mountain bike, have a more comfortable upright position, generally have derailleur gears, mudguards and might have a pannier rack and lights.
- Tandem: A bicycle designed to be ridden by two people.
- Fatbike: An off-road bicycle with oversize tires, usually around 10 cm wide, designed to allow riding over soft unstable terrain, such as sand or snow.

Some of the sports, according with the UCI (Union Cycliste Internationale, 2016), and their respective bicycle types, are the following:

- Road (Figure 2.6): Designed to be light, stiff and efficient over asphalt roads and have a low aerodynamic drag without having a geometry that compromises the rider's comfort and maneuverability.
  - Time Trial: Designed to have the lowest aerodynamic drag possible, having an aggressive geometry that allows the rider to employ a more aerodynamic position, used only on time trials and triathlon races.
- Track (Figure 2.7): Like time trial bicycles, these are designed to have the lowest aerodynamic drag possible, but are simpler, having only one fixed gear and no brakes, intended to be used only on velodromes.

- Mountain Bike: Bicycles intended to be ridden off road. Depending on the climbing ability needed and the technical exigence of the descends, there are different types of mountain bikes that can be classified as:
  - Cross Country (Figure 2.8): The lightest and most efficient type of mountain bike, having decent descending capabilities but designed mostly to climb fast.
  - Enduro (**Figure 2.9**): Designed to be fast on the descends and still having decent climbing capabilities.
  - Downhill: Designed only to be fast on the descends, it is the best option for the steeper, rougher trails, but has minimal climbing capabilities.
- Cyclo-cross (**Figure 2.10**): Based on road bicycles, these have wider and treaded tires for increased grip and cantilever or disc brakes for better mud clearance, intended to be ridden on muddy circuits.
- BMX: Simple, agile and robust single-speed bicycles used for BMX Racing or BMX Freestyle.

Figure 2.5. World Bicycle Relief trekking bicycle.

Figure 2.6. Felt road bicycle.

Figure 2.7. Cervélo track bicycle.

Figure 2.8. Focus cross country mountain bicycle.

Figure 2.9. Canyon enduro mountain bicycle.

Figure 2.10. Trek cyclo-cross bicycle.

2.6.2. Parts

A bicycle is composed by several interchangeable components, as demonstrated in Figure 2.11, thanks to a large number of different mount standards.

Figure 2.11. Scheme of the components on a Scott mountain bicycle.

The frame is the main component of a bicycle, the one to which most other components are assembled to. A typical bicycle frame is composed by seven tubes or sets of tubes, identified in Figure 2.12: head tube, top tube, down tube, seat tube, seat stays, chain stays and bottom bracket shell. The rear end of the frame, where the rear wheel is mounted, is called dropout.

Figure 2.12. Scheme of the tubes on a Cannondale mountain bicycle frame.

A full suspension mountain bike frame also has pivots, linkages and a rear shock. The materials mostly used for the construction of a bicycle frame are aluminum alloys, carbon fiber reinforced polymers, steel alloys and titanium alloys.

2.6.3. Drivetrain

A common geared chain driven drivetrain shifts gears by selection at the gear shifters on the handlebars. The rear and front, if there is one, derailleurs are actuated by the shifters cable pull, moving a spring tensioned parallelogram that transforms the cable movement into a lateral movement that shifts the chain across the cassette’s cogs or between chainrings. Electronics ca also be utilized to perform the gear selection and shifting.

The drivetrain’s main goal is to deliver the power generated by the cyclist, at his feet, to the rear wheel. The rider’s force is applied to the pedals, that are connected to the crank arms, which creates a moment in the crankset spindle. The chainring is linked to the cranks and applies a force pulling the chain, that by turn create a tangential force applied on the cassette's cog, delivering a moment to the rear wheel.

In the Figure 2.13 there are identified the main components, apart from the shifters, of a bicycle drivetrain.

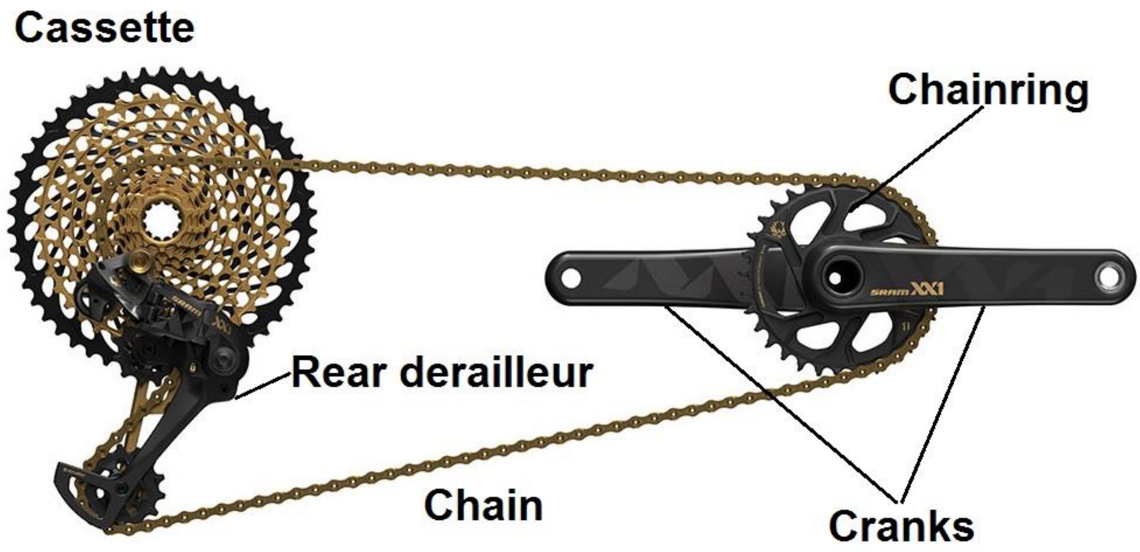

Figure 2.13. Scheme of a SRAM XX1 Eagle mountain bicycle drivetrain.

2.6.1. Chain

Chain driven bicycle drivetrains use a simplex roller chain for power transmission. The constituting parts of a roller chain are the outer plate (1), the inner plate (2), the pin (3), the bushing (4) and the roller (5), as schematized in Figure 2.14.

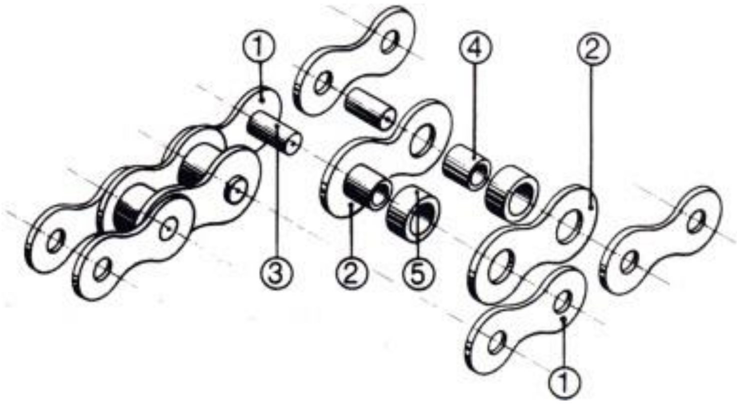

Figure 2.14. Constituting parts of a roller chain.

Most bicycle chains don´t have bushings, instead the outer plates are deformed to form a ring on the inner side around the holes. This design allows the chain to have more lateral flexibility, a necessity for multi-geared drivetrains.

Although a bicycle chain allows some parallel misalignment, cross chaining, as illustrated in Figure 2.15, should be avoided, as it will decrease the drivetrain's efficiency, fatigue life and increase the operating noise.

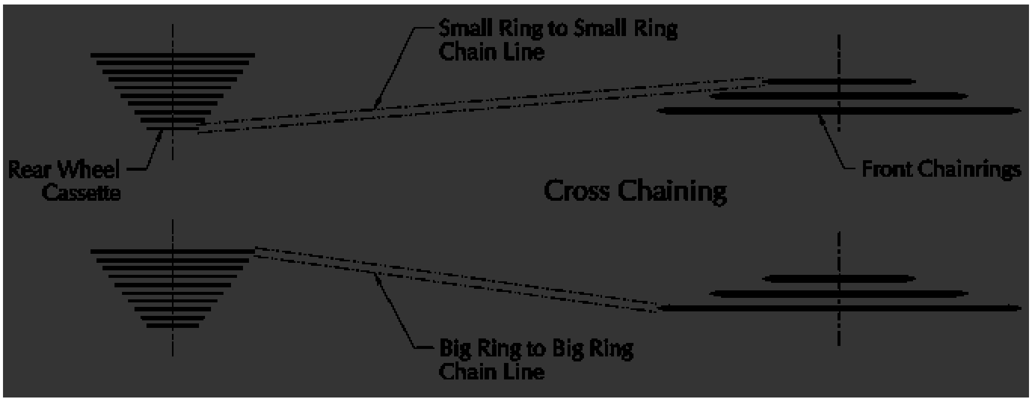

Figure 2.15. Cross chaining.

As a chain is composed by articulated links rather than a flexible body, when it goes around a cog it acts as a polygon, with vertices at the rollers and as many sides as the cog's teeth number, as illustrated in Figure 2.16. This causes a variation in the longitudinal and transverse speeds of the chain with the cog rotation, a phenomenon called polygonal effect.

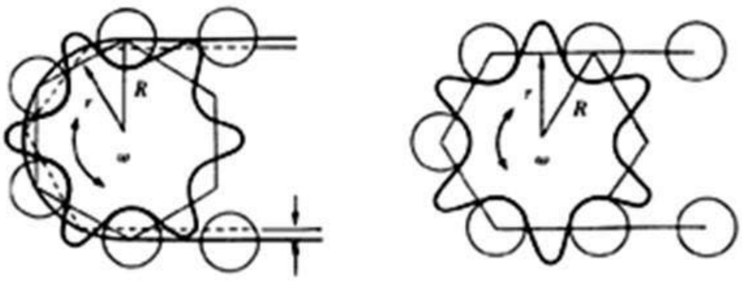

Figure 2.16. Polygonal effect.

The less teeth a cog has, the biggest is the polygonal effect, decreasing speed precision, fatigue life and increasing noise.

3. COMPANY, EQUIPMENTS AND METHODOLOGY

3.1. About SRAM

SRAM LLC is bicycle component manufacturer based in Chicago, Illinois, USA. The company is currently present in 16 locations around the world, distributed in Australia, China, Germany, Ireland, Netherlands, Portugal, Taiwan and USA. (SRAM LLC, 2012).

3.1.1. History

The company, founded in 1987, originally produced one single product, the Grip Shift (Figure 3.1), an innovative gear shifter that permitted to shift gears by twisting without needing to move the hands away from the handlebar. In 1989, SRAM filed a complaint against Shimano in federal court for violating the tying provisions of antitrust law, that ultimately opened the OEM (Original Equipment Manufacturer) market in the cycling industry to SRAM and other manufacturers. This motivated the start of SRAM’s growth and the first oversea factory was stablished in Taiwan in 1992.

Figure 3.1. 1990 SRAM Grip Shift.

SRAM has since been growing and launching innovative technologies and high-end new products, while acquiring other companies that allowed the expansion of their product range (SRAM LLC, 2016). Those acquisitions, schemed in Figure 3.2, included the Sachs Bicycle Company (chains and metallurgy knowledge) in 1997, RockShox (suspension forks) in 2002, Avid (brakes), Truvativ (cranksets, handlebars, stems and seatposts) in 2004, Zipp (road wheels and carbon fiber composite knowledge) in 2007 and Quarq (power meters) in 2012. SRAM is also responsible for the foundation, in 2005, of World Bicycle Relief, an organization that aims to reduce the barrier of distance in developing countries through the distribution of bicycles (World Bicycle Relief, 2016), and SRAM Cycling Fund, in 2008, an advocacy found destined to build a better environment for cycling in North America, Europe and Taiwan (SRAM Cycling Fund, 2009).

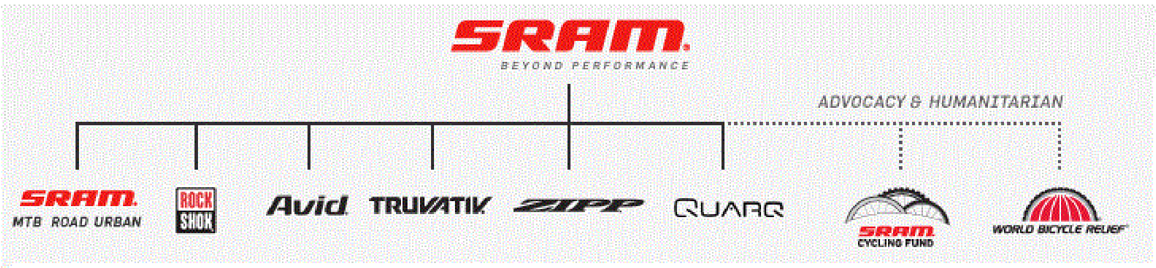

Figure 3.2. SRAM brand line up.

Some of the innovative technologies implemented in SRAM products includes 1:1 exact actuation shifting ratio, DoubleTap road single lever shifters, 1x single chainring drivetrains and eTap wireless electronic shifting.

3.1.2. SRAMPORT

SRAMPORT is a Portuguese metallurgical sector factory founded in 1968, then named TRANSMECA and owned by Peugeot and a Portuguese citizen. It was acquired in totality by the Peugeot group in 1980 and by Fichtel & Sachs in 1987. In 1997, Fichtel & Sachs was renamed Mannesmann Sachs AG and the Sachs bicycle division, in which TRANSMECA was included, was acquired by SRAM. The Portuguese factory, located in Zona Industrial da Pedrulha, Coimbra, was then renamed SRAMPORT.

It is responsible for every the production of every chain in SRAM’s product line, as the one in Figure 3.3, as well as the assembly of Zipp road wheels, as the ones in Figure 3.4, for the European market.

Figure 3.3. SRAM XX1 Eagle gold chain.

Figure 3.4. Zipp 404 NSW road wheels.

3.1.3. Products

SRAM currently has the following road and mountain drivetrain groupsets, sorted from higher end to lower price (SRAM LLC, 2016):

- Road:
    - SRAM RED eTap, 2×11 speed
    - SRAM RED, 2×11 speed
    - SRAM Force 1, 1×11 speed
    - SRAM Force, 2×11 speed
    - SRAM Rival 1, 1×11 speed
    - SRAM Rival, 2×11 speed
    - SRAM Apex 1, 1×11 speed
    - SRAM Apex, 2×10 speed
- Mountain:
    - SRAM XX1 Eagle, 1×12 speed
    - SRAM X01 Eagle, 1×12 speed
    - SRAM XX1, 1×11 speed
    - SRAM X01, 1×11 speed
    - SRAM X01 DH, 1×7 speed
    - SRAM EX1, 1×8 speed
    - SRAM X1, 1×11 speed
    - SRAM X01, 1×11 speed
    - SRAM GX 1x11, 1×11 speed
    - SRAM GX 2x11, 2×11 speed
    - SRAM GX DH, 1×7 speed
    - SRAM NX 1x11, 1×11 speed
    - SRAM GX 2x10, 2×10 speed
    - SRAM X5, 2×10 / 3×10 speed

3.2. Bicycle Drivetrain Noise

The noise produced by a bicycle's drivetrain when riding is mostly originated by the engagement and disengagement of the chain on the teeth of the crankset's chainring, the cassette's cog and the rear derailleur's pulley wheels. Those impacts lead to vibration that is spread through the components of the drivetrain and the bicycle's frame, causing the noise a rider can hear while riding. It should be noted that these vibration and noise emitted by a bicycle drivetrain are far below any level that would call into question the rider's health.

This is a case of non-harmonic, periodic, forced vibration, where the bicycle is the vibrating system and the chain engagement impacts are the time varying external force. The frequency of this external force, f [Hz], is proportional to the chain linear speed and so can be calculated, based on the value of cadence, C [rpm] and the chainring teeth number, T, using the following equation:

$$f = \frac{C}{60} \times T \tag{3.1}$$

The calculated chain engagement impact frequencies for the most common chainrings teeth number for mountain and road drivetrains, at the reference cadence values of 60, 80 and 100 rpm, are shown in Table 3.1.

Table 3.1. Chain engagement frequencies for most common chainrings at reference cadence values.

	60 rpm	**80 rpm**	**100 rpm**
22 T	22.0	29.3	36.7
24 T	24.0	32.0	40.0
32 T	32.0	42.7	53.3
34 T	34.0	45.3	56.7
36 T	36.0	48.0	60.0
39 T	39.0	52.0	65.0
50 T	50.0	66.7	83.3
53 T	53.0	70.7	88.3

It should also be noted that the vibration correspondent to the crankset rotation happens at frequencies below 2 Hz, and to the rotation of the rear wheel at frequencies up to 8 Hz, so the chain engagement occurs at distinct frequencies.

3.3. Setup Equipment

To quantify the noise a bicycle's drivetrain produces in real world riding, while doing so in controlled conditions that won´t affect the reproducibility of the results, it was decided that the best approach is to use a bicycle on a stationary trainer.

The bicycle selected for the initial configuration and tests was a Cinelli Proxima aluminum road bicycle equipped with a SRAM Apex 2x10 speed drivetrain, with 36T and 50T chainrings and a 11-32T cassette. As cadence and power values are variables that can affect the results, a Quarq RIKEN R power meter was installed on the bicycle and paired with a Garmin Edge 510 cycling computer to obtain instantaneous values of both cadence and power. The bicycle was then mounted on an Elite MAG Alu stationary trainer. All this equipment can be seen on Figure 3.5.

Figure 3.5. Setup equipment.

3.4. Measuring Equipment

The two hypothesis tested for measuring a bicycle's drivetrain noise level were vibration recording and audio recording.

To measure vibration, two PCB 608A11 accelerometers were at disposal. As the electrical signal the accelerometers generate while measuring is too weak to be directly acquired, a PCB 482A22 amplifier was used to amplify the signal before it is acquired by a Pico ADC-100 computer oscilloscope. The computer oscilloscope converts the electrical signal from analog to digital, so it's values can be read by a computer. All the mentioned devices are shown, from left to right, in Figure 3.6.

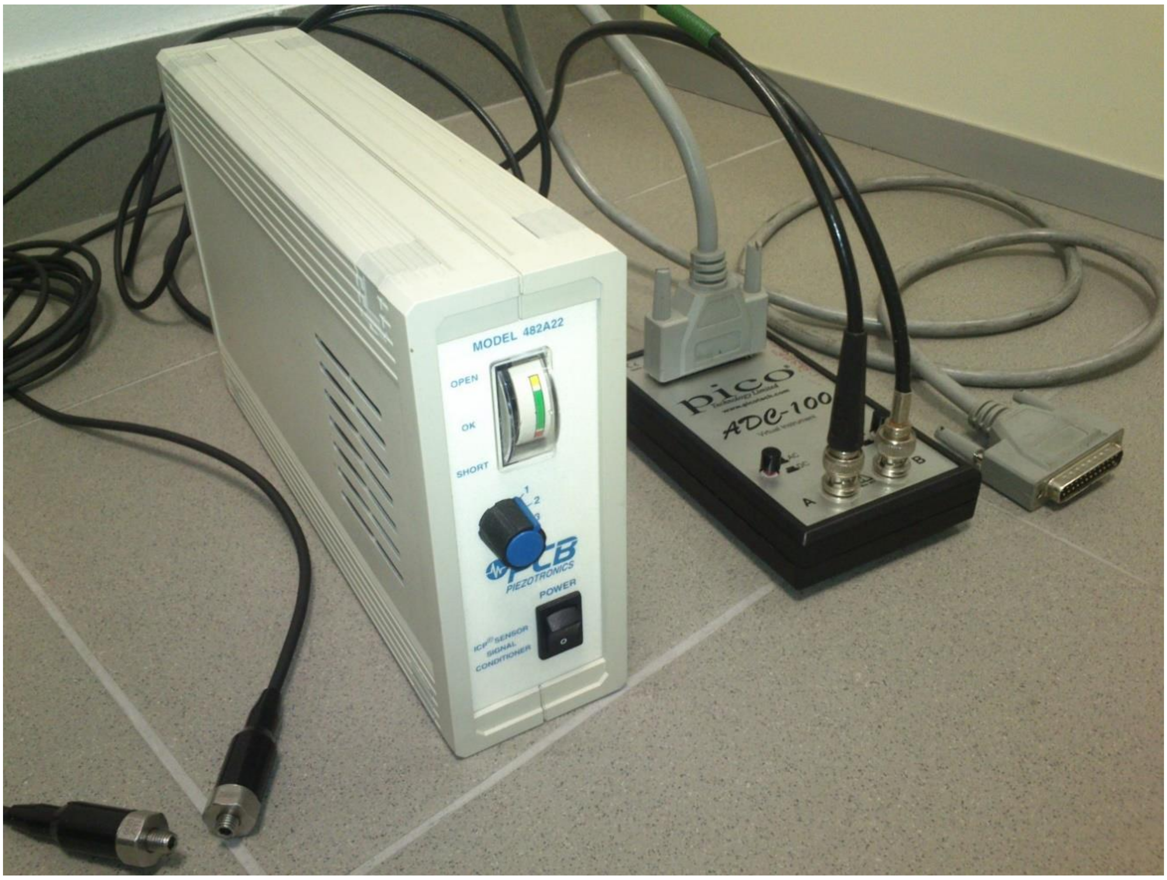

Figure 3.6. Vibration measuring equipment.

To do the audio recording it's simply utilized a desktop microphone, a Plantronics .Audio 300, connected to a computer. The microphone is placed near the drivetrain, behind the trainer's structure, as illustrated in Figure 3.7, making sure it isn't in contact with the trainer.

Figure 3.7. Microphone placement.

This simple microphone is enough for comparing results when utilized in the same conditions and attest the potential of audio measuring for evaluating bicycle drivetrain noise, but the amplitude values obtained lack reference units and will vary according to the hardware and software of the computer. To surpass those limitations, a sound intensity probe should be utilized.

3.5. Accelerometer Fixation

To measure the vibration level on the bicycle, one or both accelerometers were fixed onto it. Five different placements were tested, four of them directly on the frame, using metal clamps, and one using a mounting plate.

The fixations directly on the frame were on the chain stay (Figure 3.8), the down tube (Figure 3.9), the seat stay (Figure 3.10) and the seat tube (Figure 3.11), with the accelerometer positioned longitudinal to the respective tube.

Figure 3.8. Chain stay fixation.

Figure 3.9. Down tube fixation.

Figure 3.10. Seat stay fixation.

Figure 3.11. Seat tube fixation.

The fixation on a mounting plate, as shown in Figure 3.12, consists on a steel plate with two holes, one with a bolt and a nut for the accelerometer to attach to, and another to go on the rear derailleur fixing bolt so the plate can be fixed in between the rear derailleur and the frame dropout. The plate is bent so the accelerometer gets positioned on a radial direction.

Figure 3.12. Rear derailleur fixing plate.

Three tests were repeated for each accelerometer placement, all on the same gear, 50T front 19T rear, and riding with the same cadence and power values, 80 rpm and 280 W, respectively. The goal was to determine which placement can achieve results with the best reproducibility. Table 3.2 presents the RMS acceleration values, in m/s^2, of each test and their RSD (Relative Standard Deviation) for each placement. The rear derailleur mounting plate achieved the higher RMS acceleration values and the lower RSD percentages, so this fixation was determined preferential.

Table 3.2. RSD of 3 RMS test values for each accelerometer placement.

	RMS 1	RMS 2	RMS 3	RSD
Chain stay	0.717	0.664	0.690	3.87 %
Down tube	0.624	0.744	0.715	9.03 %
Seat stay	0.961	0.999	1.03	3.50 %
Seat tube	0.705	0.667	0.652	4.08 %
RD plate	1.58	1.64	1.65	2.25 %

3.6. Movement and Load Generation

Three movement generation methods were initially considered: by hand, riding and using a screwdriver. By hand, the power output was limited, more than 50 W starts to be a hard effort, and it was found to be difficult to maintain a cadence value while testing. Using a screwdriver, the power output was very limited, at around 30 W, and the noise generated by the device noticeably overrides that from the drivetrain. Riding was the movement generation method selected for further testing, as it is far less limited in power output and reassembles real riding.

To generate load on the rear wheel, the trainer's roller could be used, but the load it can generate is limited and controlled in wide spaced steps. The bicycle's rear brake was utilized for load generation, with elastics employed to secure the brake lever.

3.7. Data Collection

The vibration or audio data were recorded while the desired values of cadence and power were being achieved by the operator riding the bicycle on the stationary trainer.

Vibration data was recorded using the software PicoScope, with the sampling interval settled at 100 ms/div, which records 2500 measurements during a 1 second period, giving a sampling rate of 2500 Hz. Other possible sampling intervals had either a too short recording period or a too small sample rate, providing less consistent results. The results were then stored on an Excel spreadsheet.

Audio recordings were done using the software Audacity, setting a project length of 3 seconds, quality Mono 44100 Hz 16-bit PCM and exporting the .wav file.

3.8. Data Processing

Two software were used for data processing, Excel for general calculations, unit conversions, RMS and statistics and Origin for frequency filtering.

The vibration data's time and amplitude units were converted to s and m/s^2, respectively. The sensitivity of the accelerometers is 10.2 mV/(m/s^2).

The band frequency filtering was accomplished using the FFT Filter analysis feature on Origin. The third octave frequency bands were calculated on Excel based on an initial central frequency of 1000 Hz, Table 7.1, in annexes, contains the calculated lower limit, central frequency and upper limit of several bands.

The RMS of a discrete set of n values of amplitude, a, were calculated on Excel using the following equation:

$$RMS = \sqrt{\frac{1}{n}({a_1}^2 + {a_2}^2 + \cdots + {a_n}^2)} \tag{3.2}$$

For the quantification of the vibration data, different frequency ranges were filtered, to establish which one, after their RMS has been calculated, provided the best correlation with the SPL instantaneous value measured simultaneously with a Simpson 897 sound measuring system. Those frequency ranges were:

- Unfiltered
- Entire range containing possible engagement frequencies: A large frequency range in which is probably contained the external force frequency, as it comprehends frequencies from a variety of pedaling cadences and chainring teeth number. Goes from 17.42 Hz to 110.6 Hz, based on the information from Table 3.1 and Table 7.1.
- Two largest bands in the possible engagement frequencies range: The 2 bands with the largest RMS amplitude from the 8 first bands in Table 7.1.
- Two nearest bands to the calculated engagement frequency: The two bands with a central frequency immediately above and immediately

below the engagement frequency based on cadence and tooth number, as calculated on Table 3.1.

Table 3.3 presents the coefficient of determination, R^2, between the RMS values of vibration data for every gear of the drivetrain unfiltered or filtered by the frequency ranges listed above and the SPL measurements.

Table 3.3. Coefficient of determination between different frequency ranges and SPL.

Frequency range	Unfiltered	Entire range	2 largest	Engagement frequency
R^2	0.847	0.537	0.500	0.536

Although there was some correlation between the vibration at the external force's frequency and the noise measured, the RMS of the unfiltered vibration data, which includes frequencies up to 1250 Hz, half of the sample rate according to the Nyquist-Shannon sampling theorem, had by far the best correlation, demonstrated in Figure 3.13, thereby this simpler method was selected for the quantification of vibration data.

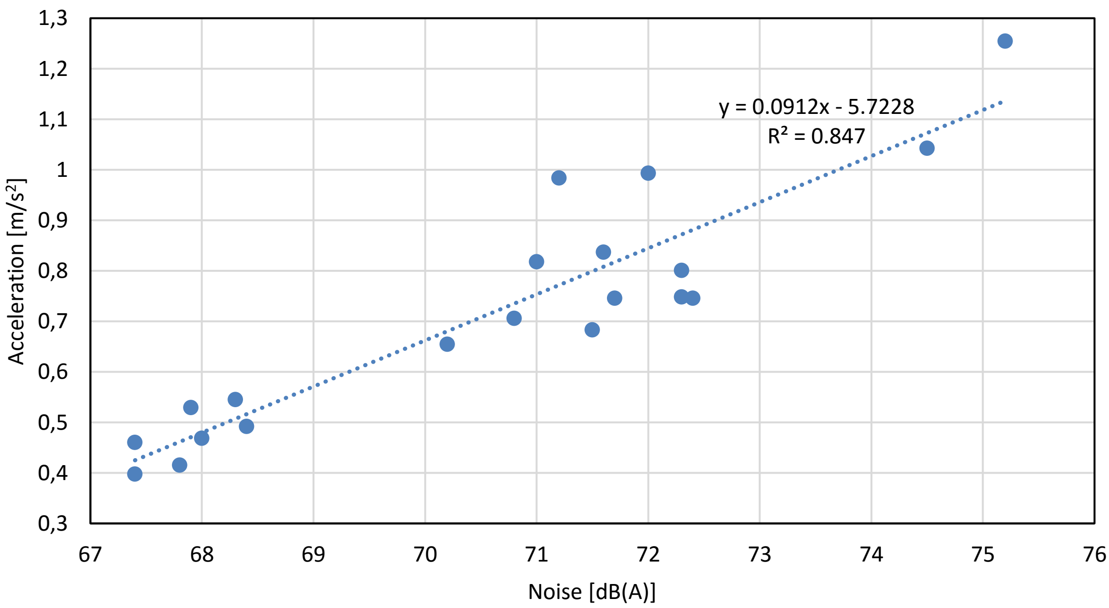

Figure 3.13. Correlation between unfiltered RMS vibration and SPL.

After listening to audio recordings of the tests filtered by varied frequency ranges and then reconverted to audio files, it was audible that the rattling noise characteristic of a bicycle drivetrain occurs at frequencies between around 3000 Hz and 14000 Hz, while sounds below those frequencies were constant lower tones and sounds above those frequencies were constant higher tones. Using the limits on Table 7.1, the audio tests were quantified by calculating the RMS of the audio filtered to a band from 2810 Hz to 14160 Hz.

This filtration will contribute to attenuate the influence of background noise and atmospheric air pressure variations on the RMS results, focusing on the noise originated on the bicycle.

4. TEST PROCEDURES

4.1. Vibration Test Procedure

- Install a Quarq power meter on the bicycle.
- Install the accelerometer support plate where the rear derailleur is mounted to the bicycle frame.
- Tightly fix the bicycle to the trainer.
- Tighten the accelerometer to the fixing plate.
- Turn on the Garmin cycling unit, rotate the Quarq cranks, pair and calibrate the power meter.
- Turn on the amplifier.
- Open PicoScope, select a scope timebase value of 100 ms/div.
- Start riding and adjust the rear brake so the load generated achieves the desired value of power at the intended cadence.
- With PicoScope as the active window, once the desired cadence and power values are achieved and maintained, press space to record the last second.
- Go to Edit, Copy as Text.
- Open the Excel spreadsheet “Drivetrain Vibration”.
- On the “INPUT” sheet, fill the green cells on the first row with each correspondent gear of the drivetrain and paste the data on the cell below.
- Repeat the last five steps for every gear of the drivetrain, filling the “INPUT” sheet from left to right with every gear from first to last.
- On the sheet “Vibration”, fill the data describing the drivetrain in the green cells.
- On the sheet “Quantification”, the vibration level for each gear and the global average are available.

4.2. Audio Test Procedure

- Install a Quarq power meter on the bicycle.
- Tightly fix the bicycle to the trainer.
- Place the microphone near the transmission, as shown in Figure 3.7, make sure it isn't in contact with the trainer.
- Turn on the Garmin cycling unit, rotate the Quarq cranks, pair and calibrate the power meter.
- Open the Audacity project "Audio Recording".
- Start riding and adjust the rear brake so the load generated achieves the desired value of power at the intended cadence.
- With Audacity as the active window, once the desired cadence and power values are achieved and maintained, press space to record. The recording stops automatically after 3 seconds.
- Press Ctrl+shift+E to export the audio. Export to "Audio Files" folder, name the audio file according to the gear tested.
- Press Ctrl+Z to clear the record.
- Repeat the last four steps for every gear of the drivetrain.
- Open the Origin project "Drivetrain Noise Filter" and the Excel spreadsheet "Drivetrain Noise Analysis".
- On Origin, go to File, Import, Sound and import one of the audio files.
- Copy the data from the third column named "Filtered Y1".
- On the sheet "INPUT" of the Excel spreadsheet, fill the green cells on the first row with each gear of the drivetrain and paste the data on the correspondent cell below.
- Repeat the last four steps for every gear of the drivetrain, filling the "INPUT" sheet from left to right with every gear from first to last.
- On the sheet "Noise", fill the data describing the drivetrain in the green cells.
- On the sheet "Quantification", the noise level for each gear and the global average are available.

5. RESULTS ANALYSIS AND DISCUSSION

5.1. Frequency Analysis

A frequency analysis of both vibration and audio recorded data was executed to detect similarities and possible interesting phenomena. The data used for this analysis was from tests realized at 80 rpm of cadence and 100 W of power on gear 2x5.

Figure 5.1 illustrates the frequency spectrum of the vibration data. There was a noticeable increase on vibration levels at bands with 62.5 Hz and 125 Hz central frequencies, corresponding to the chain engagement frequency and double the chain engagement frequency, respectively. Frequency bands with central frequencies above the double of the chain engagement frequency registered severally higher vibration levels than those below. An abrupt increase in vibration level was manifested at the 250 Hz frequency band, possibly related to it being a multiple of the excitation frequency and a resonant frequency of the system, as Figure 5.2, the vibration frequency continuous spectrum of a hammer impact on the frame, suggests that the system has a preference to vibrate at frequencies nearly between the lower and upper limits of that band, 221.2 Hz and 278.8 Hz, respectively.

The fact that, for a 1 second recording duration, the sample rate of the utilized measuring equipment was only enough to analyze frequencies of up to 1250 Hz, represents a considerable limitation to the realized vibration tests.

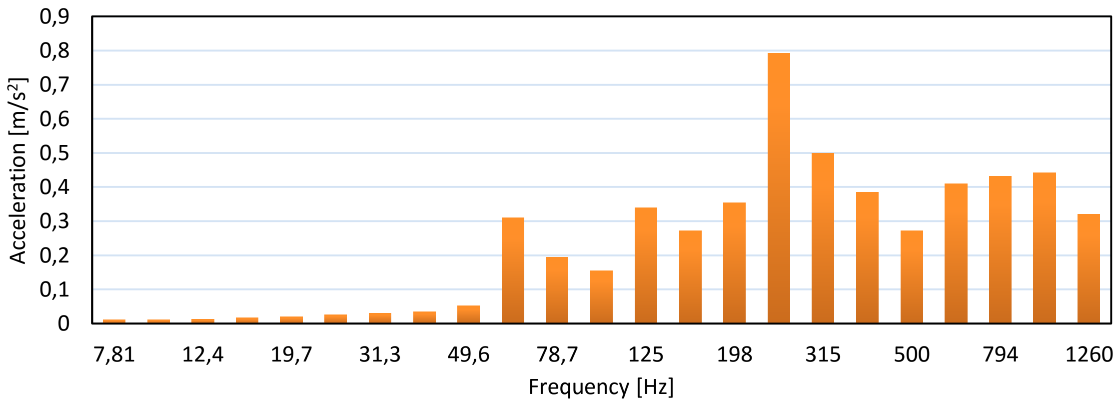

Figure 5.1. Vibration frequency spectrum at 80 rpm, 100 W, gear 2x5.

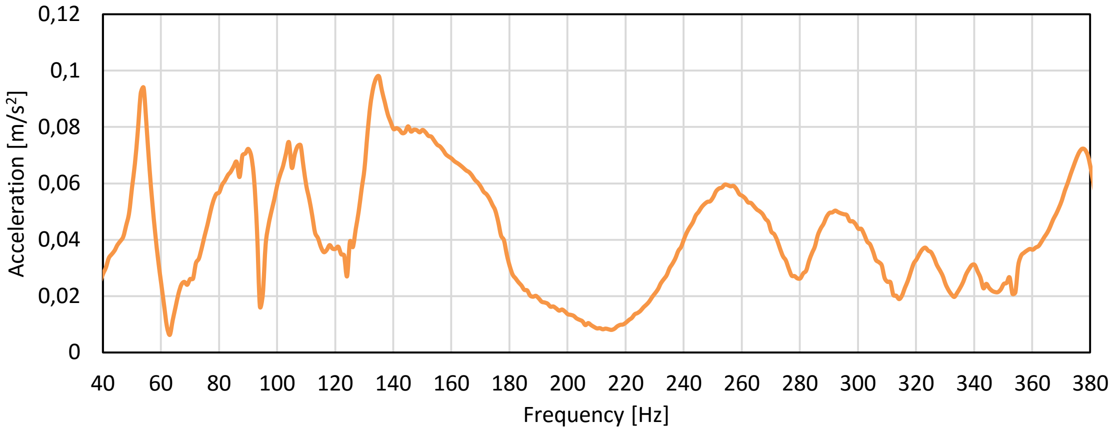

Figure 5.2. Vibration frequency continuous spectrum of an impact on the frame.

The frequency spectrum of the audio data, illustrated in Figure 5.3, also registered an increase in audio levels on the frequency bands corresponding to the chain engagement and double the chain engagement frequencies, at 62.5 Hz and 125 Hz, respectively. The first frequency bands up to a central frequency of 31.3 Hz, and particularly up to 12.4 Hz, showed elevated audio levels, possibly due to a variation in air pressure caused by the movement of the operator's legs. An audio level increase was noticed at frequencies around 2000 Hz, partially explained by the audio frequency spectrum of the background noise, shown in Figure 5.4, which also registers an increase in audio level at similar frequencies. Finally, elevated audio levels were registered at frequencies between 4000 Hz and 16000 Hz, coincident with the frequencies where a rattling noise characteristic of a bicycle drivetrain was audible.

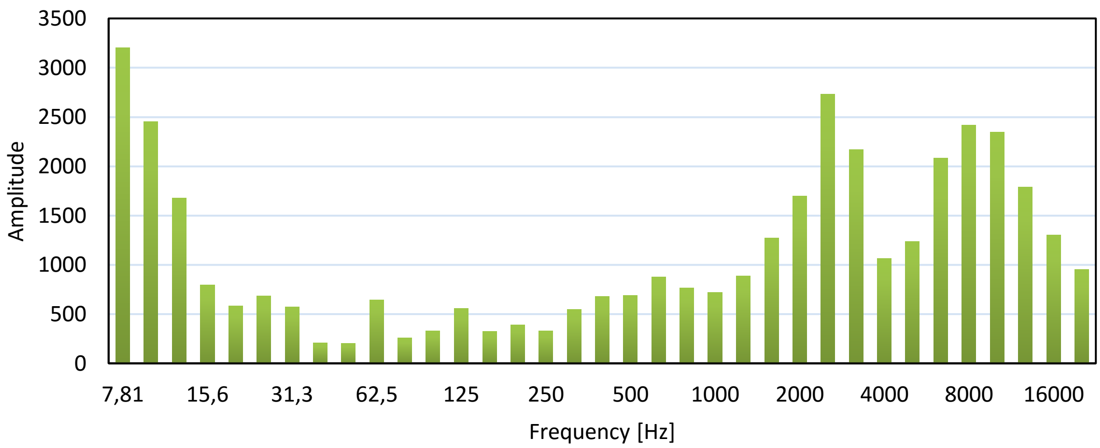

Figure 5.3. Audio frequency spectrum at 80 rpm, 100 W, gear 2x5.

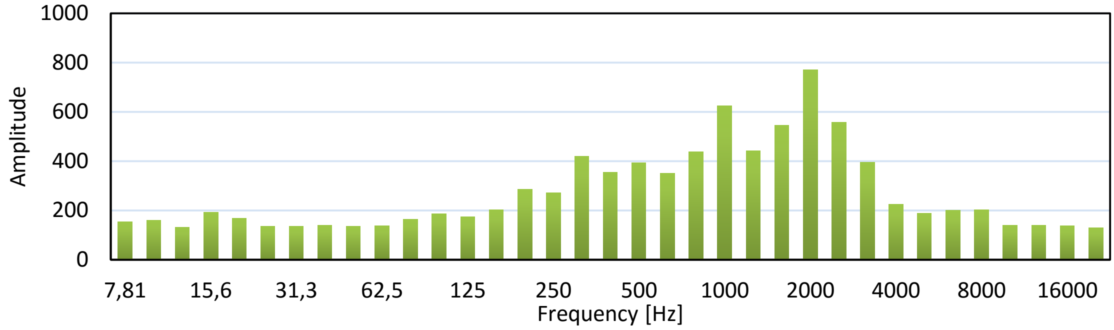

Figure 5.4. Audio frequency spectrum of background noise.

5.2. Cadence and Power

To determine the influence that the values of cadence and power have on the noise generated by a bicycle's drivetrain, multiple tests were realized covering, for every gear of the drivetrain, three values of cadence: 60, 80 and 100 rpm, and two values of power: 100 and 200 W. For each test, three measurements were acquired: vibration, audio and SPL.

Generally, for the same gear, the three mentioned measurement methods obtained consistent results regarding the influence of cadence and power on the vibration level, audio level and SPL, as shown in Figure 5.5, that illustrates all test results realized on gear 2x5. It was possible to conclude that rising the value of cadence causes a significant increase in noise, apparently with a linear response, while doubling the value of power causes a less significant increase.

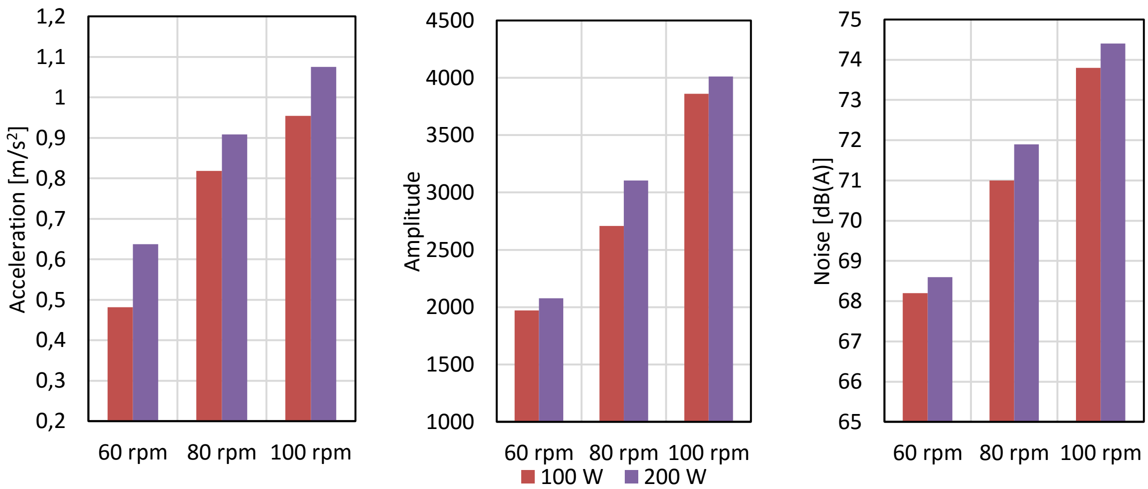

Figure 5.5. Influence of cadence and power on vibration, audio and SPL tests, respectively from left to right.

Figure 5.6 illustrates the SPL results at a power value of 100 W, for every gear at 60 rpm, 80 rpm and 100 rpm, in function of the calculated bicycle speed, in km/h, based on a 700x23C rear wheel with a circumference of 2096 mm, according to Cateye (2015). It is possible to observe that the SPL values had a similar response variation along the gears, despite having been obtained with different values of cadence.

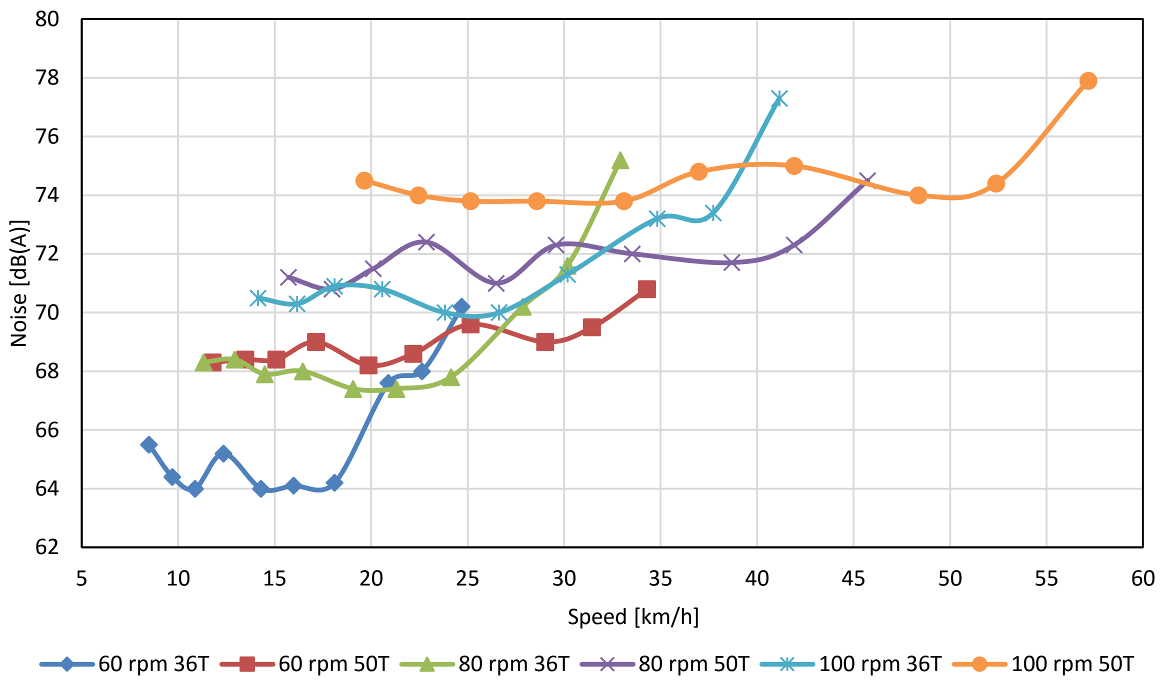

Figure 5.6. SPL variation with speed, depending on gear and cadence, at 100 W.

It was concluded that this two variables, particularly cadence, have influence on the noise emitted by a bicycle drivetrain, so their values must be kept constant while testing. It was also noticed that variations on this two variables values caused proportional noise results, so testing with multiple values of cadence and power isn't imperative.

As a value of 60 rpm is hard to maintain at higher values of power, and of 100 rpm seemed unnatural unless at higher power values, the following tests were realized at a cadence of 80 rpm, a value close to the average in professional cycling, and at a power of 100 W, as, since the variation with power wasn't significant, it requires less effort for the test operator.

5.3. Drivetrains Tested

5.3.1. SRAM Apex

This 2010 SRAM Apex drivetrain is an entry level road group set. It has 2 chainrings, 36T and 50T, and a 10 cogs 11-32T cassette. The rear derailleur is the WiFLi version.

Table 7.2, on annexes, contains the results of 3 vibration tests, their means, standard deviations and RSDs. The overall means of every gear for the 3 vibration tests, their means, standard deviations and RSDs are presented on Table 5.1. The mean of the 3 tests for every gear is illustrated in Figure 5.7, where each gear is identified by the chainring number, from the smallest to the biggest, and by the cog number, from the biggest to the smallest.

Table 5.1. Mean results of SRAM Apex vibration tests.

gear	test 1 [m/s^2]	test 2 [m/s^2]	test 3 [m/s^2]	mean [m/s^2]	SD [m/s^2]	RSD [%]
mean	1.147	1.252	1.251	1.217	0.060	4.93

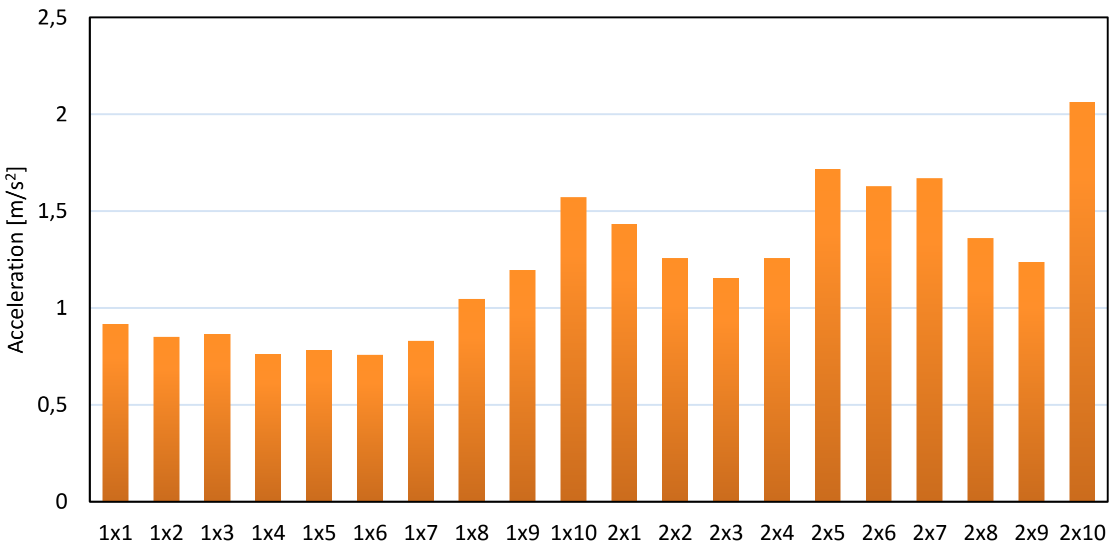

Figure 5.7. SRAM Apex mean vibration level per gear.

Table 7.3, on annexes, contains the results of 3 audio tests, their means, standard deviations and RSDs. The overall means of every gear for the 3 vibration tests, their means, standard deviations and RSDs are presented on Table 5.2. The mean of the 3 tests for every gear is illustrated in Figure 5.8.

Table 5.2. Mean results of SRAM Apex audio tests.

gear	test 1	test 2	test 3	mean	SD	RSD [%]
mean	5299	5156	5289	5248	80	1.52

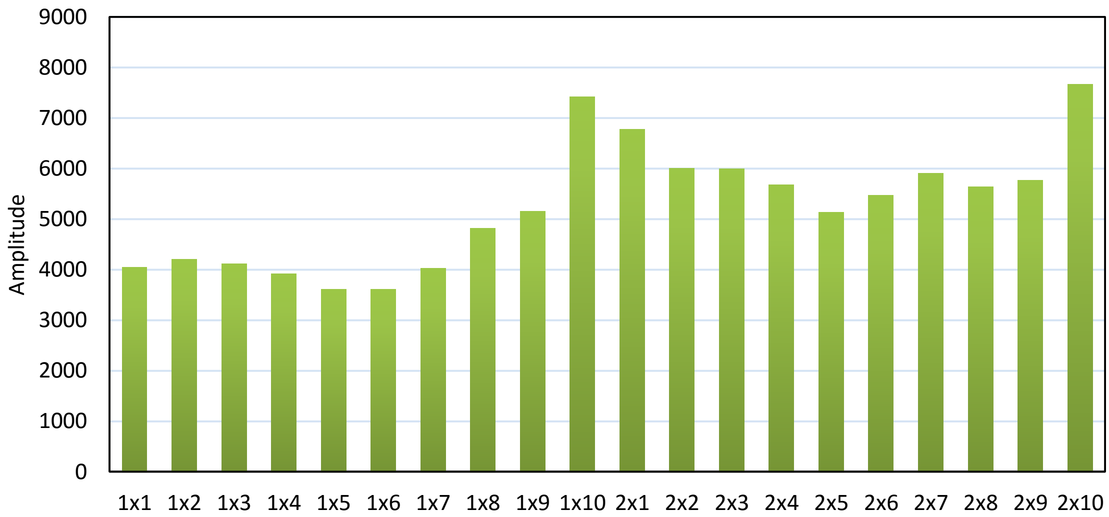

Figure 5.8. SRAM Apex mean audio level per gear.

Both vibration and audio test results showed that there was a noticeable increase in noise on the last three cogs when on the smaller chainring (1x8, 1x9 and 1x10) and on the first cog when on the bigger chainring (2x1), presumably due to cross chaining. Also as expected, the results showed larger noise levels when on the bigger chainring, due to the larger chain speed, and when on the smallest 11T cog, due to polygonal effect.

The results demonstrated a fairly good correlation between the vibration and audio results, as can be observed in Figure 5.9, with a coefficient of determination, R^2, of

0.717. Only three points displayed a larger discrepancy, due to unexpectedly higher vibration levels on gears 2x5, 2x6 and 2x7, as can be perceived in Figure 5.7.

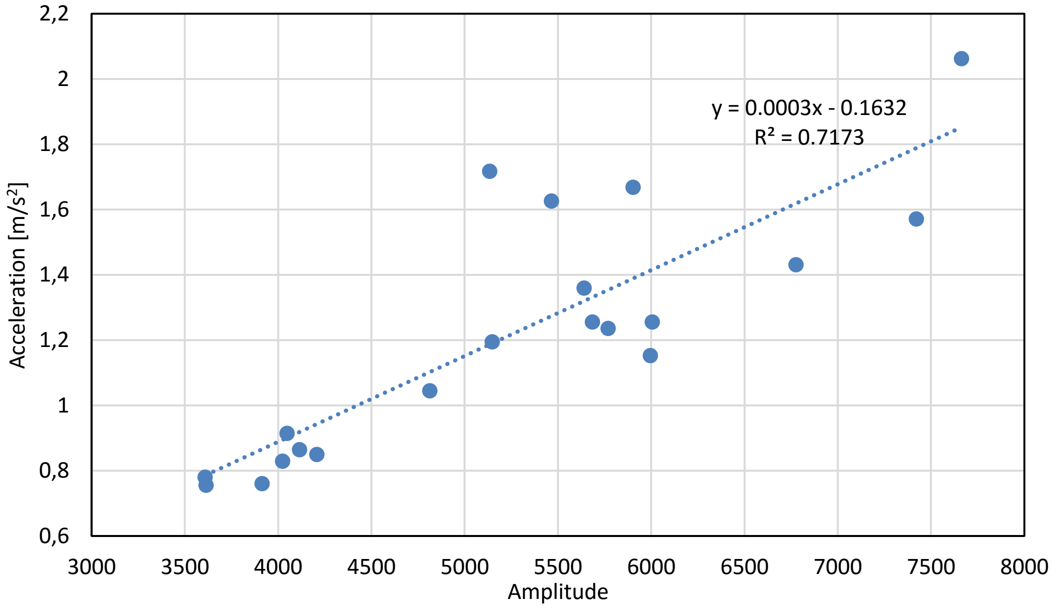

Figure 5.9. Correlation between vibration and audio levels on SRAM Apex.

5.3.2. SRAM XX1

This 2012 SRAM XX1 drivetrain is a high end mountain group set. It has a single 32T chainring and an 11 cogs 10-42T cassette. The gear shifter is the GripShift version.

Table 7.4, on annexes, contains the results of 3 vibration tests, their means, standard deviations and RSDs. The overall means of every gear for the 3 vibration tests, their means, standard deviations and RSDs are presented on Table 5.3. The mean of the 3 tests for every gear is illustrated in Figure 5.10.

Table 5.3. Mean results of SRAM XX1 vibration tests.

gear	test 1 [m/s²]	test 2 [m/s²]	test 3 [m/s²]	mean [m/s²]	SD [m/s²]	RSD [%]
mean	0.869	0.839	0.847	0.852	0.015	1.80

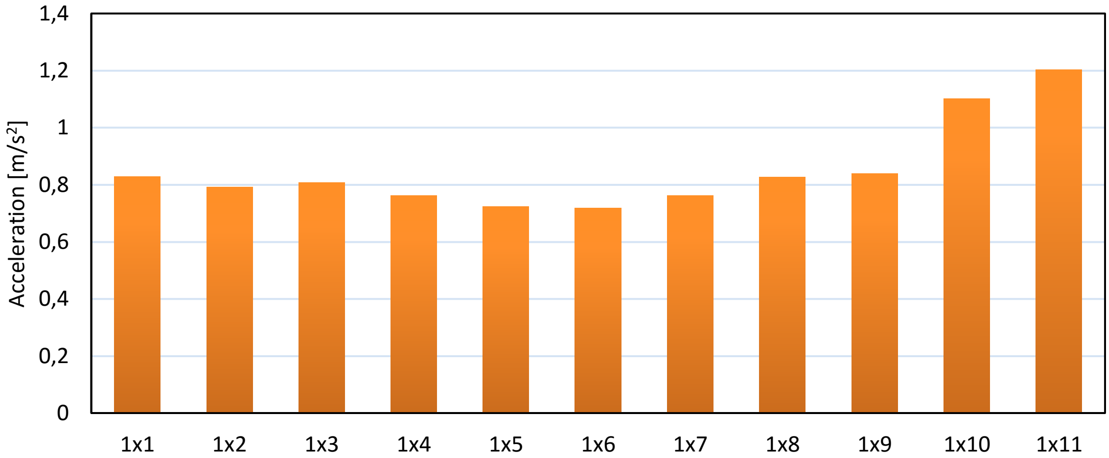

Figure 5.10. SRAM XX1 mean vibration level per gear.

Table 7.5, on annexes, contains the results of 3 audio tests, their means, standard deviations and RSDs. The overall means of every gear for the 3 vibration tests, their means, standard deviations and RSDs are presented on Table 5.4. The mean of the 3 tests for every gear is illustrated in Figure 5.11.

Table 5.4. Mean results of SRAM XX1 audio tests.

gear	test 1	test 2	test 3	mean	SD	RSD [%]
mean	3249	3390	3374	3338	77	2.31

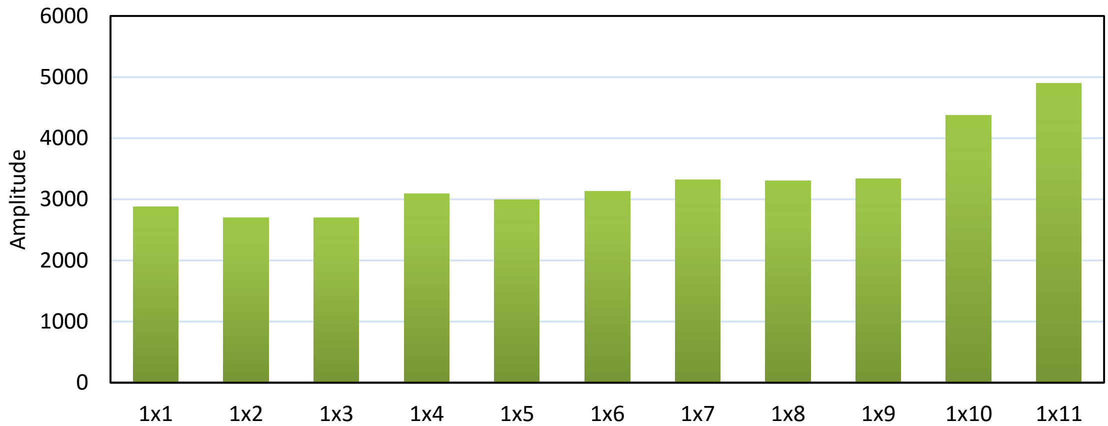

Figure 5.11. SRAM XX1 mean audio level per gear.

Both vibration and audio test results showed that there was a noticeable increase in noise when near the extremes of the cassette, first and last gears, as expected due to cross chaining. The results showed larger noise levels when on the last two gears: 1x10, 12T cog, and particularly 1x11, 10T cog, due to the polygonal effect on the cogs of the cassette with the less number of teeth.

The results demonstrated a good correlation between the vibration and audio results, as can be observed in Figure 5.12, with a coefficient of determination, R^2, of 0.831, and no obvious discrepancies.

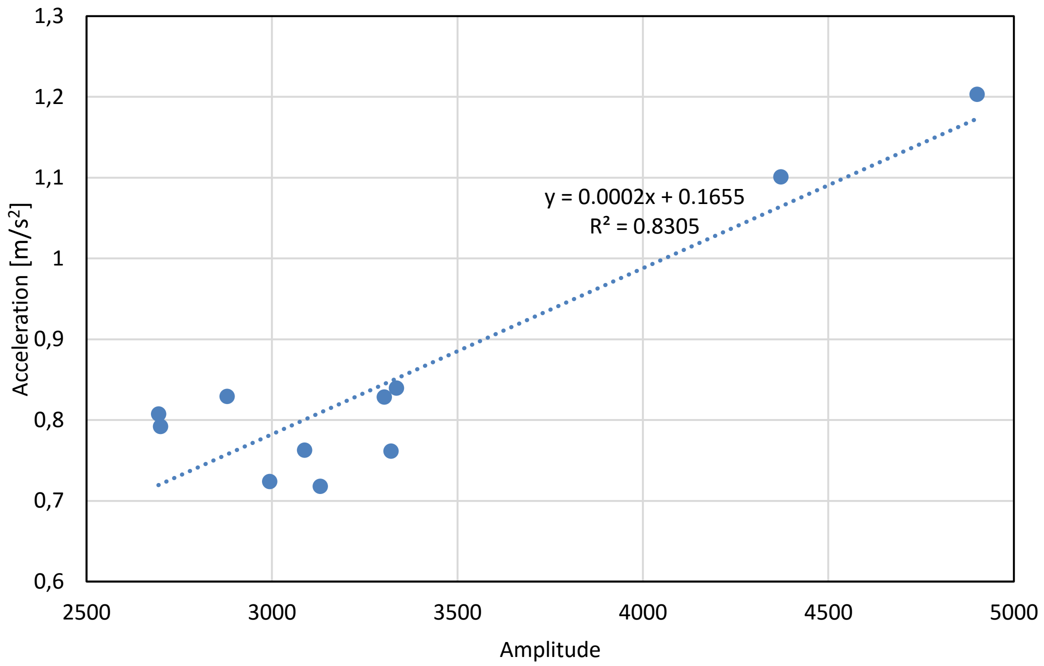

Figure 5.12. Correlation between vibration and audio levels on SRAM XX1.

5.3.1. SRAM Red

This 2008 SRAM Red drivetrain is a high end road group set. It has 2 chainrings, 39T and 53T, and a 10 cogs 11-26T cassette. This group set was criticized by media and clients because of the noise it produced, caused mainly by the cassette's hollow construction. That noise issue was sorted on newer SRAM Red versions.

Table 7.6, on annexes, contains the results of 3 vibration tests, their means, standard deviations and RSDs. The overall means of every gear for the 3 vibration tests, their means, standard deviations and RSDs are presented on Table 5.5. The mean of the 3 tests for every gear is illustrated in Figure 5.13.

Table 5.5. Mean results of SRAM Red vibration tests.

gear	test 1 [m/s^2]	test 2 [m/s^2]	test 3 [m/s^2]	mean [m/s^2]	SD [m/s^2]	RSD [%]
mean	1.809	1.856	1.853	1.839	0.027	1.45

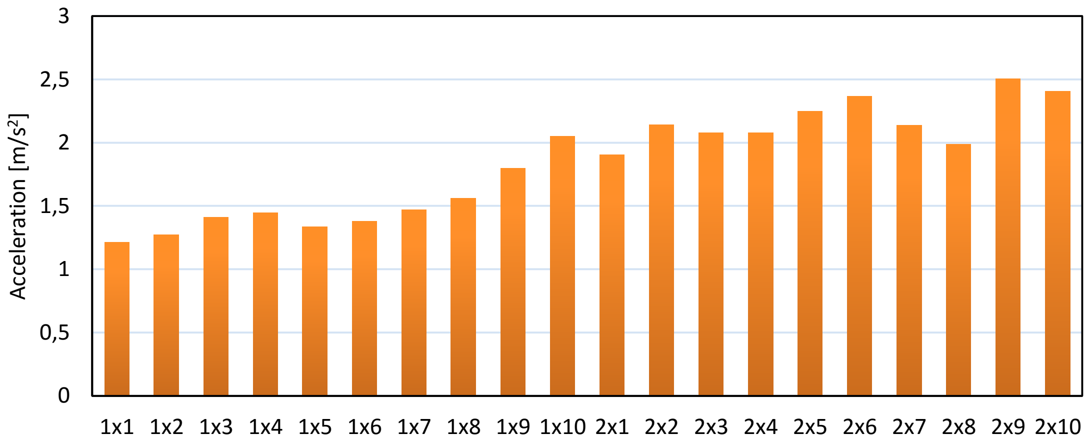

Figure 5.13. SRAM Red mean vibration level per gear.

Table 7.7, on annexes, contains the results of 3 audio tests, their means, standard deviations and RSDs. The overall means of every gear for the 3 vibration tests, their means, standard deviations and RSDs are presented on Table 5.6. The mean of the 3 tests for every gear is illustrated in Figure 5.14.

Table 5.6. Mean results of SRAM Red audio tests.

gear	test 1	test 2	test 3	mean	SD	RSD [%]
mean	7520	7502	7461	7494	30	0.40

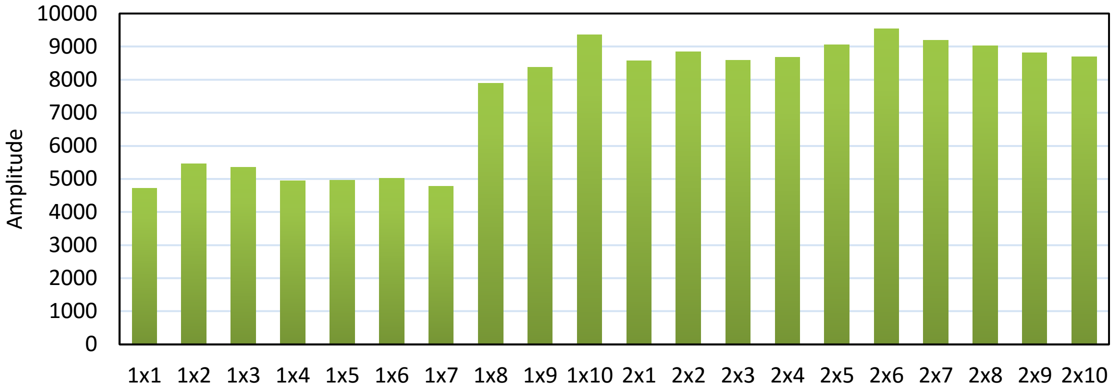

Figure 5.14. SRAM Red mean audio level per gear.

Vibration and particularly audio test results showed that there was a noticeable increase in noise on the last three cogs when on the smaller chainring (1x8, 1x9 and 1x10) due to cross chaining causing the chain to rub on the front derailleur, and on the first gear when on the big chainring, due directly to cross chaining. The results demonstrated an obvious increase in noise levels when on the bigger chainring, due to the larger chain speed. An increase in noise levels due to polygonal effect was only apparent on the results of the vibration tests, at the two last gears, corresponding to the 12T and 11T cogs of the cassette. The results demonstrated a good correlation between the vibration and audio results, as can be observed in Figure 5.15, with a coefficient of determination, R^2, of 0.813.

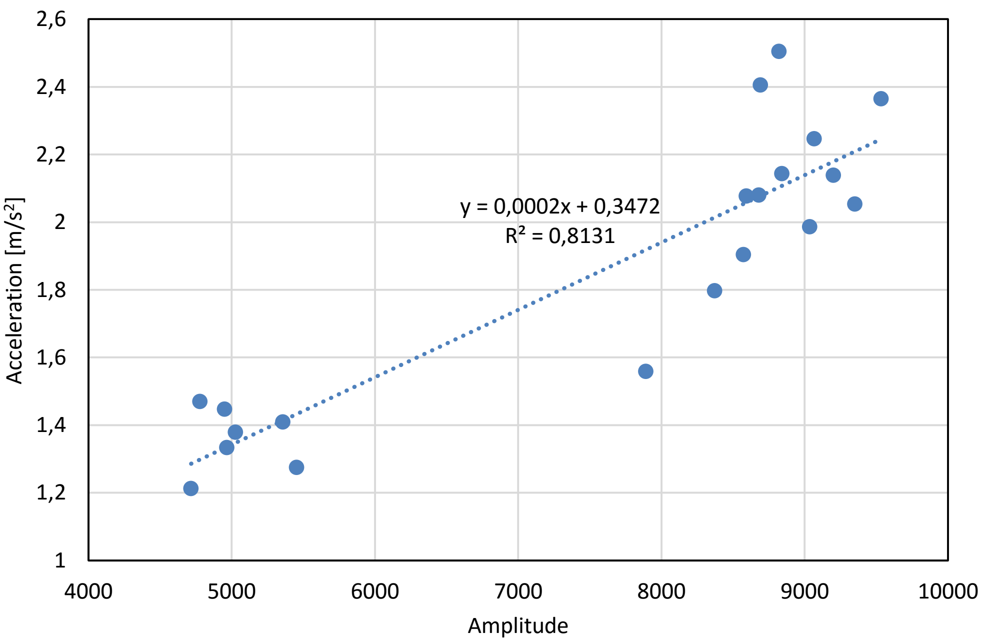

Figure 5.15. Correlation between vibration and audio levels on SRAM Red.

5.3.1. Comparison of Results

The results obtained, compared in Table 5.7, are consistent with what was expectable from theory and human perception when riding.

SRAM XX1, being a single chainring, mountain group set, has fewer chainring number of teeth, so less chain speed, suffers less from cross chaining and isn't affected by chain rubbing on the front derailleur, as there isn't one, thus achieving the lowest results. SRAM Red has the biggest chainrings, causing more chain speed, and a hollow cassette construction prone to noise emission, so it obtains the highest results, as expected.

Audio tests generally obtained more consistent results than vibration tests, possibly explained by the higher recording sample rate and duration.

Table 5.7. Mean results and RSD of the tests realized.

	Vibration	Vibration RSD	Audio	Audio RSD
SRAM Apex	1.217 m/s^2	4.93 %	5248	1.52 %
SRAM XX1	0.852 m/s^2	1.80 %	3338	2.31 %
SRAM Red	1.839 m/s^2	1.45 %	7494	0.40 %

6. CONCLUSIONS

As the utilization of the bicycle gets more and more popular, from commuting to competition, the bicycle market gets ever more competitive and every detail is important. While the noise originated by the bicycle's drivetrain won't reach levels that can cause physiological effects, it can cause psychological effects on the rider, such as annoyance or focus loss, thus being a determinant factor for the client when choosing a bicycle or bicycle drivetrain aftermarket parts.

This investigation employed two hypotheses for measuring the drivetrain noise: vibration measurement and audio recording. Both hypotheses recorded the variation of an amplitude signal over time, that was then analyzed in frequency domain using FFT filters and quantified by RMS. The frequency analysis verified that higher noise levels occur above the chain engagement and disengagement frequency, particularly at that frequency and at it's double. Hearing filtered audio tests determined that the rattling noise characteristic of a bicycle drivetrain occurs at frequencies nearly between 3000 Hz and 14000 Hz, which permits the audio tests to focus on the noise coming from the drivetrain. Vibration tests achieved better results unfiltered.

The procedures for data acquisition, analysis and quantification were set. The results concluded that factors like power output, chain speed, cross chaining, polygonal effect and component's design have influence on noise emission. Power output revealed to have little influence, as doubling the value of power caused a small increase in vibration and audio results. Pedaling cadence and chainring teeth number are the two variables that chain speed is dependent on, and both caused important increases in noise level. Cross chaining could be noted on the results, particularly when it caused chain rubbing on the front derailleur, although if used correctly, gear combinations that cause cross chaining should be avoided. Polygonal effect was visible on the results of the gears that used the smallest cogs of the cassette, particularly on cogs with 12T, 11T and 10T. Component design has a big influence on noise emission, as demonstrated by the results of the 2008 SRAM Red group set with a hollow cassette construction.

Vibration testing was limited by the recording sample rate and duration of the measurement equipment utilized. A purpose built, stiffer mounting plate would also possibly achieve more consistent results. A higher sample rate would possibly allow to obtain filtered results that focus on the noise originated by the drivetrain, as it was done with audio, which is of interest for obtaining drivetrain noise results on real world riding, using portable vibration measurement and recording equipment.

Audio testing obtained consistent results, but is limited to indoor recording, as airflow noise would overlap drivetrain noise. To adopt this method, a sound intensity probe should be utilized and placed with a specific position and orientation, in order to obtain results that can be used as reference.

BIBLIOGRAPHY

Brüel & Kjær (1982), "Measuring Vibration".

Cateye (2015), "Tire Circumference Chart", Accessed on June 20 2016, at: http://www.cateye.com/files/manual_dl/0/415/Tire_size_chart_ENG_151106.pdf.

Ebert, T., Martin, D., Stephens, B., Withers, R. (2006), "Power Output During a Professional Men's Road-Cycling Tour", International Journal of Sports Physiology and Performance, 1, 324-335.

Instituto do Ambiente (2004), "O RUÍDO E A CIDADE".

Lépine, J., Champoux, Y., Drouet, J. (2013a), "A Laboratory Excitation Technique to Test Road Bike Vibration Transmission", Experimental Techniques, Society for Experimental Mechanics, 227-234.

Lépine, J., Champoux, Y., Drouet, J. (2013b), "Road bike comfort: on the measurement of vibrations induced to cyclist", International Sports Engineering Association.

Lucía, A., Hoyos, J., Chicharro, J. (2000), "Preferred pedalling cadence in professional cycling", Medicine & Science in Sports & Exercise, Official Journal of the American College of Sports Medicine, 1361-1366.

Olieman, M., Marin-Perianu, R., Marin-Perianu, M. (2012), "Measurement od dynamic comfort in cycling using wireless acceleration sensors", Procedia Engineering, 34, 568-573.

Redfield, R. (2014), "Bike braking vibration modelling and measurement", Procedia Engineering, 72, 471-476

SRAM Cycling Fund (2009), "FUND OVERVIEW", Accessed on June 9 2016, at: http://www.sramcyclingfund.com/fund-overview.html.

SRAM LLC (2012), "SRAM 25th Anniversary".

SRAM LLC (2016), "About", Accessed on June 9 2016, at: https://www.sram.com/company/about.

SRAM LLC (2016), "SRAM Mountain", Accessed on June 9 2016, at: https://www.sram.com/sram/mountain.

SRAM LLC (2016), "SRAM Road", Accessed on June 9 2016, at: https://www.sram.com/sram/road.

Union Cycliste Internationale (2016), Accessed on June 9 2016, at: http://www.uci.ch/.

World Bicycle Relief (2016), "Our Story", Accessed on June 9 2016, at: http://www.worldbicyclerelief.org/our-story.

ANNEXES

Table 7.1. Third octave frequency bands

f_{min} (Hz)	f_c (Hz)	f_{max} (Hz)	f_{min} (Hz)	f_c (Hz)	f_{max} (Hz)
17.42	19.69	21.95	557.5	630.0	702.4
21.95	24.80	27.66	702.4	793.7	885.0
27.66	31.25	34.84	885.0	1000	1115
34.84	39.37	43.90	1115	1260	1405
43.90	49.61	55.31	1405	1587	1770
55.31	62.5	69.69	1770	2000	2230
69.69	78.75	87.80	2230	2520	2810
87.80	99.21	110.6	2810	3175	3540
110.6	125	139.4	3540	4000	4460
139.4	157.5	175.6	4460	5040	5619
175.6	198.4	221.2	5619	6350	7080
221.2	250	278.8	7080	8000	8920
278.8	315.0	351.2	8920	10079	11239
351.2	396.9	442.5	11239	12699	14160
442.5	500	557.5	14160	16000	17840

Table 7.2. Results and statistics of SRAM Apex vibration tests.

gear	test 1 [m/s^2]	test 2 [m/s^2]	test 3 [m/s^2]	mean [m/s^2]	SD [m/s^2]	RSD [%]
1x1	0.894	0.966	0.884	0.915	0.045	4.90
1x2	0.827	0.861	0.862	0.850	0.020	2.34
1x3	0.769	0.920	0.904	0.865	0.083	9.60
1x4	0.679	0.805	0.798	0.761	0.071	9.28
1x5	0.742	0.800	0.801	0.781	0.034	4.35
1x6	0.631	0.802	0.836	0.756	0.110	14.53
1x7	0.734	0.878	0.876	0.829	0.083	9.98
1x8	0.930	1.145	1.060	1.045	0.108	10.34
1x9	1.123	1.226	1.235	1.195	0.062	5.22
1x10	1.459	1.586	1.669	1.571	0.106	6.72
2x1	1.363	1.467	1.464	1.432	0.059	4.13
2x2	1.197	1.268	1.302	1.256	0.054	4.28
2x3	1.132	1.168	1.159	1.153	0.019	1.62
2x4	1.225	1.275	1.267	1.256	0.027	2.14
2x5	1.493	1.789	1.873	1.718	0.200	11.63
2x6	1.490	1.699	1.690	1.626	0.119	7.30
2x7	1.666	1.734	1.604	1.668	0.065	3.90
2x8	1.279	1.390	1.408	1.359	0.070	5.14
2x9	1.216	1.250	1.244	1.237	0.018	1.46
2x10	2.101	2.011	2.077	2.063	0.047	2.26
mean	1.147	1.252	1.251	1.217	0.060	4.93

Table 7.3. Results and statistics of SRAM Apex audio tests.

gear	test 1	test 2	test 3	mean	SD	RSD [%]
1x1	4469	3763	3911	4048	372	9.19
1x2	4547	4070	4007	4208	295	7.01
1x3	4489	4003	3855	4116	332	8.06
1x4	4239	3778	3724	3914	283	7.23
1x5	3862	3534	3433	3610	224	6.20
1x6	3557	3418	3865	3613	229	6.34
1x7	3916	3807	4352	4025	288	7.16
1x8	4466	4308	5668	4814	744	15.45
1x9	5336	5028	5082	5149	164	3.19
1x10	7506	7252	7508	7422	147	1.98
2x1	6369	7032	6929	6776	357	5.27
2x2	6145	6316	5562	6007	395	6.58
2x3	5944	6118	5929	5997	105	1.75
2x4	5622	5614	5818	5685	115	2.03
2x5	5001	5275	5126	5134	137	2.67
2x6	5412	5689	5296	5466	202	3.69
2x7	6186	5735	5792	5904	246	4.16
2x8	5327	5325	6269	5640	545	9.65
2x9	5819	5540	5952	5770	210	3.65
2x10	7769	7518	7707	7665	131	1.70
mean	5299	5156	5289	5248	80	1.52

Table 7.4. Results and statistics of SRAM XX1 vibration tests.

gear	test 1 [m/s^2]	test 2 [m/s^2]	test 3 [m/s^2]	mean [m/s^2]	SD [m/s^2]	RSD [%]
1x1	0.830	0.847	0.811	0.829	0.018	2.17
1x2	0.827	0.794	0.755	0.792	0.036	4.51
1x3	0.765	0.866	0.792	0.808	0.052	6.44
1x4	0.810	0.749	0.729	0.763	0.042	5.52
1x5	0.710	0.651	0.811	0.724	0.081	11.16
1x6	0.737	0.721	0.697	0.718	0.020	2.76
1x7	0.800	0.705	0.780	0.762	0.050	6.61
1x8	0.839	0.809	0.837	0.828	0.017	2.02
1x9	0.868	0.819	0.832	0.840	0.026	3.06
1x10	1.156	1.035	1.112	1.101	0.061	5.56
1x11	1.215	1.238	1.157	1.203	0.042	3.47
mean	0.869	0.839	0.847	0.852	0.015	1.80

Table 7.5. Results and statistics of SRAM XX1 audio tests.

gear	test 1	test 2	test 3	mean	SD	RSD [%]
1x1	2439	3059	3140	2879	383	13.32
1x2	3029	2445	2624	2699	299	11.08
1x3	2324	2754	3004	2694	344	12.76
1x4	2858	3059	3347	3088	246	7.97
1x5	3046	2920	3015	2994	66	2.20
1x6	3156	3145	3090	3130	35	1.13
1x7	3246	3410	3306	3321	83	2.49
1x8	3127	3515	3265	3303	197	5.95
1x9	3403	3491	3113	3335	198	5.93
1x10	4570	4449	4096	4372	246	5.63
1x11	4544	5044	5114	4901	311	6.34
mean	3249	3390	3374	3338	77	2.31

Table 7.6. Results and statistics of SRAM Red vibration tests.

gear	test 1 [m/s^2]	test 2 [m/s^2]	test 3 [m/s^2]	mean [m/s^2]	SD [m/s^2]	RSD [%]
1x1	1.199	1.224	1.214	1.213	0.013	1.05
1x2	1.256	1.228	1.341	1.275	0.059	4.62
1x3	1.414	1.370	1.444	1.409	0.037	2.64
1x4	1.450	1.432	1.460	1.447	0.014	0.99
1x5	1.425	1.330	1.245	1.333	0.090	6.74
1x6	1.322	1.338	1.478	1.379	0.086	6.22
1x7	1.431	1.442	1.538	1.470	0.059	4.03
1x8	1.400	1.592	1.683	1.558	0.145	9.28
1x9	1.651	1.907	1.834	1.797	0.132	7.34
1x10	2.054	2.003	2.103	2.053	0.050	2.42
2x1	1.817	1.946	1.949	1.904	0.075	3.96
2x2	2.002	2.316	2.111	2.143	0.159	7.43
2x3	2.042	2.111	2.078	2.077	0.035	1.67
2x4	2.083	2.155	2.002	2.080	0.076	3.67
2x5	2.324	2.265	2.150	2.246	0.088	3.92
2x6	2.462	2.319	2.315	2.365	0.084	3.54
2x7	2.126	2.225	2.064	2.138	0.081	3.80
2x8	1.844	2.038	2.077	1.986	0.125	6.28
2x9	2.549	2.380	2.585	2.504	0.110	4.38
2x10	2.323	2.506	2.388	2.406	0.093	3.87
mean	1.809	1.856	1.853	1.839	0.027	1.45

Table 7.7. Results and statistics of SRAM Red audio tests.

gear	test 1	test 2	test 3	mean	SD	RSD [%]
1x1	4524	4892	4732	4716	184	3.91
1x2	5215	5753	5389	5452	274	5.03
1x3	5384	5487	5203	5358	143	2.68
1x4	5028	5022	4799	4950	130	2.63
1x5	4824	5102	4968	4965	139	2.80
1x6	5061	5037	4978	5025	43	0.85
1x7	5002	4780	4552	4778	225	4.71
1x8	8330	7732	7609	7890	386	4.89
1x9	8787	8388	7941	8372	423	5.06
1x10	9685	9107	9257	9350	300	3.21
2x1	8300	8527	8890	8573	298	3.47
2x2	9048	8823	8649	8840	200	2.26
2x3	8299	8479	9002	8593	365	4.25
2x4	8562	8604	8874	8680	169	1.95
2x5	9167	8718	9317	9067	312	3.44
2x6	9443	9501	9655	9533	110	1.15
2x7	9228	9392	8981	9200	207	2.25
2x8	8938	9146	9021	9035	105	1.16
2x9	8952	8810	8696	8819	128	1.45
2x10	8622	8735	8715	8691	60	0.69
mean	7520	7502	7461	7494	30	0.40