End-of-degree Project

Master's degree in Automotive Engineering (MUEA)

Machine to Measure the Characteristics of the Dampers of a Radio Control Vehicle

MEMORY

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Summary

This project aims to find the best way to build a machine to measure the characteristics of the dampers of a radio control vehicle making it not only a machine that actually works, but also one that is accomplished by sticking to a budget that suitable to be better than the machines offered by different developers and can deliver the data and information that wants to be obtained.

First the project digs in into the world of suspensions, their components and how they are set up, studying the data that is needed to accomplish the best performance for any custom scenario any vehicle might need. Then, it submerges into the world of radio control vehicles, where either driven by the need to be competitive in radio control vehicles racing or just the hunger for knowledge, the passion for the automotive world can be satisfied by learning about these machines with their downscaled versions. Here the application of the data obtained by the shock dynos and its importance in suspensions setting is shown, seeking always for the best performance.

Then, this project makes a big emphasis on the investigation of the different shock dynos that can be found in the market and others that are used by developers for them to deliver to the public the best tested suspensions. The importance of investigating this thoroughly is that this project seeks to overcome all the difficulties that might preclude the machine either to work or to deliver the information that is wanted, and for this it needed to be built based on a proven method and a deep understanding of data acquisition and post processing.

Finally, after investigating, analyzing and evaluating all the options, a set of instructions to build the shock dyno was developed, in which a clear step by step on its built and data acquisition method is detailed; all of this making it a machine that meets all the main performance objectives set at the beginning for the shock dyno that this project was aiming for.

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1. Preface

This project aims for a potential way of building a machine that can measure the characteristics of the dampers or shock absorbers of a radio control vehicle. These characteristics are used to develop better radio control vehicle's suspension parts that can fulfill all of our needs and accomplish the best suspension performance for any possible scenario.

The project was proposed by its tutor Lluis Roger Casals, who has a huge passion for the automotive world, and is always moved by the desire of knowledge and the love for radio control vehicles; and that is the motivation that we both share for such a project to be developed. Since such a machine is of great advantage, not only if someone is into serious radio control vehicles racing, but also if the automotive world is something you always want to know more about.

As it was discussed with the tutor in the first meeting, such machines are not available for the general public, as a matter of fact there is only one shock dyno that is available for sale to the public, and still it is very expensive. So, being such a resource only available to some suspension developers and really few persons that are into radio control vehicle racing and willing to pay the price, it became a really big motivation for us both to find a potential way for such a machine to be built and actually deliver the characteristics of the radio control vehicle's dampers.

Therefore, this time, we aimed to find a machine we could base the project on that would actually work and have a post processing method that would accomplish the end results, sticking always to not only the budget, but also to the machine's features and requirements set by the tutor beforehand.

These requirements where that the machine should be able to measure the characteristics of the dampers of a radio control vehicle 1/5 scale, with a stroke of up to ± 20 mm with a sinusoidal input wave of constant amplitude and preferably variable frequency. This machine also had to be built with the usage of commercially available products in order to achieve the lowest possible budget.

2. Introduction

This project starts off with a deep study of vehicle suspensions and its components, where the damper or shock becomes the main component to focus on. Then, the project digs into the internal components of the dampers and how these components are key in the performance that wants to be achieved with the suspension depending on its goals for the suspension’s use.

The development of the dampers can only be achieved by testing their performance, and this is done by testing them on shock dynos that deliver the graphs needed to evaluate and analyze the different internal components designs and setups.

This is where the project starts to explain the basics of how these graphs are used and understood in order to develop suspensions for any needs and makes a turn into the world of radio control vehicles, which are non-other than downscaled versions of real vehicles. The project investigated how radio control vehicle suspensions can be set up according to the customer needs and how having access to the graphs that the shock dynos deliver opens a world of opportunities for anyone interested in the topic willing to take the time and effort to set up their radio control vehicles suspension to the performance they seek.

Afterwards, the project submerges into the different shock dynos that are available and makes a huge emphasis on investigating, analyzing and evaluating them thoroughly, in order to find their pros and cons, so that at the end the potential shock dyno that meets all of the requirements for this project is found. This is not easy task, as many characteristics have to be taken into consideration to find a machine base that will actually work and deliver the results wanted. The project seeks for an understandable build and a detailed explanation of the post processing method, since these are the two main characteristics that can make this project fail.

The machine that this project selected as a base was proven to meet all of the requirements stablished by the tutor in the beginning of the project, and since the machine was already built by its developer and the results are available this does not only mean that the machine on which the project is based on actually works, but also that it is able to deliver de desired results after a proven post processing method.

For this reason, before explaining forward on the build of the machine, a pre-design phase was considered, since an evaluation was needed in order to prove that all of the requirements were met by the selected machine base. This phase actually helped to prove once and for all that the machine could actually do everything it was intended to, and therefore, after this phase, the detailed instructions on how to build it were developed, completed with a post processing thorough explanation on how to make the machine delivers the data that the project is seeking to obtain from this machine.

Since the machine that this project proposes is based on a machine that was already built by its developer beforehand, and it has already been testes, a lower cost in the budget for the machine could be achieved, since this was evaluated when investigating the shock dynos available and the more parts have to be design and machined from scratch, the more expensive the machine becomes.

Therefore, it can be assumed that this machine not only proves to meet the stablished requirements, deliver the results the project looks forward to obtain, but it also is the most potentially buildable machine that stays within the budget and is cheaper than buying a commercial completely built and setup machine.

3. Suspensions

In order to understand about suspensions, it is important to understand their function. Suspensions have two main functions, the first one is to damp the sprung and unsprung masses at their resonant frequencies in order to maintain the tire footprint on the track. According to (García, 2014) the suspension separates both, the sprung masses which refer to the chassis, car body, driver, etc.; and the unsprung masses which are the tire, brakes, wheels, etc.

The sprung and unsprung masses of a vehicle are defined as followed by (Martínez, 2019). The sprung masses, or sprung weight, in a vehicle with a suspension, are the vehicle's body and the chassis, internal components, passengers and cargo, and everything that is supported by the suspension. In some applications, half of the weight of the suspension itself is also included.

And the unsprung masses, or unsprung weight, in a vehicle with a suspension, are the masses of the suspension (or half of it depending on the application), the wheels and any other components that are directly connected to the suspension or the wheels; which include axles, wheel bearings, wheel hubs, tires, brakes, calipers, suspension links, driveshafts, etc. (Martínez, 2019)

Basically, the unsprung masses are all of those that are not supported by the suspension. As mentioned before, depending on the application, some other masses can be considered as intermediary masses, or for simplicity, their masses can be considered as half sprung and half unsprung masses. The sprung masses are defined as m_b and the unsprung masses as $m_r$in the figure below. (Martínez, 2019)

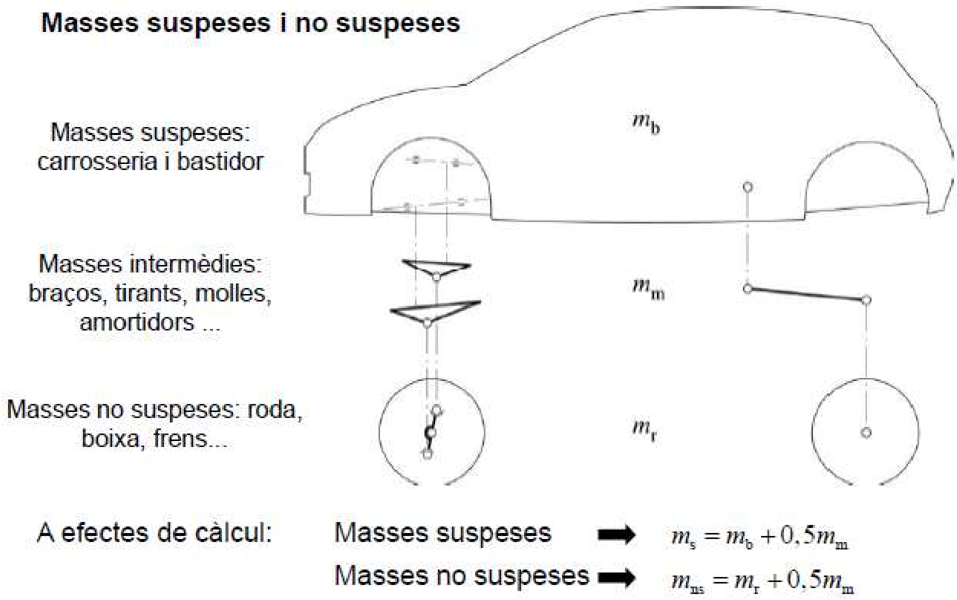

Figure 3.1. Sprung and Unsprung masses in a vehicle, and the consideration for simplicity of the intermediary masses. (Martínez, 2019)

So, as stated by (García, 2014), it is easier to obtain the best vehicle's performance when the unsprung masses are being controlled by the suspension to keep the tire footprint on the track and not having to control the whole mass of the vehicle at once. This concept allows suspension systems to be separated into two sub-systems, which will be shown later.

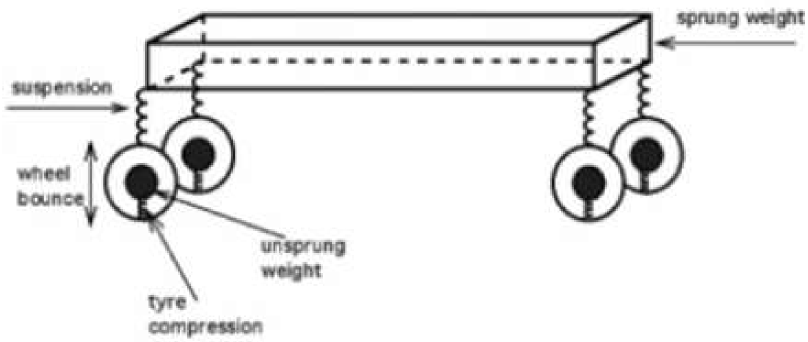

Figure 3.2. Suspension, sprung and unsprung masses. (García, 2014)

The second main function of a suspension is to control the rate of weight transfer during transient such as braking, corner entering and acceleration. (Extreme Racing Shox, 2019) And this second function has to do with setting up the suspension right in order for the vehicle to have the best performance. Therefore, it is essential to analyze suspensions in a way that everything that is involved in them is understandable.

In order to simplify the complex understanding of how the suspension of a vehicle works, the commonly known quarter car model of a vehicle suspension can be used. This model is used to simplify the analysis of the suspension modeling only one corner of the vehicle, which enables the whole suspension to be modeled with only two degrees of freedom enabled, and is a simple and effective tool to investigate basic ride behavior of the suspension. The model consists of the quarter of the total vehicle's mass (minus the wheels or unsprung masses), which is represented in the figure below as M or M_1, and the wheel mass, which would be m or M_2.The part of the suspension that links the vehicle's body to the wheel consists of a spring in parallel with a shock absorber, which are represented with their stiffness k_1 and damping coefficient c_1, respectively. (Barjau, 2019)

This model is very helpful, because it also models the wheel having a stiffness represented by k_2. Then, the model has some coordinates to take into consideration, which are $z_1$and $z_2$that measure the position of masses $M_1$and $M_2$with respect to their static equilibrium positions, or in other words, where the spring only balances the gravity forces. And the coordinate $h(t)$ which represents the input to the suspension's displacement caused by the road's surface, which is dependent on the road's profile and vehicle's speed. (Barjau, 2019)

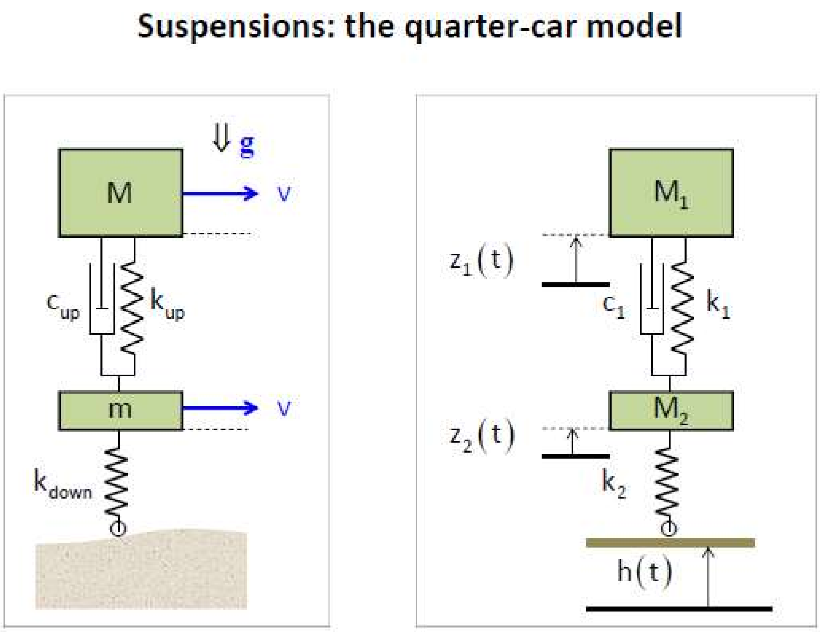

Figure 3.3. Suspensions: The Quarter-Car Model. (Barjau, 2019)

Vehicle suspensions are systems that involve more forces than only damping. Such forces can be spring and friction forces, for example, and therefore according to (Extreme Racing Shox, 2019) a suspension system can be considered as two separate sub-systems:

1. The spring, the mass (in this case the chassis which represents the sprung mass) and the damper system.
2. The tire (in this case acting as a spring), half of the the suspension parts (for example, the wishbones in a double wishbone suspension, which represent the unsprung mass) and a little bit of tire damping.

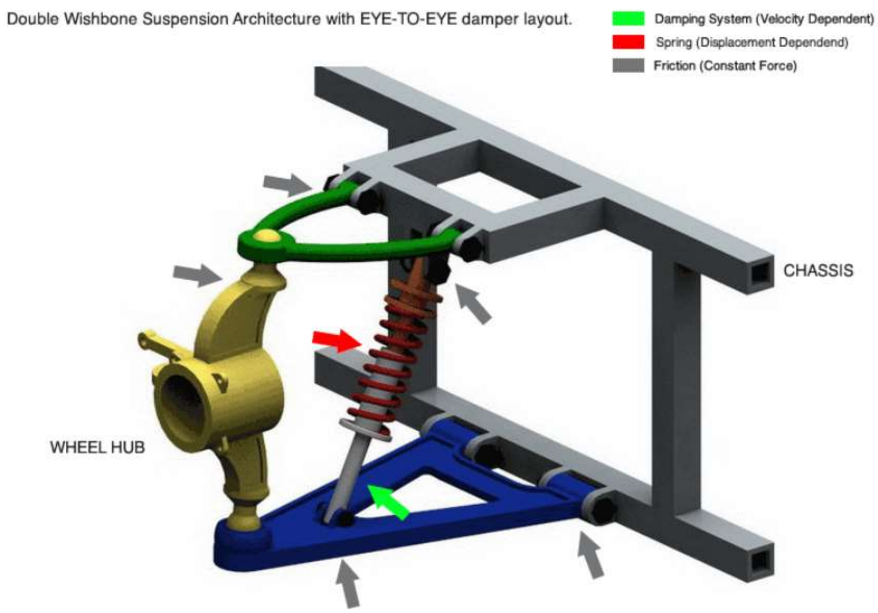

Figure 3.4. Double Wishbone Suspension example from EXT TECH LAB. (Extreme Racing Shox, 2019)

All of the forces involved in a suspension system are dependent either on velocity, displacement and even other forces, depending on the force that is being analyzed. In this project the analysis will be limited to the dampers or shock absorbers only, so, as mentioned by (Extreme Racing Shox, 2019), the damping force is velocity dependent as shown in the graph of the representation of forces involved in a suspension system below.

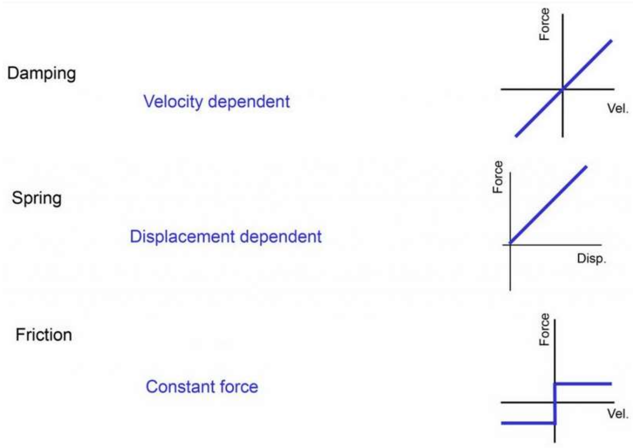

Figure 3.5. Representation of Forces Involved in a Suspension System. (Extreme Racing Shox, 2019)

3.1. Dampers or Shock Absorbers

The damping force mentioned before will be affected by all the components that can be found in a shock absorber. So, the most commonly used classification used for shock absorbers is the one that refers to the way they absorbed the variation of volume inside them. And there are basically three different types of shock absorbers: the dual tube, the monotube and the remote reservoir shock absorber, which can be either monotube or dual tube. (Alonso, 2016)

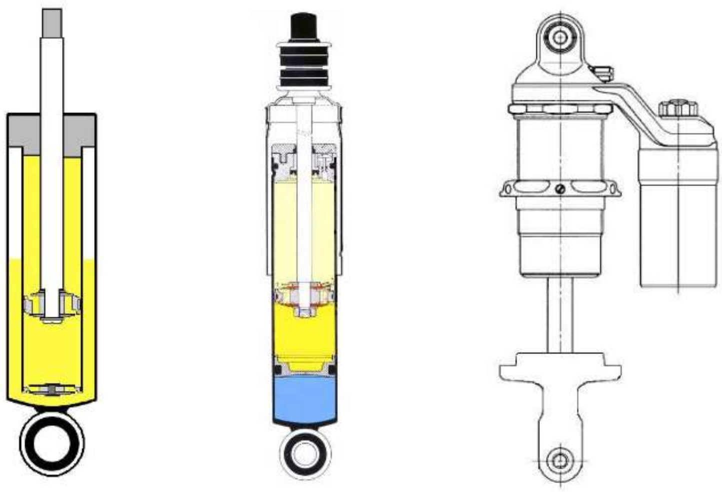

Figure 3.6. Left to right: dual tube, monotube and remote reservoir shock absorbers. (Alonso, 2016)

In this case the focus will be on non-pressurized monotube shock absorbers, since this are the shock absorbers used in radio-controlled vehicles, as stated by the tutor in the first project meeting. So, in order to see it in a very simplified way, in a non-pressurized monotube shock absorber the internal components that will be affected by the damping force are: piston and shaft (to create flow) and the orifices (for a pressure loss).

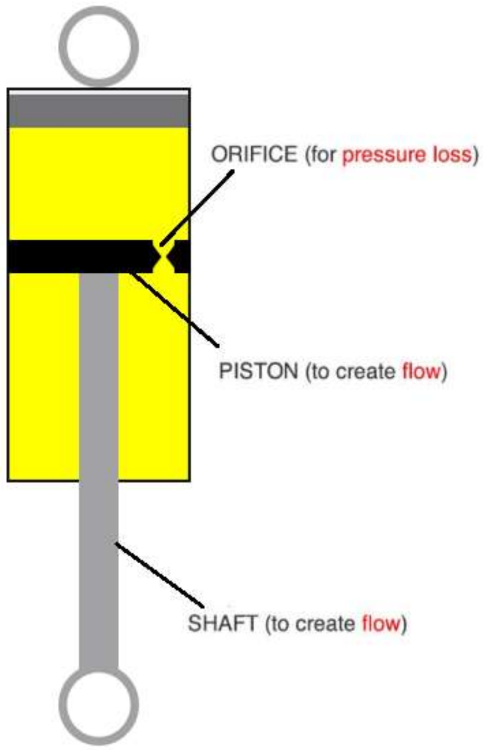

Figure 3.7. Non-pressurized monotube shock absorber components. Piston and shaft, and orifices. (Extreme Racing Shox, 2019)

The flow through the shock absorber's piston is the quantity of any hydraulic fluid, used in said shock absorber, that is moved by the piston. This is really interesting since it can be calculated just by knowing the piston's and the rod's areas and the speed in which the shaft moves. (Extreme Racing Shox, 2019)

$$Q_{piston} = (A_{piston} - A_{fhaft}) * V_{shaft} \quad \text{(Eq. 1)}$$

Now, the other flow that also is important here is the flow through the valve, which is the flow through the orifices, and this is important since it creates pressure loss. This flow can be calculated by the next formula. (Extreme Racing Shox, 2019)

$$Q_{valve} = A_{valve} * V_{shaft} \quad \text{(Eq. 2)}$$

So, basically, the functionality of the shock absorber is based on the flow of the shock absorber's hydraulics fluid through the internal components, such as the valves the generate a flow resistance of the shock absorber's hydraulic fluid between the chambers separated by the piston. This way the oscillations of the suspension system can be controlled. (Gabriel México, 2019) This movements or oscillations on the shock absorber will make the shock absorber's fluid to flow, and therefore create a pressure loss, which will be converted either in force on the shaft, which is equal to damping force; or energy dissipation, by heat. This can be seen in the diagram below. (Extreme Racing Shox, 2019)

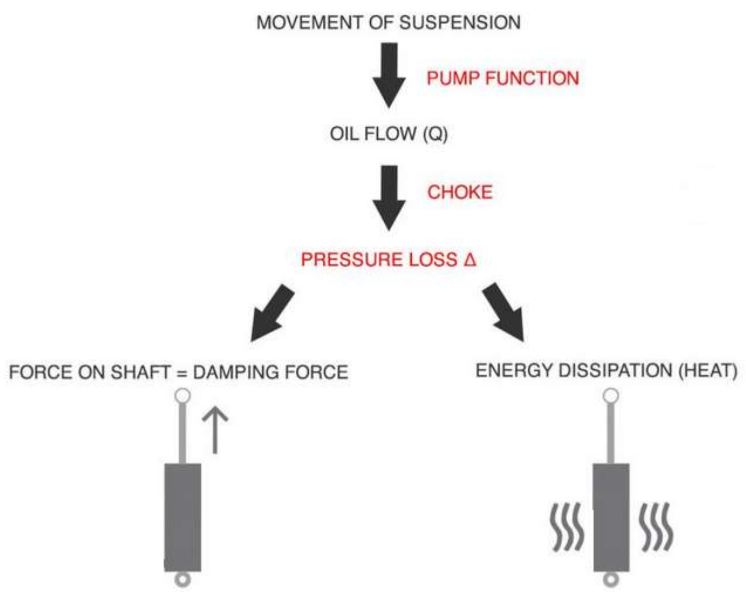

Figure 3.8. Shock Absorber's movement to damping force and energy dissipation. (Extreme Racing Shox, 2019)

3.2. Damping Forces and their Graphs

When the damper piston is attempting to move through the shock absorber's hydraulic fluid, said fluid must flow through the orifices going from one side of the piston to the other. In other words, it must flow from one side of the chamber to the other, which are separated by the piston. This movement will generate forces, called damping forces, that can be represented by graphs. In order to understand these graphs, it is important to see that the damper piston moves in two different phases. One is the extension, also called rebound, when speaking about suspensions; and the other one is the compression, also known as bump. Both phases of the damper movement while working are shown in the picture below. (Extreme Racing Shox, 2019)

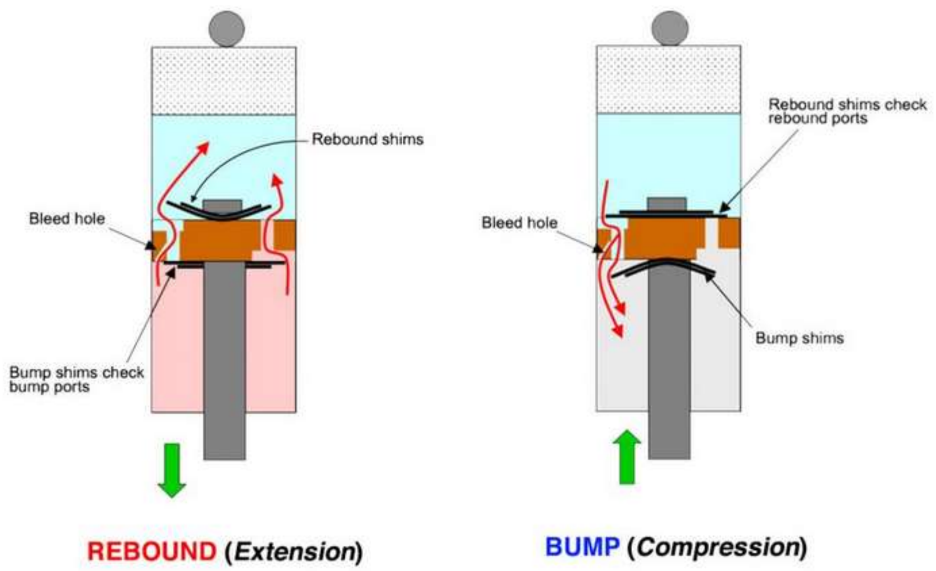

Figure 3.9. The two phases of the movement of the damper while working: rebound (extension) and bump (compression). (Extreme Racing Shox, 2019)

The shims located on the upper and lower part of the shock absorber's piston are the ones that restrain the shock absorber's hydraulic fluid flow when it goes through the piston. These shims will be pushed by the shock absorber's hydraulic fluid and it will cause them to bend. Depending on the combination of shims, the stack will open at a certain pressure. Providing this way, a direct pathway for the fluid to pass through the valve to the other side of the piston. It is important to mention that there is also a bleed hole, which will only be affected when the piston is moved at low speed. (Extreme Racing Shox, 2019)

And here is where the damping force graphs find their origin. All of this shock absorber's hydraulic fluid passing through the piston from one side to another can be represented on graphs that show the two phases of damping by velocity and force. The most interesting about these graphs is that they even show how the bleed orifice and shim stack influence the damping system. An example for a better understanding of the force vs. velocity graphs is shown below. (Extreme Racing Shox, 2019)

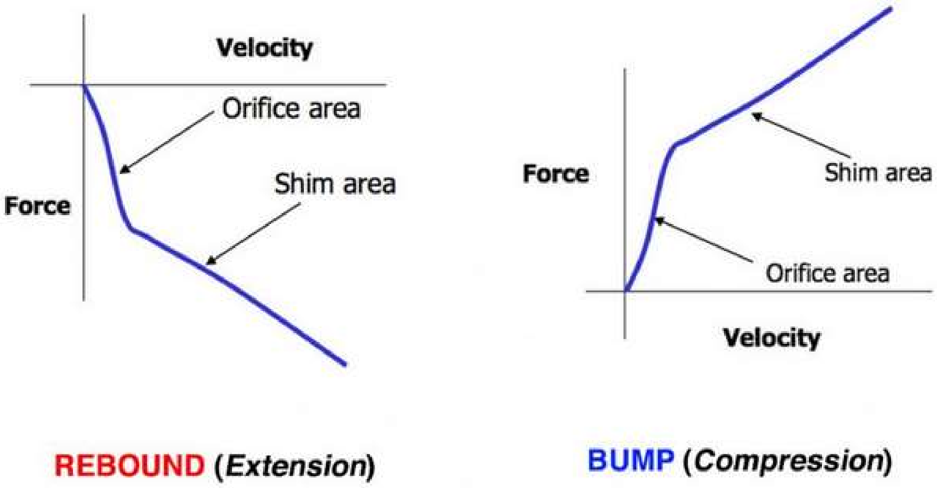

Figure 3.10. Force vs. Velocity graphs in the two damping phases. (Extreme Racing Shox, 2019)

This graphs more than being just interesting information about the shock absorbers, are also really useful when it comes not only to shock absorbers development but also in setting up the suspension for racing cars for their best performance. This can be done not only by changing the internal components of the damper, but there are also some suspensions that have an adjuster to regulate the damping forces. (Extreme Racing Shox, 2019) As far as this project's concern, this is not the case, since radio control vehicle shock absorbers will only allow us to adjust the damper performance by changing the shock absorber hydraulic fluid's viscosity. (Clovis, 2012)

But in order to understand how the information from the graphs can be used to adjust the setup of a suspension, a monotube shock absorber with a damping force adjuster will be shown as an example. The adjuster affects damping forces from fully open to fully closed. The first image shows the low speed rebound adjuster working, which consists of an adjuster and a needle. Both will act to the orifice and allow more or less hydraulic fluid to pass. And next to the shock absorber the graph shows the difference between the adjuster fully open or fully closed. One of the main things to remember to setup the suspension is that maximum clockwise on the adjuster, which is fully closed position, means "full hard" suspension setup. (Extreme Racing Shox, 2019)

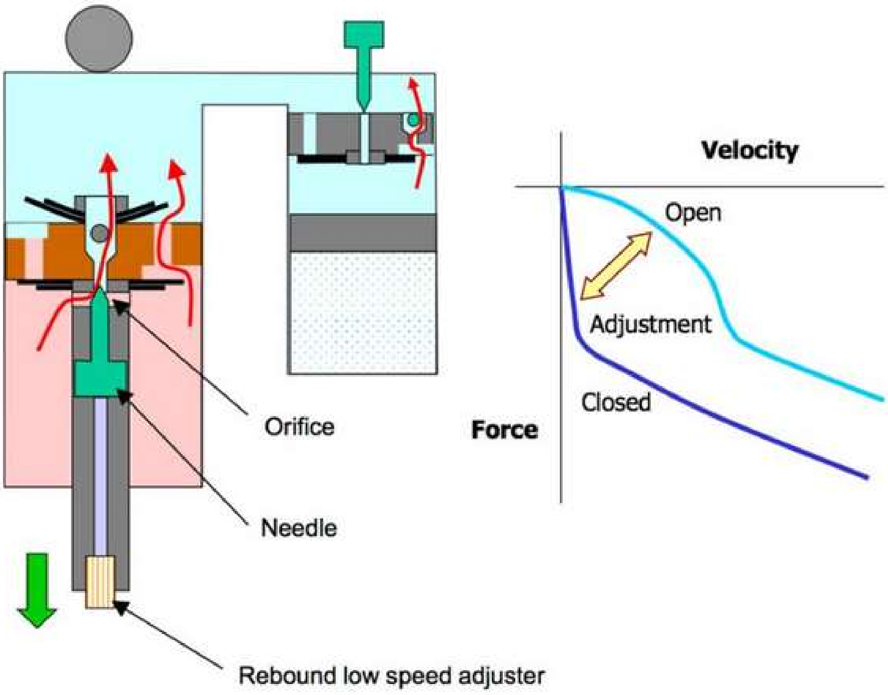

Figure 3.11. Monotube shock absorber with adjuster and force vs. velocity graph, extension side. (Extreme Racing Shox, 2019)

The same happens on the low speed compression side when the adjuster affects damping forces from fully open to fully closed. The next image shows this effect and next to the shock absorber the graph shows the difference on the force vs. velocity curve as well.

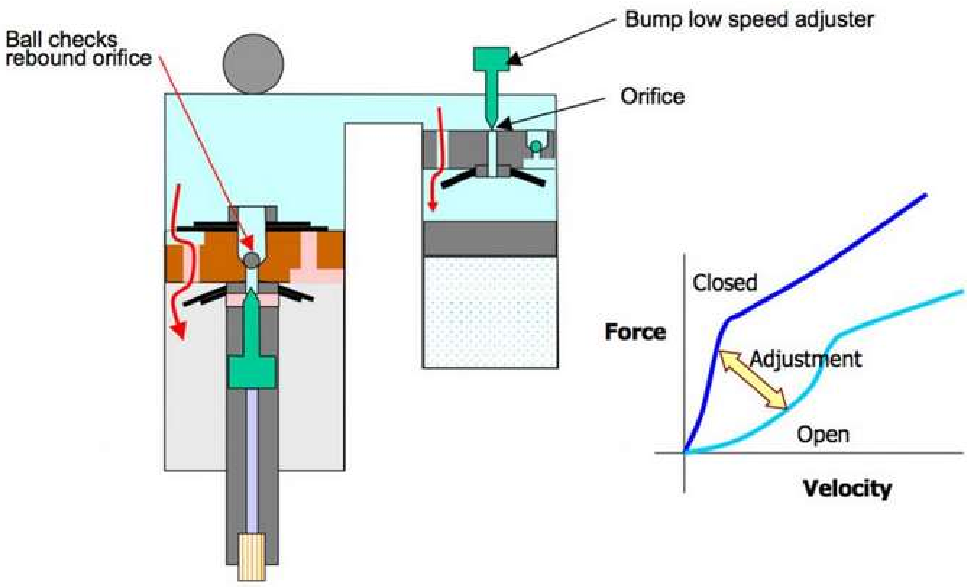

Figure 3.12. Monotube shock absorber with adjuster and force vs. velocity graph, compression side. (Extreme Racing Shox, 2019)

Now, for the high speed compression, the shims that are present on the valve can be preloaded, so that more or less force is needed to let the shock absorber's hydraulic fluid can be let through. The next image shows the preloaded shims inside the shock absorber's valve, and next to it, the graph shows the effects on the force vs. velocity curve when having a higher or a lower preload.

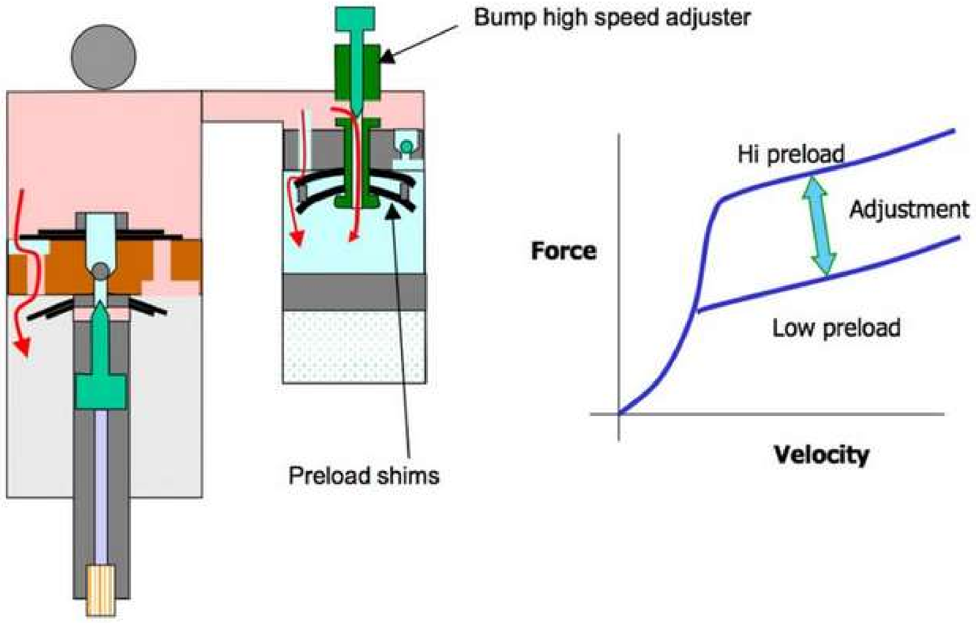

Figure 3.13. High speed compression with preloaded shims and force vs. velocity graph with high and low preload adjustment. (Extreme Racing Shox, 2019)

There are also radio control vehicle shocks that can be regulated, as are the Mechatech or the HARM adjustable radio control vehicles shocks, which can be adjusted in damper force, bump and rebound, preload and stiffness without changing the shock absorber's hydraulic fluid and are a really good option for serious racers.

Figure 3.14. Mechatech Click adjustable radio control vehicle's shock absorbers.

4. Damper Dyno: Measuring Damping Forces

In order to measure damping forces a dyno bench, also known as a damper dyno, is needed. Without a damper dyno it is impossible to obtain objective results when measuring damping forces on a shock absorber.

Figure 4.1. CTW RC Car Damper Dyno with mounted RC Car Shock Absorber. (CTW Automation, Inc., 2019)

Essentially, a damper dyno is composed by a linear actuator, a displacement sensor and a load cell. The shock absorber is mounted right between the load cell and the linear actuator and is activated by a reciprocating motion mechanism, converting the linear motion of a slider into rotational motion or vice versa, also known as a “scotch yoke mechanism”. (Extreme Racing Shox, 2019)

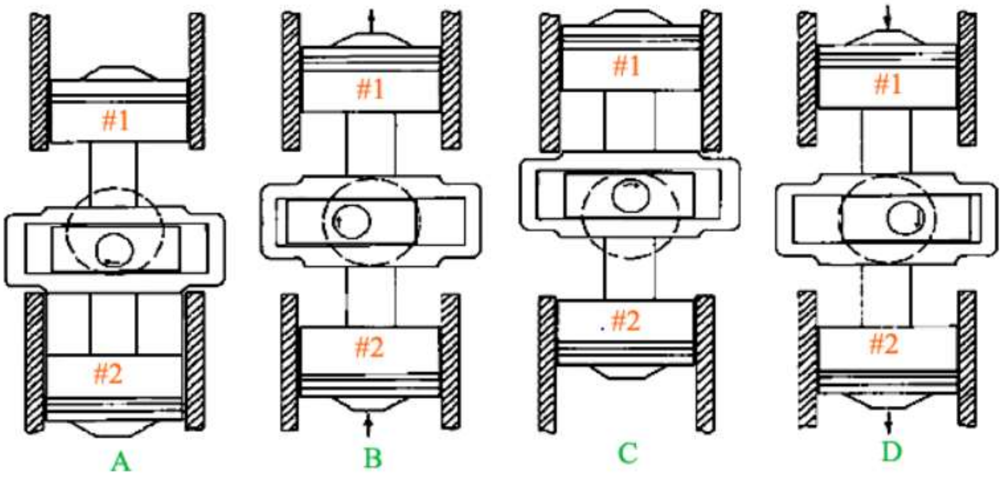

Figure 4.2. Example of Scotch Yoke Mechanism. (TechMini, 2018)

The use of a scotch yoke mechanism allows the development of a sinusoidal input/wave. So, from the components of a damper dyno the software will acquire data, such as, the velocity from the linear actuator and the force from the load cell. This way, after processing the data, either force-displacement graphs or force-velocity graphs can be generated for the shock absorber and its setup being tested. The next image shows how oscillating damper with sinusoidal input record force and velocity displacement. Under the record of the force, velocity and displacement, the force vs. displacement and force vs. velocity graphs are shown. (Extreme Racing Shox, 2019)

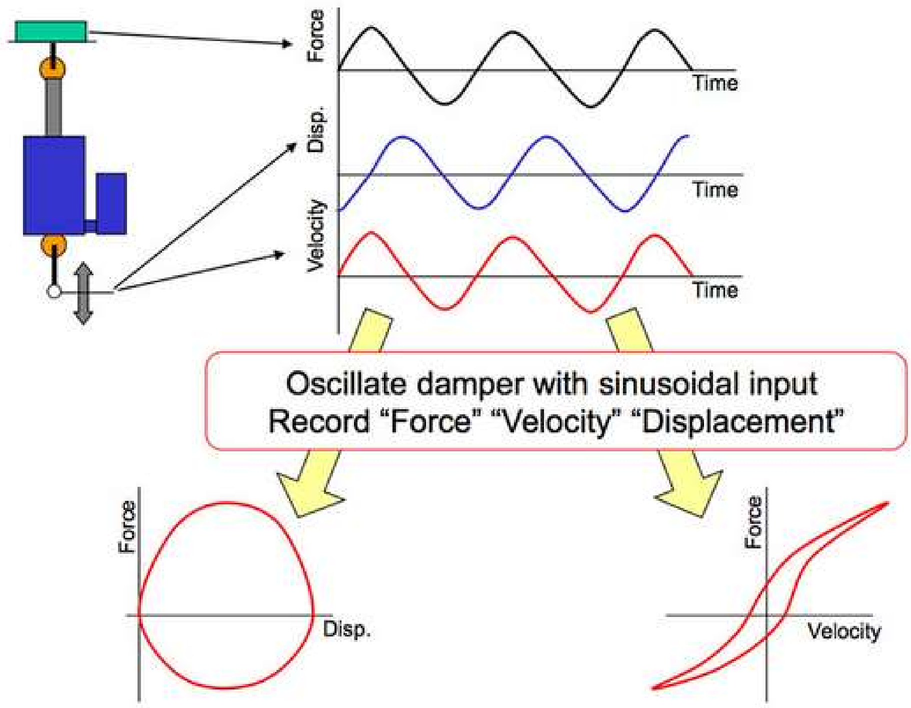

Figure 4.3. Oscillate damper with sinusoidal input record of force, velocity and displacement. (Extreme Racing Shox, 2019)

The force of the shock absorber is generated by its internal components as described before, and the load cell can read it through a software. On the other hand, both, displacement and velocity, must be generated by the damper dyno. (Extreme Racing Shox, 2019)

All the graphs used on this example of a shims valve shock absorber are references just for a better understanding on how this graph are generated, used and analyzed. So, on the next image the graph on the left shows the force-displacement graph and the one on the right shows the force-velocity graph. Both of them are essential to analyze the effective behavior and operation of the damper, to develop and set it up and obtain its best performance. The results gathered on each graph show different information on each step of the cycle and each velocity. So, what can be analyzed from these graphs is, that the general behavior of the shock absorber can be seen on the force-displacement graph, whereas the acceleration phase for the Top Dead Center (TDC) and Bottom Dead Center (BDC) are best shown on the force-velocity graph. This graph also provides information about the hysteresis of the shock absorber, which is a delay of answer of damping systems. This is represented by the area of the curve on the force-velocity curve below. (Extreme Racing Shox, 2019)

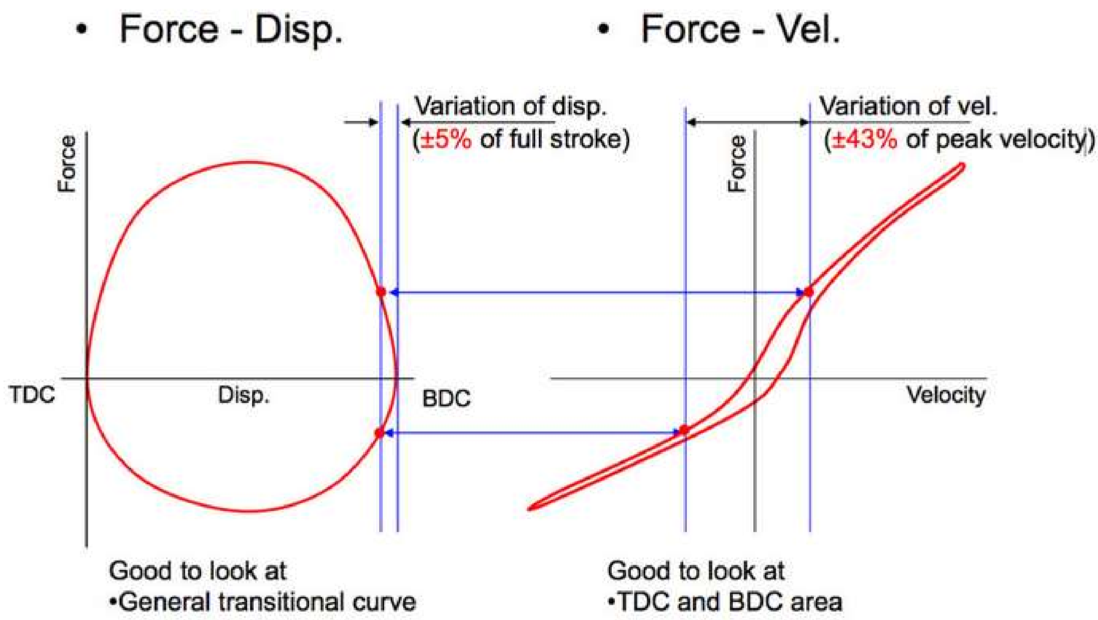

Figure 4.4. Force-Displacement and Force-Velocity curves analysis. (Extreme Racing Shox, 2019)

In order to create base shock absorbers setups or to compare the main damping force generated, and if the software allows it, another type of graph is created. This graph shown below is the Peak Force-Velocity graph, and as shown on the image, for each peak of velocity there is only one point for damping force. (Extreme Racing Shox, 2019)

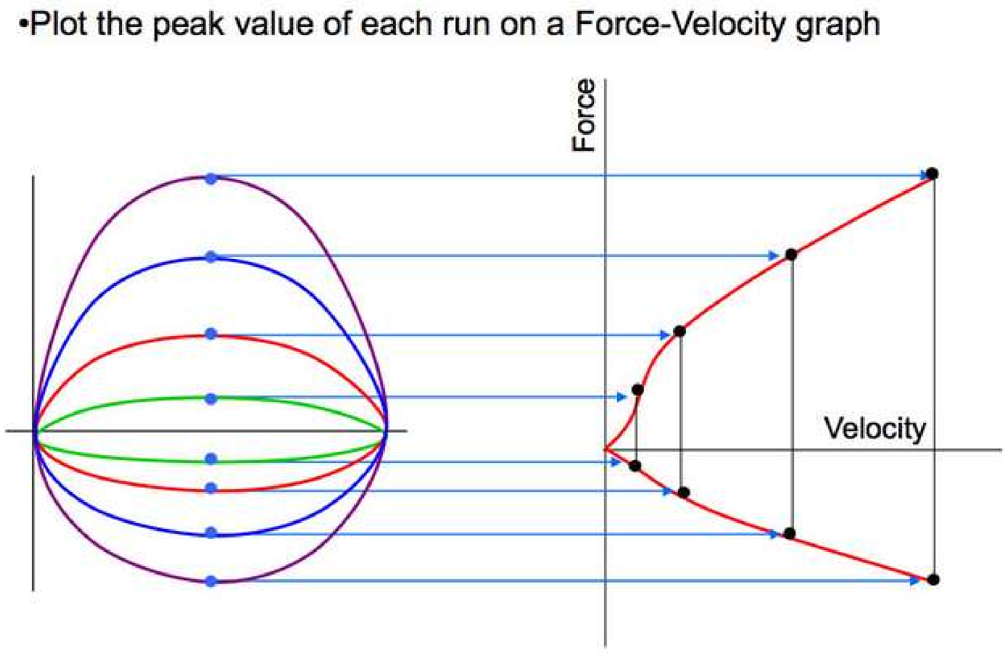

Figure 4.5. Peak Force-Velocity graph and analysis. (Extreme Racing Shox, 2019)

It is really important to mention that when analyzing two different shock absorbers, or the same shock absorber with a different setup, either the case, both of the analyzed dampers may show the same peak force, and this does not mean that both of them will have a different behavior. So, in other words, shock absorbers with totally different behaviors may have the same peak force. This can be seen easier in the graphs below. (Extreme Racing Shox, 2019)

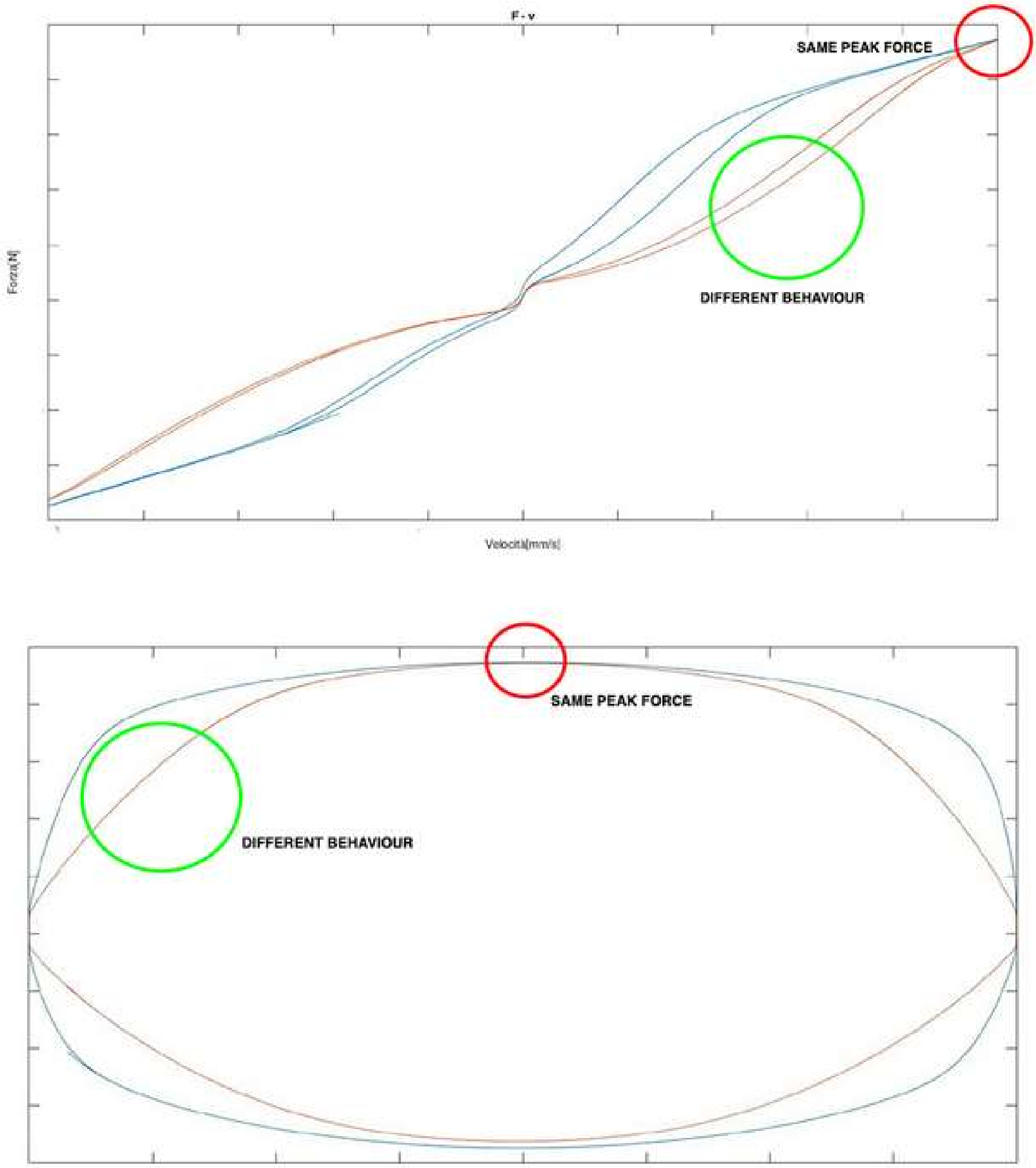

Figure 4.6. Dampers with same peak force, but different behaviors. (Extreme Racing Shox, 2019)

4.1. Using the Force-Velocity Graph: Design, Development and Setup

In order to obtain the maximum performance from the shock absorbers, a specific calibration of damping is needed. And it is for this reason that having the shock absorber’s force-velocity graphs is so important, since achieving certain damping characteristics can be analyzed on this graph and the correct internal components, such as the shim stack for example, and design of a shock absorber can be achieved by using them correctly. (Extreme Racing Shox, 2019)

So, in order to exemplify the use of the force-velocity graph for the selection of internal components and design of a shock absorber, the example of the shims stack valve shock absorber will continue to be used. Shims are not other than metal discs, typically stamped out of spring steel, and they vary in diameter and thickness. As seen before, they are positioned on the face of the piston, resist opening, and therefore create fluid pressure through this restriction. The shims need to be bend in order for the damper’s hydraulic fluid to pass from one side of the chamber divided by the piston to the other; meaning that the thinner the shims, the easier they bend, allowing more damper’s hydraulic fluid to go through, and creating therefore very little damping effect. Whereas, the thicker the shims, the more damping will be created. (Extreme Racing Shox, 2019)

This can be seen in the image below.

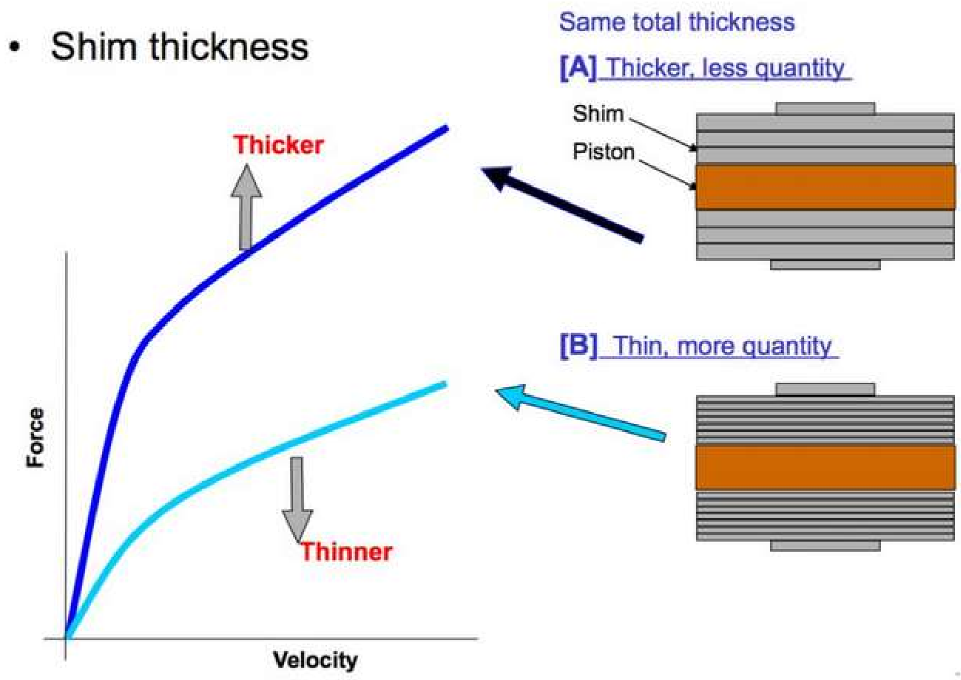

Figure 4.7. Shims thickness and its effect on the force-velocity graph. (Extreme Racing Shox, 2019)

The number of shims is also a setup that may vary the damping behavior of the shock absorber. Its effect can also be analyzed on the force-velocity graph. When having the same shim thickness, many shims mean more hydraulic force, which means more damping, and of course, fewer shims will mean less damping. (Extreme Racing Shox, 2019)

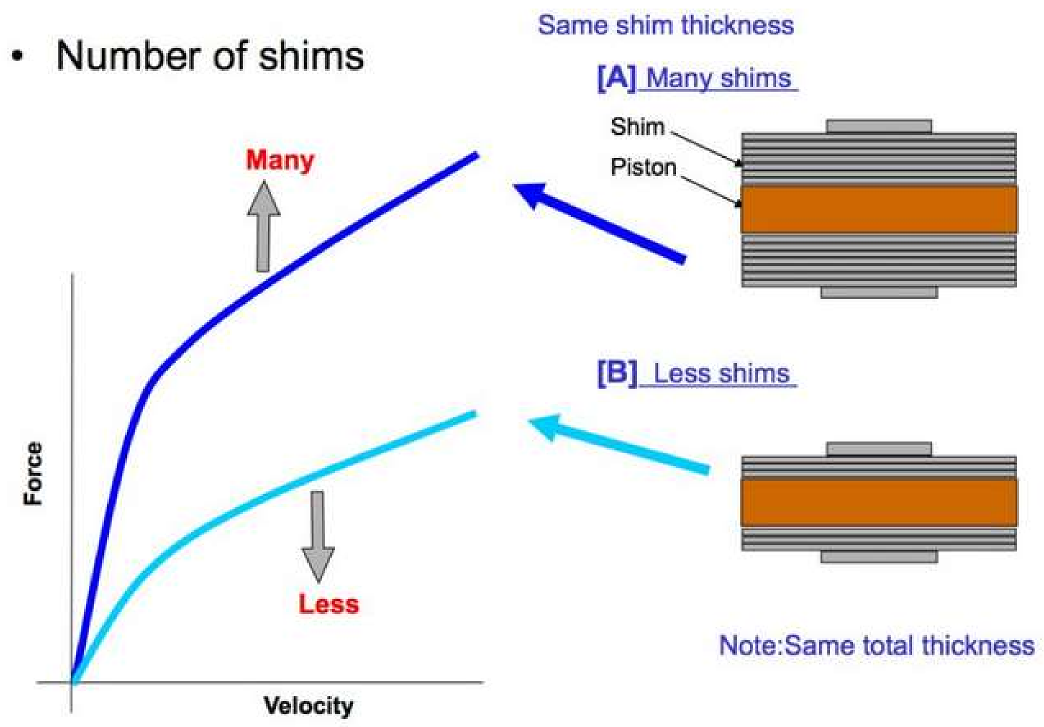

Figure 4.8. Number of shims and its effect on the force-velocity graph. (Extreme Racing Shox, 2019)

As in many other automotive components, the design and the little changes also make huge differences. As in the shim stack of the shock absorber, the different designs of it's profile make variations on the damper's behavior, and this can be analyzed in the force-velocity graph as well. The image below shows how three different shim stack profiles make the force-velocity graph vary. Keep in mind that the C profile (horn) allows the shims nearest to the piston to be less influenced by the higher ones, therefore allowing the shims nearest to the piston to open up easier. (Extreme Racing Shox, 2019)

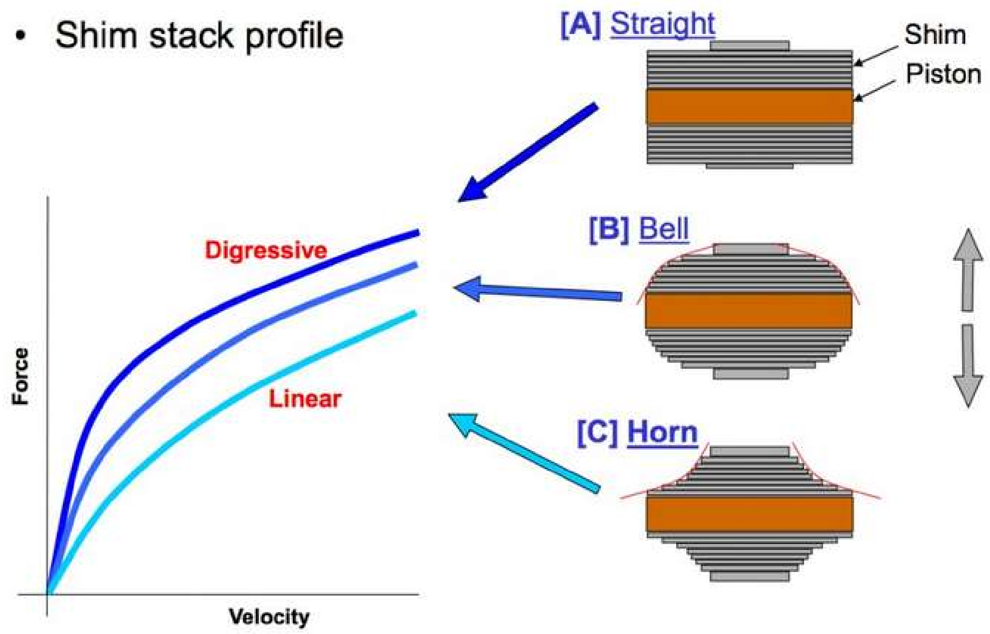

Figure 4.9. Shims stack profile and its effect on the force-velocity graph. (Extreme Racing Shox, 2019)

Other design changes in the shock absorber's internal components can be the top plate of the stack or top shim. And this will also affect the force-velocity graph, more precisely, it will affect the gradient of the curve depending on the top shim being larger or smaller. (Extreme Racing Shox, 2019)

This effect can be seen in the image below

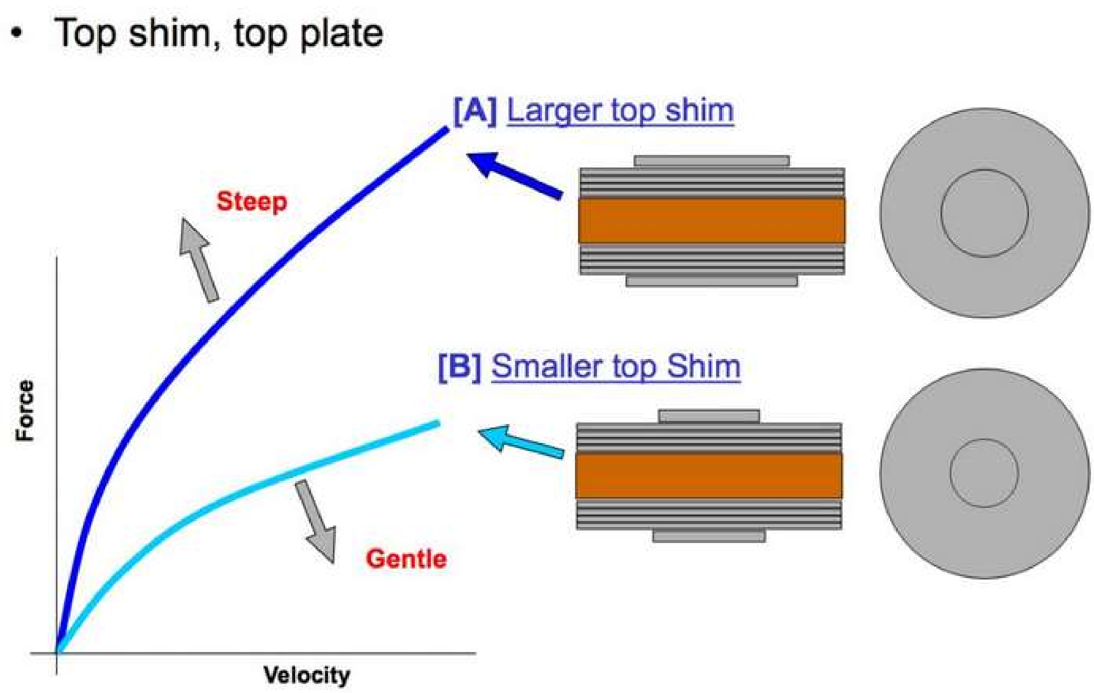

Figure 4.10. Top plate or top shim design and its effect on the force-velocity graph. (Extreme Racing Shox, 2019)

The addition of other internal components such as annular shims will also create different effects on the force-velocity graph, since annular shims can create preload on shims, and therefore increase the low speed independence range, creating this way digressive systems with linear style piston designs. Of course, this will generate a digressive curve on the force-velocity graph. (Extreme Racing Shox, 2019)

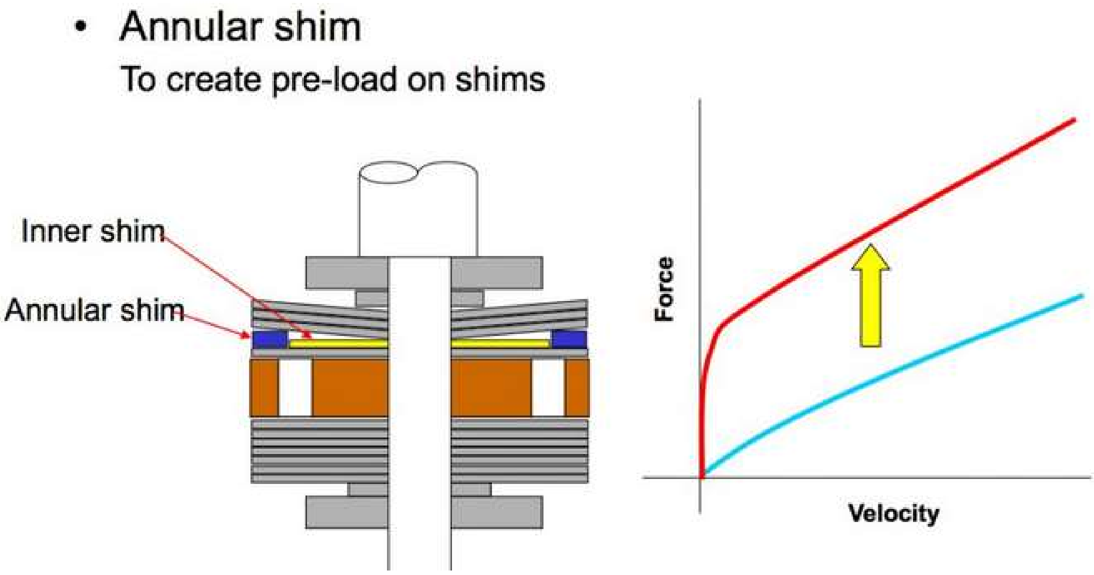

Figure 4.11. Annular shims and its effect on the force-velocity graph. (Extreme Racing Shox, 2019)

Or if generating linear force is wanted, in opposition to the annular shims, sandwich shims can generate linear force and high flow in low speed while keeping high forces in high velocity. (Extreme Racing Shox, 2019)

This effect can be seen in the image below.

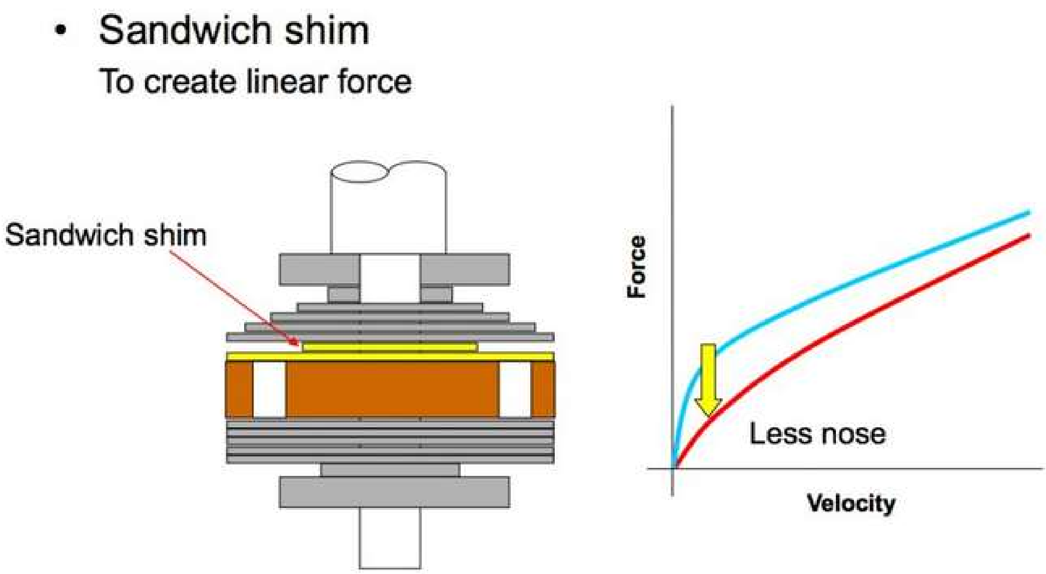

Figure 4.12. Sandwich shims and its effect on the force-velocity graph. (Extreme Racing Shox, 2019)

Also, a step further into the design of the internal components of the shock absorber, different effects such as linear, digressive or progressive curves can be achieved in the force-velocity graph, and therefore in the behavior of the damper, by the design of the shape of the piston. The next image shows different piston shape designs and their effects on the force-velocity curves for bump and rebound. (Extreme Racing Shox, 2019)

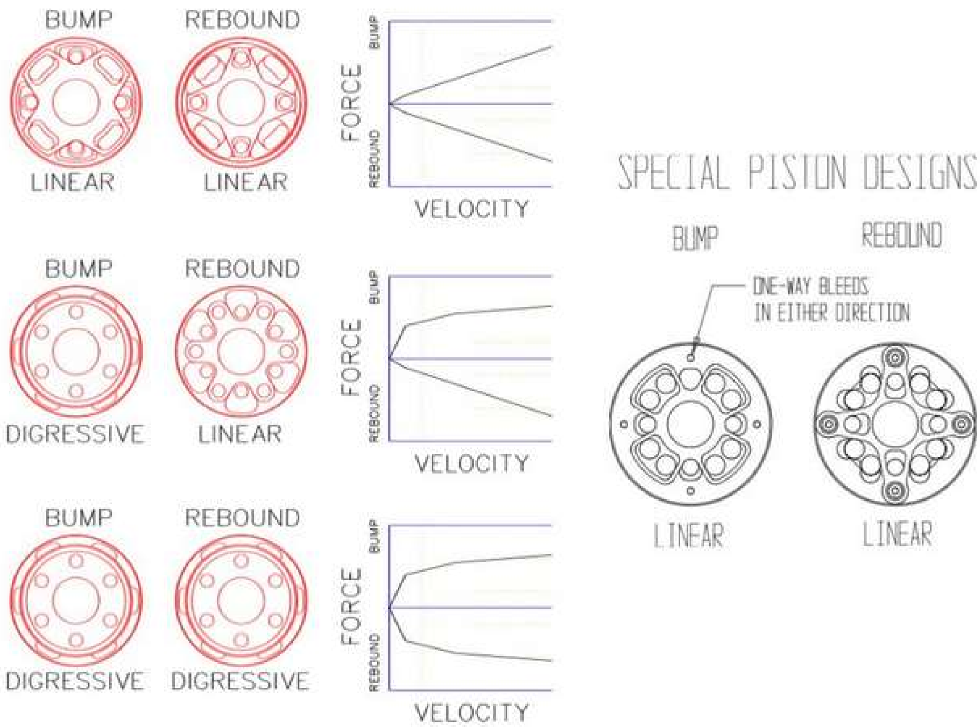

Figure 4.13. Piston shape designs and their effect on the force-velocity graph. (Extreme Racing Shox, 2019)

As for this project, the most important design and development characteristic is the viscosity of the radio control vehicle shock absorber's hydraulic fluid, also referred as damper's oil weight or thickness.

Figure 4.14. Radio Control Vehicle's Shock Absorber, changing the hydraulic fluid.

As seen before on the shims, the dampers fluid viscosity has the same effect on the force-velocity graph, since a more viscous fluid will flow through the piston easier it will create less damping; as for a less viscous fluid it will be more difficult to flow through the piston and therefore creates more damping.

Figure 4.15. Radio Control Vehicle's Shock Absorber.

5. The Monotube Shock Absorber's Mathematical Model

In order to understand better what happens with the variation of the volume inside the piston's chamber of the monotube shock absorber, a mathematical model is proposed. So first, in order to obtain the total force (F) of the shock absorber the next expressions are established by a Newtonian analysis of the shaft and piston ensemble. (Alonso, 2016)

$$F = p_2(S_C - S_V) - p_1 S_C \pm F_f \qquad \text{(Eq. 3)}$$

Or

$$F = (p_2 - p_1)\, S_C - p_2 S_V \pm F_f \qquad \text{(Eq. 4)}$$

Where p_1 and p_2 are the pressures inside the chamber on extension and compression respectively, S_C is the piston's surface, $S_V$is the shaft's surface and F_f is the friction force, on which the sign will be positive when the velocity is negative (extension) and negative when the velocity will be positive (compression). (Alonso, 2016)

This friction force can be obtained by comparison with indicative data obtained from the bibliography where according to (Alonso, 2016) a bike's monotube shock absorber's friction force can be considered around 25N and a vehicle's monotube shock absorber's friction force can be considered around 65N. Since the project works with a radio control vehicle scale 1/5, it can be assumed that for the radio control vehicle's shock absorber's friction force the data could be around 5N or less, since the shock absorber is doesn't have any pressurized gas. This data is only to be used as a reference. (Alonso, 2016)

The second equation that, even though a pressure drop between the chambers is not existent, there is always a force applied on the shaft. On the resting state, said force will only be perceive if it superior to the value of the static friction. (Alonso, 2016)

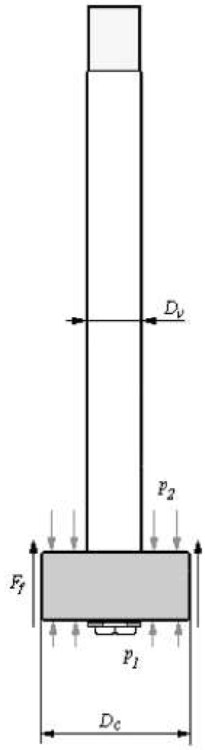

Figure 5.1. Free solid diagram of the shaft and piston ensemble. (Alonso, 2016)

To simplify the model, it will be considered as an incompressible model, and if the case of study would be a shock absorber with a gas chamber, the gas compression could be taken as a polytropic gas compression with a known exponent; but since the shock absorber in this project does not have any pressurized gas inside nor a gas chamber, it is safe to say beforehand that V_s and p_s won't considered for the model. The monotube shock absorber on which the model will be based on is shown below. (Alonso, 2016)

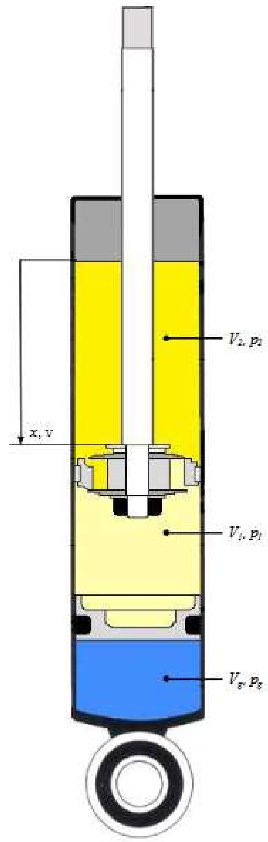

Figure 5.2. Mathematica's model monotube shock absorber. (Alonso, 2016)

For any given velocity of the shaft V, the volume variations inside the chambers are:

$$\frac{dV_2}{dt} = V(S_C - S_V) \quad \text{(Eq. 5)}$$

$$\frac{dV_1}{dt} = -VS_C - \frac{dV_g}{dt} \quad \text{(Eq. 6)}$$

Where V_1 is the volume of the shock absorber's fluid inside the compression chamber, V_2 is the volume of the shock absorber's fluid inside the extension chamber and V_g is the gas volume. (Alonso, 2016)

Then, a mass balance on the work piston establishes the expression:

$$\dot{m}_1 = -\dot{m}_2 \quad \text{(Eq. 7)}$$

$$\dot{m}_\iota = -\rho_1 - \frac{dV_i}{dt} \quad \text{(Eq. 8)}$$

Where ρ_1 is the shock absorber's fluid density inside the compression chamber, which according to the incompressible fluid's hypothesis would be the same for the extension chamber ρ_2. (Alonso, 2016)

These equations allow the deduction of the compression's chamber instant volume:

$$\int_{V_0}^{V_1} dV_1 = \int_{x_0}^{x} V(S_V - S_C)dt \;\rightarrow\; V_1 = V_{10} - (x - x_0)(S_C - S_V) \quad \text{(Eq. 9)}$$

Where V_{10} is the initial volume inside the compression chamber in the initial instant when x is x_0. (Alonso, 2016)

By the same procedure it's possible to determine the volume in the expansion chamber:

$$V_2 = V_{20} - (x - x_0)(S_C - S_V) \quad \text{(Eq. 10)}$$

Being V_{20} the volume inside the extension chamber in its initial position x_0. (Alonso, 2016)

Since the shock absorber's fluid for the model is considered as non-compressible, the inlet flow inside the expansion chamber is the one correspondent to its volume variation. Because of the signs convention that establishes that an inlet flow inside a volume is negative, the next equation is obtained:

$$Q_2 = -\frac{dV_2}{dt} = -V(S_C - S_V) \quad \text{(Eq. 11)}$$

Since a shaft's or work piston's velocity is given, the variation of the pressure of the compression chamber can be determined, as well as the flow going through the valves. (Alonso, 2016)

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The mathematical description of the valves can describe a functional relation between the inlet and outlet pressures, which allows to determine the existent pressure in the extension chamber and therefore the state of the shock absorber's internal parts at any given moment. (Alonso, 2016)

This can be better understood with the next equation:

$$p_2 = p_1 \pm \Delta p(Q_2) \quad \text{(Eq. 12)}$$

Because the flow used to know the pressure drop in the valves is the flow that they see in their inlet, strictly, the flow that enters the compression chamber (extension case, Q_1), and the flow that enters the extension chamber (compression case, Q_2) must be differenced from each other. In any case, since the shock absorber's fluid is non-compressible, the continuity equation in flow terms is fulfilled. (Alonso, 2016)

$$Q_2 = -Q_1 \quad \text{(Eq. 13)}$$

The resultant force due to the pressure (F_p) is obtained by:

$$F_p = p_2(S_C - S_V) - p_1 S_C = \pm\Delta p(S_C - S_V) - p_1 S_V \quad \text{(Eq. 14)}$$

The sign depends on if it is on an expansion or compression cycle. For an expansion cycle the sign would be positive, whereas for a compression cycle the sign would be negative. (Alonso, 2016)

The total damping force will be obtained taking into account the friction force as it was mentioned before:

$$F = \pm\Delta p(S_C - S_V) - p_1 S_V + F_f \quad \text{(Eq. 15)}$$

In order to have a better understanding of the mathematical model of the monotube shock absorber without pressurized gas and the volume variation in the chamber with the piston's movement, the shock absorber's fluid has to be considered as compressible, and therefore, a quick look at the extension and compression chambers is needed.

So, if a work chamber is supposed, which presents an approximately cylindrical geometry, internal radius r_i and length L. Because of the elasticity of the chamber caused by the increase of pressure, the change in the chamber's volume would be:

$$\Delta V_p = 2\pi r_i^2 L \beta_c \Delta p \qquad \text{(Eq. 16)}$$

Where ΔV_p is the increase of the chamber's volume due to the effect of pressure, Δp is the increase of pressure from the current pressure respect to the reference pressure $p(ref)$ originally in the cylinder and β_c is the compressibility's coefficient of the cylinder, which is considered as non-variable and is deducted from geometrical and elastic constants. (Alonso, 2016)

$$\beta_C = \frac{2}{E_C}\left[\frac{r_i^2 + r_e^2}{r_e^2 - r_i^2} + V\right] \qquad \text{(Eq. 17)}$$

Where E is the modulus of elasticity of the material, V is its Poisson module and r_e is the external radius of the cylinder. The internal and external radiuses of the shock are as shown in the picture below. (Alonso, 2016)

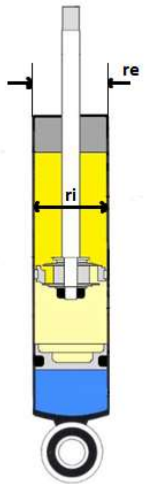

Figure 5.3. Internal and external radius of the shock.

A slight change in the chamber's volume due to temperature should also be taken into consideration, since the change of temperature will also affect the chamber's volume:

$$\Delta V_T = 2\pi r_i^2 L 3\phi_C \Delta T \qquad \text{(Eq. 18)}$$

Where ϕ_C is the cylinder's material linear thermal expansion's coefficient and ΔT is the increase of temperature from the current temperature until the reference temperature originally from the cylinder. (Alonso, 2016)

So, the total chamber's volume variation is due to pressure and temperature:

$$\Delta V = \Delta V_p + \Delta V_T \quad \text{(Eq. 19)}$$

In conclusion:

$$\Delta V = 2\pi r^2 L(\beta_c \Delta p + 3\phi_C \Delta T) \quad \text{(Eq. 20)}$$

The temporary variation in the volume increase is found as shown next:

$$\frac{d}{dt}(\Delta V) = 4\pi r L(\beta_c \Delta p + 3\phi_C \Delta T)\frac{dr}{dt} + 2\pi r^2(\beta_c \Delta p + 3\phi_C \Delta T)\frac{dL}{dt} + 2\pi r^2 L(\beta_c \frac{dp}{dt} + 3\phi_C \frac{dT}{dt}) \quad \text{(Eq. 21)}$$

Assuming that the cylinder's internal radius variations are slow allows to despise its derivate simplifying the equation as shown next:

$$\frac{d}{dt}(\Delta V) = 2\pi r^2(\beta_c \Delta p + 3\phi_C \Delta T)\frac{dL}{dt} + 2\pi r^2 L(\beta_c \frac{dp}{dt} + 3\phi_C \frac{dT}{dt}) \quad \text{(Eq. 22)}$$

And the introduction of the theorical non-deformable cylinder's volume (V_I) simplifies the equation's nomenclature:

$$\frac{d}{dt}(\Delta V) = (\beta_c \Delta p + 3\phi_C \Delta T)\frac{d}{dt}(V_I(L)) + V_I(\beta_c \frac{dp}{dt} + 3\phi_C \frac{dT}{dt}) \quad \text{(Eq. 23)}$$

Where it's noticeable that the non-deformable volume's derivate it's dependable only on the length L. (Alonso, 2016)

Now that chamber's volume variation has been modeled, this can be applied to the project's shock absorber's model. So, in order to model the case of study of this project, the monotube shock absorber without pressurized gas with its volume variation due to the piston's movement inside the chamber can be modeled as the monotube shock absorber's compressible fluid model. Its objective is to determine the shock absorber's damping force when its fluid is non-compressible and the work chamber's walls aren't infinitely rigid. (Alonso, 2016)

For a position x and a shaft's velocity V, beginning with the work chamber's expansion equations, the volumes of the chambers take the values of:

$$V_2 = V_{2I} + V_{2I}\beta_c\Delta p = [V_{20} + (x - x_0)(S_C - S_V)][1 + \beta_c\Delta p_1] \quad \text{(Eq. 24)}$$

$$V_1 = V_{1I} + V_{1I}\beta_c\Delta p = [V_{10} - (x - x_0)S_C][1 + \beta_c\Delta p_2] \quad \text{(Eq. 25)}$$

Where V_{1I} is the theoretical non-deformable chamber's volume and $\Delta p_i$is the pressure increase that the chamber suffers respect from the reference pressure originally from the chamber. (Alonso, 2016)

Now, the equation that describes the density of the shock absorber's hydraulic fluid is needed. This equation won't be temperature dependent and allows the determination of the mass that exists in the chambers and their temporary variations: (Alonso, 2016)

$$\frac{dm_1}{dt} = \rho_1\frac{dV_1}{dt} + \beta_f V_1\rho_1\frac{dp_1}{dt} \quad \text{(Eq. 26)}$$

$$\frac{dm_2}{dt} = \rho_2\frac{dV_2}{dt} + \beta_f V_2\rho_2\frac{dp_2}{dt} \quad \text{(Eq. 27)}$$

Using these equations allows the determination of the two governing equations. (Alonso, 2016)

$$\frac{dp_1}{dt} = \frac{-Q_1 + VS_C(1 + \beta_c\Delta p_1)}{V_1\beta_f + V_{1I}\beta_c} \approx \frac{-Q_1 + VS_C(1 + \beta_c\Delta p_1)}{V_{1I}(\beta_c + \beta_f)} \quad \text{(Eq. 28)}$$

$$\frac{dp_2}{dt} = \frac{-Q_2 - V(S_C - S_V)(1 + \beta_c\Delta p_1)}{V_2\beta_f + V_{2I}\beta_c} \approx \frac{-Q_2 + V(S_C - S_V)(1 + \beta_c\Delta p_1)}{V_{2I}(\beta_c + \beta_f)} \quad \text{(Eq. 29)}$$

Since there are two equations with four unknowns $(Q_1, Q_2, \frac{dp_1}{dt}; \frac{dp_2}{dt})$ another two equations are needed to solve the system, and the first one comes from the mass conservation: (Alonso, 2016)

$$m_1 + m_2 = cte \rightarrow \frac{dm_1}{dt} + \frac{dm_2}{dt} = 0 \rightarrow \dot{m}_1 = -\dot{m}_2 \qquad \text{(Eq. 30)}$$

And if it refers to the volumetric flows the equation of continuity is deducted:

$$\rho_1 Q_1 = -\rho_2 Q_2 \qquad \text{(Eq. 31)}$$

So, the second functional relation that is being searched comes from the drop of pressure that exists in the valves. If pressures and their temporary evolutions are given, the volumetric flow can be determined, and so does its temporary evolution, and this allows the model to be closed. (Alonso, 2016)

6. State of the Art

Shock dynos or damper dynos are an essential element when obtaining the characteristics and performance of shock absorbers. All of this is really important not only to offer shock absorbers as a product in the market, but also to improve in the development of new technologies and in the application to race shock absorbers, the data obtained from shock dynos, is used to get the advantage in performance by getting the perfect setup for the race car. (Perez, 2010)

For this project, all of the machines that were investigated obtain the data of the performance of the shock absorbers working with a sinusoidal signal of constant amplitude and variable frequency. The data obtained by the shock dyno will be used to get the correct setup for the radio control vehicle’s suspension. This can be done by applying the correct interpretation of the data, as it was shown before, and modifying the right things in the setup of the shock absorber such as the dampers hydraulic fluid or the valve setup and design, or even applying changes to the radio control vehicle’s suspension as the coils used with the dampers. (Clovis, 2012)

So, whatever the project, the goal still the same; obtaining the right data from the shock dyno and using it to improve the performance of the suspension. For this matter, the key to get the correct data is having a shock dyno that can deliver it. Therefore, in order to know the shock dyno that this project is aiming for, the technology available nowadays has to be analyzed.

Damper dynos can be separate in two main groups, each group depending on the power station they use and the movements they allow. The first one is the electromechanical shock dyno, which power station is basically an electric engine. And the second one is the servo-hydraulic shock dyno, which gets its power from one or various hydraulic actuators that deliver more force for the test of the dampers. These last ones are the most common in the automotive sector. (Perez, 2010)

It is important to mention that a national or international normative on how to test the shock absorbers is non-existent, and therefore, each manufacturer has its own processes of test and analysis. (Perez, 2010)

The electromechanical shock dynos are test machines which are powered by an electrical engine. This electrical engine rotates a flywheel, which moves a piston transforming the rotational motion into a linear one. The damper is installed on this piston and will make the damper's piston move up and down by having the upper part of the damper statically installed to the machine by its upper part. This shock dynos are actually very rare, because of the force that needs to be delivered by the electric engine to make the damper's piston move. (Perez, 2010)

A good example of this kind of shock dyno is the MecaDyn 101, which features the possibility to modify the flywheel's rotational speed to simulate different use conditions. This is really important in order to get slow and fast speed behavior data. (Perez, 2010)

Figure 6.1. MecaDyn 101. (Perez, 2010)

The servo-hydraulic shock dynos are test machines which have one or various servo-hydraulic actuators, and those are the ones in charge of making the damper's piston move by installing the damper in the machine by both of its ends. These servo-hydraulic actuators have the advantage that can easily deliver more power and generally are more versatile since they can test fatigue and perform dynamic tests with different extension, compression and flexion requirements. (Perez, 2010)

Servo-hydraulic shock dynos are more complex machines, and a good example of this is the EFH Microtest. A parts diagram of this test machine is shown next.

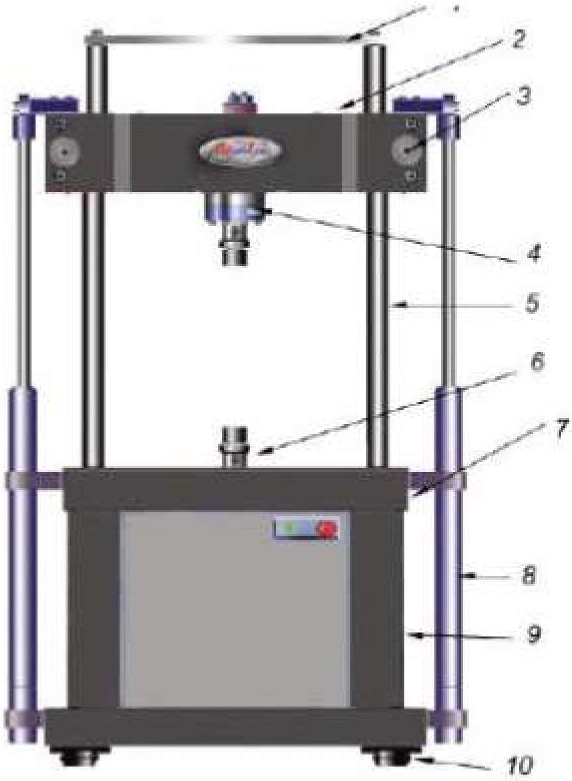

Figure 6.2. EFH Microtest parts diagram. (Perez, 2010)

1. Fixed crossbar (optional)
2. Mobile bridge
3. Head lock/unlock system
4. Force transducer
5. Chrome guard columns
6. Servo-hydraulic actuator
7. Motherboard
8. Mobile bridge's rise/lowering cylinders
9. Chassis
10. Damping support brackets

Since damper dynos are test machines that are practically used for each users' goals and requirements, damper dynos manufacturers generally offer on user demand modifications to adapt them to their necessities. And therefore, this test machines are also used for other purposes such as elastic testing of materials. Such is the case in the machine shown bellow with the coupled jaws for metals testing. (Perez, 2010)

Figure 6.3. Shock dyno with coupled jaws for metals testing. (Perez, 2010)

Position and orientation of the test frame can be also key to other manufacturers and developers. In such cases there are companies such as IST that offer exclusive test frames to test shock absorbers in different simulated situations and may go from a vertical test frame to a fully horizontal test frame if needed. (Perez, 2010)

Figure 6.4. IST MSP shock dyno with optional test frame. (Perez, 2010)

It is important to mention that in the automotive sector, the most important company of shock absorbers dynos manufacturers and developers is MTS. They have been accomplishing important developments in this industry since 1996, and offer a big range of solutions in hardware and software for any client needs when it comes to damper dynos. Therefore, damper dyno manufacturers accept the results given by MTS machines as a reference to any others. (Perez, 2010)

Figure 6.5. MTS 850.50 Model, testing 6 shock absorbers at the same time. (Perez, 2010)

For this project, the power needed to test the radio control vehicle's shock absorbers isn't such that a servo-hydraulic power source is needed; therefore, in the case of radio control vehicle's shock absorbers testing, electromechanical shock dynos are the ones used.

Having the right suspension setup is really helpful when trying to get the best performance of radio control vehicles and a very effective way to get advantage over the competition when racing radio control vehicles. That is the reason why there is a very vast market when it comes to radio control vehicle's suspensions, dampers hydraulic fluids with different densities, suspensions accessories and all the different tuning options for their suspensions systems. (Clovis, 2012)

Although this is a widely discussed topic in the radio control vehicles' community, there are really few options when it comes to radio control vehicles' shock dynos; and most of the users stick to the trial and error way to test and fine tune their radio control vehicles' suspensions on the track. And the ones owning a shock dyno are typically dampers and suspensions manufacturers and developers. Either way, the available options will be shown next, in order to decide the direction of the project. (CTW Automation, Inc., 2019)

When it comes to radio control vehicles' shock dynos, the finest available is the CTW Automation RC shock dyno, or as they called it in CTW Automation, the RC-D-Shock and Damper Machine. This radio control vehicles' shock dyno is the top-notch shock dyno available to the public, developed by a company that manufacturers shock dyno for the automotive sector since years. It is designed for RC car/truck/buggy shocks and features a 222 N. S-beam load cell to measure the damper forces with either 0.25 inches or 0.5 inches strokes, thanks to its CTW designed 2 stroke crank head for frequency variation, with a peak velocity over 12 inch per second on the 0.5 inches stroke. It has its own software, which was developed by the company and is the same software they use for the shock dynos in the automotive sector. The whole machine can be controlled from the computer via the software, and works with emulators for either Windows or Mac, and even tablets and smartphones. (CTW Automation, Inc., 2019)

Figure 6.6. The CTW Automation RC-D-Shock and Damper Machine, with a mounted radio control car's shock. (CTW Automation, Inc., 2019)

This machine by CTW Automation is available to the public for $.2650 and thanks to its advanced software, it delivers the displacement and velocity vs. force graph right away.

Is a very useful equipment, because it allows the test of any kind of radio control vehicles' dampers. The machine is an electromechanical shock dyno an it is built in heavy steel. (CTW Automation, Inc., 2019)

Figure 6.7. The CTW Automation RC-D Shock and Damper Machine's Flyer. (CTW Automation, Inc., 2019)

As mentioned before, there are other radio control vehicles' shock dynos in the industry, but they are usually kept by manufacturers and developers to themselves. Some of these will be mentioned next.

First there is the CSI (Competition Suspension Inc) shock dyno, which they disclosed in the radio control cars community back in 2013, with a post on the RC TECH Forum. (RC TECH, 2013)

Figure 6.8. CSI Shock Dyno. (CSI, 2013)

According to what was stated by the company in the forum, they finally had a working shock dyno after twelve months of design and development, and they even made a video for their machine's debut. The video is no longer available online, and seeking information about this shock dyno, it was found that the machine was only for CSI's use as manufacturer and developer, and that they wouldn't be selling the machine, neither testing users' suspensions. (RC TECH, 2013)

According to the information found on the company's web site, they no longer work on radio control cars suspensions, and there is no evidence that the radio control vehicles' shock dyno is still being used by CSI, since nowadays, all of their products are strictly for whole scale race vehicles only. (CSI, 2013)

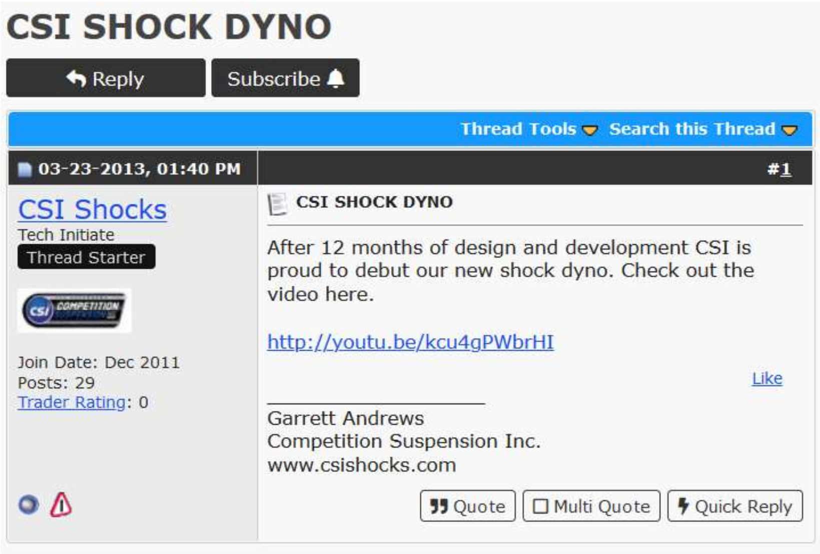

Figure 6.9. CSI SHOCK DYNO debut post on RC TECH Forums. (RC TECH, 2013)

There is even someone according to (Hobby Talk, 2013) that claims he built the shock dyno for CSI with hie brother as a project as a request of a couple shock manufacturers for RC car shocks, as he stated. The dates of the release of the CSI shock dyno are the same, and even the picture this person posted shows the same machine. What's really interesting is that in the first picture of the CSI's shock dyno, shown above, its mechanism wasn't shown, but thanks to another post by (CSI, 2013) and the post on (Hobby Talk, 2013) not only a comparison to make sure the machine discussed was the same could be made, but also the mechanism of said machine could be seen.

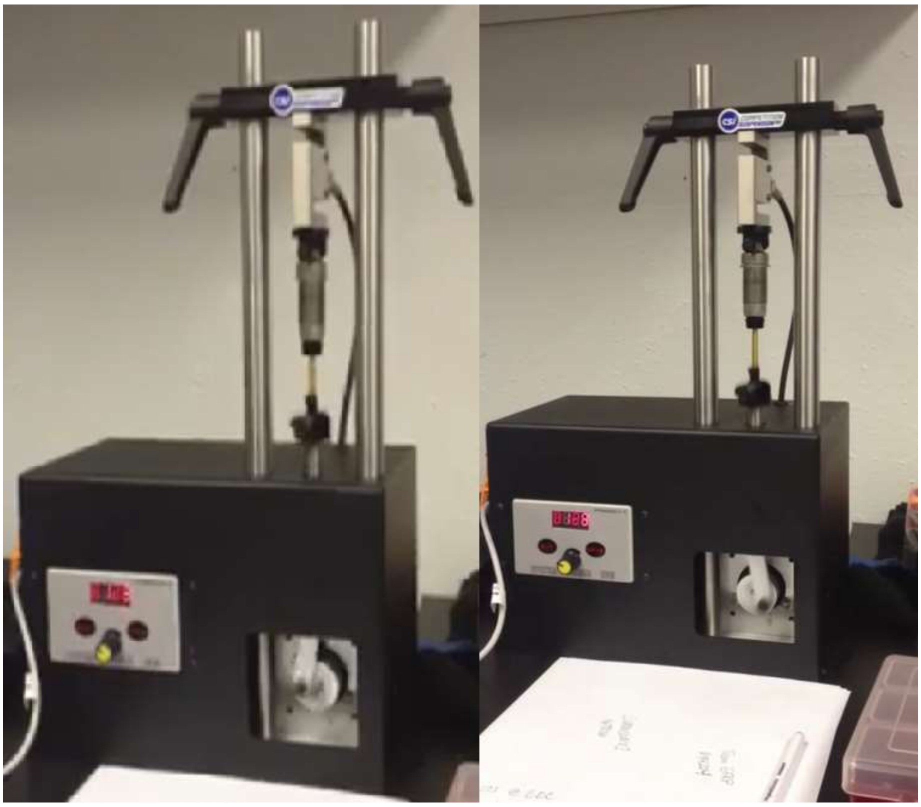

Figure 6.10. CSI's shock dyno showing its components and mechanism. (Hobby Talk, 2013)

All of the above pictures of the CSI radio control cars shock dyno where compared to a newsletter update made by the company (Performance Trends Inc, 2013), where they posted a screenshot of the debut video bac in 2013 of the CSI's shock dyno, which still no longer available online. But looking at the screenshot, shows the exact same machine shown in all of the pictures above. So, surely CSI had this machine working years ago, but they never sold shock dynos to the public and just used it for R&D inside the company when they used to manufacture and develop radio control vehicles' shocks.

Figure 6.11. CSI's shock dyno debut video (no longer available).

According to (Performance Trends Inc, 2013) they were the ones that developed the electronics and the software behind the CSI's RC shocks dyno, since as they state on their web site's newsletter from 2013, CSI turned to them in the need of an affordable set of electronics and software for the very small shock dyno for RC car shocks they developed.

The next radio control vehicles' shocks dyno isn't as controversial as the CSI's one, since there is not much information to it, neither are there so many claims of who helped to develop it or who built it; yet, it still is another radio control vehicles' shocks dyno used strictly for a radio control vehicles shocks' valves manufacturer and developer. This is the Car Sports shock dyno, and by stated by them, their shock dyno is their R&D secret to deliver the best product to the public and satisfy their needs. (Car Sports, 2018)

Figure 6.12. Car Sports shock dyno with exposed mechanism. (Car Sports, 2018)

Car Sports is a company dedicated strictly to manufacture and develop radio control shock inner parts, mainly valves, that offer different piston setups that vary in designs and solutions to fine tune radio control cars suspensions and getting their best performance. Their videos of their shock dyno are very straight forward, and they even show their dyno without any covers, revealing its whole mechanism and parts, as shown in the picture above. They even show a few runs and the data they obtain from their machine, showing and comparing the graphs of their shocks with different valves setups. They even have this really interesting damper with a transparent cover which shows the radio control shock absorber's hydraulic fluid behavior when their tests are made. (Car Sports, 2018)

According Earl, the person who runs the tests at the "Area 51 Development Lab" from Car Sports, they built their shock dyno and the clear cover radio control damper their selves. They use it to test how the suspensions behavior varies with different shock absorber's hydraulic fluid or oil, and with different piston's valves setups. They plot the force vs. velocity graphs and as Earl states in their videos, this is a really interesting way to analyze in a practical way the shock's behavior and nothing compares to being able to test this way. (Car Sports, 2018)

Figure 6.13. Earl from Car Sports at the Car Sports "Area 51 Development Lab" running tests with the Car Sports' shock dyno. (Car Sports, 2018)

Another radio control vehicles' parts manufacturers and developers are GHEA. GHEA is a Swedish company that dedicates strictly to radio control vehicles' racing parts and among a really vast catalog with different parts to tune and modify radio control vehicles, they offer their own radio control vehicles' shock absorbers piston valves and they also have their own shock dyno to test them. (GHEA, 2019)

GHEA's shock dyno has a really interesting built and setup, since as seen before, all the shock dynos so far have been all a scaled down version of actual automotive electromechanical shock dynos with different built setups as to their mechanisms, which are either a piston-crank mechanism or a scotch yoke slider, all disposed in a vertical position attached to the lower end of the damper and a load cell attached to the upper end of the damper. But the GHEA's shock dyno is displaced in a horizontal manner, as shown in the picture below. (GHEA, 2019)

Figure 6.14. GHEA's shock dyno. Horizontal build setup. (GHEA, 2019)

Analyzing GHEA's shock dyno two main ideas might be concluded. First, the horizontal displacement of the dyno might affect the result on the damper's behavior, since radio control vehicles' shocks are meant to work in mostly vertical shock displacement suspension, in some cases angled, but never closer to a horizontal setup, rather than a mainly vertical one. This won't affect their test results as long as the shock absorber doesn’t have any air bubbles inside with the hydraulic fluid, so this is something that has to be considered when setting up the shock correctly. And the second conclusion about this interesting kind of shock dyno’s built displacement and setup is that perhaps the error added by it isn’t considerable, and as a benefit a lot of spends are saved by having less parts involved, making the machine more practical in terms of making the machine more adaptable to any size of shock absorbers that needs to be tested and allowing more changes in the strokes’ size/length. Saving expenses on the shock dyno’s structure also allows the user to spend resources on a good quality electrical engine and parts that allow to play with different test setups like the stroke size, for example, by using a stroke length selector drum; as shown in the next picture. (GHEA, 2019)

The GHEA’s shock dyno has a really interesting build setup, since it might appear as if it has not many components, which make it look like an easier machine to build. Although, as shown in the picture above, it appears that the company really invested on the electrical engine they used and the stroke length selector drum they attached to it, which is a really efficient solution when it comes to the stroke length variability when testing the dampers. As all of this radio control shock dynos, there is not much information to them, neither is there any information on the development of their machines or how and why they built them as they did. (GHEA, 2019)

The next radio control vehicle's shock dyno is a user created dyno. This machine was created by Eric Nickel, yet again, there is too little information on it and all the information gathered and analyzed comes from a video where he reported and showed a few features of the machine he built and disclosed only a little bit of his built. As he states, he is not interested in selling the shock dyno's drawings, since he is looking to mass produce the dyno at some point when he is happy with the final product. That was back in 2013, and until this day there have been no news of his shock dyno either selling or mass producing, neither plans or drawings being sold or disclosed to the public. (Nickel, 2013)

Figure 6.15. Eric Nickel's first prototype shock dyno with its front scotch yoke echanism. (Nickel, 2013)

At first, it looked like a really ambitious project, but it has a few downs that have to be taken into consideration with Eric's first prototype and they are going to be analyzed next. His built is a scaled down version of an automotive shock dyno, but as seen on his report, it seems to be too little to actually work with big or too strong radio control cars' dampers, since when compared to the Car Sports or the CSI shock dynos, Eric’s machine looks really tiny and as if it wouldn’t have enough support to hold dampers that demand it or extensive test sessions. Eric explains that his shock dyno has a load cell on its upper end and a motion sensor inside, a data port for all the data obtained by the load cell and the sensor, and it works with a step motor located at the bottom of the machine. (Nickel, 2013)

Figure 6.16. Eric Nickel's shock dyno showing the bottom with the electrical step motor inside. (Nickel, 2013)

In the front it has a scotch yoke slider mechanism, just like on a conventional dyno; but in the back it has a belt system that actually drives the dyno. This belt system looks really complicated to manufacture, since its parts are so tiny, and the belt that it uses it’s pretty unique. The data port gathers all the data obtained by the machine and uses an Arduino interface to post process the results. All the data obtained is transferred to his computer, where it is processed in Microsoft Excel, using the Parallax Inc software linked to Excel to process all the information and analyze it in order to deliver the force vs velocity graphs. But as stated by Eric himself, he still was not happy with the results of his dyno, and even on his video report the post processing starts showing some failures when tested. (Nickel, 2013)

Figure 6.17. Eric Nickel's shock dyno's belt system. (Nickel, 2013)

Eric’s shock dyno shows a load cell on top and a position sensor inside, but in the back, it has a belt system that drives the dyno. This design might be efficient in some way, but is too complicated to manufacture, and the little belt it has installed must be really difficult to get, therefore having a shock dyno designed this way is not recommended. Then his dyno sensors are connected to an electronics boy where he plugs the data cable, this data box has two buttons, one for calibrating and the other one to take measurements as he states in the video. Then all of this data goes into Excel and that’s how he gets the graphs at the end. (Nickel, 2013)

Eric Nickel even states that all of the pieces of his shock dyno were machined one by one and that there is no manufacturer yet willing to work with a small production of his shock dyno. This means that this design has to be very complicated and has too many one of a kind pieces that would need too much time to be manufactured and that the design of this dyno has to be simplified. (Nickel, 2013)

So, radio control vehicles shock dynos are usually a scaled down version of automotive dynos, and since the radio control vehicles' shocks are usually monotube non-pressurized dampers they can be really simple in design as long as they can have enough structural performance as to run the tests. A really good example of this is Gary de la Rosas's RC Car Damper Dynamometer's project, which shows a functional damper dyno built with 3D printed parts, some structural steel, and electronics that can be easily purchased. (Rosa, 2016)

Gary's shock dyno was made supposedly to get the force vs. velocity curve from which a damping ratio can be extracted. As he states on his project's report, his dyno can be done with basic tools, such as soldering iron and a handheld rotary tool, most commonly known as "Dremel", and of course, having access to a 3D printer is essential. His shock dyno uses a 5 kg load cell with a Sparfun HX711 load cell amplifier, a 6 – 9 V DC motor with an Arduino UNO for all the electronics to be installed, and his data is transferred to a computer via USB. Gary's shock dyno was even designed based on testing a Traxxas damper, which is the same damper of interest of this project. (Rosa, 2016)

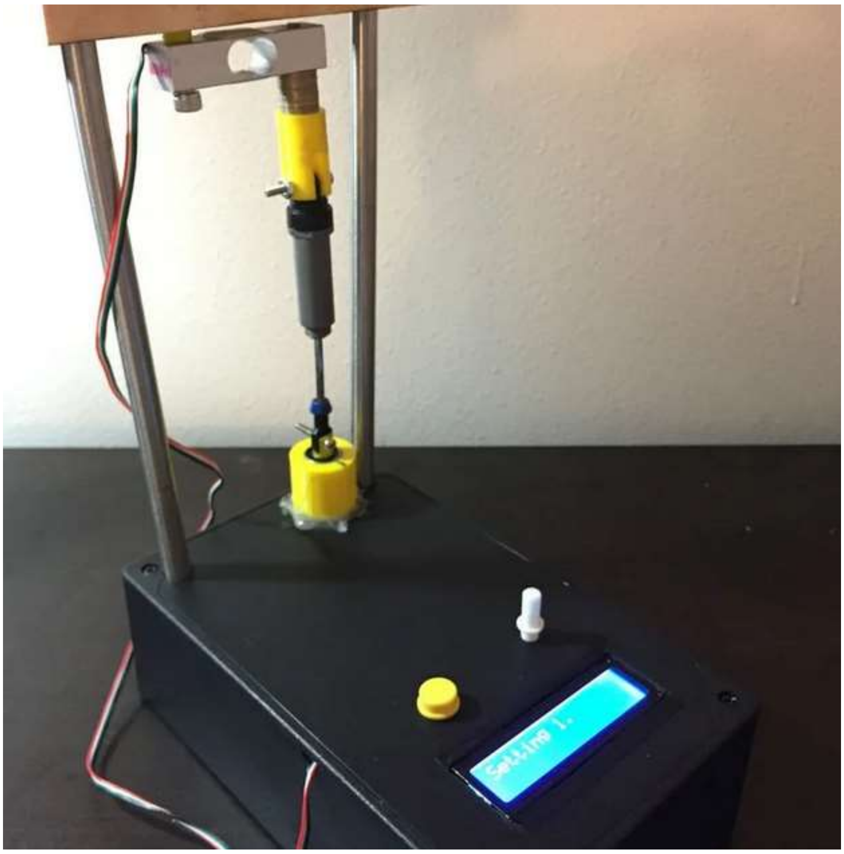

Figure 6.18. Gary de la Rosa's RC Damper Dynamometer testing a Traxxas radio control vehicle's damper. (Rosa, 2016)

Gary's design has a complete report on the design and build of the project, with a lot of information on it, which is really interesting, since so far all of this shock dynos' projects are really rare and hardly give up any information on the design and build of such machines, but still, this project doesn't present any information on the data obtained with the dyno, neither does it explain how to post process it. Gary even shows a video of his damper dyno supposedly working, which is the only information so far on other shock dynos presented until now. Gary's project has no information whatsoever on the post processing of the obtained data in order to finally get the graphs, and even on his video, he shows the shock dyno running but never shows either the acquired data on the computer, neither the post processing or the actual graphs. (Rosa, 2016)

The next shock dyno is a project made by Scott Fredrickson, and this project is not only about the build of a radio control vehicles' shock dyno, more than that, is the perfect mix of passion for something, the expertise on a topic and a lot of motivation on doing something outstanding. Scott is really passionate about radio control vehicles and their performance; and began working as a Test Engineer in 1997, having more than 15 years of expertise in the field of testing engineering he understands instrumentation, test and measurement techniques, analyzing data and is always wanting to know more; add to that that he is really motivated about putting all the “advise” there is out there about radio control vehicles performance to the test, wanting to share knowledge and proving that not only companies with their own in-house shock dynos should be able to have access to this data. Add all of that together and you have the perfect combination for an outstanding project that has a lot of dedication to it and is really worth of recognition, because it not only proves that you don’t have to own a company to have access to certain knowledge, but as Scott mentions in his work*, “Education advances technology much faster than secrets”* (Fredrickson, R/C Car Shock Dyno Test, 2015).

Figure 6.19. Scott Fredrickson's first project's paper uploaded in 2015. (Fredrickson, R/C Car Shock Dyno Test, 2015)

His work is so well written that anyone can understand it, from little kids wanting to start getting to learn about radio control vehicles’ performance basic principles to engineers wanting to apply high tech and engineering data into their radio control vehicles’ design and performance development. Scott really hopes to benefit everyone interested on the topic with his work, presenting to the world a really nice structured project where he invested his money, time, knowledge and effort; because as he states, it isn’t cheap to build the shock dyno, and it takes a lot of time to test the configurations, and it takes even more time to analyze and deliver al the information he got from this project. But he always had interest in car racing of all types through his life and is a true believer of advancing technology by sharing education and knowledge so that everyone benefits from it. (Fredrickson, R/C Car Shock Dyno Test, 2015)

As Scott states in his work, a Shock Dynamometer is a machine that cycles a damper, and it measures the resistance force based on the velocity input. And due to the mechanism's characteristics, the motion is typically a sine wave input. So, a scotch-yoke is a perfect sine wave input, and a slider-crank is a very close approximation of a sine wave, if design properly, therefore Scott's setup used a slider-crank for his shock dyno. (Fredrickson, R/C Car Shock Dyno Test, 2015)

Figure 6.20. Scott Fredrickson's shock dyno with a radio control vehicle's shock mounted on it. (Fredrickson, R/C Car Shock Dyno Test, 2015)

Then in his work, Scott describes the setup he used on his shock dyno to make the different tests and the specifications of his shock dyno. (Fredrickson, R/C Car Shock Dyno Test, 2015)

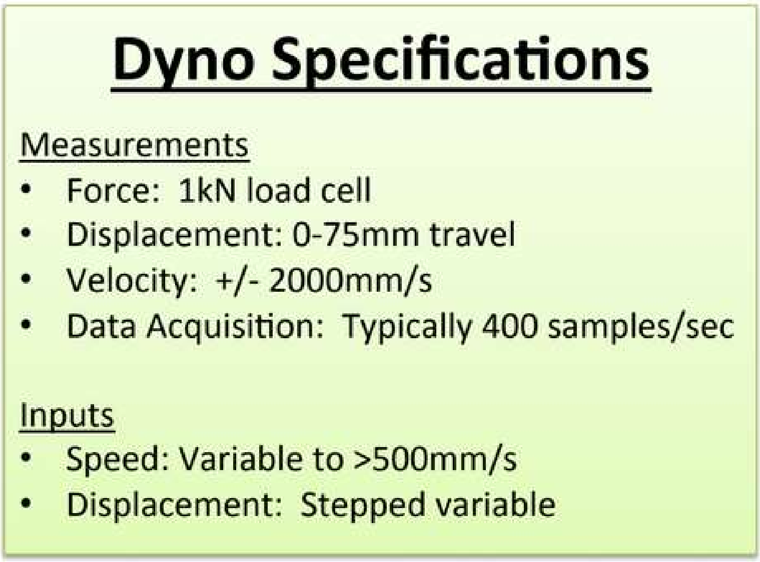

Figure 6.21. Scott Fredrickson's shock dyno specifications. (Fredrickson, R/C Car Shock Dyno Test, 2015)

Scott's shock dyno measures three properties simultaneously; force, velocity and displacement, which are all useful to produce two plots used to interpret damper performance and that are of special interest for this project; the force vs. displacement graph and the force vs. velocity graph. Scott not only describes the post processing obtained by his shock dyno, but also explains in his work how all of this gathered information and data is interpreted in terms of the suspension's performance. His work is so well structured and is such a good source of knowledge that he even explains suspension basics and principles used in the radio control vehicles' suspensions settings in order for anyone to understand how they can get the best performance out of their own radio control cars by interpreting the graphs and choosing the right type of damper, damper piston design and oil thickness. (Fredrickson, R/C Car Shock Dyno Test, 2015)

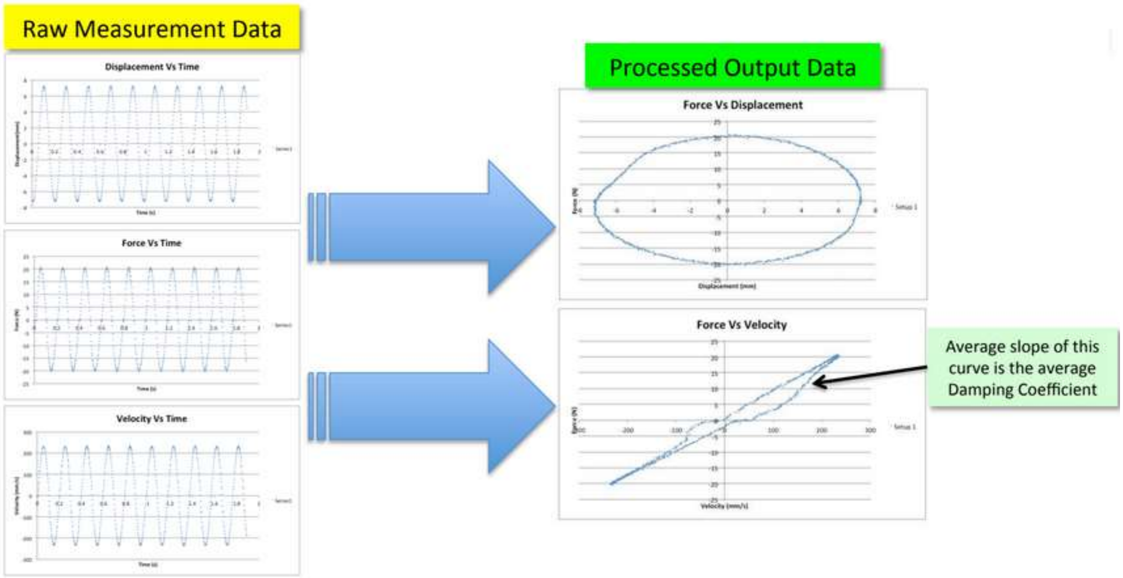

Figure 6.22. Scott Fredrickson's shock dyno's raw measurement and processed output data. (Fredrickson, R/C Car Shock Dyno Test, 2015)

Scott continued his research and the development on his project with amazing good results of having a really nicely build shock dyno that works properly and delivers effectively the data that the project was aiming for. He then uploaded other reports where data about measurements and graphs of several different specialty damper pistons that were tested on his dyno can be found and he even made a table were anyone interested on the topic can look up for the actual viscosity of different oils used in radio control cars' dampers with respect to the actual temperature of the oil. The last report he uploaded is a piston damping prediction used to make comparisons between up to four different piston and oil combinations, from different tests he accomplished with his shock dyno.

So, Scott Fredrickson's project is by far the best, and as far as the investigation for this project goes, the only one with a self-built shock dyno with consistent results in different tests getting the graphs that interest the most for this project. Scott's project also shows a very well explained work from the shock dyno setup to the post processing method used by him. And most importantly, as he mentions, his project's intention is to share knowledge and help anyone understand the radio control vehicles' suspension performance better through engineering and physics instead of just opinions and "advice" with no basis.

As Scott's project was really astonishing and he seemed to be really moved by his passion towards engineering, data acquisition and analysis, and knowledge sharing;

contact was made with his author, and he answered. He did not only read this project and analyzed the other projects presented here as well, but also shared a complete, very detailed and exclusive write-up on his project build, data acquisition, calibration and data post-processing. His work is really amazing and it totally shows all the time and effort put into it, and, of course, the years of expertise that Scott has as a Test Engineer.

Scott mentioned that some of the shock dynos presented before on this project are mostly design based on the scotch-yoke configuration, and that this is not only really difficult, but also makes the project more expensive and is totally unnecessary; referring mostly to the companies owned shock dynos. Then, Scott even took the time to see the videos and analyze the other builds of the self-built projects presented before, and he agrees that Eric’s shock dyno has a really complicated design and he made the observation that on Eric’s video the damper is not well attached to the machine and this could cause his dyno not to work properly. Then, he also saw Gary’s video and mentioned that this project is not having any results since in the video the machine can barely move the damper and that there is no way this project will ever get to deliver any results, which explains pretty much why Gary never presents information about the data obtained with his shock dyno and the post-processing of his data.

In order to select the best shock dyno to use a as base for the design and build the shock dyno a comparison with the most important characteristics of the different dynos that were investigated was done. The different characteristics were evaluated based on the information available on each dyno that was very carefully investigated in order to evaluate them from 1 to 7 being 7 the best and 1 the worst on each characteristic. The most important aspects to evaluate were the performance as seen on videos of the dynos working, the constructability based on the information that is available to actually build the dyno, the post-processing available information for each dyno and the results that each dyno was able to provide as seen in the videos and reports that is available for each dyno. According to the results of this comparative table the best shock dyno to select as a base design for the dyno build is Scott Fredrickson’s shock dyno. The results for the comparison of the shock dynos is shown in the table below.

							
Name	CTW	CSI	Car Sports	GHEA	Nickel, E.	Rosa, G.	Fredrickson, S.
Price	1	5	4	3	2	7	6
Performance	7	4	5	3	2	1	6
Constructability	1	4	3	5	2	6	7
Post-processing	3	5	6	4	2	1	7
Results	7	4	5	3	2	1	6
TOTAL	19	22	23	18	10	16	32

Table 6.1. Comparative table of all the evaluated shock dynos.

In conclusion, radio control vehicles' shock dynos is a topic on which no solid engineering data can be found, and the only one providing real data and support with it is Scott Fredrickson; because all of the very few company owned projects out there share no data on either tfheir build or their results. Scott's project is the only one, from the company owned and the self-built projects, that has proven to actually work efficiently and deliver consistent results on the data and graphs that this project seeks. Therefore, and thanks to Scott's support with this project and his exclusive write-up on his built, this project will take on with his project and build a shock dyno based on Scott's design and data acquisition model. (Fredrickson, R/C Car Shock Dyno Test, 2015)

7. Pre-Design

The pre-design of this project will review all of the project's requisites and evaluate that all of them are accomplished by the shock dyno on which the design will be based on. This is done as a measurement of good engineering practices so that the project's design is evaluated on this phase and any needed changes or decisions are done and taken now and not in the next phases.

Therefore, and as stated in the previews section, Scott Fredrickson's shock dyno will be evaluated, and the pre-design analysis will establish if this project's requisites are met by Scott's shock dyno design, so that if any changes are needed to be done on his design, those decisions can be taken here and applied on the next phases.

Machine	Project (requirements)	Scott Fredrickson
Shock type	Monotube non-pressurized	Monotube non-pressurized
Shock scale	1/5	1/10 to 1/5
Stroke length	± 20 mm	19 mm
Measuring forces	± 50 N	Up to 75 N
Velocity	Preferably variable	Up to 300 mm/s

Table 7.1. Requirements of the project's shock dyno and Scott Fredrickson's shock dyno specs.

As the table above shows, the requirements that were set for the machine that this project aims for are all met by the machine that has been selected as a base design for the project. It was design to test the same shock type of interest for this project and can be used for the same scale that the project requires, as stated by Scott Fredrickson. It also meets the requirement for the stroke length and has a variable velocity up to 300 mm/s which is enough, as discussed with the tutor in the first project meet. And last but not least, the measuring forces of the machine selected as a base for this project go up to 75 N, which accomplishes the 50 N that the project was aiming for, even providing a security margin of 25 N.

This means that this machine is perfectly suitable in order to accomplish all of the project's objectives, and this is really important, not only because this means that the project is buildable and that there are not mayor changes to be done to the project, but it also means that the project will have a significant lower cost, building a machine that has been tested before by its developer and has been proven to work and deliver the results this project seeks.

Since all of this requirements are met by the machine that was selected as a base for the project's machine and all the material provided by Scott Fredrickson and his support with this project; it can be stated that the thorough investigation into the existing shock dynos really paid off, because this machine is not only a shock dyno that meets all of the project requirements, but it is also a machine that has already been tested several times, as shown in Scott Fredrickson's work, and is proved to work and deliver the results of the graphs that this project aims to achieve. This also means a huge accomplishment for the project's budget, since as discussed before, the least parts that have to be machined for this project the better, because that helps to keep the budget as low as possible.

Therefore, in the next sections of this project, a detailed step by step building instructions procedure for the shock dyno will be developed, based on Scott Fredrickson's exclusive document written for this project. Also, a data acquisition explanation and a post processing guide will be included, since this are the most important features to make this project buildable and a success by not only making it work, but also acquiring the characteristics of the dampers of the radio control vehicle that this project is meant to obtain and making it possible with a machine's budget that is lower than the other commercial machines that can be found on the market.

8. The Shock Dyno

The shock dyno is composed of four different main components: frame, motion mechanism, instrumentation and data acquisition. Each of these main components and their build will be described below. (Fredrickson, Construction of an RC Shock Dyno, 2020)

As far as this project was able to reach, the construction main instructions will be discussed here, pointing out the most important specs on the parts and instrumentation needed to build it. For further detail please refer to the complete version of the build, construction instructions, parts description, pictures, calibration method and use of the machine added in the appendix.

8.1. Frame

The frame most be as solid as possible, since it will face all the forces and is the machine's main structure. These forces will affect only in the axial direction (z) of the shock absorber when articulating the shock up and down. Therefore, the frame should be stiffest in the z direction, and support in the x and y directions. The frame uses 25 mm style extruded aluminum bolted together with brackets and t-nut hardware for its build, and in order to mount it, a mounting platform is needed. This mounting platform is none other than a 25 mm x 50 mm extruded aluminum frame. The advantages of this material are that it is really easy to acquire and very versatile requiring no special tools to work it. (Fredrickson, Construction of an RC Shock Dyno, 2020)

The critical fabrication requirement with the frame is to cut all the bars to have square corners, this can be achieved with a metal-cutting chop saw or a horizontal band saw, because using a hack saw may result in angled cuts. (Fredrickson, Construction of an RC Shock Dyno, 2020)

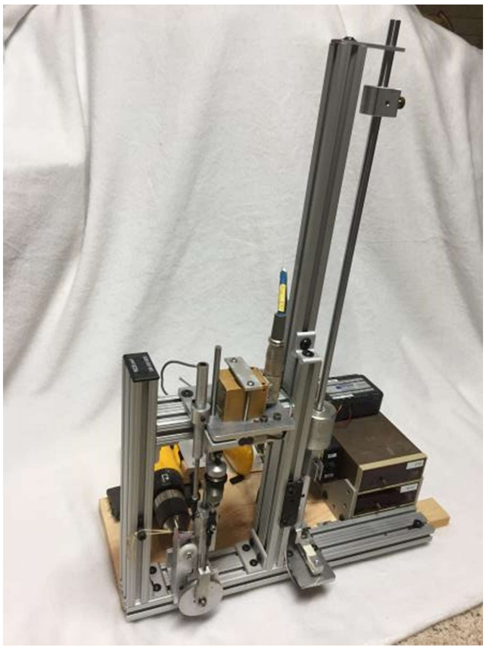

Figure 8.1. Scott Fredrickson's shock dyno. (Fredrickson, Construction of an RC Shock Dyno, 2020)

The frame consists of a horizontal base, two vertical pillars and a horizontal upper brace. Both of the vertical pillars need to be bolted to the base to be solid, and the platform is attached between the pillars so that it allows vertical adjustment. Since this dyno is built specifically for a 1/5 scale damper it will only need to be adjusted once. (Fredrickson, Construction of an RC Shock Dyno, 2020)

The base of the frame will also have attached to it the rotational mechanism and support the base of the slider joint; and the upper platform will be used to mount the instrumentation and the upper shock body. This will all be discussed in later detail. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.2. Motion Mechanism

In order to simplify the manufacturing process, a basic crank-slider mechanism was selected for the machine. The length of the arm between the crank and the slider will determine how close to sinusoidal the motion will be. The longest the arm the more achievable the sinusoidal motion will be, so for the machine a 100 mm arm is used, in order to achieve the 19 mm stroke length with a reasonable sinusoidal motion, keeping the shock dyno compact. (Fredrickson, Construction of an RC Shock Dyno, 2020)

For the rotational motion a typical cordless drill is used, like the DeWalt 18V, because they deliver an excessive amount of power and are really easy to control. It also provides a very smooth rotational motion which helps keeping the influence of the test item to the minimal. This drill is attached to a 6 mm shaft that runs through a double-bearing block attached to the frame platform. The alignment of the drill to the shaft is very important for a smooth operation, so supporting the drill with a foam block is recommended. For the shaft to be supported the bearing block had the two bearings spaced approximately 50 mm apart. (Fredrickson, Construction of an RC Shock Dyno, 2020)

The other end of the shaft is where the crank is attached. This is no other than a round disk with a hole drilled at a radius of 9.5 mm for the slider articulation in order achieve the 19 mm stroke length. The hole was tapped to accept a shoulder bolt that is the rotational joint of the crank-arm. The upper platform of the frame can be adjusted to have the stroke length intended, only paying attention not to hit the top or bottom limits of the shock travel, in order to get the damper characteristics right. (Fredrickson, Construction of an RC Shock Dyno, 2020)
For the connecting arm a typical radio control turnbuckle is used as the rod. One end is fitted to the shoulder bolt on the crank disk with a bronze bushing with some light oil applied to it, and the other end has a plastic rod eye sized to fit the turnbuckle with preferably an M4 size hole in the eye for the screw. This one is plastic so that it has zero slop in it, since it is more of a pressed/friction fit and it is replaceable as any other rod end in case it wears out. (Fredrickson, Construction of an RC Shock Dyno, 2020)

The rod attaches to the slider link in the mechanism, and the block will slide up and down along a 6 mm shaft, constraining the motion to a pure linear direction. So, the block is made out of aluminum, approximately 50 mm L x 19 mm W x 25 mm D. A hole has to be drilled through the length of the block to hold a bushing for the vertical shaft. On each end of the block (50 mm length) a bushing is installed for stability and they are also set towards the back of the depth of the block (25 mm depth) so that threaded holes on the front of the block can be used for mounting the rod end and the damper shaft rod end. (Fredrickson, Construction of an RC Shock Dyno, 2020)

Then, the vertical slider rod is attached to the top of the bearing block, and runs through a mounting plate on the upper horizontal platform of the frame. The platform can have vertical adjustment by passing the shaft through the plate. The shaft must have a polished smooth sliding surface to avoid friction. Also, to avoid the rod end to push transversally to its sliding travel, a guide wheel is installed on the block. (Fredrickson, Construction of an RC Shock Dyno, 2020)

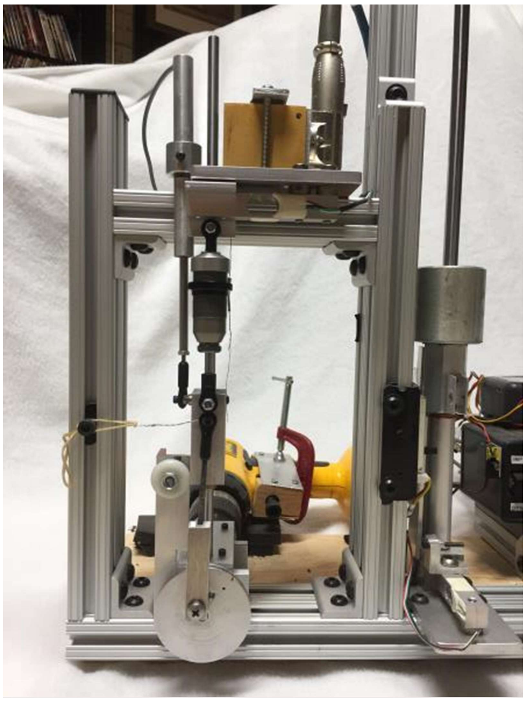

Figure 8.2. Detail on the frame and motion mechanism assembly. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.2.1. Determination of the Actuation Motor

In order to determine if the DeWalt 18V cordless drill can satisfy the requirements of our machine to work as the actuation motor, the next calculus is taken into consideration.

The maximum forces that can be applied by the shock absorber can be of 75N as determined in the predesign phase; and the maximum linear velocity reachable by our shock's up and down motion can be of 0,3 m/s. (Fredrickson, Construction of an RC Shock Dyno, 2020)

So, applying the equation,

$$T = F * r \qquad \text{(Eq. 32)}$$

Where T is the torque, F is the maximum force and r is the maximum radius where this force is applied, which in our case would be 0.095 m, as stablished in this section before, the torque needed would be of 7,125 Nm. (Castillo, 2017)

Now to determine the power, we have that,

$$PS = 2 * S * RPS \qquad \text{(Eq. 33)}$$

Where PS is the piston speed which as mentioned before is 0,3 m/s, S is the piston stroke which in our case is 0,019 m as determined in the pre-design phase, and RPS are the revolutions per second. The RPS obtained is 7,89 rev/s, which is 473,68 RPM or rev/min. (Castillo, 2017)

And finally, the power is determined by,

$$P = T * w = \frac{T * n}{\frac{60}{2\pi}} \qquad \text{(Eq. 34)}$$

Where P is the power, w is the angular velocity of the shaft and n are the RPM. The power obtained is 353,43 kW. (Castillo, 2017)

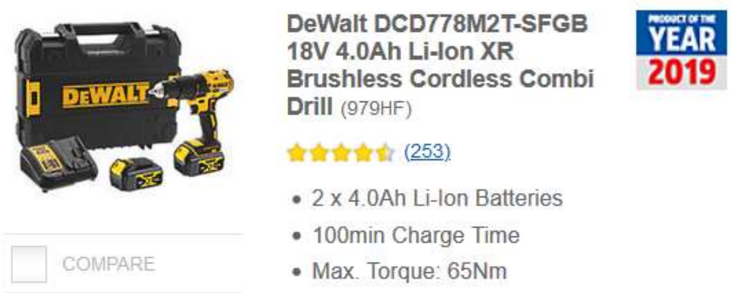

Figure 8.3. DeWalt 18V Cordless Drill specs from DeWalt seller www.screwfix.com.

This torque and rpm are compared to the specs of the DeWalt 18V cordless drill, which shows a maximum torque of 65 Nm and reachable speeds of up to 1500 RPM. So, it is established that the selected motion source for the mechanism totally covers the requirements and as Scott Fredrickson mentioned in his work, such a drill is highly recommended due to the amount of torque it delivers and the smoothness of their rotation being very user friendly and in our case perfect for the application since it won’t affect the results and its working speed offers great controllability.

8.3. Upper Platform

The upper platform is very important because here is where all the adjustments are made and also where the instrumentation is installed. It is made simply of a solid plate of aluminum with a large enough footprint to hold all the instrumentation and attach to the frame. It is critical that this platform is very stiff, since all the forces from the damper are focused on this piece. The recommended aluminum plate thickness for this piece is 6 mm and its area is kept as compact as possible to achieve acceptable resistance to unwanted deflections. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.4. Instrumentation

The instrumentation determines the quality of the data, so it is here where the budget should actually be spent. This dyno was attempting to use the least expensive instrumentation, but focusing on high accuracy. The instrumentation listed on this project is the one that Scott Fredrickson used on his shock dyno, but can be changed for other instrumentation that can acquire the data. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.4.1. Displacement Transducer

The displacement transducer measures the displacement of the rod end relative to the shock's body. The one used on this machine is a yo-yo style transducer because of its up and down motion. The string of this transducer is attached to the body in motion (rod end) and the transducer body is attached directly above the stationary platform to capture relative distance between the platform and the sliding block. It is important that the selected transducer has enough retraction speed for the 300 mm/s and the size of the string matches the 19 mm stroke length. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.4.2. Velocity Transducer

The velocity transducer is the most important instrument, because it allows a much more simplified design. This instrument eliminates all the potential error required to acquire the data from designs such as the scotch-yoke and most other designs, and allows a direct measure of the velocity of the shaft as it is reciprocating. It is also self-energizing, so no excitation voltage or signal amplification is needed. It looks similar to a radio control vehicle's shock and has to be mounted exactly parallel to the axial shaft motion. This will record the speed of the shaft in real time based on the calibrated voltage signal and is important to not use it with speeds above 300 mm/s because it begins to fail. Actually, just as an important fact, normal driving operation for radio control vehicle shocks is 250 mm/s. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.4.3. Force Transducer

This is the least expensive instrument, and is simply a flat beam style strain-gauge load cell, and doesn't have to be an expensive one, since all of them work the same. They are really cheap because they are often used in typical digital scales, and work well as long as they are not overloaded. This load cell has to be connected to the strain conditioner. They typically have four wires, two of which are the excitation voltage and the other two are the signal wires. For this shock dyno a 100 N load cell works great. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.4.4. Strain Conditioner

This instrument is the most expensive one, because cheap mass market digital scale conditioners are too slow and don't work with the shock dyno. So, the best option for the strain conditioner is to look for old used strain conditioners that are out of date for other uses but still work perfectly for the shock dyno. The recommended model is a Daytronic Model 3270 Strain Conditioner, because it gives great results and is really easy to calibrate. It is very important not to compromise the strain conditioner because the force and the timing of it relative to the velocity and the displacement are primary measurements to get the desired results ad collect the data to characterize the damper's performance. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.5. Data Acquisition

The data acquisition method shown in this project is based on Scott Fredrickson's years long work and experience, not only in testing engineering but also on the development of his shock dyno. So, this method is tested and proven to work, in order to get the results shown by Scott Fredrickson on his work and investigations on radio control vehicles dampers.

The most critical features to look for are sampling and channel count, and for the shock dyno only three channels are needed to fully characterize the dampers. The best sampling rate is 400 Hz, because it is plenty sufficient to accurately measure the basic performance of the dampers. This rate avoids missing details around high speeds and also creating too large files. For the data acquisition a DATAQ Model DI-155HS is recommended, because it delivers the results this project seeks and also isn't really expensive. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.6. Calibration

The calibration is a really critical point on making the shock dyno work properly and acquiring the data to characterize the dampers. Since this machine is built from scratch, everything has to be adjusted first and then calibrated with reference values that are measurable so that the results can be trusted. Scott Fredrickson's 15 years' as a Test Engineer experience has been applied to his method of calibrating all the instrumentation and data acquisition items in order to obtain the desired data and make the tests with the machine repeatably and accurate. The whole calibration method, information and reference pictures can be found in the appendix, since there is a lot to cover about this topic and all the details are essential when calibrating the machine properly.

8.7. Data Acquisition

After having the dyno setup, instruments calibrated, and channels connected to collect data with the correct units, the data most be collected into some processing software, mentioned later, in order to compare it and make discoveries. Here is where sampling plays a big role and the most important is to keep the information gathered as simple as possible while still being able to capture what's needed. As mentioned earlier the best sampling rate is 400 Hz, because it produces good consistent results, capturing the data needed to compare damper behavior for cycling motion at velocities under 300 mm/s. (Fredrickson, Construction of an RC Shock Dyno, 2020)

8.8. Post-Processing

The post processing is one of the most important phases. Here is where all of the gathered data gets organized in order to produce the graphs and numbers that will characterize the damper's performance and behavior. Although there are many ways to do this, talking to Scott Fredrickson we both agreed that the simplest way to do this is by using a simple spreadsheet (Excel), which is the most universal way of doing it and it gets the job done. Again, as this is one of the most important phases of the project, the whole post-processing topic can't be fully covered here without losing too many important details on how to post-process the data, so, the full explanation can be found in the appendix.

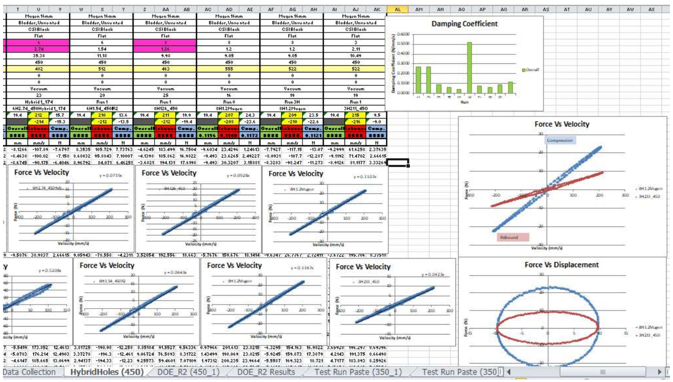

Figure 8.4. Scott Fredrickson's shock dyno results and graphs. (Fredrickson, Construction of an RC Shock Dyno, 2020)

9. Machine Design and Blueprints

After the set of instructions developed for this project were thoroughly reviewed, in order for them to be more understandable, the design of the machine was done using Autodesk Inventor based not only on the instructions and pictures of Scott Fredrickson's work, but also on all of his different opinions and advices based on his experience on testing engineering.

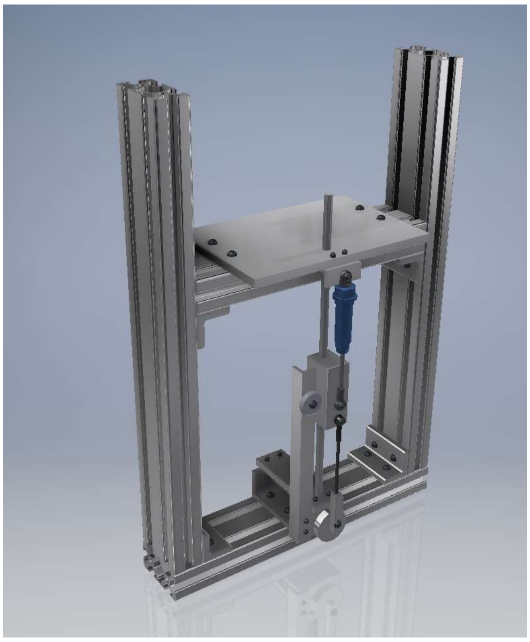

Figure 9.1. The Shock Dyno design in Autodesk Inventor.

The design consists of two main components, the frame and the motion mechanism. Each of them was designed specifically based on Scott Fredrickson's guidelines with the same materials used by him. As stablished before, the upper frame allows the whole adjustment of the machine when the damper is mounted and the upper plate has enough space to mount all the instrumentation.

Figure 9.2. The Shock Dyno's complete assembly front view with a shock mounted.

The instrumentation wasn't added to the design since the instrumentation used will depend on what the user wants to use and where the user wants to mount it, but essentially with this design the shock dyno can be completed as Scott Fredrickson's shock dyno using all the instrumentation that he recommends mainly mounted on the upper plate as stablished in the section before.

Figure 9.3. The Shock Dyno with a damper mounted as an example.

In order to test the design a damper was mounted on it, and it fitted perfectly. Then, a set of blueprints was developed, where all the different parts that complete the assembly are described one by one with their dimensions.

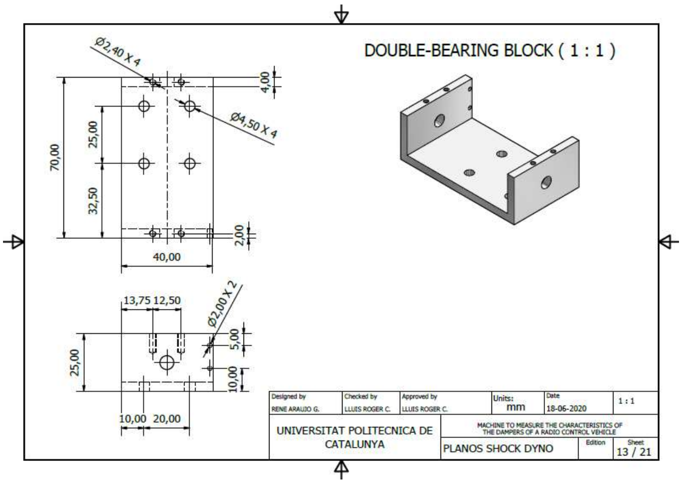

Figure 9.4. Double-Bearing Block blueprint.

And finally, to complement the set of instructions, an assembly blueprint was added for each of the main components that compose the machine.

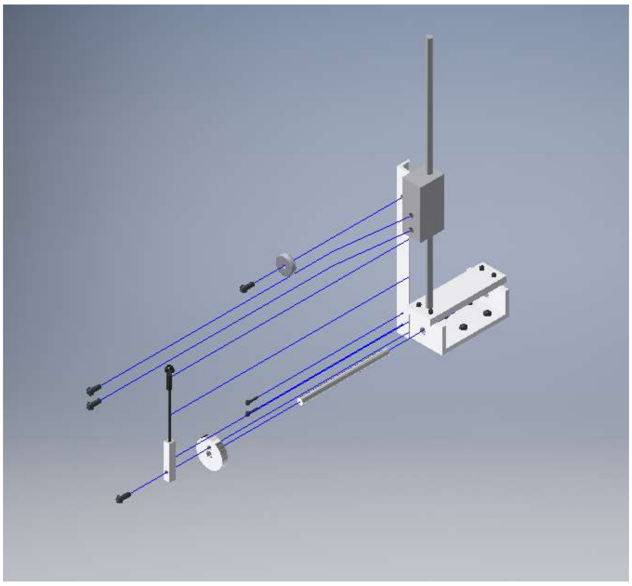

Figure 9.5. Motion Mechanism exploded view assembly being worked.

Each of the assembly blueprints was completed with its own parts list as shown in the example below.

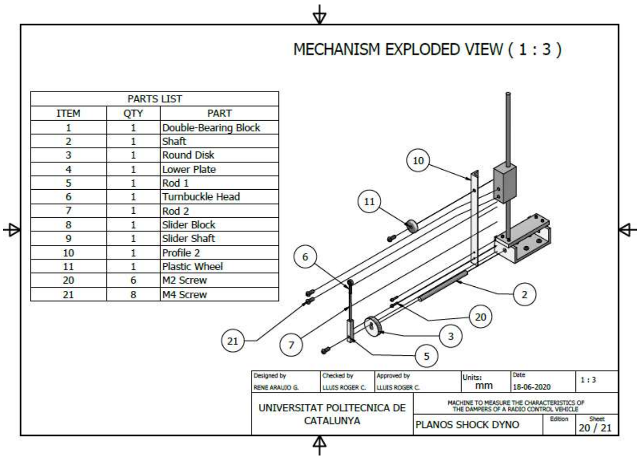

Figure 9.6. Motion Mechanism Assembly Blueprint with its parts list.

The set of blueprints of the Shock Dyno can be found in the Appendix.

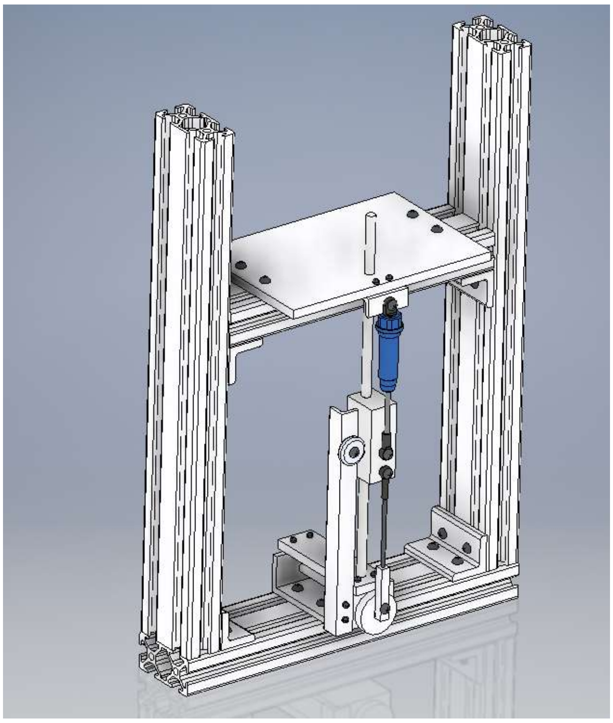

Figure 9.7. The Shock Dyno with a damper mounted, as technical drawing.

10. Environmental Impact Evaluation

The environmental impact assessment is an analysis process that predicts the future negative and positive environmental impacts of human actions, allowing the selection of alternatives that maximize benefits and minimize unwanted impacts.

In this framework, as specific direct regulation mechanisms, information generator and as a management tool, this evaluation involves costs that can be significant. Therefore, care must be taken that they do not neutralize or exceed the potential social benefits, being essential to assume efficiency criteria. For this reason it was considered:

1. The machine is mainly made of aluminum, unlike others that are made of different materials. Most components are recyclable and / or reusable, so their environmental impact is minimal.

2. The parts of the machine do not require major machining processes unlike others, so not only are costs reduced, but also the environmental impact in terms of the use of resources involved in their construction is reduced.

3. Review procedure of already proposed projects, which leads us to accommodate all aspects and requirements of the project to be effective in terms of materials, parts and costs. These aspects are: a balanced decision-making system considering the current market.

10.1. Primary Impacts

The primary impacts of an action are those direct effects that cause the action and that generally occur at the same time and in the same location, generally associated with construction, operation, and maintenance.

10.2. Secondary impacts

Secondary impacts are indirect or induced changes in the environment, in this case they cover all the potential effects of additional changes that may occur later when the accessory is already in operation.

10.3. Short and long-term impacts

Depending on their duration, the impacts can be short or long-term, their identification is important since it could be related to their duration in the environment, (duration of the accessory) that will depend on the management and place where it develops.

10.4. Other impacts

- Direct impacts: attributes by direct action to provide resistance.

- Indirect or induced impacts: these are the effects of the interaction of everything that makes up this project.

- Reversible impact: It is one whose effects on the environment can be mitigated in such a way that it is restored when the acquirer wishes.

The maintenance within the content has been considering the need to do it in a minimal way, which is based on carrying out a review and involving tests that confirm its effectiveness.

11. Budget

11.1. 1. Expenses of Materials

Concept	Cost/Lot	units	Total cost
Aluminum strip 1020 series 10 extrusion 80/20	10,05€	2	20,10€
M4 X 12mm screw	0,15€	30	4,50€
M2 screws	0,32€	20	6,40€
DeWalt 18V cordless drill	132,00€	1	132,00€
Aluminum plate 6 mm thick	9,75€	1	9,75€
Aluminum profile in L 3 mm thick	8,00€	1	8,00€
Yo-yo style displacement transducer (series 150 subminiature position transducer)	400,00€	1	400,00€
Speed transducer	200,00€	1	200,00€
Force transducer (strain gauge load cell)	150,00€	1	150,00€
Strain conditioner - Daytronic Model 3270 Starin Conditioner USAD	450,00€	1	450,00€

Data Acquisition DATAQ Model DI-155HS	100,00€	1	100,00€
WINDAQ	173,00€	1	173,00€
Totals	**1633,27€**		**1653,75€**

11.2. 2. Non-Material Costs

Concept	Cost/Hour	Hours	Total cost
Suspensions research	8,50€	75	637,50€
Research shock absorber graphics	8,50€	95	807,50€
Research on radio control vehicles	8,50€	75	637,50€
Shock dyno research (machines)	8,50€	75	637,50€
Scott Fredrickson research work	8,50€	85	722,50€
Conversations with Scott Fredrickson	8,50€	34	289,00€
Scott Fredrickson dyno shock investigation	8,50€	80	680,00€
Doubt resolution with Scott Fredrickson	8,50€	30	255,00€
Development of summary machine building instructions	8,50€	85	722,50€
Development of calibration and test methods with Scott Fredrickson machine	8,50€	90	765,00€
Machine drawings	8,50€	140	1190€
Totals		**864**	**7344€**

12. Conclusions

The whole project was done based on the rule of not inventing what's already invented, as this project wasn't developed with the normal approach of start designing based on parts that just end up in an assembly that looks good on software but doesn't work, neither delivers the results the project is aiming for. At the end, a lot of effort was made on investigating about the shock dynos thoroughly and understanding what would make the project either work or fail.

Investigating shock dynos thoroughly helped to analyze and evaluate which were the factor that could make the project fail, and at the end all of this could be avoided by focusing on building a machine that actually works, delivers the data that is needed and has an understandable way of managing the post-processing of the data in order to finally get the graphs. All of these was accomplished not only by sticking to the lowest possible budget, but also by meeting all of the machine's requirements set by the tutor at the start of the project.

Although the machine couldn't be built due to the current worldwide situation, the project was adapted to the available possibilities while it was being worked, being a success, since the shock dyno presented in this project's build instructions has already been built, tested and proven to work and deliver the graph to characterize the radio control vehicle's damper.

In order for a machine to work properly getting quality instrumentation and knowing it's limits is essential. A lot of time and effort has to be invested into calibrating and setting up the machine right in order to get the desired results and make the testing repeatable and accurate.

The whole process of building a machine from scratch takes more time and effort that one could ever imagine. This project proves that it is not possible to make such a project in so little time, and perhaps it is better to divide it in different phases that will continue the project where it was left off, since there are too many factors that have to be taken into consideration to get a machine to actually work and obtain the final results.

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