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**How a change in gas pressure can affects
damping performance in a twin tube damper**

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1-Abstract

Dampers are often known as shock absorbers but this is a common mistake as they don't directly absorb the shock dampers are instead used as a way to stop the vibration put into the suspension due to inconsistencies in the road surface, if dampers were not used the vibration would never stop (Harris, 2015). Dampers will control the amount of movement allowed in a spring, this will then allow for a more consistent ride as if the spring was left untreated the force would continue in the spring meaning it would be inconsistent and create a bumpy ride (SAE, 2001). In reality dampers need to be calculated in 4 different areas; high speed compression, low speed compression, low speed rebound and high speed rebound. The low speed damping will control the motion of the sprung mass this will be under handling such as the pitch and roll of the vehicle whilst also looking into weight transfer under braking and acceleration (Reif, 2014). Whilst the high-speed damping will control the high frequencies that are seen by the dampers whilst going over bumps. Dampers do not have a say over the weight transfer in the vehicle but instead they control the rate at which weight transfer occurs (Burke, 2011). The test procedure will include putting the damper onto the dynamometer with an initial pressure of 0 bar with it then going up in increments of 4 bar going all the way to 20 bar. These results will be analysed using a force velocity graph to see the changes that occurs when the gas pressure changes.

2-Introduction

Suspension systems play a key part in a vehicles performance as it has a major impact on a vehicle handling, the suspension system will determine what the vehicles main role is, a suspension system is capable of changing a vehicle from a car made for the track to the streets (Rowley, 2003). Dampers will play a vital role in a suspension system as if incorrectly calculated can result in an uncomfortable ride or an unresponsive suspension system. There are many different things that can affect a dampers performance including the stroke, gas pressure, valve, piston and the oils that are used. This report will look into the effects that a change in gas pressure results in damper characteristics. Damper performance and modelling will first have to be looked at to see where what the changes to a damper will result in terms of the vehicles performance including wheel rate and motion ratio upon other things (SAE, 2001). Test equipment will also be analysed to ensure that the correct machinery is being used and being used correctly to ensure the test is legitimate and valid.

3-Suspension History

Suspension is used in vehicles as a way of controlling the wheel in relation to the vehicles body, this is done for two main reasons the ride quality and handling. Suspension has been used from as early as 1200BC as the Greeks used thin willow in their wheels with only four spokes to give a springy quality to the chariots used at the time, this was seen as a way of dealing with the rough grounds (Gordon, 1978). The first spring suspension was patented by Obadiah Elliot and it included each wheel having 2 durable steel leaf springs, with each side of the spring being attached to the body of the carriage and the frame of the carriage. Within a 10 years of this it was developed into most horse drawn carriages with single horse drawn carriages using wood for the springs whilst the bigger carriages using a low carbon steel. (The Editors of Encyclopaedia Britannica, 2013). Vehicles have used various different suspension systems with the early vehicles employing leaf springs in the early 1900's (Evans, 2018). Throughout time different systems have been brought in with coils springs appearing on vehicles as early as 1906 in the Brush Runabout. Today there are a range of different suspension set up systems with each system having its own advantage and disadvantage over others. Independent suspension is widely used in both the front and rear of modern vehicles and will allow for each wheel to act upon its own axis meaning it is not affected by what is happening at the other wheels (Bastow, 2004).

3.1-Suspension Jobs

There is multiple different jobs the suspension must do for it to be considered successful. Suspension must be able to allow for vertical movement of the wheel as it will go up and down whilst going over uneven surfaces. The suspension must also be able to take the weight of the vehicle meaning that the wheels can spin freely and are not locked by the weight of the vehicle (SAE, 2001). There will be multiple different forces put into a cars suspension including the weight of the car moving down towards the ground with driving and braking forces being applied whilst accelerating and deceleration in the longitudinal axis with cornering forces being applied to the lateral axis (Reif, 2014).

Understanding your suspension system is vital to having a vehicle that handles correctly, getting the best use of your damper will involve deciding where and how to use them. Dampers although necessary take up space in a suspension system so finding a way to use

them that gives you the smallest area used whilst also being the lightest in terms of mass is vital. There are many different factors that come into play when deciding what dampers are required these include packaging constraints, wheel travel, jounce bump travel, desired wheel rates, strength requirements and maybe most important motion ratio (Kaspzak, 2019).

Motion ratios occur in both springs and dampers and is the ratio of displacement of either the spring or the damper against the wheel displacement. It is the same in so many vehicles as springs over dampers is so popular in modern vehicles (Reif, 2014). The formulas for motion ratios are below:

$$\text{Spring Motion Ratio} = \frac{\text{Spring Displacement}}{\text{Wheel Displacement}}$$

$$\text{Damper Motion Ratio} = \frac{\text{Damper Displacement}}{\text{Wheel Displacement}}$$

A motion ratio of 1 is often used, but there are benefits of using a higher motion ratio. These include a result in lower spring rates whilst allowing the same wheel rate, the lower the spring rate the lighter it then is whilst also having lower compression loads. Dampers also work better under higher velocities and this happens with greater damper travel that happens with a higher motion ratio (Kaspzak, 2019). Figure 1 below shows the affect motion ratio has on suspension components

Figure 1-Motion Ratio Affects (Kaspzak, 2019)

Motion Ratio	1:1	0.75:1	0.5:1
Wheel Travel	25 mm	25 mm	25 mm
Shock/Spring Travel	25 mm	18.8 mm	12.5 mm
Wheel Velocity	50 mm/sec	50 mm/sec	50 mm/sec
Shock Velocity	50 mm/sec	37.5 mm/sec	25 mm/sec
Wheel Rate	25 N/mm	25 N/mm	25 N/mm
Spring Rate Required	25 N/mm	44 N/mm	100N/mm
Spring Preload	50 kg	67 kg	100 kg

Ride frequencies are another thing that needs to be understood to get the most of a suspension system. Ride frequency are the frequency that a sprung system will resonate at. There are 2 different undamped frequencies these are the sprung mass and the unsprung mass and the equations for calculating these are below.

Sprung Mass

$$\omega_n(s) = \frac{1}{2\pi} \sqrt{\frac{(K_W * K_T)/(K_W + K_T)}{M_S}}$$

$\omega_n(s)$ = Sprung mass Natural Frequency (Hz)

K_W = Wheel Rate

K_T = Tire Spring Rate

M_S = Sprung Mass

Unsprung Mass

$$\omega_n(us) = \frac{1}{2\pi} \sqrt{\frac{K_W + K_T}{M_{US}}}$$

$\omega_n(us)$ = Unsprung mass Natural Frequency (Hz)

K_W = Wheel Rate

K_T = Tire Spring Rate

M_{US} = Unsprung Mass

Natural frequencies vary across vehicles with sprung mass varying from 1-2Hz for a passenger vehicle whilst they significantly increase for an Indy car and can be 5-7Hz. The unsprung mass will be higher with a passenger vehicle ranging between 10-12Hz and an Indy Car will be at 23-27Hz (Bastow, 2004). A ride frequency is the undamped frequency that the sprung mass will resonate at, the front and rear will have different frequency this is to reduce the amount of pitch that is present in the vehicle. It can depend on a vehicles balance but the ride frequency can be as different as 0.2-0.4Hz (Longhurst, 2017).

3.2-Suspension Layout

There are many different ways suspensions have been set up with all containing springs, shock absorbers and linkages. Non-independent is where the wheels will react in relation to one and other. This will mean that the wheels will be suspended by leaf or coil springs on the axle. This will mean that the forces that are put into one wheel then affect the other wheel, this will mean that when wheel goes over a bump the force affects the other wheel (Delphi Technologies, 2018).

MacPherson Strut suspension was first used in the 1940's by Earl S. MacPherson . It works by only having a single wishbone on the lower section of the upright with a spring and shock absorber on the top of the upright (J.R.Ellis, 1994). It is very popular in road vehicles today because of the low production costs and how compact it is. It is often used in the front of vehicles particularly in front wheel drive cars where the engine and transmission are both found in the front meaning that there is not the space for a bigger suspension set up. Although popular it does have its drawbacks as although it is compact it does take up space vertically meaning it is not suitable for low sports cars, the single mounting point will also result in a change of camber when body roll occurs (Reif, 2014).

Multi-Link suspension is using 3 or more connecting lateral arms from the chassis to the upright. Although wishbone can be used in multilink suspension it is often just a singular ball joint at each end (Dixon, 1996). The multiple arms mean that that camber changes can be very precise as well as toe in and out adjustments, this is why it is used in high end racing such as formula 1 (Longhurst, 2017). The multiple different mounting points mean that ride can be predicted very precisely meaning that it is easy to calculate what is going to be happening at different parts of the track.

Double wishbone suspension works by having two wishbone shaped arms connected to the chassis and the wheel hub whilst sitting parallel to one and other (Dixon, 1996). The arrangement allows for near perfect camber control, this is because it will stay parallel to the ground irrespective of the road condition. Due to its camber control, double wishbone has become a popular choice amongst race vehicles and sports cars alike. The large set up often puts off manufactures as McPhersons Strut is often adapted instead in passenger vehicles.

Non-Independent suspension will include a rigid axle fixed between left and right wheels (Dixon, 1996). The wheels are not independent, meaning that forces that are put into one wheel affect the other wheel that is sharing the axis. Both leaf and coil springs will still be used on the axle. It gains poor handling characteristics which is why it is unpopular in vehicles today, the axle also takes up large amount of space which is why it is used in the rear of vehicles not to interfere with the engine.

4-Springs

Springs are a main component in any suspension system, they work with the dampers, wheels and tires to absorb the road impact as well as supporting the weight of the vehicle whilst keeping the wheels in contact with the road. Spring sizes and arrangements will be changed to affect how the suspension will perform and this will vary from vehicle to vehicle depending on what its used for (Reif, 2014).

4.1-Leaf Springs

Leaf Springs are the oldest type of spring that were used in vehicles, with the first of these being used in horse drawn carriages. As well as suspension functionality, the major advantage of leaf spring is the low cost that is associated with them and is why they are still used today across a range of different commercial vehicles. Although early on they were seen as good enough, today their increased weight and insufficient levels of ride quality have meant they are no longer suitable for passenger vehicles. Leaf springs have damping characteristics which may be seen as a good thing because damping is required in suspension systems but leaf springs damping is not enough to control the vibrations in the spring meaning a conventional damper will provide an advantage over a leaf spring (Reif, 2014).

4.2-Torsion Springs

Torsion bar Springs are used predominantly in passenger vehicles and light vans. They work by having a metal bar that is subjected to torsion, they are fixed clamping in one end of the bar whilst the other end is mounted rotationally meaning that the shaft is elastically torsioned when a torque load is applied. The torsion bar springs are arranged in the bearing centre of the suspension arms on the body side opposite end of which the vertical wheel load force takes effect. The advantage of these are that design permitting ride height is then adjustable to suit the user (Reif, 2014).

4.3-Gas Springs

Gas Springs are different to any others mentioned so far because they are not determined by the change in shape of the metal, gas springs instead work by having a change in the volume of gas. This will then allow for a change in ride height and stiffness by changing the amount of gas that is present in the chamber. The main advantages of gas dampers are the ride quality that is given, it allows for a very smooth and comfortable ride, although this is a good thing for some passenger vehicles it is then the reason it rules itself out for race vehicles.

4.4-Coil Springs

Coil springs are the most common springs used in passenger vehicles today. In coil springs the return forces are generated by the return forces that are being generated by the elastic torsion of each coils change in length. Coil springs are able to absorb forces in the longitudinal axis meaning they are often used as body springs. Coil springs can be changed depending on the requirement of the vehicle including the number, spacing and size of each spring. There is no damping present in coil springs meaning that separate dampers can be used in the system set up meaning it can be controlled appropriately (Reif, 2014).

Coil springs are the most popular springs in vehicles today calculating the size of these will determine the ride quality of the vehicle, there are various different paramount's that determine this including:

- Free length of the unloaded spring which is the distance from the top face of the spring to the bottom face of the spring when no load is placed upon it. Symbol L for calculations (Burke, 2011).
- Shear modulus of rigidity, this will change depending on the material that the spring is made from the popular materials are ANSI 1095 spring steel is around 79.3Gpa whilst cold rolled steel is 75GPa. Symbol G for calculations (Burke, 2011).
- Wire diameter of the spring. Symbol d for calculations.
- Mean diameter of the spring, this is the distance between the centres of the springs . Symbol D for calculations (Burke, 2011).
- Number of coils, this will include the number of full coils as part coils will not contain the same characteristics. Symbol N used for calculations (Burke, 2011).

Stiffness of coil springs can be calculated using: (Burke, 2011)

$$K = \frac{Gd^4}{8ND^3}$$

This formula can then be reengineered when the stiffness is known to calculate the size of the spring.

This calculation will give the spring rate, which is how much force will be required to compress the spring over a distance often measure in N/mm or Lbs/in. The lower the spring rate the softer the spring which will then result in a more comfortable ride as the wheel will move with ease when going over bumps.

5-Dampers

Dampers are often known as shock absorbers but this is a common mistake as they don't directly absorb the shock dampers are instead used as a way to stop the vibration put into the suspension due to inconsistencies in the road surface, if dampers were not used the vibration would never stop (Harris, 2015). Dampers will control the amount of movement allowed in a spring, this will then allow for a more consistent ride as if the spring was left untreated the force would continue in the spring meaning it would be inconsistent and create a bumpy ride (SAE, 2001) Although the tire does control a small amount of the damping it is only around 2% of the forces. Dampers will work as energy convertors in converting kinetic energy into heat energy that will be spread throughout the fluid. Damping occurs in three different ways including air resistance, friction and viscous damping, Air resistance will be small compared to the force required to prevent movement in the suspension as the force applied with the sprung mass will be greater. Friction in suspension is harmful because the static force of the friction will need to be exceeded for there to be an effect leaving the suspension in a locked state meaning movement is not possible and then puts the force on to other parts in the suspension (Thyssenkrupp, 2018). This means the majority of the force will be dealt by the viscosity of the fluid in damper usually controlled hydraulically with the resistance in the fluid controlling the speed in which the damper moves. Dampers produce force depending on their velocity, this means it only produces force when moving meaning that damping produced is proportional to velocity (Skagerstand, 2014).

The force required for damping is controlled by the size of the valve or orifice as the oil will have to travel through these, the bigger the valve or orifice it will then mean the less force required for the piston to pass through (Skagerstand, 2014). The less force required for the piston to move through the fluid the softer the ride quality, meaning the force put into the suspension will be dissolved slowly causing less discomfort for the driver. Getting dampers

set up in the correct way is vital in race vehicles as it plays a big part in how long the wheel will be in contact with the road (Suspension Secrets, 2017).

Throughout time dampers have adjusted to not only take to force put upon the suspension by the road surface but also the forces that are put onto the suspension through both breaking and acceleration. There are multiple different factors that will affect the force that is put into the system during acceleration including velocity, mass, drag and speed of acceleration, these factors will have to be correctly calculated to ensure the car is controlled as desired.

5.1-Damper Cycles

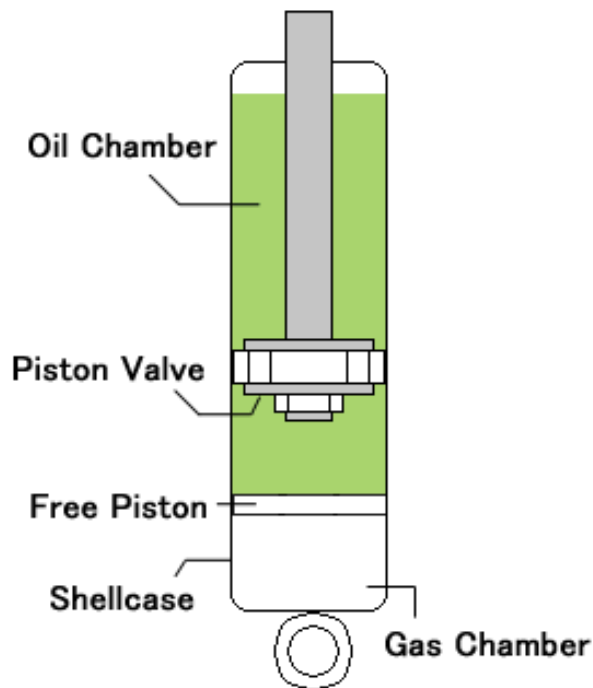
Dampers will work in two different cycles the compression and the extension (rebound) cycle of the damper. The compression cycle will happen when the piston is move downwards and to its closed state this will compress the fluid in the chamber below the piston, this will control the motion of the unsprung mass (Chahine, 2011). The rebound cycle will occur when the piston moves back to its open state and will compress the fluid in the chamber above the piston, this will have more resistance as it will be dealing with the force of the sprung mass (Chahine, 2011).

5.2 Monotube Dampers

The Monotube damper contains just a singular tube that contains just 2 chambers that is separated by a floating piston. There is a working chamber where the oil is located where the rod is moved by twin compression rebound bar (Irvine, 2010). The second compartment is the expansion chamber that is charged with high pressurised nitrogen gas, compression effect of the gas will allow for the working chamber to always be filled with oil. The nitrogen serves many purposes such as preventing the oil from cavitating, cavitation occurs when the oil moves through the piston as it must move through small holes, as it passes through these holes the velocity of the oil raises which then causes the pressure to drop, the air that is trapped in the oil is then released that causes bubbles in the oil, Bubbles in the oil are a big problem as it changes the integrity of the oil making the damper less effective (Tein, 2018). The floating piston will be made from metal and will prevent the oil and the gas from mixing with one and other. When the damper is compressed, the rod enters the working chamber which then causes the oil to move downwards moving the floating piston downwards, this

movement then causes the volume of the gas chamber to be lowered which forces the gas to compress. Then when the damper is extended the floating piston then moves upwards which means the volume of the gas chamber is increased meaning the pressure of the gas is reduced causing rebound as shown in figure 2 (Tein, 2018).

Figure 2-Monotube Damper



If the volume of the gas chamber was not able to displace due to the floating piston the damper would lock as there would be nowhere for the oil to go (Tein, 2018). The nitrogen can be changed to change the characteristics of the damper, nitrogen is pressurised between 100-300psi for a damper and can change how hard it is for the piston to move, although it will not change the spring rate of the damper it will change the initial force that is required to move the damper. Monotube damper allows for the temperature that is created by the friction to be spread out easily across the oil meaning that the performance is not restricted to heat meaning its 100% efficient through all temperatures. In a Monotube damper the piston valve is bigger allowing a wider area of pressure this will then mean that the damping forces can be calculated more precisely. The Monotube damper allows itself to be used in many different vehicles both road and racing, this is because it can be arranged in any way wanted as the gravitational forces will not make a difference to how the gas and oil will flow in the chamber.

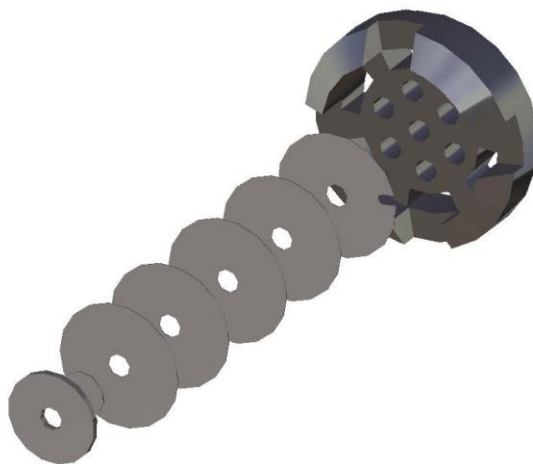
The high-pressure gas will cause a high amount of stress on the seals which will cause them to fail quicker, which can lead to high prices in repairs.

5.3 Twin-tube Dampers

Twin tube Dampers work by having 2 different chambers inside of the shell, there will be an inner cylinder that will contain a shaft connected to a piston and as this is moved through the oil. As the piston is compressed the oil is pushed down through another valve where it is then displaced into the other chamber, the rate at which this oil is moved through this valve will control the characteristics of the damper as it will control how quickly the shaft can move (Tein, 2018). The overflow chamber is also filled with pressurised gas that will force the oil back into the working chamber when the damper extends. Having a damper arranged in this way will come with a series of advantages over the Monotube arrangement including a securing that the damper is provided with a sufficient stroke as the oil and gas chambers are separated (Irvine, 2010). The gas pressure to be lower gas pressure that is required in twin tube is considerably lower than that used in Monotube this is down to multiple different factors including the base valve which allows for the pressure to be lower as it allows for opening and closing, the lower gas pressure will allow for less pressure to then be put onto the seals meaning that the chance of a valve being blown will be reduced. Although there are these positives there are disadvantages to the twin tube design including, the working chamber being smaller than the Monotube which reduces the oil capacity as well as reducing the size of the piston valve, this will then reduce performance as there is then less oil for the force to be dissolved into (Burke, 2011). A twin tube will have to be mounted vertically for the base valve to function correctly, this is because it needs to be filled with oil to work correctly and the nitrogen inside will always rise to the highest position possible because it is lighter than the oil, if it is not mounted vertically it is possible for the gas to enter the working chamber that will then have an effect on damping, although it can be worked out of the damping chamber it will create a loss in damping force whilst still there. Twin tube damper also leave high chance of cavitation within the oil because there is nothing to separate the gas and the oil meaning that they often come into contact with one and other, this is a problem as it will affect the characteristics of the oil (Eyres, 2005).

To understand how the performance of twin tube dampers vary it is important to see how they are designed. Vital components to any twin tube damper are the set of valves, the base valve is used to control the pressure in the compression chamber and is found at the base of the damper. This will be used to control low speed damping, low speed damping will not be determined by the speed of the vehicle but how quickly the damper is moving, it is not determined by a certain figure but is instead adjusted depending on the requirements of the damper (Simms, 2005). When the speed increases the second valve is then opened, the second valve is found on the piston and produces the differential pressure between the compression and the traction chamber, this will in turn generate the damping force. This second valve will consist of shim stacks, a shim stack valve is a pile of thin discs on top of a channel, when the pressure difference occurs from the top to the bottom the discs then deflect resulting in an area opening, this is displayed in the figure 3 below (Simms, 2005).

Figure 3-Shim Stack Arrangement



The valves on twin tube dampers will need to be designed correctly to make sure the valve allows the damper to work correctly, when it is known how the valves work the variables can then be looked at to see what changing each one will do to the functionality of the valve.

The low speed valve, although it never closes it is not truly a valve and more of an opening it is still considered one due to its ability to control a flow of oil.

$$Q = C_D A \sqrt{\frac{2\Delta p}{\rho}}$$

Q=Volumetric Flow Rate

C_d=Discharge Coefficient

A=Area

P=Density

(Burke, 2011)

The shim stack is more advanced as the flow will be determined by more factors.

$$Q_v = \frac{1}{2} \pi D_v y C_D \sqrt{\frac{2\Delta p_{valve}}{\rho}}$$

Q_v=Volumetric Flow Rate Through A Valve

D_v=Diameter Of The Valve For A Shim Stack

C_d=Discharge Coefficient

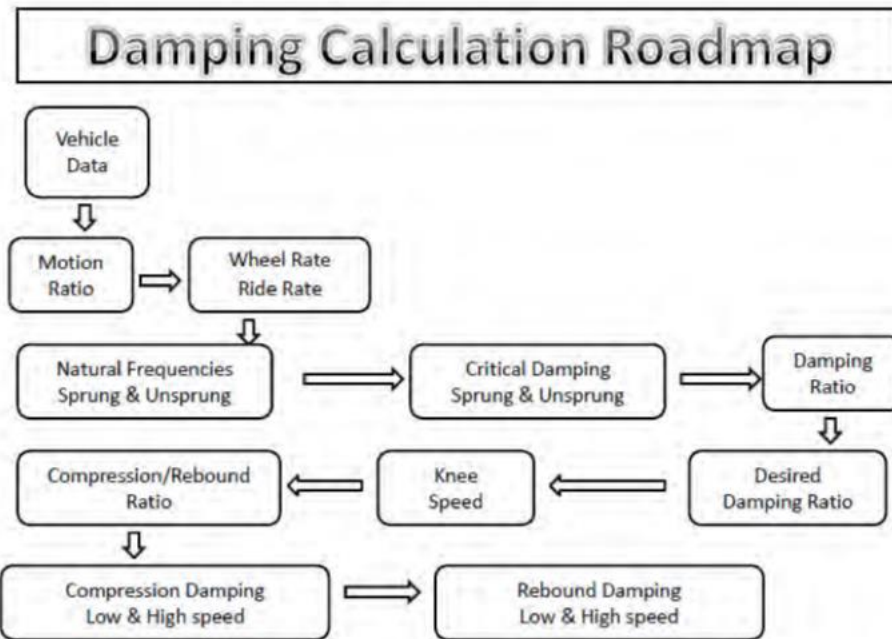
P=Density

Y=The Deflection of The Shim In A Shim Stack Valve

(Burke, 2011)

5.4-Damping Calculations

Damping theoretically is portrayed through the use of coefficients, whilst looking at real world damping it is measured in forces under compression and rebound at a damper velocity. To correctly calculate the dampers required information is needed this will then be developed stage by stage until the compression and rebound damping can be found. The flow chart below shows the step by step process that has to be followed.



(Kaspzak, 2019)

Critical damping is the amount of damping that allows for a mass to return to its steady state without overshoot. The critical damping required will stop movement as quickly as possible.

C_{cr} =Critical Damping Coefficient

$$C_{rr}=2\sqrt{K^s * M}$$

K^s =Spring Rate

M =Mass

C_s =Suspension Damping Coefficient

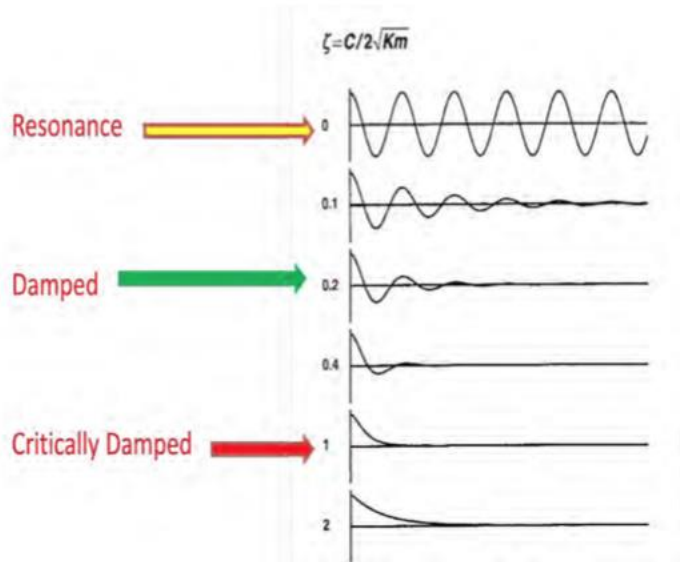
Damping Ratio= $\frac{\text{Suspension Damping Coefficient}}{\text{Critical Damping Coefficient}}$

$$\text{Damping Ratio} = \frac{C_s}{C_{cr}}$$

Damping ratios will vary across different vehicles with a damping ratio of 0 damping is not present and the vehicle will continue to resonate, the only thing to stop it will be frictions. A passenger vehicle will be at a ratio of 0.2 and at this ratio the vehicle exhibits motion and the motion will be damped within 1-2 cycles of the damper, this will ensure that the sprung mass is controlled whilst letting the vehicle move. Race cars that use full effect of aerodynamics

will have a damping ratio close to 1 which is critical damping, the vehicle will not resonate at all at this ratio, this will cause an increase in tire forces variation which may create a loss of grip (Kaspzak, 2019).

Figure 4- Damping Ratios (Kaspzak, 2019)

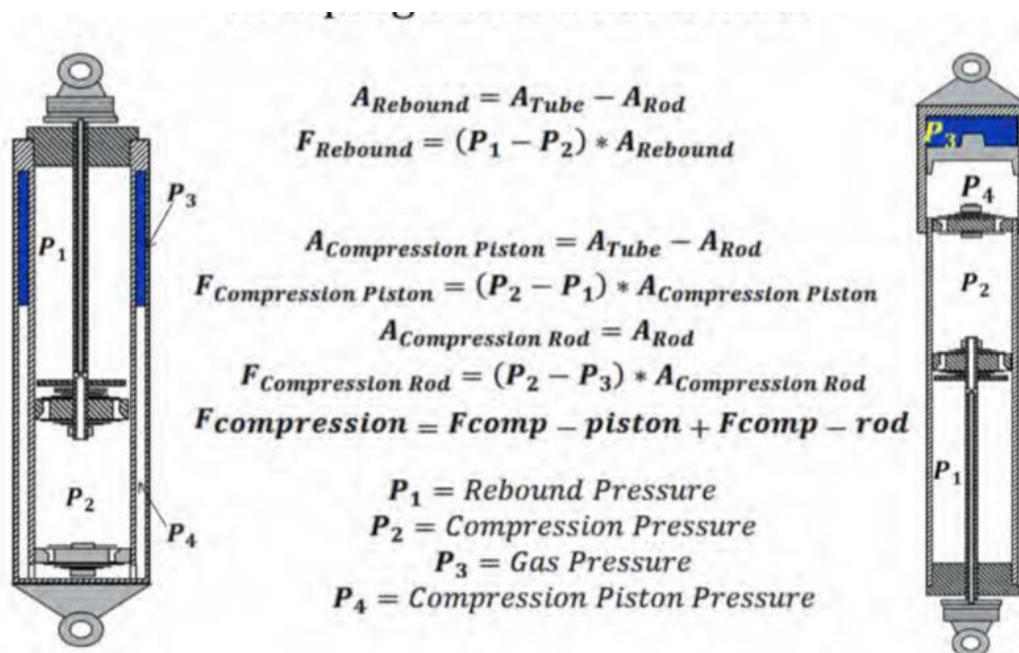


Above shows a graph of what happens under various different ratios. Although stopping the oscillation is vital it varies from vehicle to vehicle in the same way that spring rates vary across vehicles.

In reality dampers need to be calculated in 4 different areas; high speed compression, low speed compression, low speed rebound and high speed rebound. The low speed damping will control the motion of the sprung mass this will be under handling such as the pitch and roll of the vehicle whilst also looking into weight transfer under braking and acceleration (Reif, 2014). Whilst the high-speed damping will control the high frequencies that are seen by the dampers whilst going over bumps. Dampers do not have a say over the weight transfer in the vehicle but instead they control the rate at which weight transfer occurs (Burke, 2011). The compression and rebound in a damper will not often see a ratio of 1 between the pair. This is because the sprung mass is far heavier than the un-sprung mass, the rebound is controlling the un-sprung mass whilst the compression is controlling the sprung mass. This is why in passenger vehicles a 3:1 ratio is often seen compression to rebound (Kaspzak, 2019). Although race cars are using dampers differently as the road surface is known meaning that factors like bumps can be eliminated whilst comfort is no longer needed as speed is the focus.

The focus for dampers on race cars is to control the rate of weight transfer, this is because cornering forces will be far more significant in a race car as the speeds it is seen during cornering, dampers force is created by velocity not displacement meaning the high forces can be created without travel (Kaspzak, 2019).

Twin tube dampers are calculated using the same formulas that Monotube dampers with compression pistons are the same. There are additional compression forces during the compression stroke due to the pressure drop during this stage. The area of the rod will have a major Impact in the compression force generated this is because the fluid that needs to pass through is equal to the area of the rod times by the rod. The formulas are below (Kaspzak, 2019).



This shows how vital pressure is to the forces that will be created by the damper. The gas that is used inside dampers is nitrogen. Nitrogen is a chemical element appearing as number 7 on the periodic table, with a symbol of N. Nitrogen gas is a vital part of any kind of damper because if it was completely filled with no gas the shaft would not be able to move as there would be nowhere for the damper to oil to displace to as it is not compressible no matter the force that is applied (k.Nakai, 2016). Nitrogen's job within the damper is to be compressed allowing for the oil to be displaced meaning that the damper is capable of moving freely within the cylinder. In a twin tube damper, the compression will take place in the outer damper whilst the working chamber will be filled with oil (k.Nakai, 2016). Although air is

predominantly Nitrogen it is not used inside dampers as when air is compressed the hydrogen and oxygen can react with one and other that will create a moisture inside the damper. The main problem with using air is the chance of cavitation which will occur when the damper shaft is at a high velocity, this will mean that small bubbles will be formed in the oil which will create a change in damping force, this is a problem as inconsistencies in damping force will create an uncertainty in ride quality (Thyssenkrupp, 2018). Nitrogen expands at a constant rate which will result in a more consistent internal pressure meaning a more consistent damping force, this will result in a more consistent ride quality. Nitrogen is a less reactive gas than the air meaning that it will not react with either the damper or the oil which will mean there is no chance of rust from inside the chamber, the high speed the damper moves at will create an increase in temperature so it is vital the nitrogen does not combust as the damper oil is flammable which could result in catastrophic problems if it were to go up. Pressures of nitrogen will affect a damper's ability to function, this is because if the nitrogen has too much pressure it will make it hard for the damper to compress, too little will mean that the rebound force is too low to perform correctly (SAE, 2001).

5.5-Damper Cavitation

Cavitation can occur in a damper during the working cycle, this occurs when the pressure drops below the pressure of the vapours. This will then mean that oil vapour bubbles that occur in the oil, these will implode once the working pressure then surpasses the vapour pressure. Once these bubbles implode the damping force will become uncertain, this will mean that bubbles will cause a loss on damping force. Below figure shows the cavitation coming into effect whilst the damper is in compression phase. The presence of the oil vapour is instantaneous due to the temperatures, but there is a delay when the bubble then must evacuate a certain volume of oil before it reaches equilibrium volume. Rayleigh's formula can be used to calculate the time it takes for bubbles to evaporate assuming that the bubbles are created instantaneously (Kaspzak, 2019).

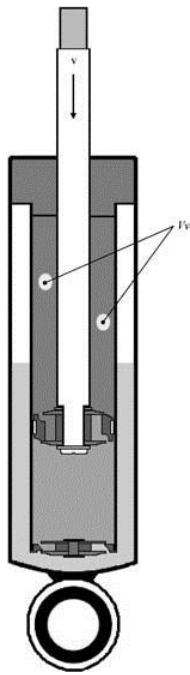
$$t=0.91R_0\sqrt{\frac{P}{P_0}}$$

R_0 is the initial bubble radius

P is the oil density

P_0 is the hydrostatic pressure which the oil is exposed.

Figure 5-Cavitation in Twin Tube



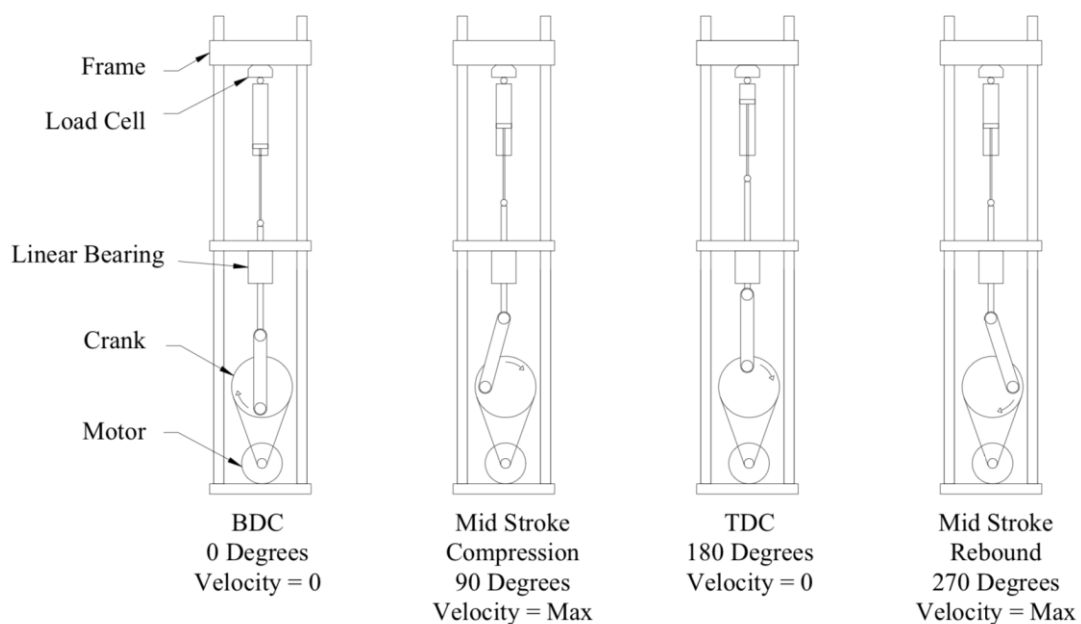
6- Damper Dynamometers

Damper dynamometers will be used in various different situations with various different teams using a range of different set up including having it at engineering facilities whilst having them on track side to change due to on track conditions, they allow teams to test and tune their dampers to allow for the optimum damper configuration. There are 3 different types of portable, standard mechanical, 3 phase mechanical a hydraulic. The portable dynamometers allow for race teams to have it as part of their pit equipment as it will allow for fine adjustments on track (Multmatic, 2018).

Dampers dynamometers work by producing a force to simulate the speed of the shaft moving, dampers will react differently under different speeds, for example if a damper is compressed slowly then it will generate less resistive force then more if moved faster. The range of different speeds that need to be tested are important as small speed will affect the feel created for the driver, whereas high speed movements will be things such as road irregularities (Multmatic, 2018).

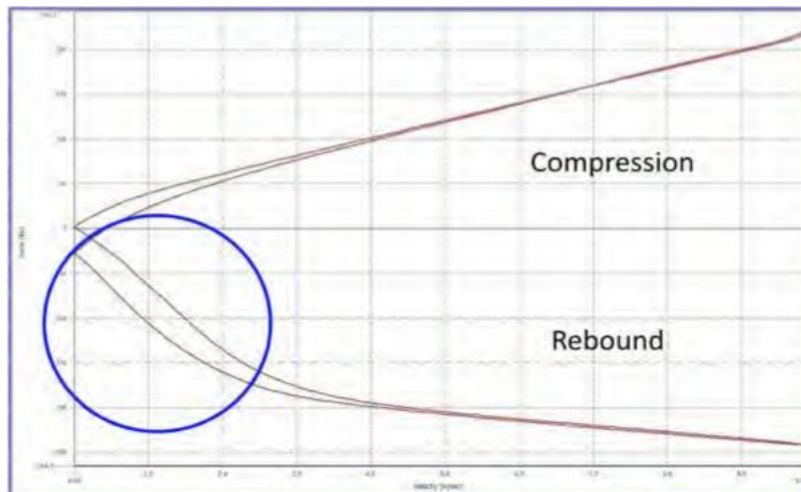
The machine will work by securing both ends of the damper to the rig with one end in the fixed into the frame, the other end will be attached to a motor that will rotate to simulate the forces put into the damper. There will be a load cell at one end to measure the forces that are being applied as shown in figure 6. The damper dynamometer will require a stroke and a RPM to be in put, this means not only are a range of different speeds are available the stroke can be changed meaning testing can be done at both full extension as well as part extension (Multmatic, 2018).

Figure 6-Damper Dynamometers



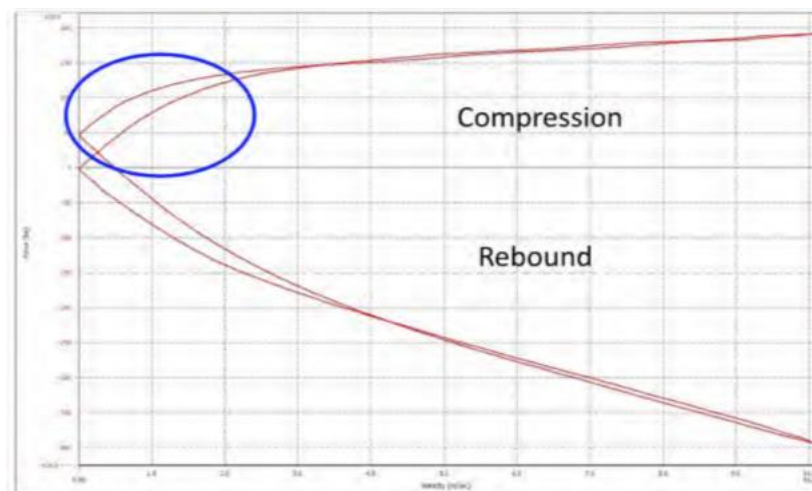
Dampers are often measured using 2 different graphs that are shown from a damper dyno this includes a force against displacement graph and a force against velocity graph. It can be split into 6 different sections and each will be shown below.

Figure 7-Low Speed Rebound (Kaspzak, 2019)



This will show the forces that are being controlled by the base valve on the rebound of the damper. This valve will have a range of different forces going through it, it will vary across vehicles but will be around speeds of 0-50mm/second.

Figure 8- Low Speed Compression (Kaspzak, 2019)



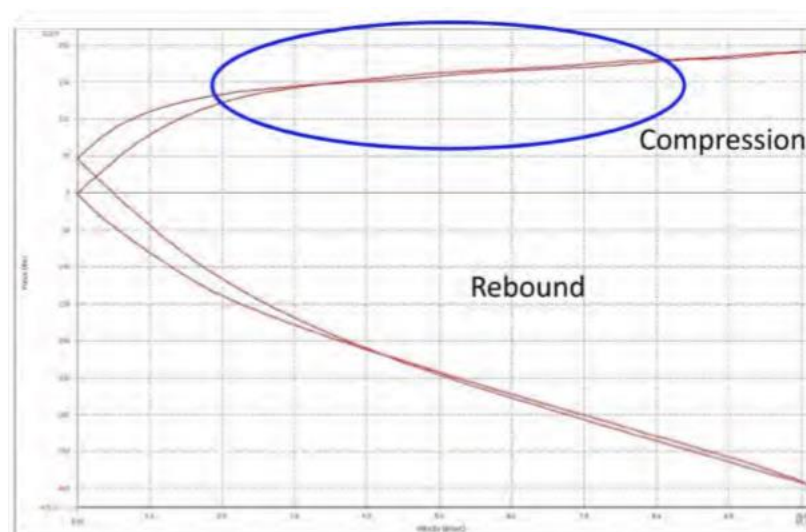
This will show the forces that are being controlled by the base valve on the compression of the damper. This valve will have a range of different forces going through it, it will vary across vehicles but will be around speeds of 0-50mm/second.

Figure 9 – Mid Speed Rebound (Kaspzak, 2019)



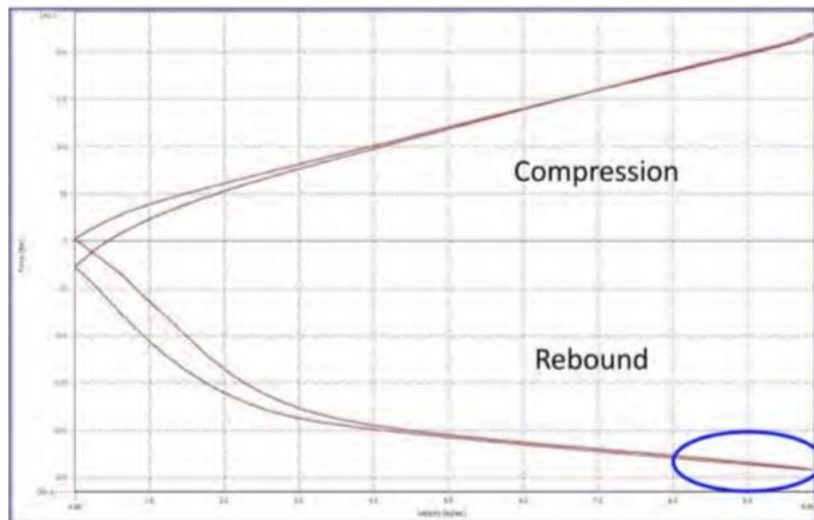
This shows the forces are controlled by the shim stack on the rebound side of the damper and does not cover a range of forces although over a greater range of speeds. The moment the base valve changes allowing for a great flow is clear to see at the start of mid speed. It will cover speeds from 50-200mm/second.

Figure 10- Mid Speed Compression (Kaspzak, 2019)



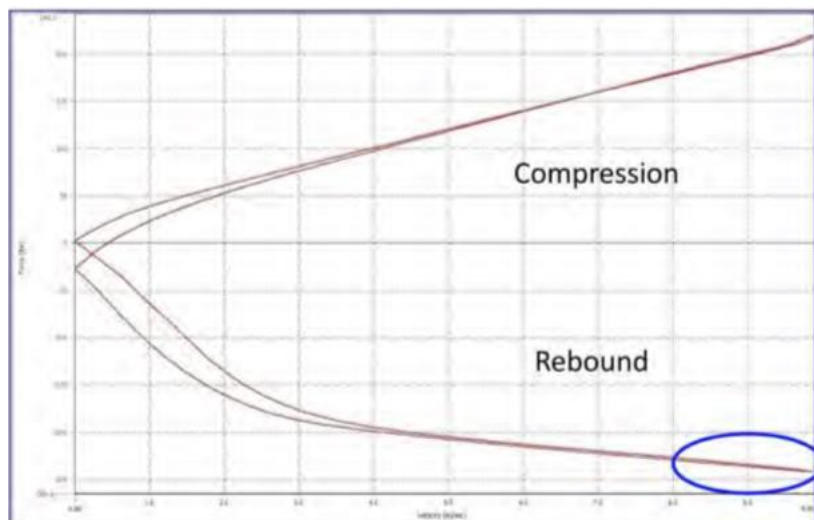
This shows the forces are controlled by the shim stack on the compression side of the damper and does not cover a range of forces although over a greater range of speeds. The moment the base valve changes allowing for a great flow is clear to see at the start of mid speed. It will cover speeds from 50-200mm/second.

Figure 11- High Speed Rebound (Kaspzak, 2019)



This shows the forces that are being controlled when the valve is fully open and all the shim stack has the most oil passing through. This will be when the speed of the damper is greater than 200m/second.

Figure 12- Compression High Speed (Kaspzak, 2019)



This shows the forces that are being controlled when the valve is fully open and all the shim stack has the most oil passing through. This will be when the speed of the damper is greater than 200m/second.

7-Test Protocol

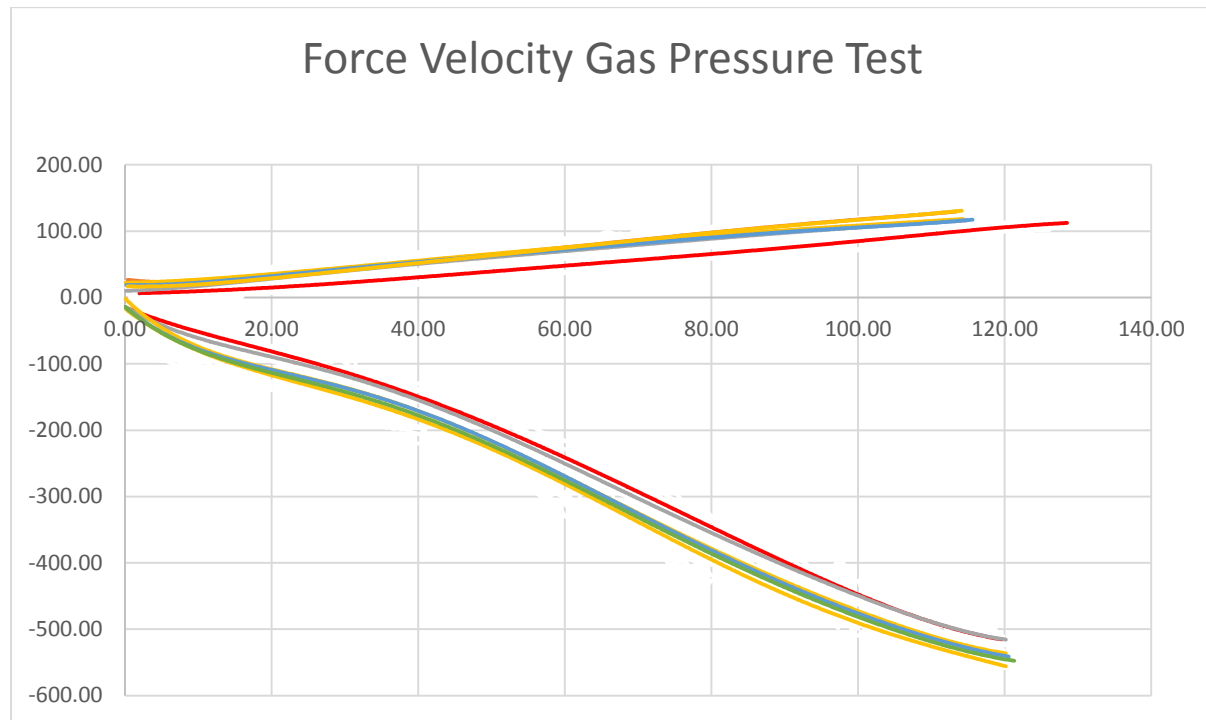
The damper that is being used in the test is an Ohlins damper and has no possible way of changing the pressure as it comes from the factory, this will mean that adaptation will be required. This will mean that the damper will require a full strip down with all fluids and components being removed so that the outer tube can then be drilled into allowing for a schrader valve to be screwed onto the outside of the damper. The valve will be placed at the top of the damper where the gas will reside when the damper is not in action. A schrader valve will allow the gas to be put into the damper with it also allowing for a sealed fit meaning the gas will not seep out whilst the damper is under testing (Reif, 2014). The shaft also does not have a suitable fitting for it to be connected into the dynamometer so a component with a thread for the shaft and a hole for the bolt to go through will need to be made so it can fit into place and be held securely throughout the tests (Multmatic, 2018).

It is essential that when the damper is put together it is cleaned extensively because any dust, metal shards or dirt could cause a blockage in either the base valve or amongst the shim stack. There's high levels of heat that can be caused throughout the cycle of a damper, if a metal shard is to be subdued this heat it could force it to be bound to the walls causing the piston wall to break resulting in a loss in damping force.

The test procedure will include putting the damper onto the dynamometer with an initial pressure of 0 bar with it then going up in increments of 4 bar going all the way to 20 bar. Once the nitrogen has been put into the damper at each pressure it will be first run for 5 cycles at a speed 3Hz, this is to make sure that any cavitation that may occur has the opportunity to take place as it may not be seen at the lower speed. The test that the data will be taken from will be in a single cycle at 0.5 Hz this is because when travelling at lower speeds it is easy to see when the low speed damping is over taken by high speed and the secondary valve is opened.

7.1-Test Results

Figure 13-Gas Pressure Testing



(0-Red,4-Blue,8-light blue,12-green,16-purple, 20-orange)

The test results are too vast to be put into a table but the results can be looked at through the use of graphs and figure above will show the force velocity plot with all the various pressure put into the damper, although it is hard to tell because the data is so similar but it shows an increase in force as pressure increases. As it can be seen there is a difference in the dampers performance across the pressure range, this backs up the formulas that have been previously stated in section 5.4 . What this does show that even at 0 gas pressure the damper is still usable, this will be as the air will take the place of oxygen as it is not a vacuum (Skagerstand, 2014), resulting in a less more compressive gas force. Cavitation is clearly present as shown by the loss in damping in low gas pressures, this loss of pressure is due to the air bubbles that are being formed in the oil. The recommended gas pressure for this damper is at 12 bar, but it is shown that there is better cavitation prevention whilst at 20 bar so it is clear to see that compromise is seen in this design as the longevity of the damper has been taken into account. The time in which the valve is opened to stop being controlled by low speed damping is present at around 100 newtons for each pressure although it is at different speed for each pressure, this is due to the change in compressability of the nitrogen

at different pressures (Reif, 2014). Dampers are often adjustable through the change in orifice size, this will control the rate at which the valves open and close and are seen desirable on race vehicles as it allows for quick changes in damping forces. These results show that a damper with adjustable gas pressure would allow for a change of ride set up quickly and easily as it would be possible within seconds whilst the damper is still mounted. There will still be problems with running high pressure as it could blow as seal if not worse (Kaspzak, 2019). There are several differences between a race damper and a road damper not only the circumstances it will be put under the longevity of the damper will need to be taken into consideration as the miles covered will be a single race where a road damper is expected to hit 80,000 miles, this will mean the pressure put upon the seals will be subdued for longer meaning a high pressure will be more damaging. If the testing shows nothing else it shows how vital damper balance is as the wrong pressure can have effects on the valve openings, as it will cause the damper base valve to open earlier or later meaning that the damper does not perform as required. This will mean that a damaged seal will show a loss in damping force as the intended pressure will drop over time meaning the damping force will lower resulting in a loss of damping force (SAE, 2001).

8-Further Study

For further study, there is many tests that can be carried out, this includes completing the same test using a mono tube damper although there is inherit problems with this testing as to change the pressure it will require entering the working chamber or sealing it as a complete unit which will require a full assembly and disassembly between each test as it will be time consuming (Irvine, 2010). Further testing including a twin tube damper could also include making a glass damper so its physically able to see the cavitation that takes place by seeing the bubbles that are in the oil. A glass damper will be highly impractical but simply to see what effect the gas is having would be beneficial. A glass damper will be hard to get a seal on the valve so a concealed unit will be required disassembly for each pressure change. A further test will be a test to destruction, only by doing this it will be clear to see when the pressure gets too high and causes damage to the damper. The seals will be the first to go and this will cause a loss in damping force so the damper dyno will show the exact moment that damper fails. The destructive test will be done in industry to work out multiple different things including warranties that is applied for vehicles (Suspension Secrets, 2017).

9-Conclusion

This report finding show that gas pressure plays a major part in a dampers performance, it also shows that when cavitation is present there is a loss in damping force. It also shows that dampers are capable of running past there intended pressure with an increased raise in performance in terms of cavitation prevention. This report shows how delicate a vehicles suspension systems are and the many different elements that go into making it as manufactures want. Dampers are often seen as a dark art and the tampering with such is seen as a hard task with few out there truly understanding how they work, but throughout this report it is shown that if a mathematical approach is taken in steps the required damping can be calculated. Although a correct damping force can be achieved it is like other suspension components and is often seen as driver preference, in production vehicles it is very hard because although a vehicle has a target market it is used by various different people in different situations.

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