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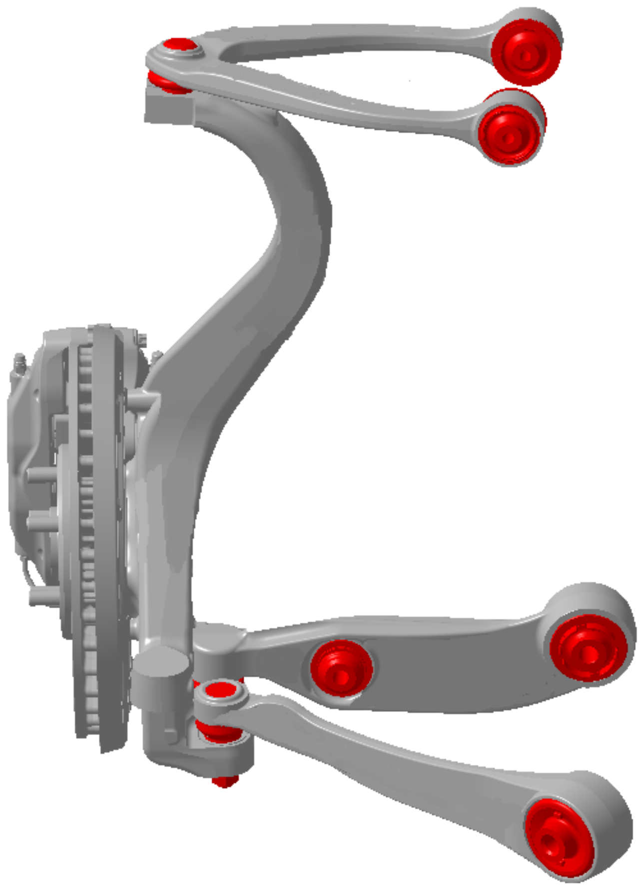

Library of Bushings and Ball Joints in CAD Environment

Bachelor thesis within mechanical engineering

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Abstract

In the early phase of a chassis development it is of great importance to establish a suitable concept for the wheel suspension and the surrounding components. If the prerequisites are met in the early phases of development the lead time is shortened, leading to a more effective design loop and lower cost. One way to do this is to standardize some of the components in the suspension. With a library of components to choose from, the development time can be reduced.

The purpose of this work was to create initial placeholder models for bushings and ball joints which should be as close as possible to the final component. This is done by creating a library of parametric CAD models that are possible to change with desired characteristics.

The work took place at ÅF Automotive and consisted of a pre-study on independent suspensions, where the focus was on the positions for bushings and ball joints. One suspension of each kind, front and rear, were selected to study further. A study was performed of the current market on bushings and ball joints and some components were purchased. Relevant information has been gathered in data sheets and calculations have been made in order to create the models. The calculations are underlying in a spreadsheet and generate values to the parameters which then can be used to modify the CAD models.

The end result is a useful increase in precision in size of placeholder models for bushings and ball joints in the early stages of a chassis development. It’s a beginning of a library of components for different positions in the suspension that can be extended over time.

Preface

This bachelor thesis was conducted at Chalmers University of Technology in cooperation with ÅF Automotive between January 2017 and June 2017. The work took place at ÅF Automotive in Trollhättan and we have also had the opportunity to use office space at ÅF's office in Gothenburg. The work has been carried out in cooperation with the Department of Product and Production Development, Chalmers University of Technology, Sweden. Examiner of this thesis was Andreas Dagman at Chalmers. The work was supervised by Daniel Bäck and Johan Hällsås at ÅF.

We would like to thank Andreas for his guidance and valuable inputs throughout the work. We would also like to thank Daniel and Johan along with other helpful personnel at ÅF for their advice and support during the work.

Notations

4WD - Four-Wheel Drive
CAD - Computer-Aided Design
CAE - Computer-Aided Engineering
FEM - Finite Element Method
KBE - Knowledge Based Engineering
KBS - Knowledge Based System
NVH - Noise, Vibration and Harshness
OEM - Original Equipment Manufacturer
SAE - Society of Automotive Engineers
SLA - Short-Long-Arm

[G] - Shear modulus
[k] - Shape factor
[E] - Elastic modulus

Table of Contents

1 Introduction

A car is a complex construction which can be designed in countless ways to meet the requested performance. Under the surface of the car, among other are the chassis. The chassis is the frame of the car on which the body is mounted. There are tons of solutions for the same problem but a lot of compromises have to be made in the end product. Both handling and comfort have to be taken in consideration when designing a chassis. Bushings and ball joints are two components that play a vital part in car safety, ride comfort and handling. A bushing is a rubber connection unit between two metal parts that allowing some movement between their interface. A ball joint connects the frame to the wheels while allowing steering as well as up and down movements. A bushing and a ball joint can be seen in Figure 1.

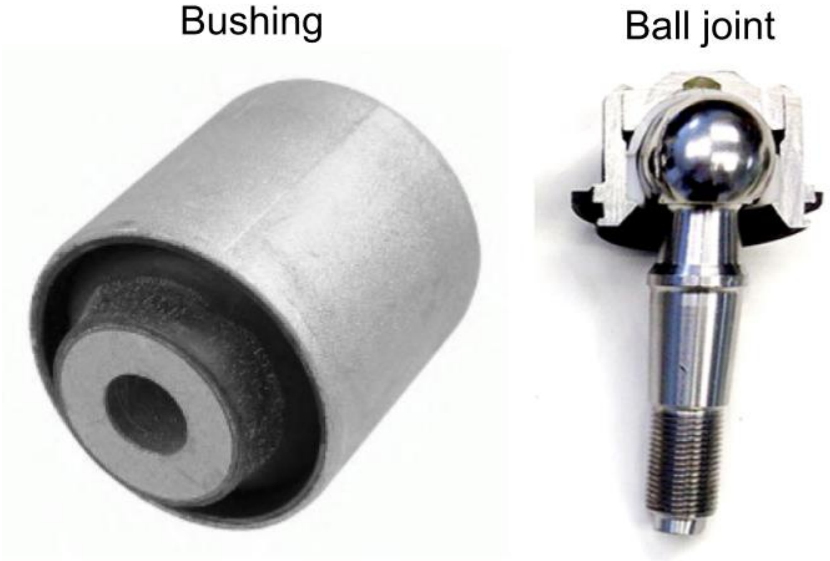


Figure 1. Bushing and Ball joint

1.1 Background

When a new chassis is developed an initial draft of the hard points are set by the engineers. The hard points represent the coordinates of the connection points for the components in the wheel suspension. These points are used for setting up a kinematic model, which is used for simulations to capture the movements of the components under pre-defined loadings. The movements are used to create an initial design volume for each component in the suspension.

During the concept development the prerequisites are set by the CAD engineers. This increases the variability of the process and is dependent on experienced designers. Some components are outsourced to be developed by suppliers. For these components, a placeholder model is made to claim the space by the CAD engineers. Ball joints and bushings are both components that are outsourced to suppliers. In later stages of the development the suppliers hand over the real models. If the initial placeholders differ a lot from the supplier models, costly and time-consuming changes can be needed. Now a more reliable way to decide dimensions for the placeholder models is wanted. With a library of models to choose from, the development time in design loops can be reduced. The models should also be described and connected to data sheets which presents information about the models in an efficient way.

ÅF is an engineering and consulting company with assignments in the energy, industrial and infrastructure sectors. ÅF Industry in Trollhättan offers technical consulting services for the automotive industry, [1]. Mainly focused on large scale inhouse projects, one which is chassis development.

In this project, the focus will be on creating parametric placeholder models using Knowledge-Based Engineering (KBE). Parametric meaning that the models will be made with parameters that decides the geometry of the model. The measurements are linked together. If you change one measurement, others change as well. KBE is a computerized system that uses a knowledge base to solve problems. The system captures engineering knowledge systematically into the design system, supporting experience re-use an improvement in engineering activities, [2].

The parametric placeholder models are also made with influences from the product development process. A product development process can be defined as follows: planning, concept development, system level design, detail design, testing and refinement and production ramp-up, [3], see Figure 2. This project will end at the detail design phase where geometry and materials are decided.

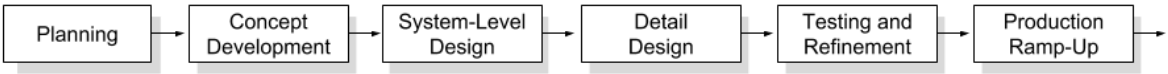


Figure 2. Product development cycle, [3].

1.2 Objectives

The purpose for this thesis is to do more accurate initial placeholder models to reduce the need of adjustment in later stages of chassis development.

To achieve this a study of the current market is going to be made on bushings and ball joints. Calculations on bushings and ball joints should generate parameters to a data sheet which will be connected to CAD models. By using KBE, the parametric models should be able to change with ease.

1.3 Deliverables

In order to fulfill the objectives this should be delivered:

- Parametric CAD models of bushings and ball joints.
- Data sheets that are connected to the models.
- Calculations and FEM that validate the models.

1.4 Delimitations

This thesis is limited to only include bushings and ball joints that are in the suspension system for passenger cars. Only independent suspension systems will be investigated. The types of bushings are limited to only cylindrical shapes. This project ends at the detail design phase with CAD models of the components. Calculations for bushings are limited to cylindrical and symmetrical shapes. To validate our models there will be comparisons with real data and not advanced simulations. The impact from fatigue has been neglected for both components.

2 Theory

This chapter briefly introduces vehicle dynamics and different types of suspensions, followed by more extensive information about bushings and ball joints.

2.1 Vehicle Dynamics and Chassis

Dynamics means how forces affect the movement of bodies. Vehicle dynamics is partly about how the vehicle is influenced by external conditions like road and wind but also how the vehicle responds to the driver's input like steering, throttle and brake, [4]. The car should respond to the driver's maneuvers as well as possible. It should have high steering precision, directional stability and braking control. The vehicle should have a good grip on the road and be stable even in bad conditions. To describe these different circumstances in an effective way, a defined coordinate system is used, see Figure 3. A vehicle has six degrees of freedom. Three translations and three rotations called yaw, roll and pitch, [4].

Figure 3. Global coordinate system for a car. [5]

Both handling and comfort should be taken in consideration when designing a chassis. Handling means the driver's ability to control the vehicle. There are lateral forces that occur by turning the vehicle and longitudinal forces that occur when applying gas or braking torque. For comfort, as little vibrations as possible is wanted, [6].

The suspension is the system that connects a vehicle to its wheels. The suspension has primarily two functions, to keep the tire in contact with the road at all times and limit the transfer of road irregularities to the vehicle. The objective for the suspension is to get good maneuverability and handling with a comfortable ride and as little vibration and noise as possible. These objectives contradict each other and compromises between them must be done to find the right properties for the right car, [7].

2.2 Suspension Geometry

When designing a suspension there are some important factors to take into consideration.

- **Camber angle** is the tilt of the wheels from vertical as viewed from the front of the vehicle. When the top of the wheels is tilted towards the car it's called negative camber. This is common because of better grip while cornering, [8], see Figure 4.

- **Toe angle** is the angle between the wheels seen from top of the car. When the tires are leaning towards each other it’s called toe-in. A small angle of toe-in is good for helping the vehicle to keep straight, [8], see Figure 5.

- **Caster angle** is the forward or rearward tilt of the steering axis in reference to a line vertical through the wheel center. A small angle helps to keep the tire straight and absorb bumps better, [8], see Figure 6.

- **The kingpin axis** is the imaginary line drawn between the upper and lower pivot points for the wheel while steering. The kingpin axis sets the scrub radius which is the distance between the line through the steering axis and the centerline of the wheel at the road surface. It's desired to have a small scrub radius since it requires less steering effort and minimizes tire wear, [8], see Figure 6.

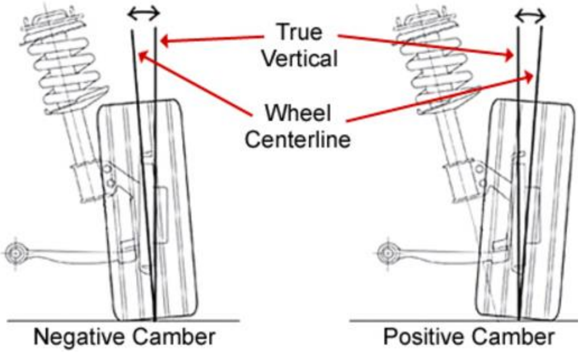


Figure 4. Camber angle, [9].

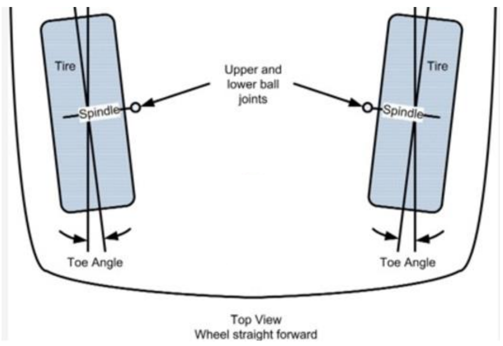


Figure 5. Toe angle, [9].

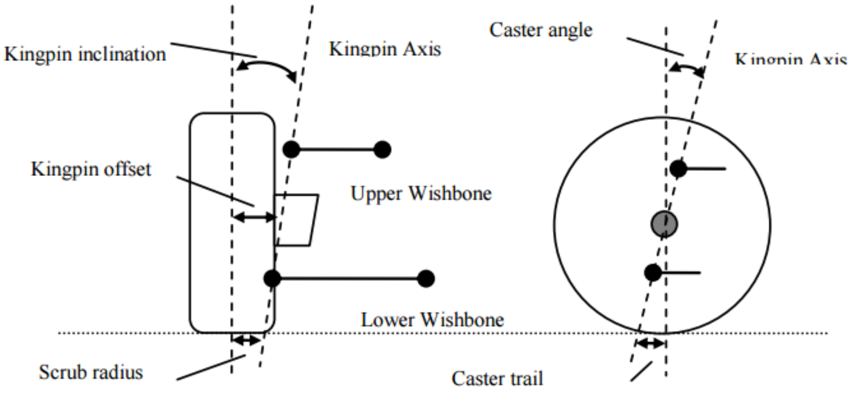


Figure 6. Suspension geometry, [7].

2.3 Front suspensions

Only independent suspension systems have been considered for this thesis due to limitation reasons. An independent suspension is a decoupling of the wheels which means that the movement of one wheel is not transferred to the other. Each wheel is assembled to the car body individually.

2.3.1 MacPherson suspension

The MacPherson strut was invented by Earle S. MacPherson 1958 when working a Ford, [4]. The suspension is widely used because of its compact and low-cost design due to fewer parts than other types.
The system uses a load carrying damper mounted directly into the steering knuckle and into the body where its free to rotate. At the bottom there is a single control arm to support the strut. Since both the knuckle and damper will rotate while steering the kingpin axis is set, see Figure 7, [4].

The negative sides with a MacPherson strut is the few connection points. Because of that it's hard to get good properties for camber, kingpin and caster trail. As the strut is a part of the body, both the strut and the tire will lean in the corners and make the handling worse than other suspension types, [4].

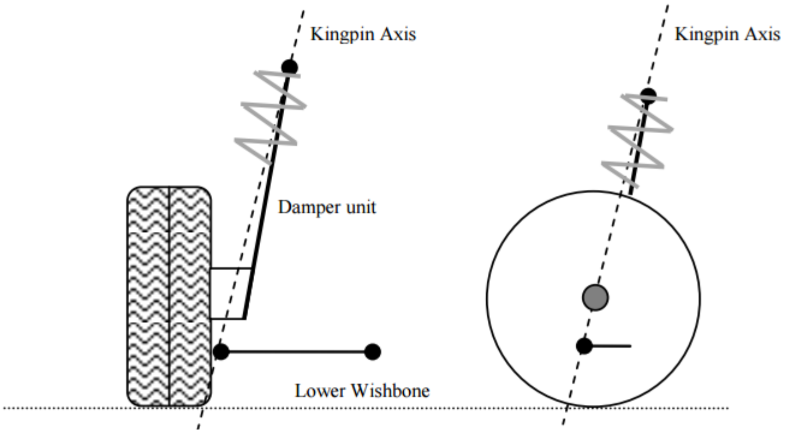


Figure 7. MacPherson suspension, [7].

2.3.2 Hi-Per strut suspension

The Hi-Per strut is a development of the MacPherson strut. The main improvement is that the knuckle is not directly locked into the damper strut. The damper strut is instead connected to the control arm outer ball joint with a unit called a yoke. Because of this the knuckle is free to rotate while steering without affecting the damper strut. The kingpin axis is determined by the joints in the knuckle instead of damper mount and lower control arm, see Figure 8.
The Hi-Per strut will have improved handling but with downsides as higher cost, mass and package space. One advantage is the similarity to MacPherson which makes lesser changes needed than if changing to other suspension types, [7].

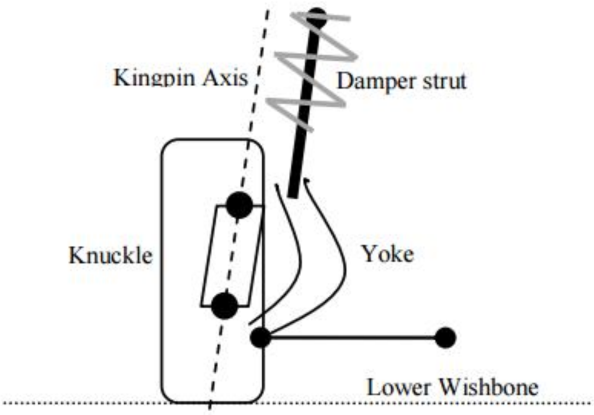


Figure 8. Hi-Per strut suspension, [7].

2.3.3 Double wishbone suspension

Double wishbone suspensions are made with two separate control arms. It has good handling performance but worse Noise-, Vibration- and Harshness- (NVH) properties. This type is more common on racing cars or 4WD trucks which have more space in the transverse direction. A designer can change the alignment of the wheel to meet desired factors for kingpin position. The basic concept for double wishbone together with Short-Long-Arm (SLA) is shown in Figure 9, [10].

2.3.4 Short-Long-Arm suspension

The upper and lower control arms are usually of unequal length from which the acronym SLA (Short-Long-Arm) gets its name. It is best suited to vehicles with a subframe for mounting the suspension and absorbing the loads which most of the cars have today. The SLA requires careful refinement to give superior performance. When steering, the geometry of an unequal-arm system can improve camber at the outside wheel and less-favorable camber at the inside wheel, [4].

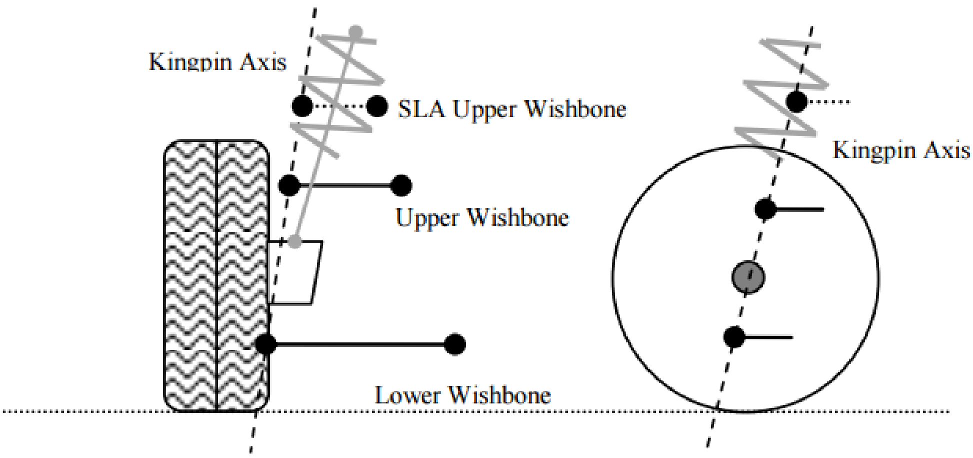


Figure 9. Double wishbone and SLA suspension, [7].

2.4 Rear suspensions

For the same reasons as in the front suspension, only independent suspension systems have been considered.

2.4.1 H-arm suspension

The H-arm suspension is a simplified name for the trapezoidal (integral) link suspension. The name comes from the solution of the lower control arm where two links have been connected to each other in the form of the letter H (Figure 10). One end of the arm is connecting to two locations of the car body while the other end connects to two locations of the wheel hub. If this kind of link is used only two degrees of freedom must be eliminated by the remaining links. This is solved an upper control arm for camber, one for toe and a short vertical arm to resist breaking moment. The H-arm has good rotational stability which enables use of softer bushings with good damping ability, [10].

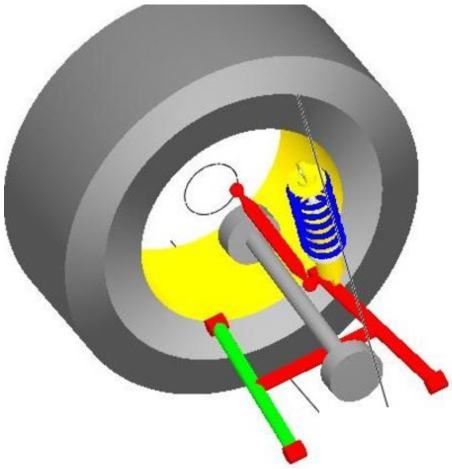


Figure 10. H-arm suspension, [11].

2.4.2 Multi-link suspension with 4 or 5 links

The multi-link suspension offers great design possibilities with regard to the geometric definition and kinematic behavior. The idea behind these systems is to separate the various suspension functions from each other, isolating the ride quality components from the handling components. Four or five links (Figure 11) are used to control wheel forces and torque, there are a wide scope for design for this type of suspensions to optimally control these forces. The arrangement of links comes down to the amount of available space and the expense, [12].

The 5-link gives the freedom to fully exploit the kinematic properties without requiring compromises in the system. Because of the arrangement each parameter can be tuned separately. Disadvantages of the system are the required package space, complex design and tuning difficulties which makes it expensive, [5].

The 4-link are a more common solution where the system consists of one longitudinal link and three lateral links. It’s a less complex design but on the other hand the NVH-properties isn’t as good, [5].

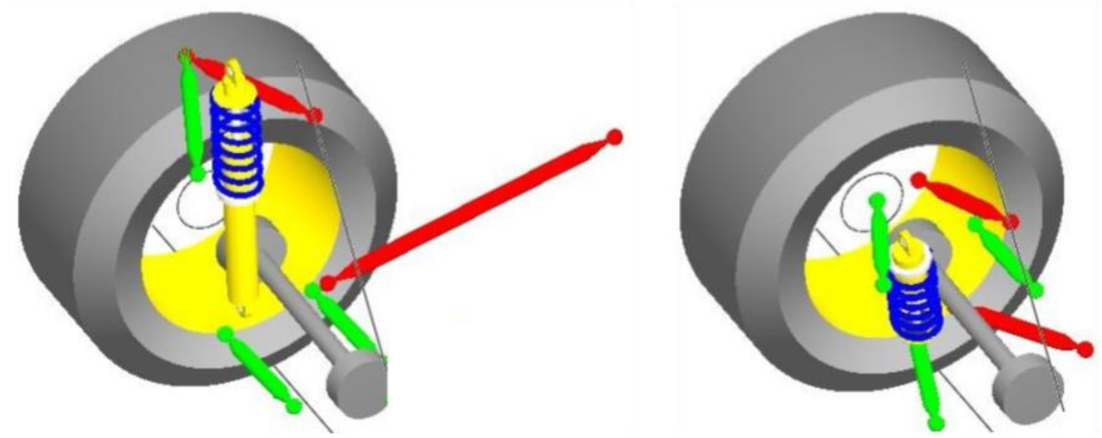


Figure 11. 4-link and 5-link rear suspension, [11].

2.5 Bushings

A bushing is a rubber connection unit between two metal parts that allowing some movement between their interface. They play a vital part in car safety, ride comfort and handling. One of the primary functions is to insulate the vehicle from road vibration and noise due to irregularities. Bushings are made to do all the small movements needed to reduce the road input. When the wheel is exposed to bigger movements the dampers do the work, [10].

There are many different kinds of rubber bushings in cars, see Figure 12. This thesis is limited to only suspension bushings and will not cover bushings in subframes and sway bars. An example of the bushings positions in a suspension is shown in Figure 13. Suspension bushings can vary from big soft bushings used for comfort to small stiff bushings mainly used to improve the handling of the vehicle. Comfort bushings absorb smaller movements of the wheel and handling bushings secure good steering and response for the driver. Rubber bushings provide damping in all directions but the damping rate can differ in each direction, [10][13].

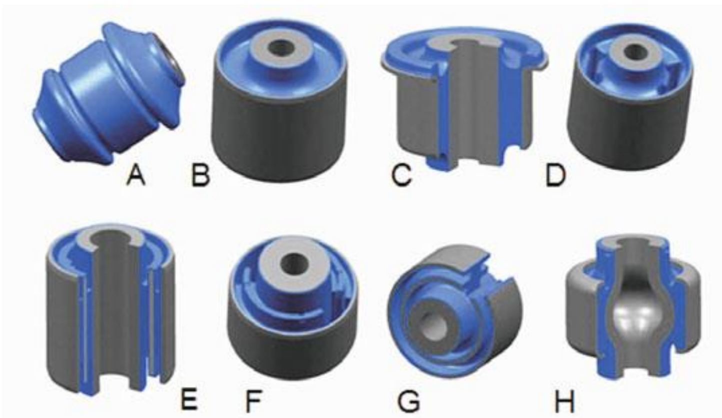


Figure 12. Bushing variations, [10].

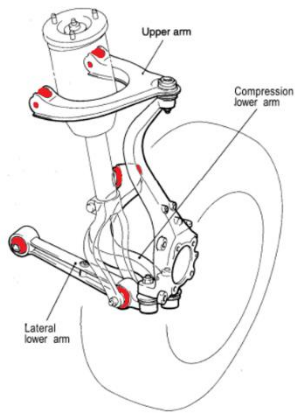


Figure 13. Bushing positions, [14].

Since a bushing can be mounted in various directions it has its own local coordinate system that differs from the global coordinate system for the whole car. The bushing joint is free to rotate about its longitudinal (Z), lateral (X), and vertical axes (Y), see Figure 14. A typical bushing can allow movements up to approximately ±20° to 25° in rotational direction, ±5° for the cardanic angle and ±1 to 3 mm for axial and radial direction. For smaller movements, rubber bushings grant six degrees of freedom. For larger movements, the motion is limited to one degree of rotational freedom, [10].

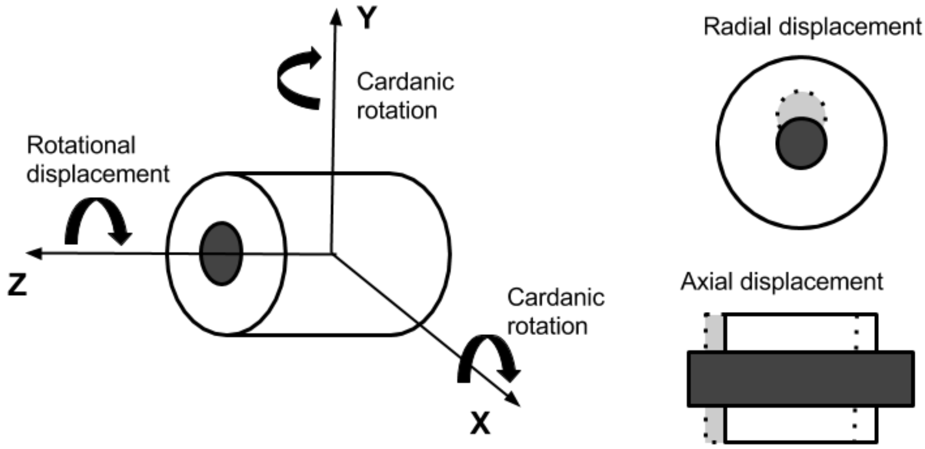


Figure 14. Bushing movements.

Another important task for the rubber bushing is to implement the desired elastokinematic (kinematics with material properties taken into consideration) behavior of the wheel control system. Bushings have a wide range of possible applications because they make up for tolerances and are flexible in all three loading directions. The force-dependent movement of the bushing can be specified differently in each of the three directions. The volume of rubber remains constant even though rubber deforms elastically. This requires free space to allow those deformations, [10].

2.5.1 Bushings dimension criteria

The maximum load which can be put on safely to the bushing is settled by the rubber structure used and the resulting deformations. The projected surface area of the inner sleeve and the resulting specific loads also needs to be considered. One of the most important material parameters, when selecting rubber structure, is the shear modulus [G]. The shear modulus is dependent on the shore hardness of the material (Figure 15) and is used along with a shape factor [*k*] when calculating the modulus of elasticity of the material. The factor *k* varies with applied stress, leading to a progressive force-displacement curve. The shape factor can be increased by adding deformation limitations like metal discs and can be reduced by removing material, [10].

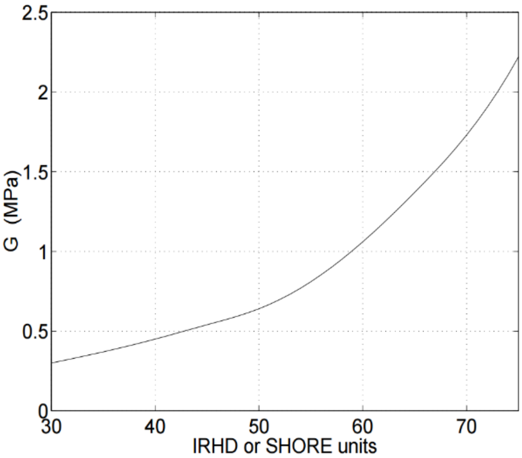


Figure 15. Shear modulus vs SHORE, [15]

The inner sleeve is held in place by a through-bolt connection. The force between the sleeve and the interface must be high enough to prevent rotation from torque. To achieve this, the sleeve must be large enough and have a suitable surface roughness, [10].

A bushing can be made to behave in different ways in each direction depending on how it is constructed. By adding holes, the stiffness in the loading direction is reduced as well as aligning torque. By adding intermediate sleeves the radial stiffness is increased. If the bushing is exposed to large axial loads, bump stops can be used to delimit the movement in the axial direction (Figure 16). A bumpstop is an extra rubber disc mounted in axial direction. It can be integrated with the bushing or a separate part, [10].

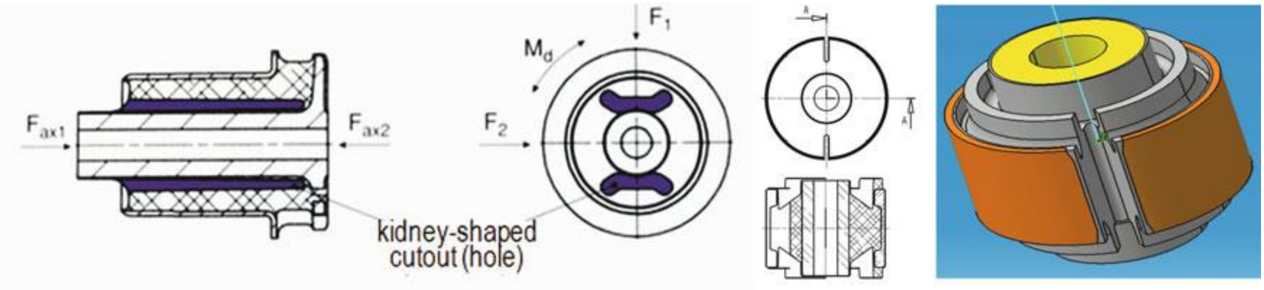


Figure 16. Bushing with holes and integrated bumpstop left. Bushing with intermediate sleeve right, [10].

2.5.2 Bushing or ball joint?

In some cases it is possible to replace a ball joint with a bushing joint. If the ball joint is used mainly for rotation in just one direction and the movements in the other directions are very small, the replacement can be done. Rubber bushings are resistant to moisture, corrosion, short-term excessive loading and the elastic deformation instead of sliding motion of the mating parts require no maintenance. This result in, for many applications, rubber bushings are a more cost-effective solution than ball joints. A disadvantage though is that they apply forces which counteract rotation and cardanic displacements. The inner sleeve must be longer than the outer sleeve to allow movement during cardanic and axial deformations of the joint, [10]

2.6 Ball joints

The linkage components in a vehicle suspension must be in contact but still be able to move relative to each other. One effective way to solve this is by using ball joints. There are many important parameters for the characteristics of the joint. For example the material, dimensions, surface roughness, lubrication and the ability to support loads, [10].

A ball joint connects the steering knuckles to the control arms next to the wheels. It allows three degrees of rotational freedom. They are used to move front wheel up and down, rotate when steering and change of position and orientation, see Figure 17. A ball joint transfers the wheel forces without implementing any torque. An example of ball joint positions is shown in Figure 18. The joint needs to be free from play but have low internal friction. If there is play in the joint it can be a source of vibration in the suspension, [10].

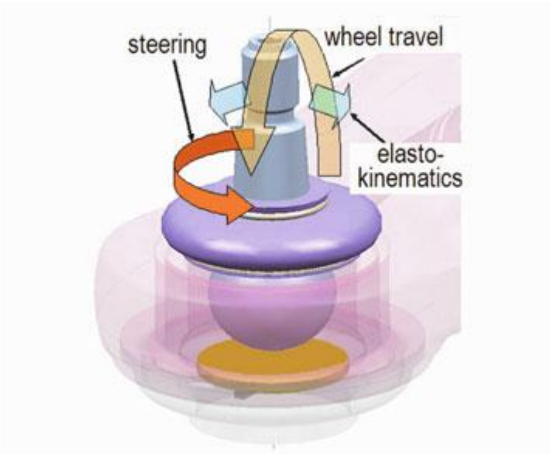


Figure 17. Ball joint surroundings, [10]

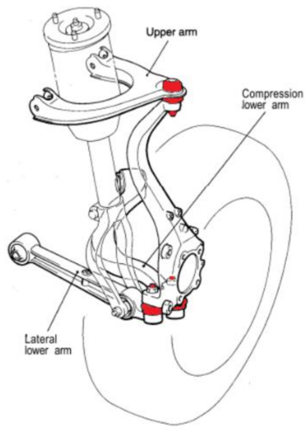


Figure 18. Ball joint positions, [14]

Depending on the suspension construction, either the upper or lower ball joint is the load-carrying ball joint. Ball joints are mainly used in three places in the car. There are wheel joints used for control and support of the wheel. They are also used in tie rods (steering) and stabilizer links (roll control). The two latter are not in focus in this project, [10].

2.6.1 Ball joint Components

If a ball joint breaks the driver lose the ability to handle the car. Therefore they are manufactured with great care and with a large safety factor. Because of the cyclic nature of applied loads they are generally designed to handle at least 10 million cycles, [10]. The ball joint components are shown in Figure 19.

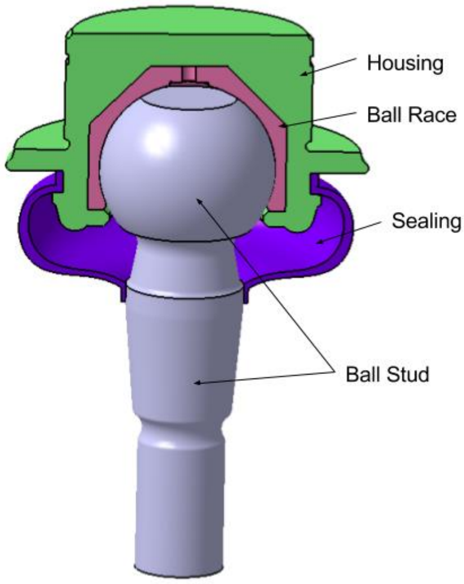


Figure 19. Ball joint components.

Housing - The most used material for housing of the ball joint is steel (30MnVS6). It could be made by forging, cold extrusion or drawing. The housing must be made with very tight tolerances usually less than 0,1 mm. Steel housings are rarely heat treated but for aluminum housings it can be important. The outer surface must have a protective coating against corrosion, [10].

Ball stud - The most common material for ball studs is 41Cr4 steel. It's a very strong steel since the ball stud is exposed to high forces. The ball stud consists of a ball and a stud linked with a tapered neck. The neck is needed to give space for the joint to move. It's desired to have a freedom of around ±35°.
The ball stud has even tighter tolerances of 0,05 mm. The spherical tolerance is also a significant factor. The surface of the ball is important. It can't be too smooth or too rough since it increases friction. The stud can be conical or cylindrical but conical should be used when possible due to better possibility to seal the system, [10].

Ball Race - The ball race is a plastic cap to prevent metal to metal contact between the ball stud and the housing. The standard material is POM (polyoxymethylene) because of its low friction and wear coefficients but high strength. A ball race should have at least 1.5 mm thick walls and have one or more slits. This helps the ball joints to have low internal resistance. The plastic ball race is the weakest part of the ball joint and it's vulnerable to higher temperatures. Since POM begins to creep when the temperature rises it should not be used if the operating temperature goes over 80°C. Then PEEK (polyether ether ketone) which does well up to 140°C could be an alternative, [10]. When designing a ball joint there will be a max allowed pressure for the ball race. The pressure increases when the material creeps. Since the ball joints should have no play, the gap between the ball stud and the housing is specified smaller than the thickness of the ball race. Therefore there will always be some pressure in the ball race even when its unloaded, [10].

Sealing System - It's very important that a ball joint is well sealed to prevent dust, liquids or moisture to enter the ball race system. This would cause increased internal friction in the short run and in the long run it can cause additional wear and corrosion. Corrosion could make the stud break. To prevent this from happening there is an elastic sealing boot over the opening between the housing and the ball stud, [12].

2.6.2 Control Ball Joints

The task for a wheel control joint is to control the motion of the wheel carrier and allow it to rotate about the wheel's steering axis. Ball joints that are used for wheel control are mainly taking loads in the radial direction. The forces in the radial direction are about 4 to 8 kN which are much smaller than the axial forces that preloaded ball joints are designed for. As a result, smaller ball joints are used. The most common sizes are 22, 25 and 27 mm in ball diameter which is enough for most passenger cars, [10].

2.6.3 Preloaded Ball Joints

Preloaded ball joints are larger than control ball joints because they are subjected to both axial and radial forces. The axial forces that comes from springs and dampers and are much larger than the radial forces. The preloaded ball joints should be mounted so the largest loads are in the compression direction. The most used sizes are 30, 32 and 35 mm for the ball diameter, [10].

2.7 Product development process

The purpose of a well-defined product development process is to improve and simplify the quality assurance, coordination, planning and management. According to [3] a generic product development process can be defined as follows:

0. **Planning** - The preface in product development is the planning. This is the link to research and technology development activities. The output of this process is the mission statement.

1. **Concept development** - In the phase of concept development the targets are identified. Several concepts are generated and one or more are selected for further development.

2. **System-level design** - In this phase, the product is decomposed into subsystems and components. Early plans for production and assembly are usually set in this face as well. Output of this phase is geometric layout of products, specification of subsystems and early flow diagrams for the assembly process.

3. **Detail design** - In the detail design phase a final specification of the geometry, materials and tolerances for the unique parts are made. Drawings are made for the parts and the tooling is designed for the production. Specifications are made for purchased parts.

4. **Testing and refinement** - This face is focused on building prototypes to test the performance and reliability of the product. Preproduction versions are made to determine if the customer need is satisfied.

5. **Production ramp-up** - In the last phase of product development the production is slowly increasing. The personnel are trained and the remaining problems are hopefully solved.

The product development process is shown in Figure 20.

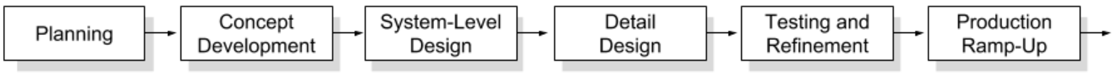


Figure 20. Product development process, [3]

2.8 CAD Tools

Catia is a software used for computer-aided design (CAD) and computer-aided engineering (CAE) developed by Dassault Systems. Catia offers a wide scope of workbenches which support the product development process in multiple stages. Mechanical design, structural simulation and manufacturing are some examples of applications, [16].

2.9 Knowledge-Based Engineering

According to [17] Knowledge-Based Engineering (KBE) can be defined as:

> *"The use of advanced software techniques to capture and re-use product and process knowledge in an integrated way."*

A Knowledge-Based System (KBS) preserves the capability of individuals within a particular field, and incorporates it within a computerized application. KBE is a subsystem of KBS that focuses to the field of manufacturing design and production, [18]. A company's experience from its own product development and manufacturing process offer unique insights that provide a competitive advantage. Methods and tools that captures this experience in an efficient way could have a positive impact on a company's ability to stay competitive. Knowledge is not automatically captured and shared within the organization and therefore a need for knowledge management strategies and systems to support the process. KBE tools support experience re-use and improvement in engineering activities, [2].

A KBE application typically consists of the following components - geometry, configuration and engineering knowledge.

- Geometry - there is often a substantial element of computer-aided design (CAD).
- Configuration - refers to the matching of valid combinations of components.
- Engineering knowledge - enables manufacturing and other considerations to be built into the product design.

If a high degree of integration is needed of the above elements, KBE is likely to be the best method for its integration, [18].

The main objective with a KBE system is to reduce lead-time by automating work activities of the product development process. Preserving knowledge from staff is another objective, it makes the company more resistant to staff turnover. The core of the system is the product model where product and process knowledge is stored. Input to the KBE system is usually customer's specifications, which gives several kinds of output when being processed. The system is object-oriented and can therefore perform demand-driven calculations, [19].

3 Method

This chapter presents the methodology used for this project as well as the “execution of work”. Starting with a description of the foundation for the project followed by the procedure to achieve the deliverables.

3.1 Pre-study

For background information regarding vehicle dynamics and types of suspensions several books were studied together with education material from the company. For more specific information regarding bushings and ball joints, Chassis Handbook was the main source of information. Articles, reports and SAE papers were investigated to overview what’s been done before within the subject.

Previous projects at the company were a source for inspiration in the different phases of the thesis. In particular, a complete chassis construction has been the most important source for information and as a reference. In the beginning it was important to understand the former issues and solutions. Analyzing the existing models and data sheets gave helpful inputs what to focus on and which parameters that are important.

The workflow for this thesis was based on the chart shown in Figure 21.

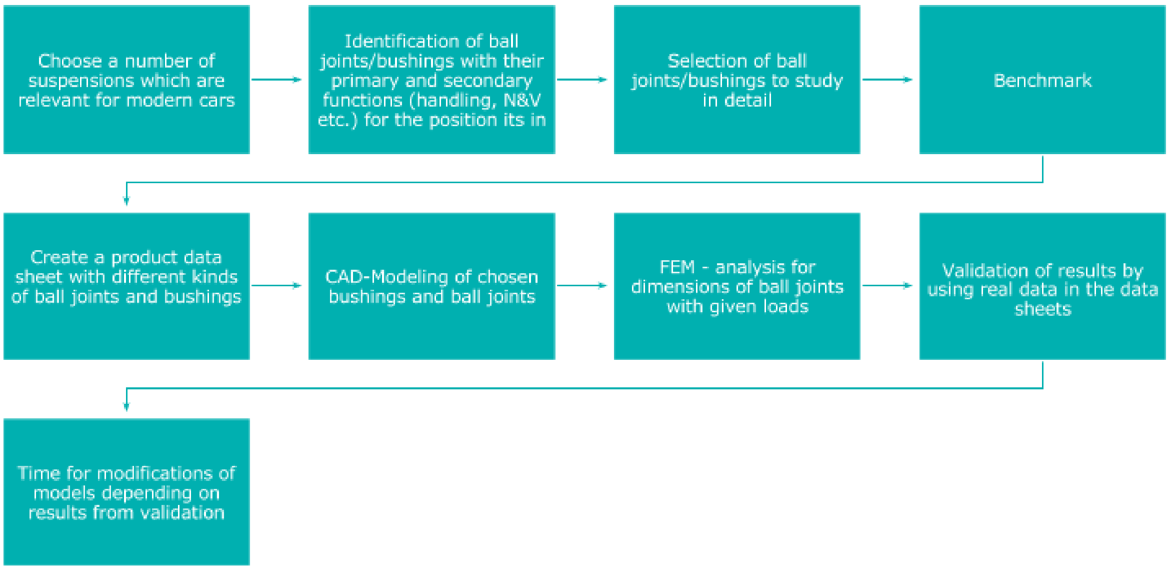


Figure 21. Thesis workflow

Selecting suspension type

The benchmark program a2mac1 has been a helpful software for reference. Especially the tool “auto reverse” has been used for studying disassembled cars. With the help of a2mac1 a study of current suspensions was made. Cars made from 2010 and later were investigated.

They were divided into normal and premium cars. Cars were considered as premium with a price over 500k SEK. The software also helped to identify various solutions between different cars with the same type of suspension. [20]

A selection process on which kind of suspensions types to investigate had to be done to narrow down the extent of the thesis. Two Pugh matrices [21] were made to decide which type of front and rear suspension to start with. The factors to consider were for instance, if the suspensions are relevant for modern cars and the coverage of information available. The CAD files from the company along with specific literature about suspensions was taken into account.

Supplier information
When the type of suspensions had been chosen the next step was to contact suppliers. The goal was to get some external information from companies with specific know-how. For both components the information asked for where about dimensions and material data. In this phase of the project, a mapping of suppliers and dealers were done. Since the reference material at the company was from a SUV, similar cars like BMW X5, Audi Q5 and Volvo XC90 were the main focus. Webpages and online catalogs were searched for information at OEM's (Original Equipment Manufacturer) as well as aftermarket suppliers. Many emails were sent and phone calls were made to people at these companies.

3.2 Benchmark

3.2.1 Benchmark bushing

The next step in the process was to investigate which bushings to do a benchmark study on. A number of bushings were going to be purchased for a more detailed study. As for the suspension selection the number of cars had to be narrowed down. Then a decision was made about which parts that were going to be purchased. Since the budget was limited the focus was to get as many interesting parts as possible and still cover all the positions in the front and rear suspension. The parts were from BMW X5 and Audi Q5. A total of 13 bushings and ball joints were purchased, see appendix 1.

The stiffness is a parameter of importance when a bushing is constructed. Since the suppliers did not share any information of this kind, the stiffness had to be measured. There are special machines to examine the stiffness on the rubber for the different kinds of bushings. Unfortunately, neither Chalmers or ÅF could provide resources to do reliable measurements of displacements when a force was applied.

A basic test rig was built in an adjacent workshop to ÅF's office where simplified measurements could be done. The rig consisted of a pull-back ram with a dynamometer attached to it, which was bound to the fixed bushing, see Figure 22. The movement was recorded at different magnitudes of force and in the directions that diverge from each other. After the measurements had been done the bushings were sawed apart to see how they'd looked inside the cover. Then the construction could be examined in detail and the exact measurements could be taken.

Figure 22. Test rig

3.2.2 Benchmark ball joint

A benchmark study on ball joints was also performed. A difference when it comes to ball joints is that they are much more alike between different suspensions. The strength of material and certain details in dimensions can separate them, but the focus in this project was to make a general solution. Because of this, a decision on which cars the ball joints where from were not as important. As for the bushings, a number of ball joints were purchased. The ball joints came from the manufacturer *Delphi Autoparts*, from various cars like Ford and Mercedes.

The strength of materials is the most important parameter for ball joints as a safety detail. The suppliers did not share either material data or load serviceability. A typical material for ball joints could be chosen with help of literature. Then the loads could be approximately calculated. The ball joints were also sawed apart to get the exact measurements. This was compared with data from the reference project.

3.3 Data Sheets

Creating a data sheets that are connected to the parametric models is one of the deliverables for this project. During the project it was decided that a data sheet with just information also was going to be made. It would include all kinds of measurements, stiffness, material data, etc. The point with this kind of data sheet was to gather everything from the reference project and the benchmark in one place. Every position in the suspensions have one sheet each. This makes it easier to identify similarities and differences for each positions. Another advantage is that relations between various parameters can be detected in a simple way.

Using Knowledge-Based Engineering (KBE), it will be easy to create new variants by changing parameters and then store them, leading to a larger library of components. One of the tasks was to decide the input and output parameters and find the right equations for them. The specifications are set by the designer, underlying calculations gives recommended new values which are support for the parameters in the CAD models. In that way, the designer can choose or create the right component by a number of given criteria.

3.3.1 Product data sheet bushing

For a bushing, there is a lot of dimensions that are important. A significant connection is that the bolt size that decides both the hole- and inner diameter of the bushing. Normal sizes for the bolts are between M8-M16. The rubber thickness decides the rest of the diameter for the bushing in many cases because thickness of the outer sleeve is almost standardized. The length of the bushing is dependent of the available space, together with the rubber compound and the loads that the bushings are exposed to.

3.3.2 Product data sheet ball joint

For a ball joint, the most important part is the ball itself. It's the ball dimension that decide the strength of the joint along with the material. There are important relations between the size of the ball, the neck diameter and the lever arm. These are commonly in the same proportions and they decide the geometry of the ball joint. The height of the ball stud and housing are other dimensions that are important, due to the size of the whole ball joint.

3.4 Calculations

3.4.1 Calculation bushing

Rubber is a nonlinear elastic material, meaning that it has a complex stress-strain relationship. These formulas are estimations for a bushing that is cylindrical and rotation symmetric. The calculations have been made with formulas from [22] together with [23].

A shape factor [S] is used to calculate the radial stiffness. The shape factor is defined as the ratio of the loaded bonded area to the force-free lateral surface area, [22]. Where [a] is the inner diameter and [b] is the outer diameter of the rubber cylinder.

$$S = \frac{2L(b^3-a^3)}{3(b^2-a^2)^2} \tag{3.1}$$

Then the shape factor is inserted in formula:

$$K_X = \frac{4 \cdot \pi \cdot G \cdot L}{\frac{S^2+2.45}{S^2+1.45} \cdot Ln\left(\frac{b}{a}\right) - \frac{b^2-a^2}{b^2+a^2}} \tag{3.2}$$

Another way to compute the radial stiffness is with a formula from, [10]. The same shape factor has been used in that calculation.

$$E' = 3 \cdot G(1 + S + S^2) \quad (3.3)$$

Where E′ is inserted in formula:

$$K_X = E' \cdot \frac{\pi \cdot a \cdot L}{h} \quad (3.4)$$

For the axial direction the bushing can be seen as a rubber spring, see Figure 23. According to [24] the displacement is calculated as:

$$s = \frac{F \cdot ln \cdot (d_0/d_i)}{2 \cdot \pi \cdot l \cdot G} \quad (3.5)$$

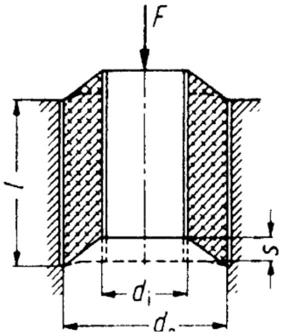


Figure 23. Axial stiffness, [24]

Therefore, stiffness which is force divided by displacement is calculated as:

$$K_Z = \frac{F}{s} = \frac{2 \cdot \pi \cdot G \cdot l}{ln \cdot (d_0/d_i)} \quad (3.6)$$

3.4.2 Calculation ball joint

The strength of materials for ball joints has been calculated by using Euler-Bernoulli beam theory, [25]. The calculations are limited to the neck region because it's the critical dimension for a ball joint, [5]. The ball joint has been assumed as a beam with a solid circular cross section and only static load cases has been taken into account, see Figure 24.

Normal stress due to normal force F_N & bending moment M is computed with:

$$\sigma = \frac{F_N}{A} + \frac{M}{W_b} \quad (3.7)$$

Where,

$$A = \frac{\pi d^2}{4} \quad (3.8)$$

$$M = F_T \cdot a \quad (3.9)$$

$$W_b = \frac{\pi d^3}{32} \quad (3.10)$$

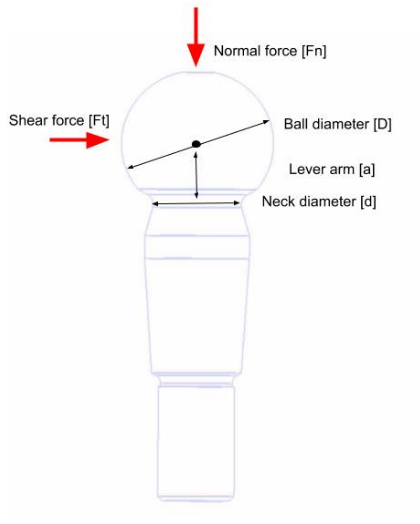


Figure 24. Ball joint measures

The shear forces are summed as a resultant because of the symmetric shape in X- and Y-direction.

$$F_T = \sqrt{F_X^2 + F_Y^2} \tag{3.11}$$

The shear stress is calculated with the Jouravski factor (μ = 1,33) for a circular cross section, [25].

$$\tau = \mu \cdot \frac{F_T}{A} = \mu \cdot \frac{F_T \cdot 4}{\pi d^2} \tag{3.12}$$

Then the von Mises stress can be computed and be compared with the material properties, [26].

$$\sigma_e = \sqrt{\sigma^2 + 3\tau^2} \tag{3.13}$$

3.5 CAD modeling

The goal with the CAD models were to make a library with different types of bushings and ball joints that could be used as initial placeholder models. The models should be flexible and easy to adjust until desired form.

All the purchased bushings from the benchmark were made into Catia models. To extend the library further, supplier models of bushings and ball joints were also remade into parametric models. A CAD model from a supplier comes as one solid part with no features. The part is saved without history and is called a “dead model”.

The first key to a flexible model was to understand which measurements that vary a lot and which do not. If you for example make the model x amount longer. Important things to consider was if all measurements should scale up proportionally or if some are fixed.

Another key factor was to link sketches properly. A very useful tool in Catia is “project 3D elements” which let you import parts of other sketches into a new sketch. This was used a lot when making the sketches for the rubber. This was an efficient way to make the rubber stick to the sleeves, see Figure 25.

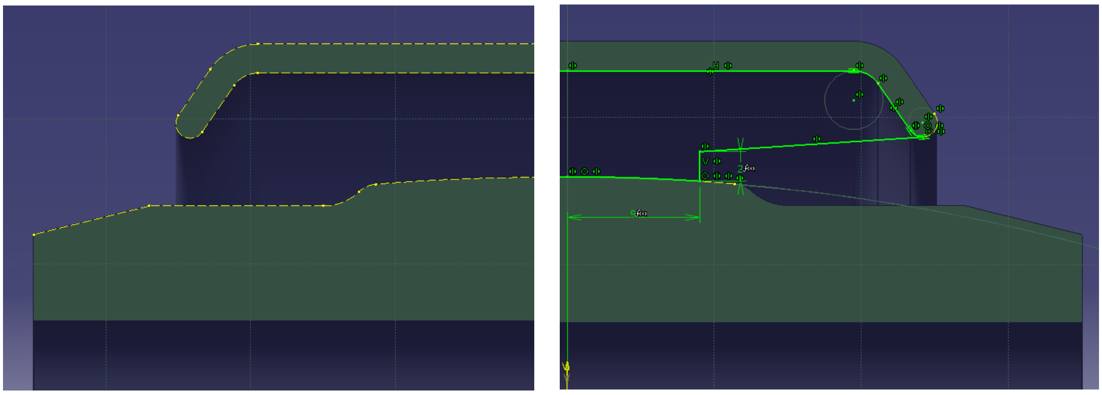


Figure 25. Sketch linkage (left side before, right side after).

The last key factor was to use parameters and formulas to be able to make quick changes in the model. With formulas you can set up relations like one length should always be 30% of another and so on. Measurements can be renamed to highlight important parameters. Another important aspect is that you can change the dimensions directly in the specification tree. This saves time compared to search in the sketches to find the right measure to change This can be seen in Figure 26.

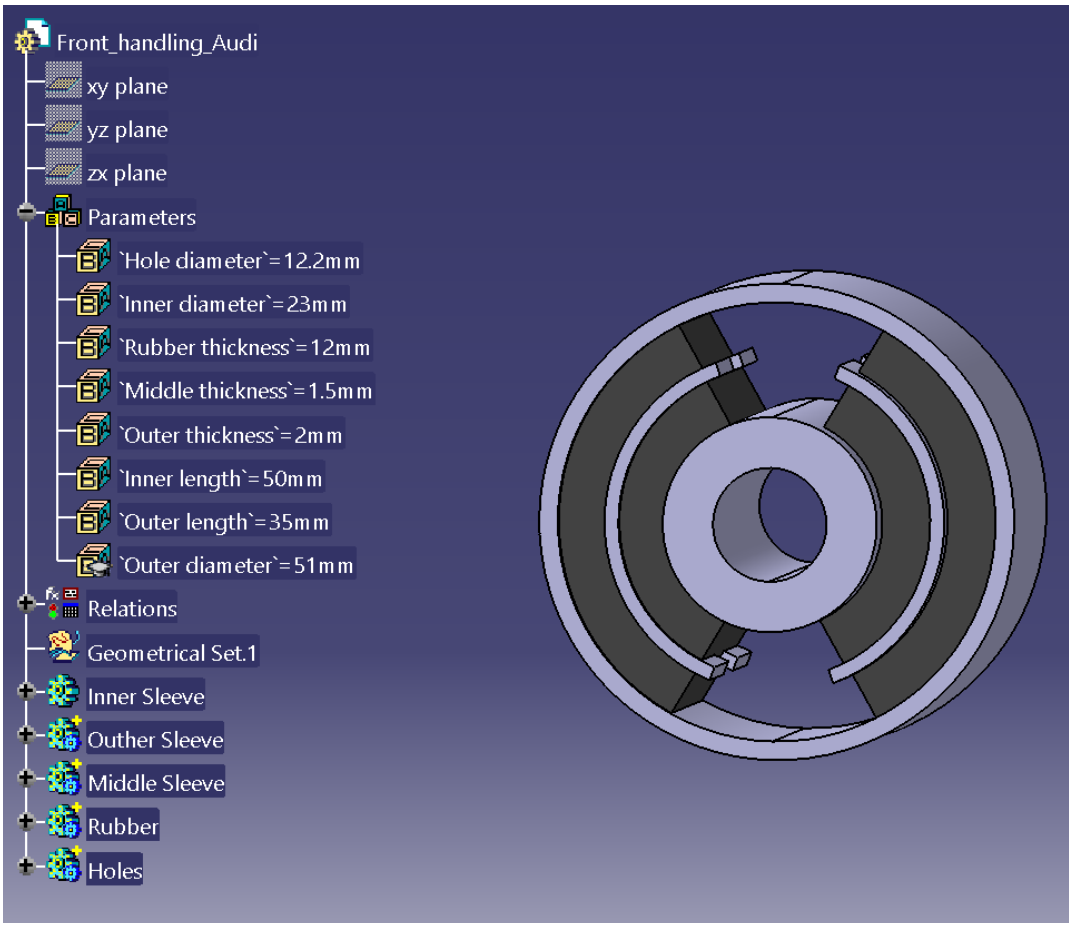


Figure 26. Parameters

The models were made with a logical structure that is supposed to be easy to follow. The most important dimensions are able to change directly in the tree but if you want to finetune some specific details you might have to modify the sketches. Each metal or rubber part inside in the bushing got its own body. But the whole bushing is made as one part and not by an assembly. The advantage is that there is less files to keep together. Since a bushing is not possible disassemble without breaking it there no point in making it into separate parts.

3.6 FEM

Due to limitations FEM-analysis (Finite Element Method) were only made on ball joints. The analysis was made in Catia by using the workbench called "Generative Structure Analysis".

The boundary conditions for the ball joint were that the tapered part of the ball stud was completely clamped. The ball joint is mounted in a conical hole with a bolt underneath. The force is a distributed load applied on a vertical plane through the ball center. Since Catia does not have a good tool for applying loads through materials the best solution was to cut off the upper part of the ball joint in the FEM-analysis. The amplitude of the loads comes from reference projects at the company.

Seen in Figure 27 is the displacement amplified times 50.

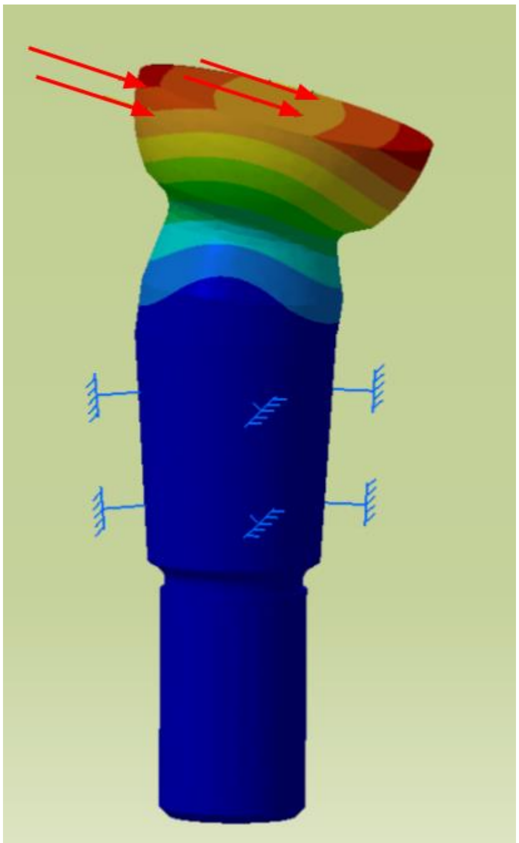


Figure 27. FEM displacement

The mesh is made with Octree tetrahedron parabolic elements. The size is 1 mm and the sag is 0,1 mm. The analysis converges well, there is only a tiny change in result when making the size and sag smaller for the mesh. The mesh is shown in Figure 28.

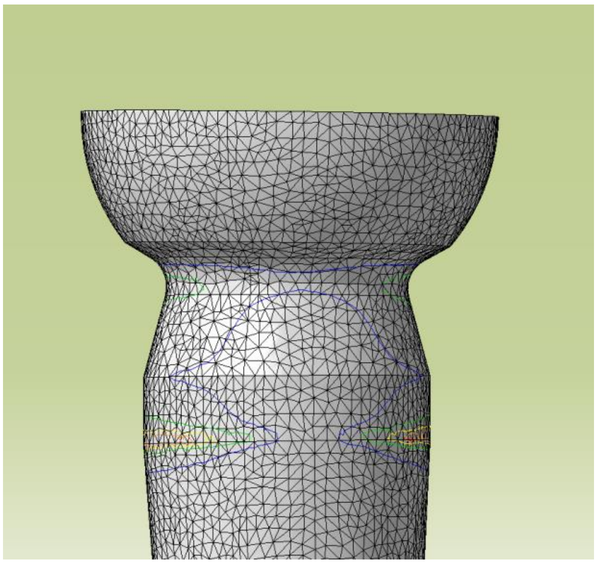


Figure 28. FEM Mesh

4 Results

In this chapter the results are presented from each part of the project with the same headings as in chapter 3.

4.1 Pre-study

A benchmark analysis was made of 60 cars as a study of which suspensions are used most since 2010. Regular cars were considered with a price lower than 500k SEK and premium cars over. For this project the premium segment was in primary focus due to previous projects at the company. For the 60 cars investigated only SLA and MacPherson were used as front suspension. For the rear suspension it was a wider range of solutions. In the premium segment were SLA most used as front suspension and H-arm most used as rear suspension, see Figure 29.

Benchmark analysis			
Front		Regular	Premium
	SLA	0	14
	MacPherson	39	7
Rear			
	4 link	13	7
	5 link	4	4
	H-arm	1	10
	Semidependent	21	0
60 Cars made after 2010			

Figure 29. Benchmark analysis

The Pugh matrices shows the factors which were in consideration when selecting the front and rear suspension for the project. These factors represent the available information about the suspensions compared to the reference. The grade "1" meaning better, "0" equal and "-1" less information. The result was that that SLA as front suspension and H-arm as rear suspension was further investigated, see Figure 30 and 31.

ÅF	Pughmatrix: Choosing front suspension			
	Concept Grades -1 to 1			
Criteria	Ref MacPherson	SLA	Hiper Strut	Double whishbone
CAD-data	0	1	0	0
Benchmark-data	0	0	-1	-1
Literature	0	-1	-1	0
Used in new cars	0	0	-1	-1
Used in premium cars	0	1	1	-1
Sum grades	0	1	-2	-3
Rank	2	1	3	4
Decision	SLA			

Figure 30. Choosing front suspension

Pughmatrix: Choosing rear suspension			
	Concept Grades -1 to 1		
Criteria	Ref H-arm	Multilink 4	Multilink 5
CAD-data	0	-1	-1
Benchmark-data	0	0	0
Literature	0	1	1
Used in new cars	0	0	0
Used in premium cars	0	-1	-1
Sum grades	0	-1	-1
Rank	1	3	3
Decision	H-arm		

Figure 31. Choosing rear suspension

4.2 Benchmark

The measured values from the test rig gave a force-displacement curve which can be seen in Appendix 2. The mean values from the curves was filled into the data sheets. Due to the relatively small load that was applied, only bushings with low stiffness showed any impact.

The sawed apart bushings gave some hidden details that wouldn’t be seen otherwise. The bushing in Figure 32 has a middle sleeve with an “S-form” and the inner sleeve is smaller than what it looks from the outside. Both of these solutions makes the bushing stiffer in axial direction than if the sleeves where straight.

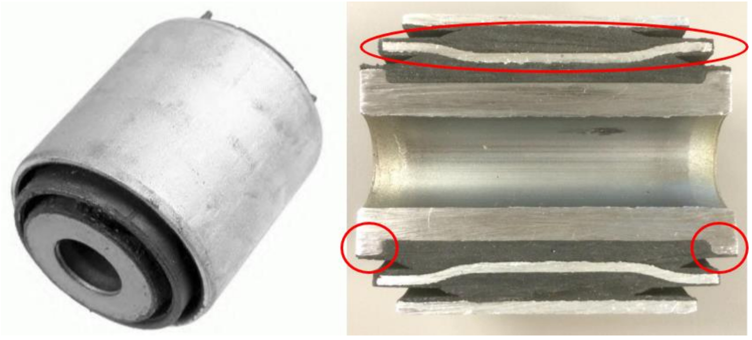


Figure 32. Rear handling bushing

The bushing in Figure 33 has an inner sleeve which is curved which also makes it stiffer in axial direction than a normal straight one.

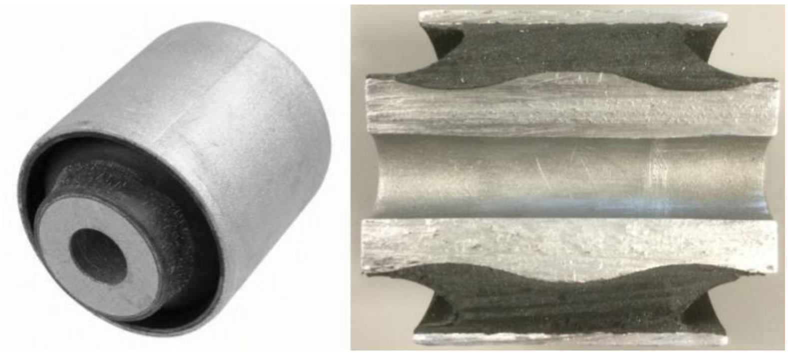
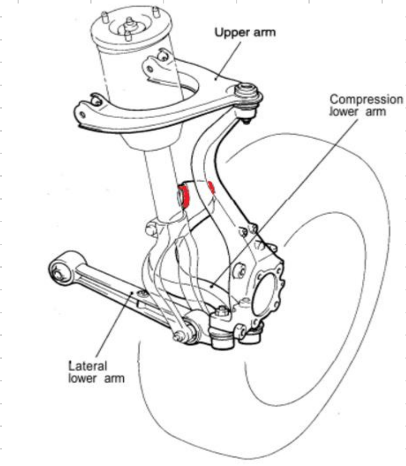


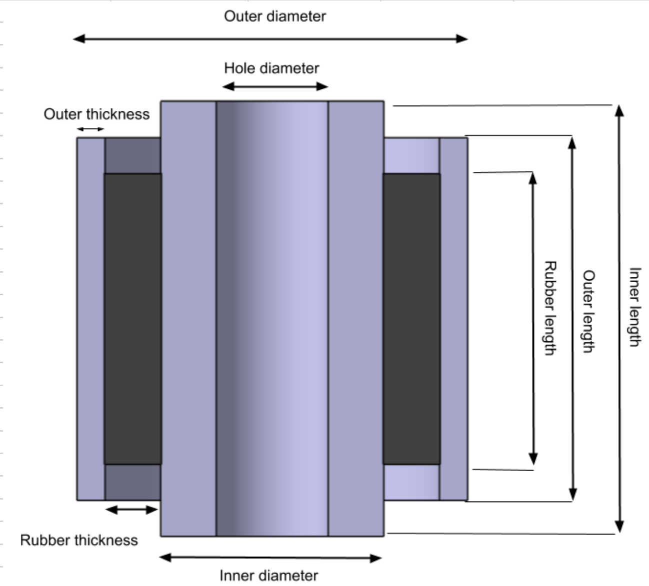
Figure 33. Front handling bushing

4.3 Data Sheets

The data sheets gathers all relevant information regarding measurements, stiffness, material and weight of bushing. At the top of the sheet, the type of component is named followed by which car it's in and the component manufacturer. The green-colored part displays all important measurements. The purple presents the stiffness and the orange presents the material properties. A simplified sketch explains the measures and the position in the suspension is highlighted next to the table. Pictures of the benchmarked bushings are also shown. An example of how a data sheet is presented can be seen in Figure 34. The data sheets for the other positions is done in the same way.

Type	Comfort			
Car	BMW X5	Audi Q5	Audi Q5	ÅF
Manufacturer	Lemförder	ABS before 2009	Swag after 2009	
Position	Lower front ctrl arm	Lower rear ctrl arm	Lower rear ctrl arm	Lower front ctrl arm
CAD Name	Front Comfort 1	Front Comfort 2		Front Comfort 3
Hole diameter	12	12	13	16.2
Inner diameter	irreregular shape	28*33	26(oval) & 29	33.1
Rubber thickness	irreregular shape		22,5 och 21	20
Outer thickness	2.5	2.5	2	2
Outer diameter	70	65	75	77
Inner length	90	80	80	80
Rubber length	42		40	47
Outer length	67	66.3	65	57
Kx [N/mm]	2398	1194	846	502
Ky [N/mm]	5707	2512	3180	1121
Kz [N/mm]				231
Tx [Nmm/deg]				
Ty [Nmm/deg]				
Tz [Nmm/deg]				2330
Material inner	Aluminium	Aluminium	Aluminium	Aluminium
Material outer	Aluminium	Aluminium	Steel	Aluminium
Irregularities			hydro	Hydro
Weight [g]	360	300	420 without liquid	





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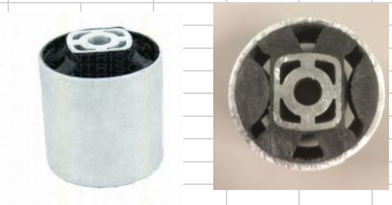

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BMW

Figure 34. Front comfort bushings

A comparison between the bushing size and the curb weights of the cars was done, curb weight being the mass of an unloaded car. A relation between the bushing size and curb weight could be seen for the bushings that were in the same positions and were designed in the same way. This is further discussed in chapter 5.

4.4 Calculations

An excel sheet with calculation of stiffness for bushings has been made with integrated formulas from 3.4.1, see Figure 35. The inner diameter of the rubber cylinder is set by the inner sleeve of the bushing. The inner sleeve gets its dimensions from bolt size and material. More input parameters are the shear modulus of the rubber together with the length and outer diameter of the rubber cylinder.

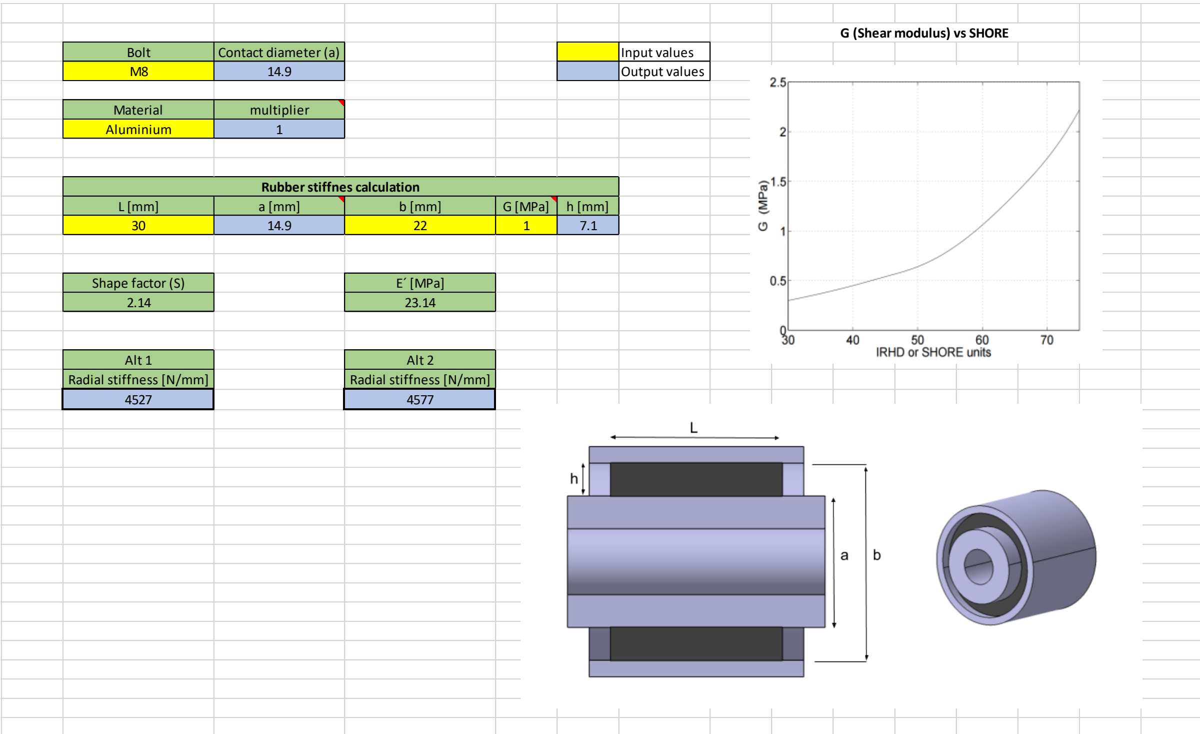
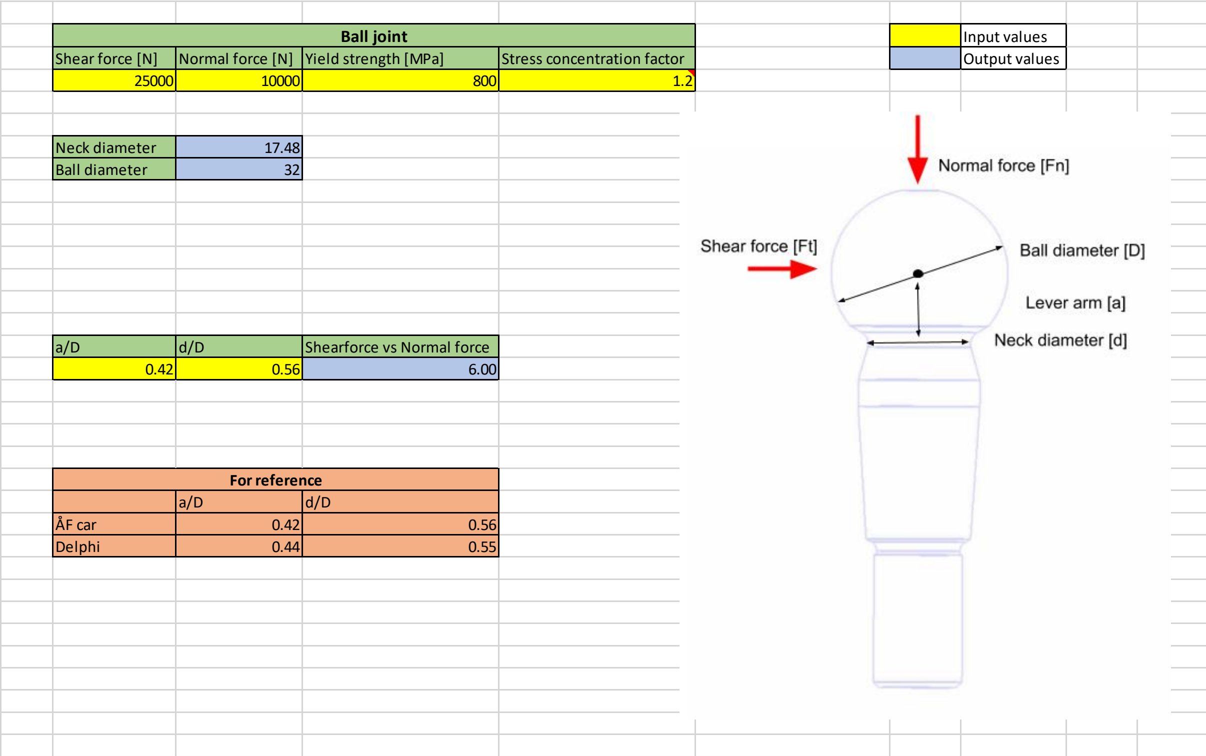


Figure 35. Bushing stiffness calculation

To dimension ball joints, an excel sheet with integrated formulas from 3.4.2. has been made, see Figure 36. Input parameters are the maximum forces on the ball joint, the yield strength of the steel and some geometry relations. The output is the estimated required neck and ball diameter to withstand these forces.



Ball joint			
Shear force [N]	Normal force [N]	Yield strength [MPa]	Stress concentration factor
25000	10000	800	1.2

Input values	
Output values	

Neck diameter	17.48
Ball diameter	32

a/D	d/D	Shearforce vs Normal force
0.42	0.56	6.00

For reference		
	a/D	d/D
ÅF car	0.42	0.56
Delphi	0.44	0.55

Figure 36. Ball joint calculation

4.5 CAD modeling

A total of 18 CAD models of bushings and ball joints were made. The CAD models has the same parameters as the data sheets. With the data sheets as a reference the models should be easy to quickly adjust. The relations are made to maintain the shape of the models. For example, in Figure 37, the relations are set up to keep the wavy shape when the diameter or length of the sleeve is changed. The relations are shown in appendix 3.

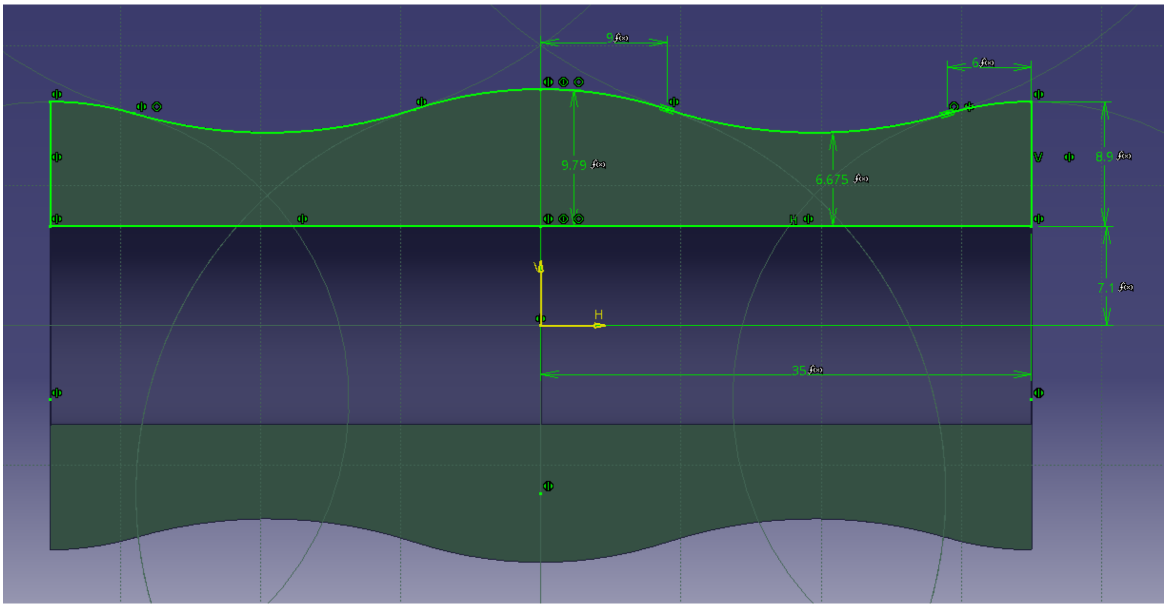


Figure 37. Sleeve relations

A selection of the models is shown in Figures 38-40. The rest of the library of models can be seen in appendix 4.

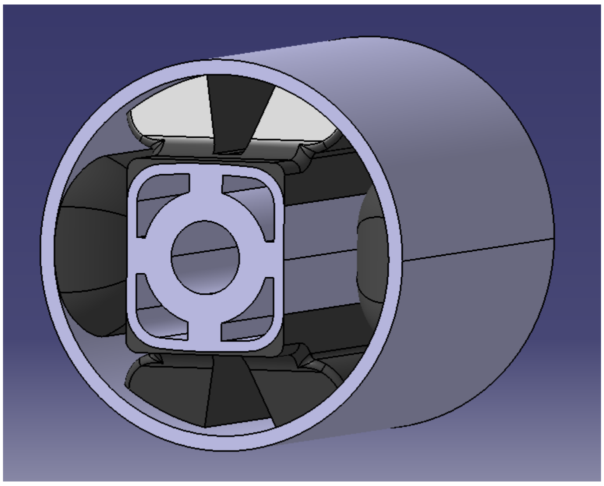


Figure 38. Front comfort bushing

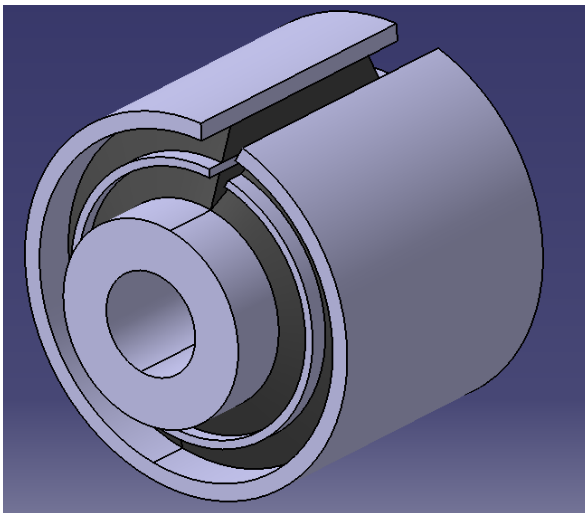


Figure 39. Rear camber bushing

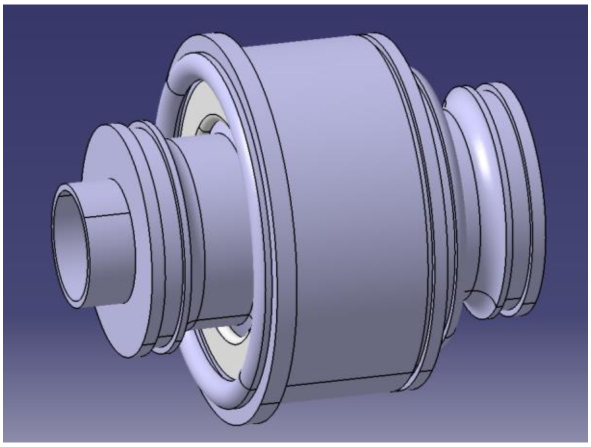


Figure 40. Rear biaxial ball joint

4.6 FEM

The FEM-analysis of the ball joints showed a higher stress than the calculations made by hand. This is because the calculations by hand did not take stress concentration around the neck area into consideration. The results when comparing several calculations by hand and with FEM shows that a stress concentration factor of around 1,2 - 1,4 could be an appropriate estimation.

Figure 41 shows a von Mises stress plot where the stress at the neck region is the critical dimension. As described in chapter 3.6, the tapered part is clamped and force is applied through the ball center. The area right next to the clamped area is not displayed correctly because it's too close to the fixed elements

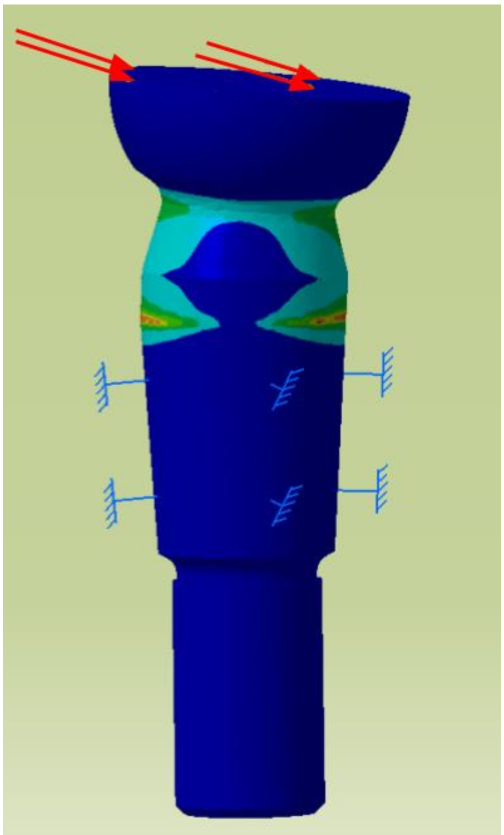


Figure 41. FEM von Mises stress

5 Discussion

This chapter includes our thoughts during the project together with suggestions for future work in the subject.

5.1 Pre-study

External information from suppliers of bushings and ball joints is something that would benefited the work. The possibility to exchange knowledge with a supplier of these components would have given a better understanding, especially in the beginning of the work. Next time a project like this is done, a suggestion is that it's made in cooperation with a supplier of bushings and ball joints.

A2mac1 was a very powerful tool for benchmarking and understanding how the suspension is designed in different cars. Otherwise time-consuming studies at workshops with disassembled cars would have been needed to get the same information.

5.2 Bushings

It can be concluded from the benchmark that bushings can vary a lot, even if it’s the same type of suspension. Bushings at the same position in different cars can look completely different when they’re studied in detail. This is because there are many things to consider when designing a bushing. Some manufactures want a more sporty suspension which is more focused on handling while other wants a softer more comfortable suspension. There are also many ways to design a bushing that have the same characteristics. For example there can be holes in certain directions and intermediate sleeves in other

5.2.1 Rubber

Rubber as a construction material is very complex. There is a lot of research in the area where advanced models for the behavior is being made. For this project where an early part of the product development process is the focus, very little is known regarding the rubber and the desired characteristics. Therefore, it has not been of great interest to examine rubber as a material thoroughly. However, accurate models to estimate the required thickness and length of bushings would have been very interesting. Unfortunately we didn’t find that kind of information when researching rubber.

When designing a bushing, the rubber thickness depends on the desired movement of the bushing in the radial direction. A simplified assumption is that rubber can be compressed to 50% of the original size. This is of interest to investigate further and maybe find a more accurate model.

Another assumption is that the required length for the bushing depends on the mechanical strength needed. A shorter bushing will have higher load per unit area and therefore a shorter lifespan. Unsuccessful studies were made to find a relation between the load on the bushings and the length of them. But that's an area that may be interesting for future work. FEM-analysis (Finite Element Method) of bushings together with experiments could be a way forward if it's not possible to find in literature.

5.2.2 Size vs weight

When comparing bushings a simplified theory is that heavier cars generates greater loads which results in larger bushings needed. A study was made to see if there was any relation between the size of the bushings and weight of the car. The curb weights were 1800kg for Audi Q5, 2150kg for BMW X5 and 2500kg for the reference car.

The study shows that there could be a relation between weight and size when bushings and suspensions are designed in a similar way. The bushings in BMW X5 had an outer diameter which was around 80% of the ones in reference car in many positions. It was harder to see any form of relation for the Audi. This could be because the suspension has a slightly different setup even though it’s an SLA (Short-Long-Arm). For the purpose of this project a more extensive study of weight-size relations could be interesting. But it's very time-consuming to do benchmarks by hand and analyze each suspension separately.

5.3 Ball joints

For ball joints, only static load cases have been taken into account when making an estimation for the required size. As for now, it is the supplier that grants that the ball joint will last during a lifetime of the vehicle. It could be fatigue that is the limiting factor. Therefore a study on fatigue is necessary to make sure that the placeholder models follow the right criteria.

6 Conclusions

This is the conclusions from the work based of the objectives from chapter 1.

- **Placeholder models**
  The accuracy has increased the precision in size of the initial placeholder models for bushings and ball joints. Based on calculations along with data from the benchmark less adjustments are going to be needed.

- **Data sheets**
  A gathering of relevant information for every position in the suspension is collected in data sheets that is easily overviewed. The information is a guidance when designing bushings and ball joints for a new suspension.
  The designer decides some data in a spreadsheet with added calculations. The output parameters from the spreadsheet can be transferred as new parameters in the CAD models. The data sheets with calculations is easy to use and saves a lot of time in concept development.

- **Calculations and validation**
  The calculation model for stiffness of bushings seems to work well when compared to test data. However it's made for bushings that is rotation symmetric and cylindrical. Most bushings appear to have some kind of irregularity. Therefore, the benefits from the calculation model is limited.
  The calculations for ball joints dimensions have not been validated due to lack of test data. But it's made from well-known formulas for strength of materials and the output seems reasonable when compared to common sizes.

7 Bibliography

[1] ÅF, "At a glance," afconsult.com, 2017. [Online]. Available: http://www.afconsult.com/en/about-af/at-a-glance/. Retrieved: May, 2017.

[2] P. Andersson, O. Isaksson, T. Larsson, "A case study of how knowledge based engineering tools support experience re-use", Indian Institute of Science, Bangalore, India, 2011.

[3] K. T. Ulrich & S. D. Eppinger, *Product Design and Development*. 5th ed, New York, USA: McGraw-Hill, 2012.

[4] T. D. Gillespie, *Fundamentals of Vehicle Dynamics*. Warrendale, USA: Society of Automotive Engineers, 1992.

[5] K. Hansen Andreasson & M. Linder, "Optimization of Wheel Suspension Packaging," master thesis, Department of Product & Production Development, Chalmers University of Technology, Göteborg, Sverige, 2016. [Online]. Available: http://publications.lib.chalmers.se/records/fulltext/238565/238565.pdf. Retrieved: April, 2017.

[6] G. Olsson, "Vehicle Dynamics and Chassis", unpublished.

[7] A. Johansson & P. Roubert, "Development of a Hi-Per strut Suspension," master thesis, Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sverige, 2011.

[8] J. D. Halderman, *Automotive Chassis Systems*. 6th ed, Boston, USA: Pearson, 2014.

[9] vBulletin Solutions Inc. "Jimny Caster Correction Bushes," 4x4community.co.za, 2014. [Online]. Available: http://www.4x4community.co.za/forum/showthread.php/202875-Jimny-Caster-Correction-Bushes. Retrieved: May, 2017.

[10] B. Heissing & M. Ersoy, *Chassis Handbook: fundamentals, driving dynamics, components, mechatronics, perspectives*. 1st ed, Wiesbaden, Germany: Vieweg + Teubner, 2011.

[11] R. D. Small. "Suspension types," susprog.com, 2016. [Online]. Available: http://www.susprog.com/susptype.htm. Retrieved: April, 2017.

[12] H. Heisler, *Advanced vehicle technology*. 2nd ed, Oxford, UK: Butterworth-Heinemann, 2002.

[13] S. Dzierzek, "Experiment-Based Modeling of Cylindrical Rubber Bushings for the Simulation of Wheel Suspension Dynamic Behavior," SAE Technical Paper 2000-01-0095, 2000, doi:10.4271/2000-01-0095.

[14] Internet Brands Inc. "Suspension Geometry comparison FD to RX8?," rx7club.com, 2013. [Online]. Available: https://www.rx7club.com/3rd-generation-specific-1993-2002-16/suspension-geometery-comparison-fd-rx8-1037333/page3/. Retrieved: April, 2017.

[15] P-E. Austrell, "Konstruktionsberäkningar För Gummikomponenter," Lund University, Lund, Sverige, LUTVDG/TVSM-0281-6679, 2000. [Online]. Available: http://www.byggmek.lth.se/fileadmin/byggnadsmekanik/publications/tvsm7000/web7131.pdf . Retrieved: Feb, 2017.

[16] Dassault Systèmes, "CATIA:s 3D CAD-lösningar från Dassault Systèmes," 3ds.com/se, 2017. [Online]. Available: https://www.3ds.com/se/produkter-och-tjaenster/catia/. Retrieved: April, 2017.

[17] M. Stokes. *Managing Engineering Knowledge-MOKA: Methodology for Knowledge Based Engineering Applications*, ASME Press, 2001.

[18] P. J- Lovett, A. Ingram, C. N. Bancoft, "Knowledge-based engineering for SMEs: a methodology," Journal of Materials Processing Technology, Vol. 107, Issues 1-3, pages 384-389, nov. 2000.

[19] M. Sandberg, "Knowledge Based Engineering: in Product Development," Luleå University of Technology, Luleå, Sverige, LTU-TR-1402-1536, 2003. [Online]. Available: http://www.student.luth.se/~niceri-2/mtm117/KBE-in-product-development.pdf. Retrieved: April, 2017.

[20] A2Mac1, "A2Mac1: Automotive Benchmarking," a2mac1.com, 2017. [Online]. Available: https://www.a2mac1.com/home/loginpage/default.asp. Retrieved: Jan. 2017.

[21] H. Johannesson, J-G. Persson, D. Pettersson, *Produktutveckling: effektiva metoder för konstruktion och design.* 2nd ed, Stockholm, Sverige: Liber, 2013.

[22] J. M. Horton & G. E. Tupholme, "Approximate radial stiffness of rubber bush mountings," *Materials & Design*, vol. 27, issue 3, pages 226-229, 2006. doi:10.1016/j.matdes.2004.10.012, [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0261306904002808. Retrieved: May, 2017.

[23] J. E. Adkins, A. N. Gent, "Load-deflexion relations of rubber bush mountings," *British Journal of Applied Physics*, vol. 5, number 10, page 354, Jan. 1954. doi:10.1088/0508-

3443/5/10/305, [Online]. Available: http://iopscience.iop.org/article/10.1088/0508-3443/5/10/305/meta. Retrieved: May, 2017.

[24] W. Beitz & K-H. Küttner, *Dubbel: Handbook of Mechanical Engineering.* London, UK: Springer, 1994.

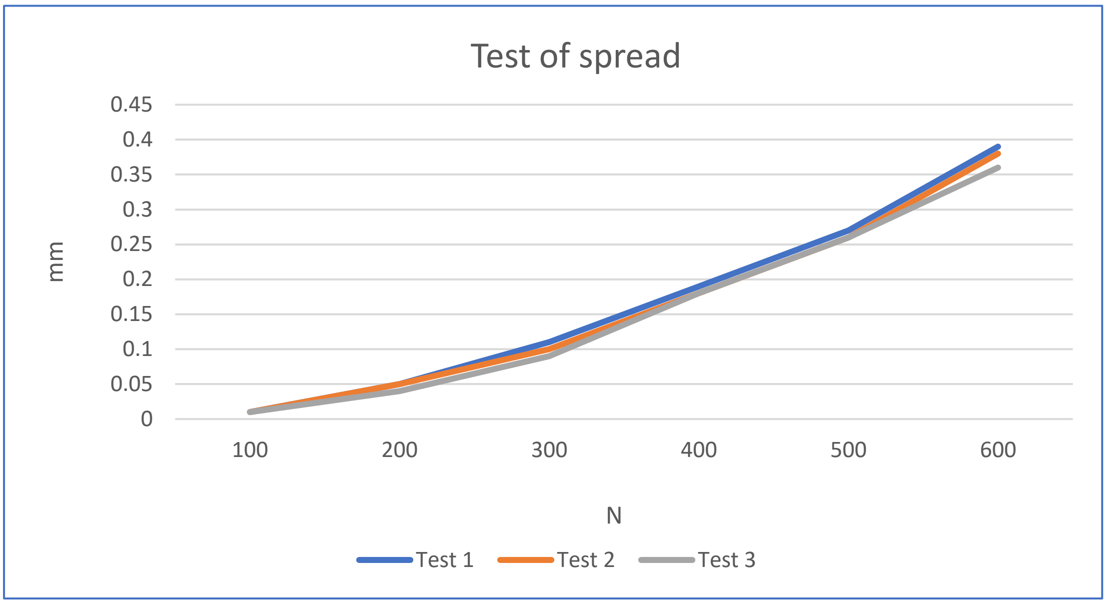
[25] T. Dahlberg, *Teknisk hållfasthetslära.* 3rd ed, Lund, Sverige: Studentlitteratur, 2001.

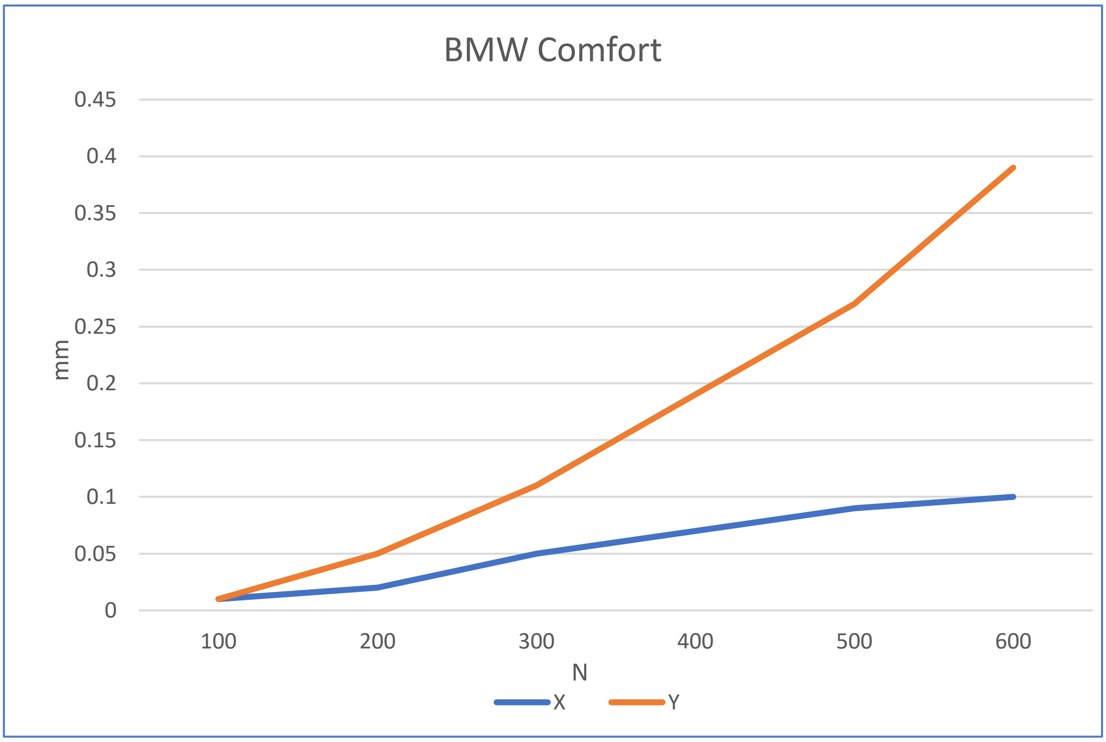
[26] M. Mägi & K. Melkersson, *Lärobok i maskinelement.* Göteborg, Sverige: EcoDev International, 2006.

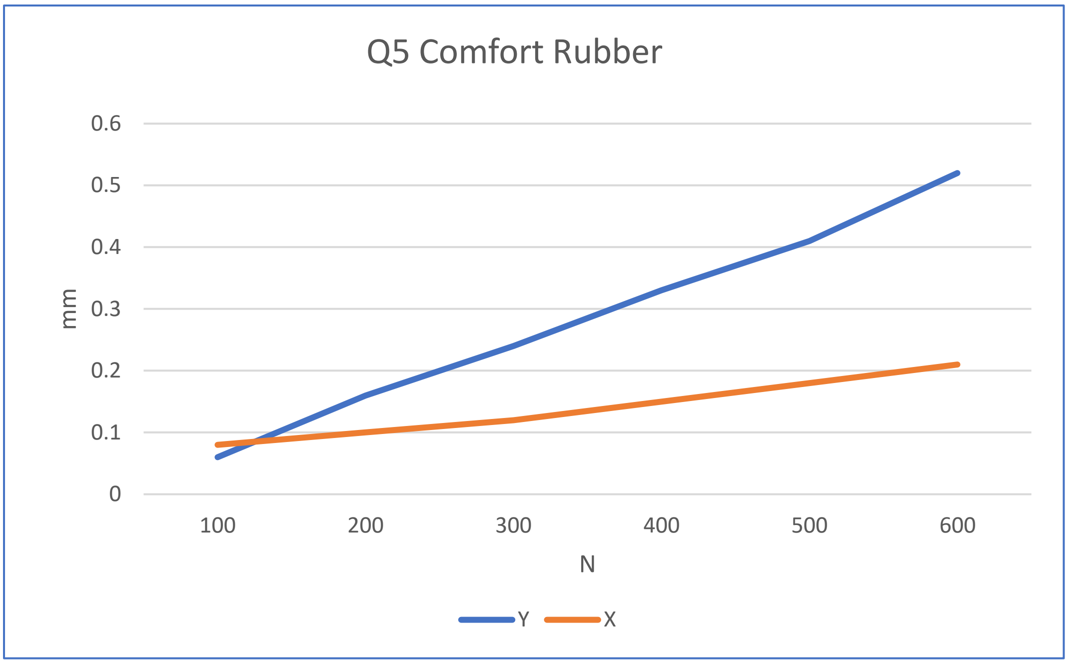
Appendix 1, Purchase of bushings and ball joints

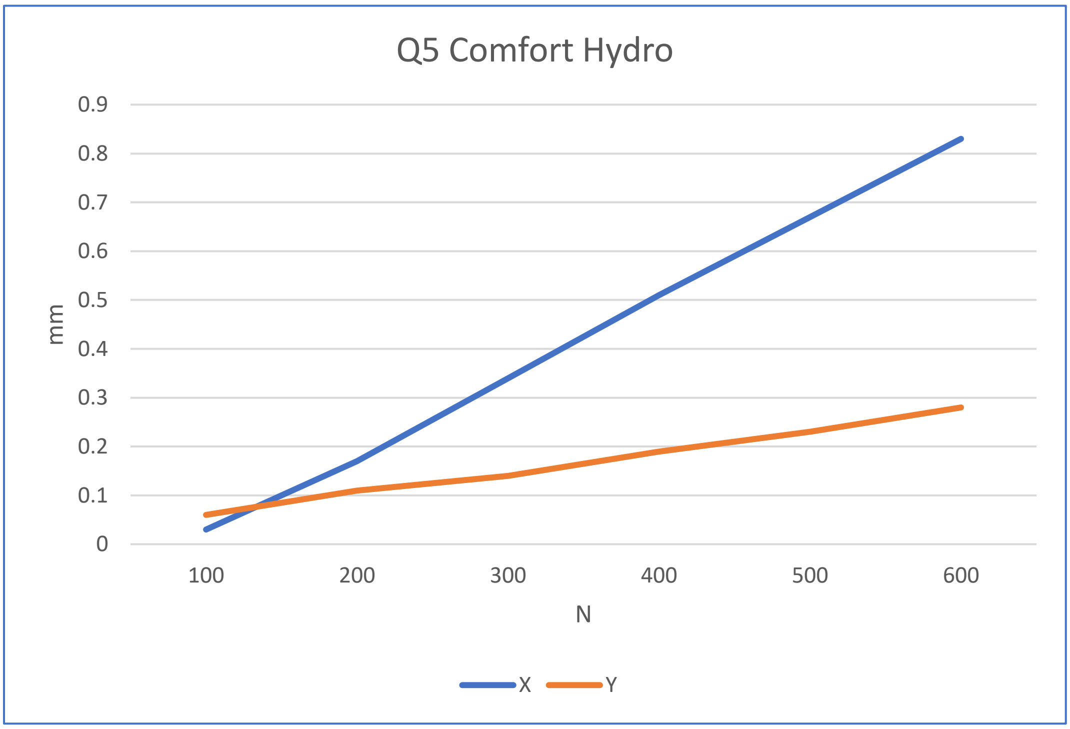
		Purchase of bushings and ball joints			
BMW X5 f15 x40d					
	Front				
	SLA	**Manufactrurer**	**Type**	**Price**	**OEE - number**
		Lemförder	Handling	180	31126864000
		Lemförder	Comfort	185	31 12 6 851 693
		Mapco	Upper	281	31126863333
	Rear				
	H-arm	Lemförder	Handling H-arm	280	33 32 6 770 951
		Lemförder	Comofort H-arm	290	33 32 6 770 951
		Vaico	Biaxial ball joint	309	33326770985
		Lemförder	Biaxial ball joint	309	33326770985
Audi Q5 2.0 TDI 170hk					
	Front				
	SLA	**Manufactrurer**	**Type**	**Price**	**OEE - number**
		Moog	Upper	57	8K0 407 515
		Mapco	Handling	82	8K0407182A
		Vaico	Damper connetction	87	4E0407181B
		ABS	Comfort (before 2009)	101	8K0 407 183 A
		Swag	Comfort hydro (after 2009)	207	8K0 407 183 D
	Rear				
	H-arm	Swag	Upper transversal (camber)	104	8K0501541
				2472	

Appendix 2, Measurement of stiffness for bushings



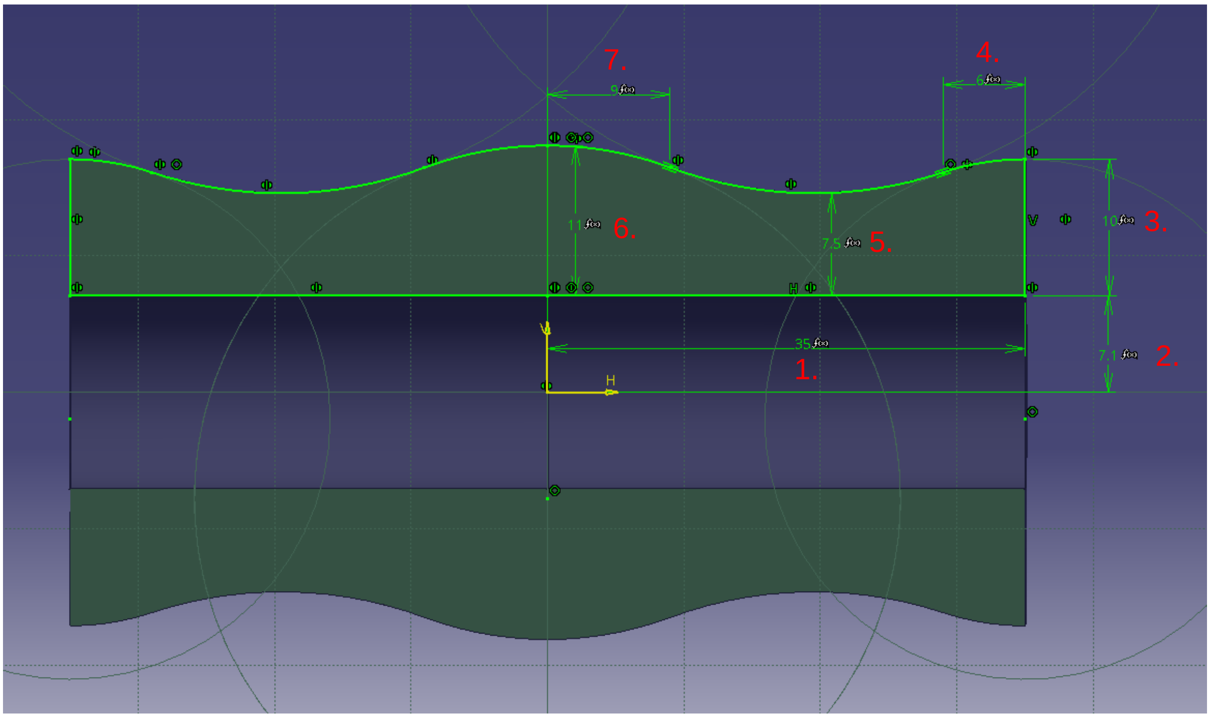



Q5 Comfort Rubber
0.6
0.5
0.4
0.3
0.2
0.1
0
mm
100
200
300
400
500
600
N
Y
X


Q5 Comfort Hydro
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
mm
100
200
300
400
500
600
N
X
Y

Appendix 3, Relations

Here is the same sketch as Figure 37 but the inner sleeve has the original measurements.



Parameters:
Inner length = 70 (Sleeve length)
Hole diameter = 14.2
Inner diameter = 34.2 (Outer diameter of inner sleeve)

Relations:
Length 1 = Inner length /2
Length 2 = Hole diameter /2
Length 3 = Inner diameter/2 – Length 2
Length 4 = Length 1 * (6/35)
Length 5 = Length 3 * (7.5/10)
Length 6 = Length 3 * (11/10)
Length 7 = Length 1 * (9/35)

Appendix 4, CAD models