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DESIGN OF EQUIPMENT FOR CHARACTERIZATION OF ELASTOMERS USING IMPACT TESTING

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Structural Mechanics

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DESIGN OF EQUIPMENT FOR CHARACTERIZATION OF ELASTOMERS USING IMPACT TESTING

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Lund, November 2010

Fredrik Axelsson and Per Sjöberg

Abstract

The carton based packaging material consists of layers of polymer, paperboard and aluminum. Tetra Pak® uses rubber coated rollers in the converting process when producing packaging material. In the nip unit the paperboard is fed between two rollers, a smaller rubber coated nip-roller and a larger steel chill roller. The smaller rubber coated roller is pushed towards the chill roller thus compressing a specific rubber element in the rubber coating each time the smaller roller completes a full turn. Due to the high angular velocity and small area being compressed the compression time is very short. Stationary material models can therefore not be applied to predict the rubber behavior during the compression. A good understanding of the dynamic properties of the rubber is essential to accurately describe how the rubber reacts during each compression. Simulations are done in the development process to predict the behavior of the rubber coated rollers. Today Tetra Pak® uses suppliers and external testing facilities to do this kind of testing of material properties. The test method described in this Master Thesis could provide a time efficient way of measuring the dynamic properties of rubber in house at Tetra Pak®.

The objective of this master thesis work is to design a test rig for dynamic testing of rubber materials according to the theory proposed in the paper "Dynamic characterization of elastomers using impact testing" by Per-Erik Austrell, LTH. The basic principal is a drop test where the loading rate and load amplitude are controlled by the drop height and the weight of the dropped body. The dynamic modulus and damping are calculated using the measured data. The test results are compared to harmonic tests previously performed at an external testing facility.

The tests show an error in the laser sensor measuring the displacement. The error is a "step rise" in the sensors output signal when an object moves into the sensor's visual range. Without being able to determine the correct starting point for the displacement curve the damping property cannot be determined for materials with high shore values. The dynamic modulus can be determined since the error does not affect the maximum and minimum stress and strain

values. High speed filming confirms that the error in the displacement sensor only affects the start of the displacement curve.

The test results show that it is difficult to get a wide frequency and strain range with an even spread of data points. The method could be supplemented with a low frequency cyclic test method for producing material data in the lower frequencies of the material being tested. The impact method alone does not necessarily cover the whole frequency and compression span.

Comparison against the reference tests show that the dynamic modulus from the impact tests is higher than the dynamic modulus from the harmonic tests. This could be partially explained by insufficient reconditioning of the material prior to tests.

The damping is affected by the step rise and the measured values do not fully match the reference tests. The measured dynamic modulus is roughly a factor two higher than in the reference tests. The reason for this is not fully identified.

Sammanfattning

Ett viktigt moment vid tillverkning av kartongmaterial till livsmedelsförpackningar är laminatorn. I laminatorn täcks råpappersmaterialet av smält polymer i det så kallade nypet. Nypet i sin tur består av en stor kylvals och en mindre gummiklädd nypvals. Genom att styra kraften som verkar på nypvalsen kan kontakttrycket i nypet regleras. Vinkelhastigheten med vilken nypvalsen roterar är stor och detta ger upphov till att ett tänkt gummielement i nypvalsens beläggning utsätts för en hög cyklisk belastning. För att kunna simulera gummimaterialets beteende vid snabba kompressionsförlopp krävs goda materialmodeller som beskriver materialets dynamiska egenskaper. Nuvarande materialmodeller bygger på testdata från harmoniska skjuvningstest där test vid höga frekvenser är svåra att utföra. Detta examensarbete syftar till att utvärdera en alternativ testmetod presenterad av Universitetslektor Per-Erik Austrell i "Dynamic characterization of elastomers using impact testing, 2009".

Metoden bygger på ett enkelt falltest där ett gummiprov belastas genom att en känd massa släpps på materialet samtidigt som den resulterande kraften och förskjutningen i materialet mäts simultant.

För att utvärdera metoden designades och byggdes en testrig innehållande mätutrustning med hög uppdateringsfrekvens och noggrannhet. Förskjutningen i provkroppen mättes med en triangulerande laser och kraften i stödet av en piezoelektrisk kraftgivare. Testresultaten från mätmetoden jämfördes med motsvarande testdata från ett harmoniskt skjuvtest. Testerna visade på ett fel i den triangulerande lasern. Felet kom att påverka förskjutningskurvans startpunkt och därmed göra mätningar av dämpningen i materialet felaktiga eller osäkra. Påverkan av felet i lasern undersöktes även genom att tester filmades medelst en höghastighetskamera och laserns mätdata utvärderades med bildanalysmjukvara. Resultatet visade felaktiga datapunkter i början av kompressionskurvan, efter några felaktiga mätpunkter returnerar lasern åter rätt värden. Felet påverkade ej mätningen av den maximala förskjutningen i provkroppen.

Med kunskap om maximal förskjutning och kraft möjliggörs beräkningar av gummikroppens dynamiska elasticitetsmodul vid aktuellt belastningsfall.

Utvärderingen påvisade svårigheter i att erhålla en bred spridning av frekvens och töjningsamplitud i testdatan. Jämförelser med de harmoniska referenstesterna visade även att den dynamiska modulen från falltestet är en faktor två högre. Detta kan delvis förklaras med att materialet ej är tillräckligt rekonditionerat innan testning. Dock har en fullständig förklaring ej kunnat finnas.

Contents

Chapter 1

1 Introduction

1.1 Background

Tetra Pak uses rubber coated rollers in the converting process when producing packaging material. Together with chill rollers different protective layers are applied onto the paperboard to achieve desired properties in the material. Simulations are done in the development process as a tool to predict the behavior of the rubber coated rollers. One important component in the simulation model of the roller is material models covering the dynamic behavior of the rubber. Dynamic testing of rubber materials is however a time and cost consuming process. Today Tetra Pak uses suppliers to do material testing. The dynamic test method evaluated in this master thesis could provide a time efficient way of measuring the properties of rubber in house at Tetra Pak and thereby speed up the lead time from material tests to simulations.

The packaging material is produced in different machines at the material factory, first of which is the printing station, where the graphics are being printed onto the paperboard. The paperboard is then creased as it passes between different rollers at the creasing station. The next station is the laminator where the paperboard is bonded with the aluminum and/or polymer coating. The process takes place in the nip unit.

Every step in these stations demands high precision and accurate control of the process parameters to avoid material flaws that weaken or otherwise damage the packaging material. The nip roller has a rubber coating surrounding it. An accurate way of determining the dynamic characteristic of rubber is necessary since the rubber characteristics determine how the pressure varies along the nip.

1.2 The Company

Since its founding by Mr. Ruben Rausing in the early 1950s Tetra Pak has grown into being one of the largest carton package manufacturer companies in the world. Already from the start one of the company's primary objectives was to replace bulk selling of goods with consumer adapted carton based packaging for flour, sugar, salt and later on milk. It established itself on the market as one of the first carton based packaging companies for milk.

Tetra Pak's early involvement in both the required machinery for packaging and filling as well as the development of the packaging material has given it a unique roll on the global market.

During the start up years the company continued to divide attention towards creating a packaging of cylindrical shape for milk, where the paper web is continuously formed into a cylinder and then filled with fluid and sealed. Their efforts resulted in the creation of the classic packaging based on the geometrical figure tetrahedron, the classic package Tetra Classic was created, see Image 1.

Image 1: Tetra Classic®

The original idea of creating, filling and sealing the package from a continuous supply of carton based packaging material is still very much alive at Tetra Pak, over a half century later. Today Tetra Pak produces a wide range of packages for many different contents.

Today Tetra Pak produces both the material for packages as well as the filling machines that are used to fill the packages with their content and sealing them. By manufacturing the packaging material, the filling machines as well as downstream equipment Tetra Pak can ensure costumer full control of both the filling and the packaging process. This concept has proven successful as shown by the numbers in Table 1.

Table 1: Tetra Pak in numbers

Number of packaging machines in operation 2010	9 048
Delivered packaging machines 2009	351
Process units in operation 2010	51 859
Delivered process units 2009	1 699
Distribution equipment in operation 2010	16 641
Delivered distribution equipment units 2009	1 113
Factories for machine assembly	11
Production plants for packaging material and seals	42
Number of markets	>170
Number of employees	21 672
Million liters of products delivered in Tetra Pak® packages 2009	70 674
Million packages delivered by Tetra Pak® 2009	145 030
Numbers up to date January 2010[1]	

1.3 The Nip unit

An important step in the production of the package material is the lamination process. During the lamination process the paperboard is coated with a thin layer of melted polymer to protect the inside, the printed outside and/or to add a thin layer of aluminum foil to the paperboard. The paperboard is fed between two rollers. A smaller rubber coated nip roller and a larger steel roller ("chill roller"), see **Error! Reference source not found.**.

The nip's main purpose is to:

[1] http://www.tetrapak.com/se/about_tetra_pak/the_company/facts_and_figures/pages/default.aspx

- Produce controlled adhesion between the polymer coating, the aluminum foil and the paperboard.
- Solidify the polymer by removing heat (chill roller).
- Give the polymer surface the right structure and gloss.
- Drive the web at the right speed and tension.

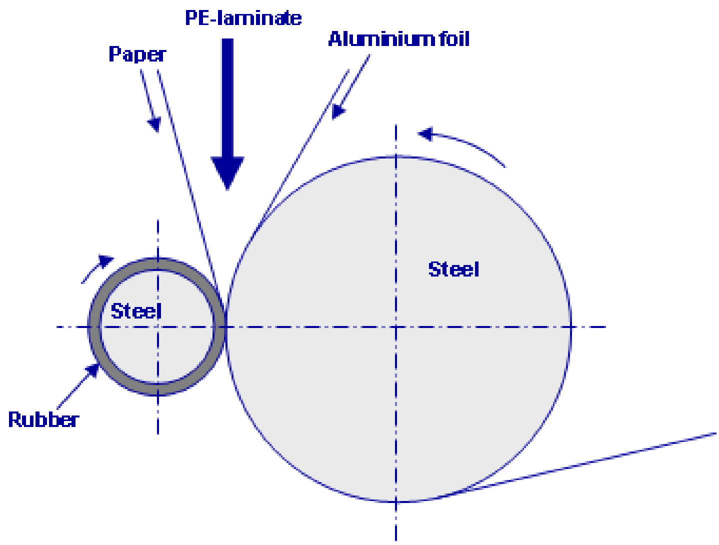

Figure 1: Cross section illustration of the Nip

1.4 Objectives

One objective of this master thesis is to design equipment for dynamic impact testing of rubber material according to the method proposed by PhD P-E. Austrell in the paper "Dynamic characterization of elastomers using impact testing[2]". The basic principal is a drop test where the loading rate and load amplitude are controlled by the drop height and the weight of the dropped body.

The force acting on the rubber specimen and the compression of the specimen are to be measured simultaneously so that the phase angle between them can be determined. The contact time during the impact cycle is very short, ranging down to a few milliseconds.

By measuring the maximum force in the specimen as well as the maximum compression the dynamic modus for that specific impact can be calculated.

[2] Dynamic characterization of elastomers using impact testing - Austrell, P-E. , Olsson, Anders K

Theory states that the phase angle between the compression and the reacting force can be interpreted into a damping in the rubber specimen. The damping is an important parameter in characterizing the dynamic behavior of elastomers.

To ensure that the friction coefficient between the specimen and the rig isn't too high the specimen shape during impact must be evaluated.

The objectives summarized are:

- Design a mechanical drop test device including measuring equipment according to the method proposed by Per-Erik Austrell.
- Basic principal is a drop test where compression and force are measured **simultaneously**
- Compare **damping** and **dynamic modulus** with previous harmonic test results
- Evaluate specimen shape during impact

1.5 Limitations

Given the time for the master thesis work some limitations for the work itself are done. The first focus of the work is to quickly construct a prototype test rig for the initial verification of the theory and test rig design, using existing components at the Tetra Pak® plant in Lund in as great extent as possible.

The next step is to design of a second test rig where the drop tests can be performed with high accuracy. Since the design and assembly of the test rig takes time there is only time for two design loops before the testing. The necessary software must also be written.

Harmonic tests have been performed at an external testing facility using a displacement controlled sinusoidal testing method. Rubber specimens of the same materials that are used in the harmonic tests will be tested using the impact testing method. The results from the two test methods will then be compared.

The rubber specimens in the harmonic tests have different size than the rubber specimens in the drop tests. The drop test rubber specimens must be cylindrical with a height of 25 mm and a diameter of 25 mm for the results to be comparable.

The drop heights and impact masses must also to be determined.

Chapter 2

2 Theory

2.1 Rubber

Rubber components are influenced by the load rate[3]. For low frequencies a rubber specimen subjected to a harmonic load will experience a rise in dynamic modulus for increased frequencies. The rate dependent loss comes from the internal resistance against reorganization within the polymer chains during loading. Since the reorganization cannot occur instantaneously the energy loss will be rate dependent.

Rubber also has amplitude dependence which can be observed as a decrease in dynamic modulus for increased amplitudes for harmonically loaded rubber. The amplitude dependence is traditionally seen as a result of the breakdown and reforming of the filler structure.

Rubber materials are often classified by their shore value. Shore is measured with a durometer[4]. This device works similar to the Rockwell hardness test by measuring the indentation depth in the material made by a standardized presser foot as a result of a given force. The shore value is an empirical way of classifying a material's hardness. The higher the Shore value the harder the material.

Apart from amplitude and frequency dependence, rubber's mechanical properties are also affected by temperature. Cyclic testing may result in the specimen heating up due to material damping. The temperature change in the material can affect the dynamic properties by lowering the dynamic modulus. No par-

[3] Finite element procedures in modelling the dynamic properties of rubber - Olsson Anders K
[4] Development of a test method for the dynamic mechanical properties of rubber – Oros Johanna

ticular rise of temperature should occur in the drop tests described in this report.

2.1.1 Mullins effect

Mullins effect can be observed as a decrease in stiffness during the first load cycles for cyclic testing. The stress- strain curve depends on the maximum load previously encountered. If a rubber product is cyclically pre-stressed prior to use the viscous component is reduced, reducing both the creep and stress relaxation. The effect is often called “mechanical conditioning” or “scragging” of the rubber. Mullins effect is not fully reversible, however if left alone for a few hours most of the structural integrity is restored[5].

2.2 “Dynamic characterizing of elastomers using impact testing”

The theoretical prerequisites of this master thesis are based on foregoing work, *“Dynamic characterization of elastomers using impact testing”* by PhD P-E. Austrell. The theoretical study investigates the possibilities and limitations of using impact testing at different masses and velocities as an alternative to the harmonic test method to characterize dynamic behavior of elastomers. Harmonic testing in a fixed test rig is both complicated and demanding. Testing on higher frequencies imposes extreme requirements on the stability and stiffness on the test rig making the equipment expensive. The heat generated from the hysteresis work as a result of the cyclic loading also creates problems.

By using the impact testing method it is easy to achieve high strain rates without the need for a very stiff test rig as the impacting force is generated by the use of a falling weight. The method only requires a stable support stand for the rubber specimen.

The foregoing study is focused on theoretically comparing the method of using stationary dynamic sinusoidal harmonic testing against the impact testing method.

Below is a comparison between the two test methods.

In the harmonic tests a full cycle T is completed but in the impact test the specimen is only exposed to the compression, the impulse time is therefore one half harmonic cycle. This is shown in Figure 2.

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[5] An introduction to rubber technology - Andrew Ciesielski – Page 127

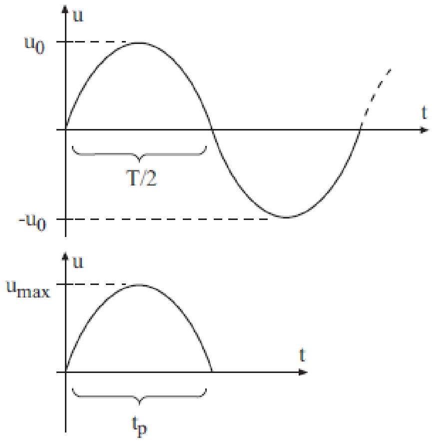


Figure 2: Impulse time t_p and period time T

To get approximately the same loading rate and level the following is assumed.

$$t_p = \frac{T}{2} \quad (1)$$

The rubber material to be tested is also assumed to have the same properties as a linear spring with stiffness *k*. A mass *m* with a velocity, v_o, hits the test sample at time *t=0*.

The impact on the spring made by the mass can be written as follows:

$$u(t) = u_{\max} \sin(t\sqrt{\frac{k}{m}}) \quad (2)$$

A simple energy equation between the kinetic energy of the impacting mass and the strain energy in the specimen in its maximum deformed state, gives the maximum deformation u_{max} as a function of the impacting velocity v_0, the mass *m* and the stiffness *k*.

Small strain levels apply, the stiffness k for a spring can be written as:

$$k = \frac{EA}{H} \quad (3)$$

Assuming incompressibility and Poisson's ratio of ~0.50 gives

$$E = 3G \quad (4)$$

The rubber specimen is a cylinder shape with the diameter and height of 25 mm. Knowing this the impact time and maximum strain can be derived.

$$t_p = \pi \sqrt{\frac{mH}{3G_{dyn} A}} \quad (5)$$

The impulse time t_p only depend on the impacting mass *m*.

$$\varepsilon_{max} = \frac{u_{max}}{H} = v_0 \frac{t_p}{\pi H} \quad (6)$$

The maximum strain will only be dependent on the impact velocity v_0 which is only dependent on the drop height.

With this known the dynamic modulus, damping and frequency can be calculated. The damping is illustrated as Δt in Figure 3.

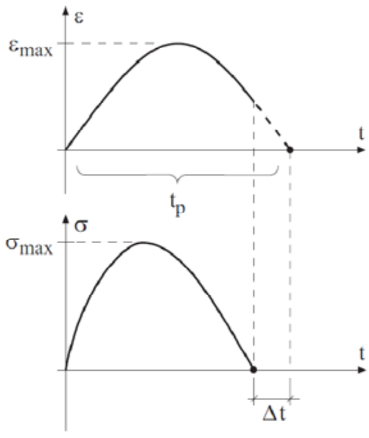


Figure 3: Stress and strain curves as a function of time.

$$E_{dyn}^{eq} = \frac{\sigma_{\max}}{\varepsilon_{\max}} \tag{7}$$

$$\delta = \pi \frac{\Delta t}{t_p} \tag{8}$$

$$f^{eq} = \frac{1}{2t_p} \tag{9}$$

These are parameters that can be directly studied from the drop test. They only require knowledge of the impulse time, the maximum compression and force.

2.2.1 Energy volumetric comparison

The theoretical comparison between the harmonic test method and the impact test method is based on a volumetric comparison of the energy levels in a hypothetic volume element.

The comparison between a shear strain and normal strain test method follows these equations.

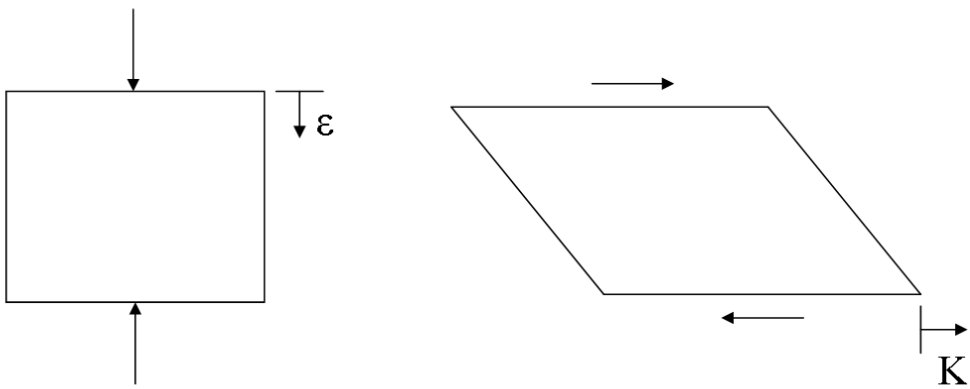


Figure 4: Normal and shear strain specimens

Energy balance gives

$$W_{Compression} = W_{Shear} \tag{10}$$

Expressed in strain and shear strain

$$\frac{1}{2}E\varepsilon^2 = \frac{1}{2}G\kappa^2 \tag{11}$$

Assuming Equation 4

$$3G\varepsilon^2 = G\kappa^2 \tag{12}$$

The relation between Kappa and Epsilon becomes

$$\kappa = \sqrt{3}\varepsilon \tag{13}$$

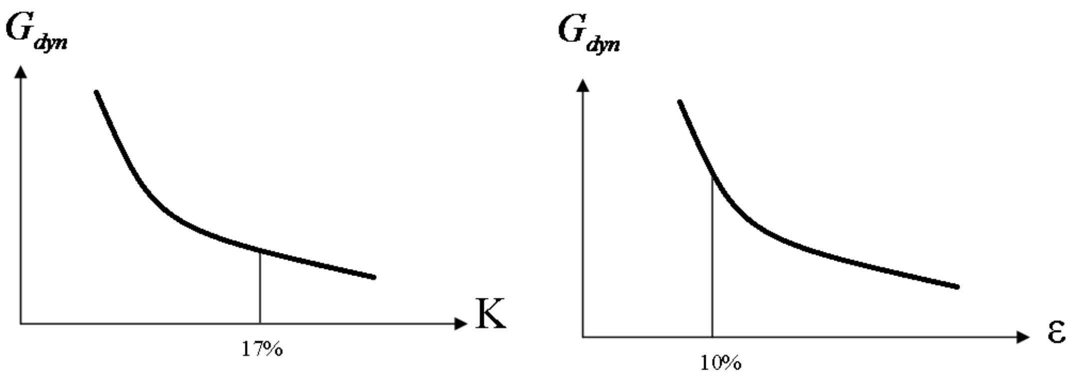


Figure 5: Dynamic shear modulus vs. Shear strain and normal strain

A 10% strain in the drop test must be compared to a shear strain of ~17%. The reason is that a pure strain ε has higher ”energy density” per unit volume than the shear strain κ as shown in Figure 5.

Chapter 3

3 Method

3.1 Design loop 1

The development of the test rig is divided into test cycles. Each test cycle begins with setting up target specifications and the test equipment is then designed in accordance to the specifications. Ending each test cycle material and equipment tests are done and the results are evaluated.

The parameters that are to be studied are the:

- compression in the rubber specimen
- reacting force in the support
- impact time

3.1.1 Target specifications

First a project group is put together to discuss and clarify the general direction of the project. The project group is presented in short below.

Table 2: Project group

	Fredrik Axelsson	Student
	Per Sjöberg	Student
	Mattias Månsson	Development Engineer Tetra Pak Mentor Tetra Pak
	Per-Erik Austrell	Assistant Professor Structural Mechanics LTH Mentor LTH
	Petra Käck	Measurement engineer

It is decided that first focus should be to swiftly design a prototype test rig for the initial verification of the theory as well as the target specifications.

Table 3: Target specifications

	Dynamic hardness of samples	60-90 shore
	Measuring resolution time	1 ms
	Equivalent frequency	30-180 Hz
	Maximum strain level	15 %

Calculations are performed to verify that the measuring time of 1 ms is accurate. A minimum of ten samples must be used to accurately describe one impact. At least ten samples during the fastest impact time decides what sample rate is needed. The shortest impulse time is achieved by using the material with the highest dynamic modulus and using as low drop weights as possible. The highest frequency is chosen to be roughly 10% above the theoretical maximum impulse frequency of 180 Hz.

3.1.2 Sampling rate

An impulse frequency of 200 Hz has an impulse time of 2.5 ms.
With a sampling rate of at least ten samples per impact period the measuring equipment is required the following samples per second.

$$s_r = 10 \cdot \frac{1}{t_p} = 10 \cdot \frac{1}{0.0025} = 4000 \tag{14}$$

Where s_r is the number of samples per second. The sampling rate of the equipment should be no less than 4000 samples per second.

3.1.3 Impact acceleration

The impact acceleration is calculated. This is the minimal force that the force measurement equipment must be able to withstand without breaking. The impact compression is approximated as half sinus function as seen in (15).

$$u(t) = u_{\max} \sin(t\sqrt{\frac{k}{m}}) \qquad (15)$$

By deriving (15) with respect to time the new equation describes the velocity of the weight as a function of time.

$$\dot{u}(t) = u_{\max} \sqrt{\frac{k}{m}} \cos(t\sqrt{\frac{k}{m}}) \qquad (16)$$

By deriving it a second time with respect to time the maximum acceleration is determined.

$$\ddot{u}(t) = \frac{-u_{\max} k}{m} \sin(t\sqrt{\frac{k}{m}}) \qquad (17)$$

If equation (17) is expressed using amplitude and angular velocity the new equation becomes

$$\ddot{u}(t) = -u_{\max}\omega^2 \sin(t\omega) \qquad (18)$$

Where

$$\omega = \sqrt{\frac{k}{m}} = 2\pi f = 2 \cdot 200\pi \approx 1256.6 \,\text{rad/s} \qquad (19)$$

The frequency f is set to 200 Hz and the strain $u_{\max}$ is set to 5 mm. The theory states that the strains should not be greater than approximately 15 % and in order to be on the safe side a 20 % compression is chosen. These values are inserted into (19) and the acceleration is determined.

$$\ddot{u}(t) = -0.005 \cdot (2\pi 200)^2 \approx -7896 \ \frac{m}{s^2} \approx -804g \qquad (20)$$

This is the maximum acceleration the falling weight will be exposed to.

3.1.4 Rig design

The problem is decomposed into smaller problems so that each problem can be handled individually. Solutions to the problems are both sought within Tetra Pak® and externally.

The key parameters, displacement, force and impact time must be measured simultaneously so that the required phase angle between the compression and reacting force can be calculated from the measured data. In order for the parameters to be studied several different functional areas are identified and isolated. The idea is to look at *what* the different areas are supposed to do, not *how* it is done. This is to ensure that no possible options are overlooked in an early phase of the work. The following functional areas are identified:

1. Supporting structure fixating the components
2. Unit measuring the compression of the rubber specimen
3. Unit measuring the impact force
4. Data recorder
5. Weight package
6. Linear transportation

The solution to each functional area is presented in short below. For a more detailed presentation see Appendix A.

1. Supporting structure

Two alternatives are found for the frame of the prototype. The options are to use a welded steel structure or a modular based aluminium system. A modular system is easier to rebuild than a welded structure and is therefore chosen. The Item system is a modular system that already exists as a standard component at Tetra Pak and is used for similar applications. It is therefore chosen.

2. Measuring of compression

The meeting with the project group concluded that there are two ways of measuring the compression in the rubber specimen.
Both ways require the use of a laser. One way is to place a laser beneath and to the side of the rubber specimen. The laser then measures the distance to the

bottom side of the falling weight. The other option is to place a laser to the side of the rubber specimen and measure the height of the rubber specimen. The laser can detect the difference between the rubber specimen and the surrounding air. It is unknown if the laser is able to distinguish the rubber from the weight during the impact. It is therefore decided to use a laser placed beneath the rubber specimen. The measuring department can supply the project with a suitable laser.

3. Measuring of force

The impact force can reach high levels as shown in previous equations. The impact time is short so the measuring equipment's sampling rate should be high enough to plot the process. The measuring department has a strain gauge, forces up to 5000 N, that can be used. They also have a suitable data recorder that can be used together with the strain gauge and the laser sensor.

4. Data recorder

A data recorder from the measuring dept. is chosen. The data logger stores the measured data on an onboard memory module and the data can later be uploaded to a personal computer for further evaluation.

5. Weight package

The weight package consists of one or several weights that are dropped onto the material specimen. The weight package must move as one unit during the impact. No suitable weight package is found and therefore it must be designed.

6. Linear transportation

The weights must be dropped along a straight vertical axis, providing sufficient support during the impact. Several alternatives are possible. The weights can be dropped inside a tube, a vertical axis with bearings or a profile rail guide can be used. The solution with an extruded aluminum profile is chosen. It may be more sensitive to friction during the impact than the other alternatives. This is acceptable in the first design loop as it is important to swiftly finish designing the rig. The tests will show if there are any problems using the extruded profile.

Some additional components must be designed before the tests can begin. The frame should stand on four adjustable feet to ensure that it stands steady on all surfaces. A solution for attaching the sensors and feet to the frame must be designed. The weight package must also be designed.

1. Sensor package

The impulse created from the impact of the weight package must be transferred to the ground in an as straight and short line as possible. The rubber specimen and the strain gauge will be placed on top of the support foot and connected using a short aluminium profile. The laser and the strain gauge are attached to each other using a L-profile. The laser, strain gauge and the foot act as one unit during the impact and the impact impulse is directed in the shortest straightest line directly from the rubber specimen to the ground. They are mounted as seen in Figure 6.

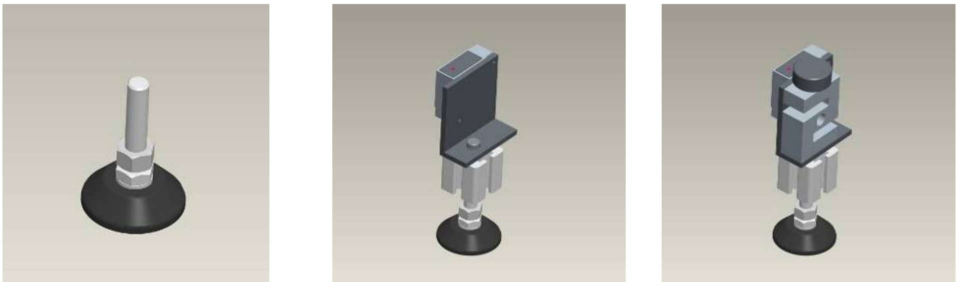


Figure 6: Sensor package

2. Weight package

The weight package consists of two parts; the weight holder and the weights. The weight holder is cylinder shaped with a shallow outtake at the bottom end and a deep outtake from the top. In the shallow outtake a polished metal plate is inserted and held in place by a threaded rod. The metal plate is the only part of the weigh package that is in contact with the rubber specimen during the impact. The threaded hole along its geometric axis holds the weights together. The weights consist of cylindrical steel discs of different thickness that are held together along their geometry axis by a threaded rod and a wing nut in the dimension M6, see Figure 7. By using different heights on the discs the total weight can be changed in steps of roughly 150 g.

Figure 7: Weight package

3. Foot package

To make sure the frame stands stable on uneven surfaces four level adjustable feet are used. The bottom rectangular frame and the feet are perpendicular and a connector must be used to avoid having to drill through the frame. A short element of the extruded aluminum profile is used and in the centre a hole is drilled and threaded. The foot is then screwed into place and locked with the nut as shown in Figure 8. The t-slot nut is then inserted and a self threading screw is used to lock the foot package to the bottom frame.

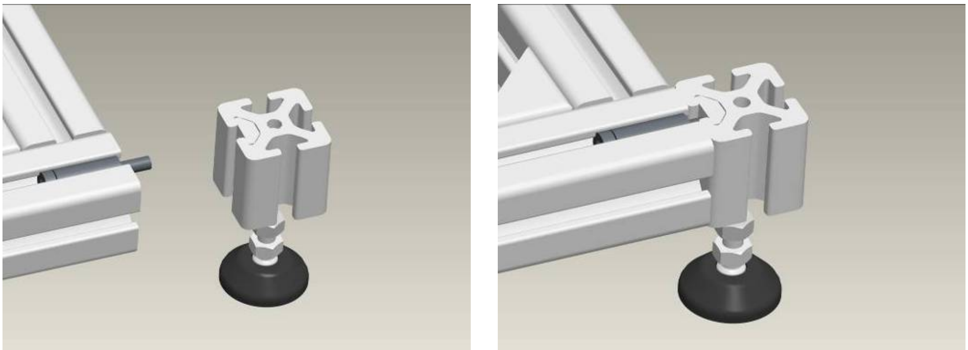


Figure 8: Foot package

The complete rig is shown in Figure 9.

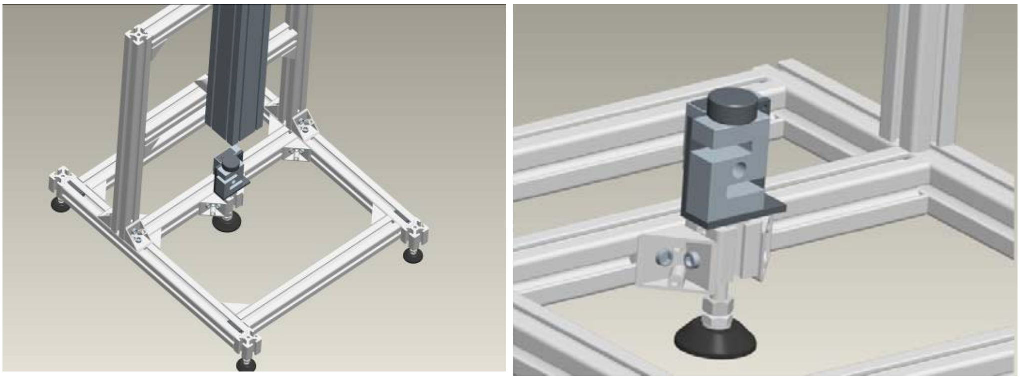


Figure 9: The assembled test rig

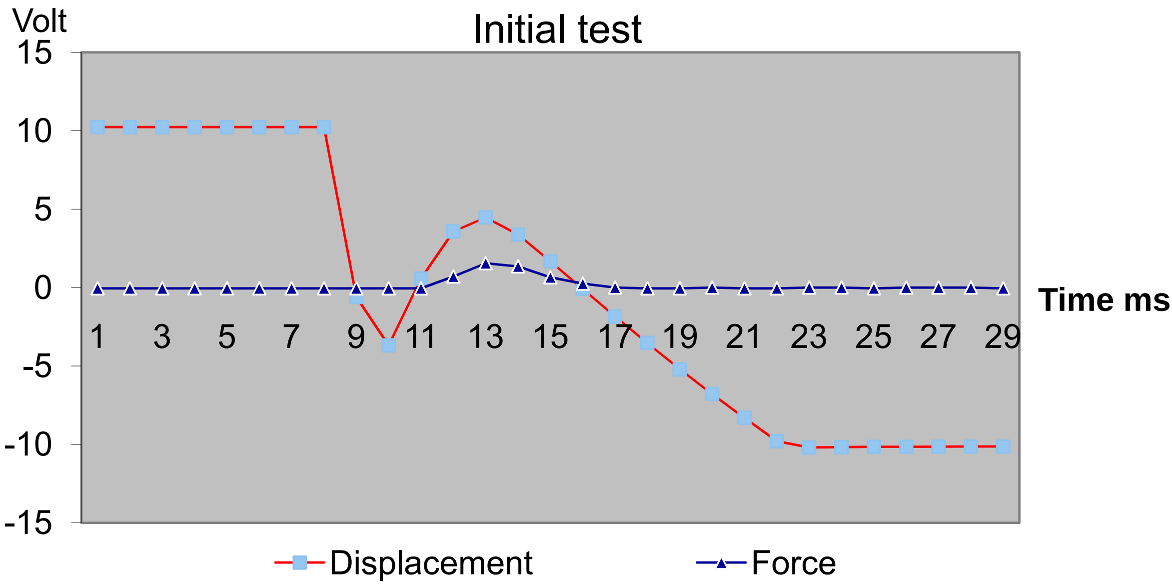
3.1.5 Startup test

After the test prototype is assembled the initial testing can begin.
The test should reveal any design flaws before the expensive measuring equipment is bought. The only components that have been bought are the frame and the weight package. For the initial test a softer rubber material having a hardness value of 65 shore is chosen. This is mainly done so that the impact time t_p would be as long as possible.
For the same reason the highest drop height possible, approximately 1.2 meters, is chosen.
From the start it is apparent that the 1000 samples per second limitation (1 ms between measurements) of both the logger and the laser displacement sensor results in inaccurate data. The choice is nevertheless to go ahead with the preliminary tests, using aforementioned equipment, in the hope that it would supply valuable information about unpredictable or unforeseen behavior in the rig design or the materials used.

The test schedule is described below.

- A rubber material is fitted on the supporting base plate.
- To recondition the material the weight package is dropped a few times from the correct release height.
- The impacting weight package is raised to the release height.
- Before releasing the weight package the data logger is put into recording mode.
- The weight package is released and the actual test is performed.
- The recording is stopped and the data is transferred to the computer for further analysis.

Graph 1shows the impact force and displacement data from one impact.



Graph 1: Scaled displacement and force

The time delay between the force and the laser displacement sensors can be seen in the chart above. The delay time between the laser displacement sensor data and the load cell data is approximately 2 ms and it is probably due to delays in the amplifying equipment of the laser.

In the graph above the data has been modified to change the zero value of the impacting force. The displacement is zeroed when the weight package is resting on the test specimen. The compression in the rubber specimen only produces a minor error of approximately 1-3 N due to the weight of the weight package. The force of the impacting weight package is small compared to the impacting force during the test. This is a simple and accurate method to determine the laser displacement zero value. The largest benefit of this method is that the zero value can be read automatically using computational equipment and methods.

The laser displacement sensor data ranges from approximately +10V to -10V. The laser shows a +10V value when no reflecting surface is found. When the impacting weight package come into the measuring range, during the test, the voltage changes to -10V. This is the reason why the laser displacement data is not symmetric and the values starts on the +10V instead of -10V.

The results shows that the number of measurements made under the impact are too few resulting in inaccurate curvature. This is expected because of the low sampling rate in the test equipment.

The tests also show a time delay between the force and laser displacement sensors. This is a probably because the force and the displacement sensors are using different signal amplifiers.

To avoid having rubber specimens being shot all across the room some kind of fastening mechanism should be made. This fastening mechanism must not interfere with the pure axial load state, it must also allow for fast changing between test specimens.

Apart from these reflections on the equipment there seems to be significant reasons to continue. Using equipment with higher resolution and sampling rate should produce the results with enough accuracy to determine the dynamic parameters. The actual rig has worked well, no noticeable resonance frequencies are found in the test results.

3.2 Design loop 2

The results of the first design loop shows that the measured curves need higher sampling rate and resolution. They also show that the general design of the rig worked well. The new test rig is designed given the results and conclusions from the prototype test rig. The main parameters that are to be studied simultaneously are:

- compression in the rubber specimen
- reacting force in the support
- impact time

3.2.1 Rig design

The initial tests show that the sampling rate of at least 4000 samples per second is crucial. The frame of the test rig is working as foreseen with no resonance frequencies or other effects detected. If a lighter weight holder and linear transportation can be found it would allow a lower minimum weight and lower equivalent frequencies. The same principal of interchangeable weights should be used.

The same key parameters as for design loop 1 are to be studied in design loop 2. The test rig is divided into the same functional areas as before:

1. Supporting structure holding the components
2. Unit measuring the compression in the rubber specimen
3. Unit measuring the impact force
4. Data recorder

5. Weight package
6. Linear transportation

Since there is no need to change a solution that is working the functional areas 1 and 5 are not changed for the test rig unless the need arises along the way. The solution to each functional area is presented in short below. For a more detailed presentation of the different design solutions see Appendix A.

A. Supporting structure holding the components

The current option using the modular Item system is working without problems. There is no need for a replacement solution.

B. Unit measuring the compression in the rubber specimen

A laser placed beneath the rubber specimen worked well in design loop 1, the same principal is used in design loop 2. The laser must have a sampling rate of at least 4000 samples per second. The resolution should also be higher. The manufacturer MEL is recommended by the measuring department. MEL has a range of models suitable for the application. It is decided to supplement the laser with an accelerometer. The velocity and displacement can then be calculated by integrating the accelerometer data with respect to time. By doing this the laser data can be verified.

The M7L/10 laser from MEL has a visual range of 10 mm and a resolution of 5 µm. Compressions of 15 % give compressions of ~4 mm, the visual range of 10 mm is enough to spot the falling weight long before impact. This laser is chosen.

C. Unit measuring the impact force

In the first design loop a strain gauge with too low sampling rate is used. The measuring department recommends using piezoelectric sensors from the manufacturer Kistler. Kistler is one of the world's leading manufacturers of measuring equipment based on the piezoelectric technology for the measuring principle of forces, pressures and accelerations. The sensors have very high sampling rate, around 10000 samples per second. Piezoelectric sensors can be made very small but still strong enough to resist the forces of the impact. The force values can also be verified with the accelerometer. The Kistler Type 9313AA1 is chosen. It is a one axial force sensor able to measure forces up to 20 kN and is very small ~10x10x10 mm.

D. Data recorder

A faster data logger is needed. The sampling rate must be equally high or higher than the measuring equipment. It must also be fully controllable from a computer, preferably with Matlab. Depending on the other measuring equipment the data logger must have sufficient analog and digital channels to connect the required equipment.

The National Instruments USB 6216 is an isolated, USB bus powered, multi in and out, data acquisition device with plenty of analog and digital connections. The logger acts as a central for all incoming signals. The signals are received and “logged”, or sampled, against time producing a matrix data table with a sampling rate of well above 10000 samples per second. For each time step the incoming signal levels from the measuring equipment are recorded. The recorded values are sent to the host computer where data acquisition software is used to read and store the data for further use.

E. Weight package

The weight package worked without problems and is not replaced.

F. Linear transportation

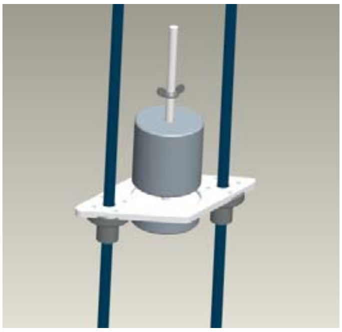
Different design ideas for transporting the weight during the drop and impact are investigated. The alternatives include dropping the weight inside a profile, guide the weight package using vertical shafts and bearings or guide the weight package using rail guides.

The main purpose is to control the movement as the weight falls towards the rubber specimen, at the same time maintaining a high rigidity in the fixating equipment.

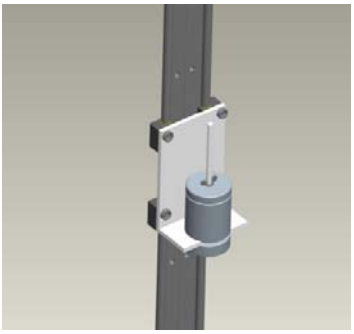
The mass of the fixture that holds the weights and enables the linear movement should be as low as possible but still offer adequate support. The fixtures structure should be rigid and light weight.

The linear transportation can be divided into two different functions; to allow a linear movement and to fixate the weights during the linear movement and the subsequent impact.

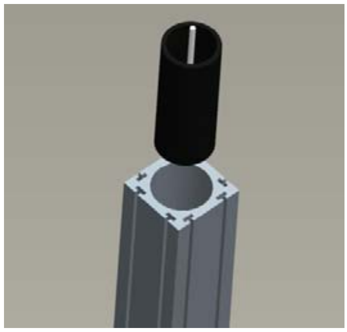
Three possible solutions are designed and evaluated using different objective and subjective parameters. The result is presented in short below.



A1 Linear bearings



A2 Carriage



A3 Extruded profile

Figure 10: Different design solutions

All solutions must be able to handle drop heights of 1.2 m. The drop and impact should also be as unaffected by friction as possible but still provide enough support during the impact. A1 and A2 are compared to the existing option A3.

A1 consists of two vertical shafts and two housed bearings. Both sliding bearing/bushings and roller bearings are possible. The slide bearing solution is made of plastic, it is lighter but has greater friction losses than the roller bearings which only has metal housings. The shaft diameter and connecting plate determines the minimum mass and also the how rigid the solution is. Calculations are made to determine the minimum weight. The minimum weight is roughly twice that of A3 depending on if roller or slide bearings are chosen.

A2 consists of four slide bearings and a carriage that fixates the weights. It is also possible to use a metal rail guide. It is however unknown if the friction is low enough to use a rail guide together with the falling weight. The minimum weight of the slide solution is higher than A3 given the high bending stiffness in the weight holding plate, white in Figure 10.

It is decided to continue using A3. The main reason for this is that it is the lightest option and that it has worked well in design loop 1.

3.2.2 Sensor package

The sensors are attached to each other and to the frame. It is decided to attach a steel plate to the frame and then mount all equipment to the plate. The laser will be attached to an L-profile that is screwed to the plate. By using distances and elongated holes the laser can be adjusted in height, see Figure 11. The foot from the first rig is then attached beneath the force sensor via a nut that is welded to the plate.

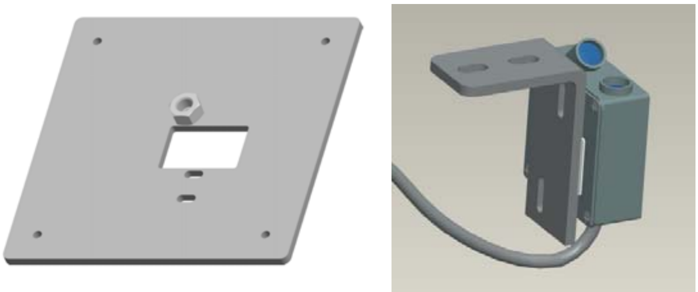


Figure 11: Mounting plate and bracket

The impulse created from the impact of the weight package must be transferred to the ground in an as straight line as possible. The idea is that the rubber specimen and the force sensor will be placed on top of the support foot connected by the nut. The laser and the strain gauge are then attached to each other using an angle iron, see Figure 12.

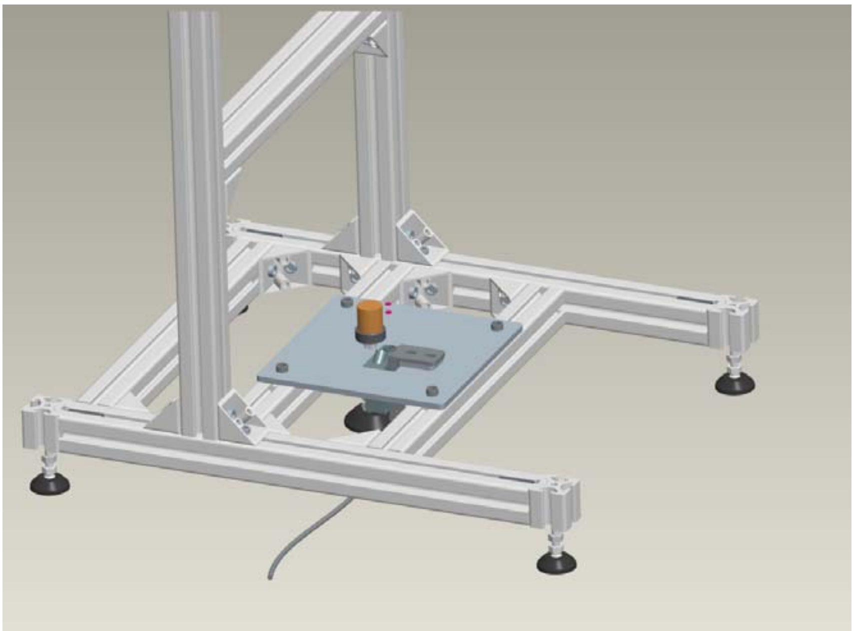


Figure 12: Equipment plate mounted to frame

3.2.3 Software

The necessary wiring is soldered and the needed software is programmed and tested. Several programs are needed to control the data logger, save the data and do the post processing. These programs are written before the tests begin.

3.2.4 One test cycle

When testing a material the only changeable parameters are the drop height and the impacting mass. The drop height is kept at a constant level as the weight is increased in increments of 150 g. Each drop is repeated three times before the weight is increased. A test cycle is performed as described below:

- A rubber material is fitted on the supporting base plate. The material is lubricated on the upper and lower side using a spray can of silicon lubricant.
- The load sensor is calibrated and the weights are then placed on the material.
- With the weights resting on the rubber material the logger is started.
- The weights are lifted to the drop height and then released thus performing the test.
- The recording is stopped and the data is loaded into the Logsoft 6000 graph window.
- The equivalent frequency and compression in Volt are read from the Logsoft 6000 graph window. The values are then inserted into in an excel file and the data file is saved.
- The test is repeated with the current weight or the weight is changed before the next test.

In between test the load sensor and weight package assembly are controlled and screws are tightened if needed.

Figure 13 and Figure 14 shows the output force and displacement data from one test.

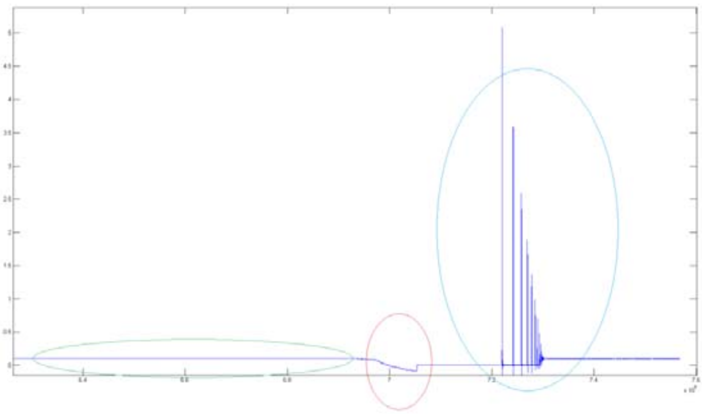


Figure 13: Unedited force test file

The green ellipse shows the force measurement before the weights are raised to perform the test. The force curve is constant and the signal is greater than 0V.

The red ellipse shows a decline in the force curve. This is a result of the weights being lifted to the drop height. Notice that the force shows a negative value before changing into an almost 0V output. This is due to the lubricants capillary force which makes the rubber specimen, the weights and the specimen supporting "stick together".

The light blue ellipse shows the several peaks in the force measurement. Each peak constitutes an impact. When the weights have stopped the force measurement once again shows a constant value.

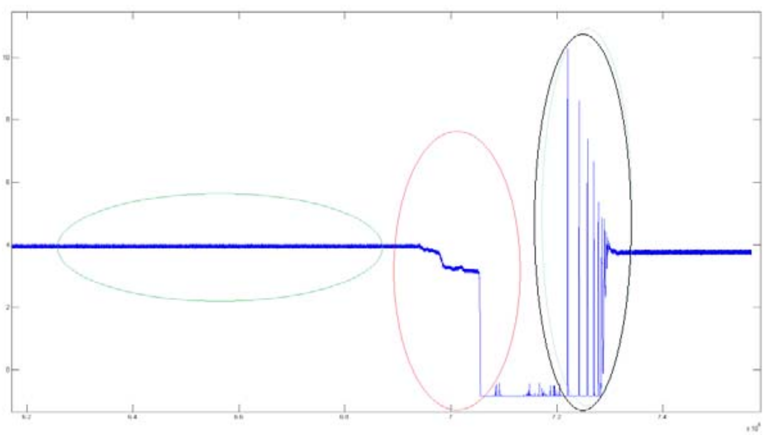


Figure 14: Unedited displacement test file

The first area, marked with the green ellipse, shows the displacement data when the weights are resting on the specimen.

The red ellipse marks the area where the weights are raised to the drop height. When this is done the laser looses the weights and the voltage output drops to a constant value.

The black area shows the actual test with a number of impact peaks. After the weights are settled again the laser shows a constant value approximately the same as in the blue ellipse area.

Between the red and the blue area some interference can be seen. The interference varies in size but is almost always present. The probable reason for the occurrence of interference in the laser data is reflection of the laser in the pipe and the weights.

From these raw data files the information for the actual impact is retrieved.

Chapter 4

4 Results

The first objective

> *Design a mechanical drop test device including measuring equipment according to the method proposed by Per-Erik Austrell*

is fulfilled with the completion of the test rig.

4.1 Sensor tests

The equipment must be tested to confirm that all sensors return correct values and that there is no delay between signals.

4.1.1 Force sensor

The force sensor is tested in two ways. First a static test where a known weight is placed on the sensor, then a dynamic test where force data is compared to the accelerometer data.

The static test returned a value of 3 kg. For the dynamic test a complete test cycle is performed and the data from all three sensors is collected. The maximum force for each test is compared to the maximum acceleration multiplied with the dropped mass for each test. The result is shown in Figure 15.

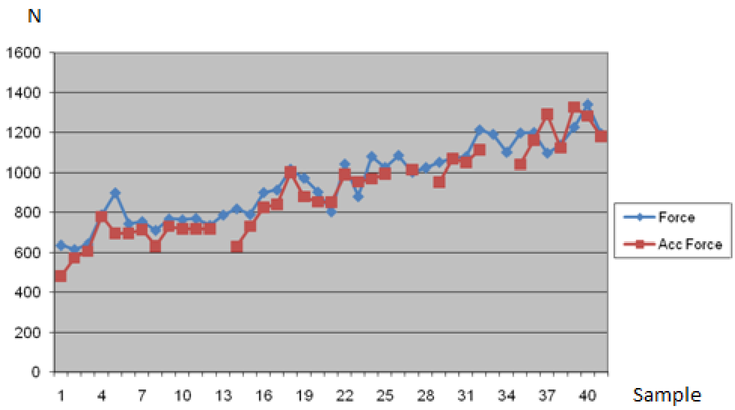


Figure 15: Forces vs. acceleration times mass

4.1.2 Displacement sensor

The displacement sensor is tested by placing the weight package at a certain height and then change the height 5 mm. The output data is used to calculate the distance the weight package is moved. The sensor returns a value that corresponds to a 5 mm displacement.

4.1.3 Simultaneous measures

The objective

> *Basic principal is a drop test where compression and force are measured* ***simultaneously***

is evaluated in this section. A steel compression spring is purely linear elastic, the maximum force and displacement therefore occurs at the same time. A weight is dropped onto the spring and is then allowed to bounce until resting on the spring. The top values for each "bounce" is used to determine if any delay between signals exist, see Figure 16. Any such delay should be a pure signal delay.

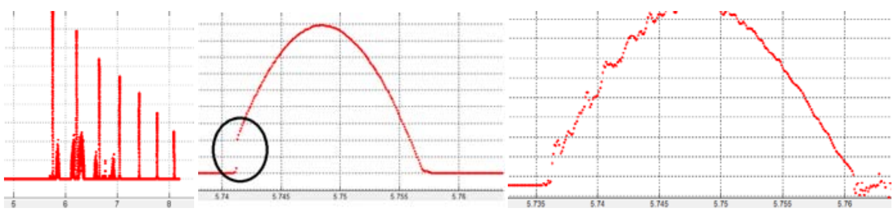


Figure 16: Steel spring tests

The plots above show one impact. The displacement sensor shows a step rise error, shown in black in the middle plot.

The plot to the left is the displacement curve for the first seven impacts. The middle and right plots are describing the displacement and force as a function of time.

4.1.4 Specimen shape

To evaluate the objective

Evaluate specimen shape during impact

several tests are made while using a high speed camera and tracking software.

The impact is recorded as a film and studied to detect any barrelling. FEM-simulations show that too high friction in the surface between the specimen and the weight results in barreling as shown in Figure 17. The figure to the left is an impact with the friction value 0.05, the right is an impact with high friction, 0.30.

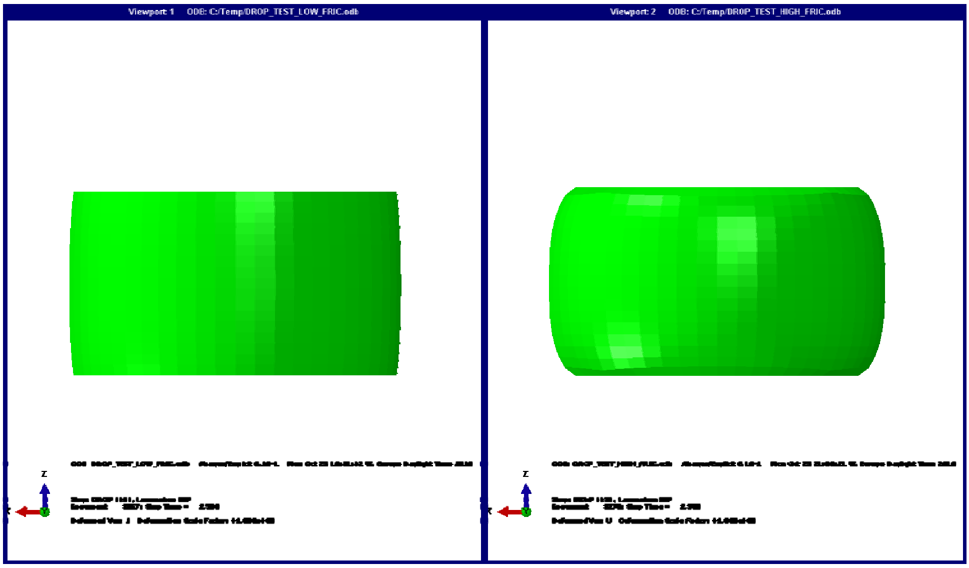
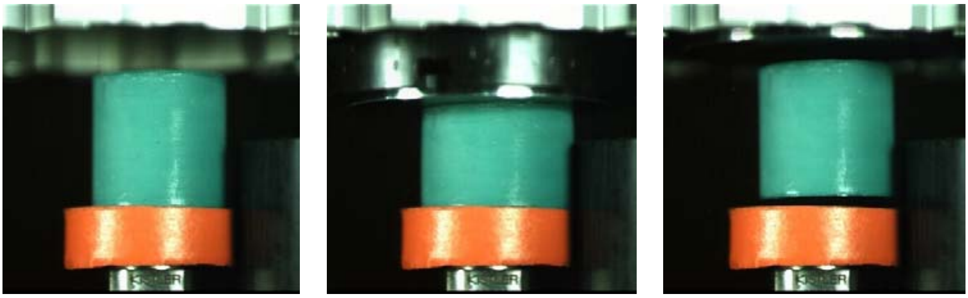


Figure 17: FEM-simulation of low and high friction drops

Image 2 shows the material filmed with high drop height and weight.



Before impact Maximum compression After impact

Image 2: High speed filming of a drop test

Several materials are tested at different compressions and frequencies.

4.1.5 High speed tracking data

Tracking software is used to measure the deformation in the rubber specimen from the high speed film. The compression from the tracking data is plotted against the compression from the laser.

The displacement curve taken from the tracking software and the lasers displacement curve are shown in Figure 18. The high speed film is recorded at 5000 samples per second, the laser has 10000 samples per second. The laser values are therefore twice as many as the tracking data points.

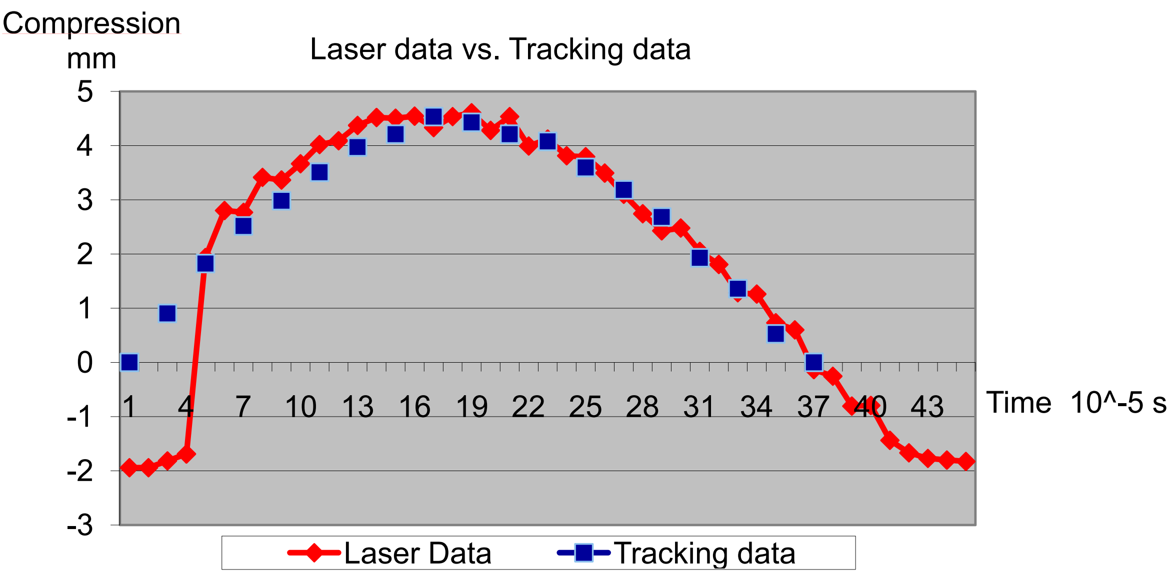


Figure 18: Laser data vs. tracking data

The plots show that the laser provides the right zero and maximum values. It also shows that several values before the step rise are incorrect.

4.2 Material tests

The final objective

*Compare **damping** and **dynamic modulus** with previous harmonic test results*

is being investigated.

The tests are performed in test cycles as described earlier. Each drop is repeated three times before the weight is increased. The drop height is roughly 0.3 m and the weight starts at 665 g and is then increased in increments of 150 g until it reaches almost 3000 g. That is equal to 14 weight increases per material and at least three tests per weight level, it amounts to around 40 impact tests per material. All tests are performed at a room temperature of 21°C.

4.2.1 Material selection

Only the materials that are tested in the reference tests can be evaluated. Materials affected by the step rise are not evaluated.

A material with both frequency and amplitude dependence is compared to the reference tests. The material has a stiffness of 65 shore.

The material is tested with force, laser and accelerometer sensors to rule out any error in the sensor equipment. It is a soft material and is therefore less subject to the step rise. It is chosen for the comparison against the reference tests.

Several other materials are also tested and compared with similar results. The results are not shown in this report.

4.2.2 Results comparison

Figure 19 and Figure 20 show a comparison of the results between the two test methods. In Figure 20 the dynamic modulus is plotted against the frequency at different compression levels. The values compared are paired by colored rings. The unfilled rings show the values received in the impact tests and the filled rings show the comparable values from the harmonic tests.

Figure 19 shows the dynamic modulus as a function of frequency for different compressions. The tests are performed at 20°C.

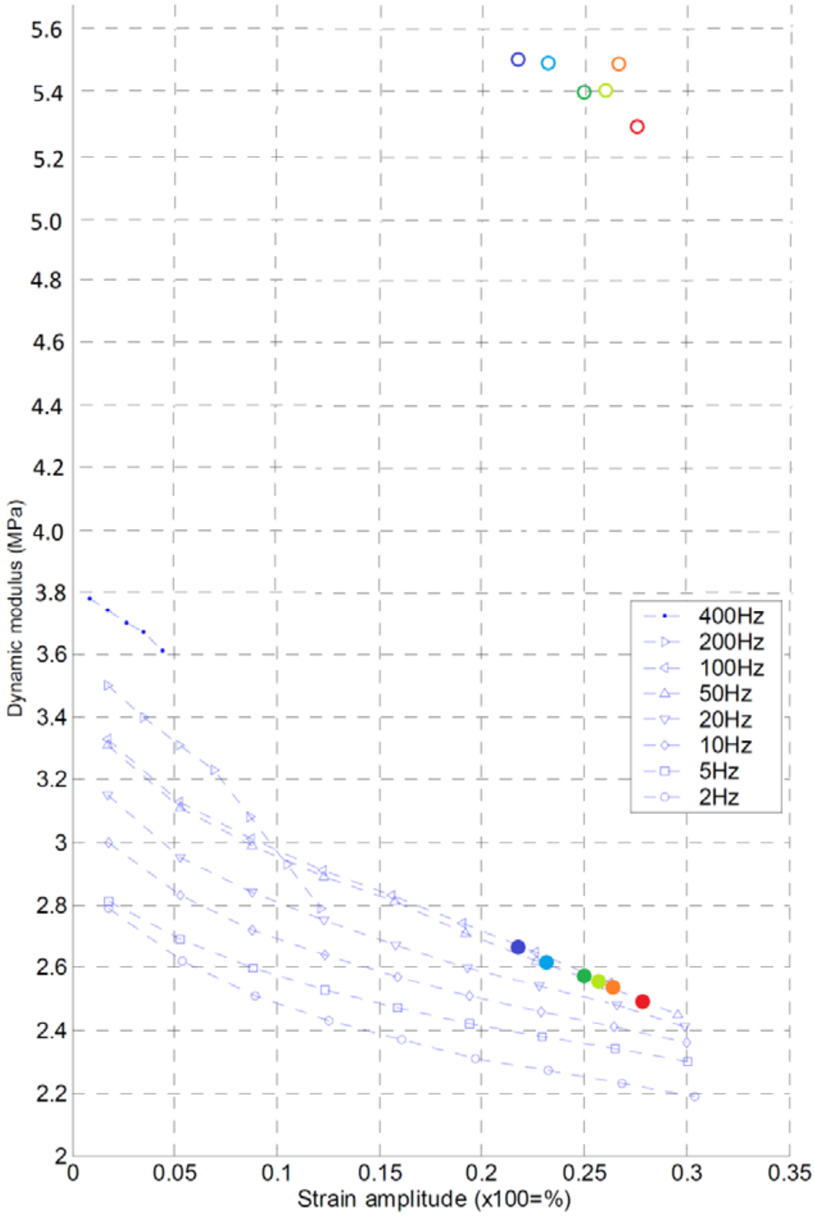


Figure 19: Comparison harmonic vs. impact tests

Figure 20 shows the dynamic modulus as a function of frequency for different compressions. The tests are performed at 20°C.

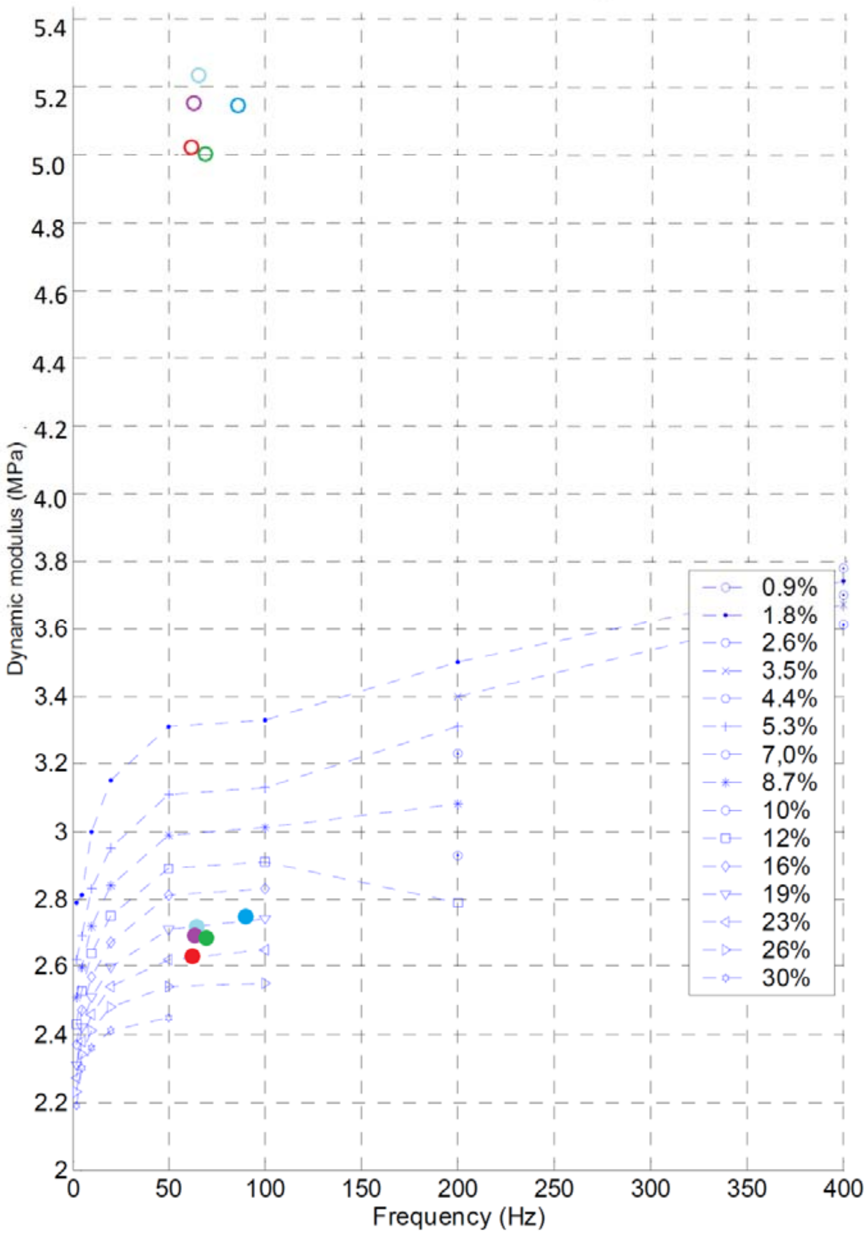


Figure 20: Comparison harmonic vs. impact tests

Figure 21 shows the dynamic modulus as a function of frequency for different compressions. The tests are performed at 20°C.

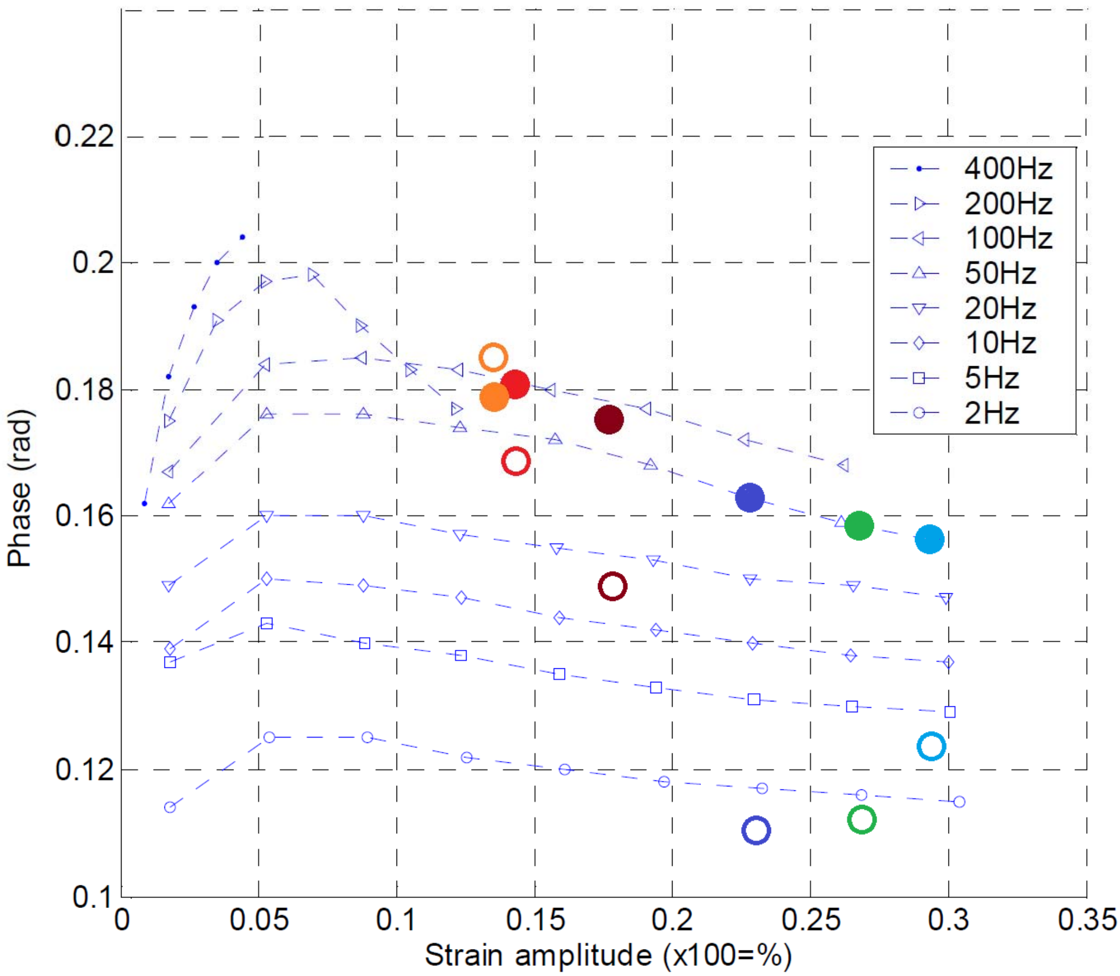


Figure 21: Damping vs strain amplitude

Chapter 5

5 Conclusions

The objectives for the project are:

- Design a mechanical drop test device including measuring equipment according to the method proposed by Per-Erik Austrell.
- Basic principal is a drop test where compression and force are measured **simultaneously**
- Compare **damping** and **dynamic modulus** with previous harmonic test results
- Evaluate specimen shape during impact

The first objective is completed, the test rig is designed and tested. The step rise in the laser is reducing what type of materials can be tested at this point. Softer materials can be tested without interference from the error, materials with high shore values cannot. A third design cycle using another laser might resolve this problem.

The second objective is completed, a small delay between the signals is detected. This is unavoidable as it probably is a result of an unavoidable input/output lag in the electronics. Since no faster electronics exists it is impossible to correct the error by using other equipment. It can be compensated for by giving the two impact curves the same start time. This does not affect the dynamic modulus, frequency or damping in any way.

The specimen shape should be investigated during impact. Tests using a high speed camera show that the specimen shape stays intact even for very high strain levels and frequencies.

The last objective is to compare the test results to the reference tests. The comparison shows that both the dynamic modulus and damping are too high, almost by a factor two. All measurements are checked but no explanation to this deviation is found. If the measured dynamic modulus are divided by two the values are close to the reference tests.

5.1 Sensor tests

5.1.1 Force sensor

A difference between the force values of the force sensor and the accelerometer are noticable however the difference is in most cases small in size. Comparing the force sensor and the accelerometer curves show that the force curve is much smother than the accelerometer curve. It is harder to produce good values using the accelerometer than the force sensor. The accelerometer is more sensitive to disturbances than the force sensor. This could be a result of the placement of the accelerometer in the weights. The weighs are not designed with a good placement of the accelerometer sensor in mind.

It can be concluded that the force sensor is working correctly and that it returns correct values.

5.1.2 Displacement sensor

The spring tests show some disturbances in the force plot, probably because of insufficient fixation of the spring. This does not affect the comparison.

A small delay between the sensor signals exist and the delay is not constant in each bounce. This is a result of delays in the electronics and cannot be avoided or predicted in advance.

5.1.3 Laser step rise

A problem presented in the dynamic tests is a step rise in the laser’s output signal. As the falling weight enters the laser’s visual range 50 mm from the lens, the first data points are erroneous. After returning a few faulty data points the output signal is corrected and the following data points are correct, this is seen as the “step rise” in Figure 22.

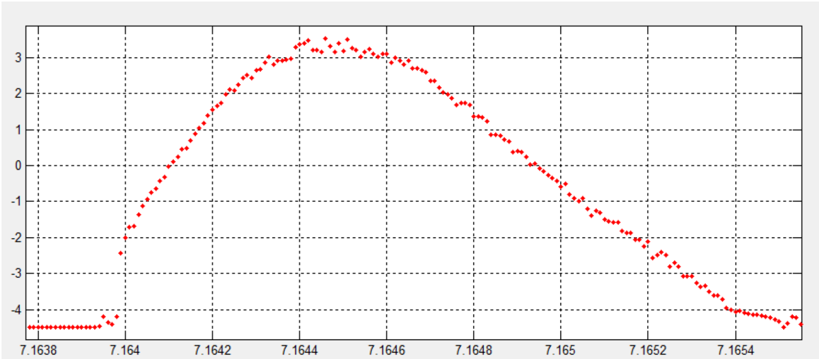


Figure 22: Laser displacement curve displaying the step rise

This is a serious problem as it makes the identification of the displacement's start time hard or almost impossible to find.

Several attempts are made to either solve the problem with the step rise or to adapt the test data in such a way that the step rise becomes irrelevant.

The measuring department is contacted about what causes the step rise and how it can be eliminated or compensated for. It is believed to be a result of the weight entering the visual range of the laser, the laser is "awoken" and the output signal starts from an end position ±10V. The cause a delay somewhere in the electronics. It is most probable that the delay originates in the electronics of the laser and in that case nothing can be done to resolve the error.

The following is tested to try and **eliminate** the error:

- Move the laser up thus detecting the falling weight at an earlier point. This moves the "blind spot" so that it is detected earlier, earning one or two extra measuring points. Since the laser has 10 mm visual range, moving it upwards also decreases the maximum compression that can be detect.

- The bottom side of the weight package is painted. According to the data sheet the laser should suffer smaller disturbances when measuring against a black surface compared to a polished. This did not affect the step rise in any way, the paint is removed.

- Another object is placed in the lasers path making it detect this surface before the falling weight passes. As the weight passes it pushes the foreign object away so the laser measures the distance to the weight instead. This arrangement proved to be hard to do and is therefore cancelled.

-

The following is tested to try and **minimize** the error:

- Test if the curve can be approximated as being symmetrical around the maximum value. If so the incline of the right side (as the weight is pushed upwards by the rubber) can be inverted and super positioned on the left side of the curve. The curves are clearly not symmetrical, see Figure 22, therefore this approach cannot be used.
- Use polynomial approximation on the left side of the curve thus "re-creating" the missing data points based on the continuation of the curve. The problem with this approach is that the missing data points show a behavior that the rest of the curve does not. The "scatter" in the beginning of the compression curve in Figure 22 is most likely erroneous, simply a result of the step rise. The unreliability of these data points makes it impossible to estimate when the actual compression begins.
- Use linear approximation based on the estimated inclination of the left side of the compression curve. A program to do this is written, the user must choose what inclination is suitable by an estimation based on the average curve shape. This requires a great deal of subjective user input as no mathematical function to do it automatically works satisfactory, the curves simply varies too much for different material samples, drop heights and weights.

Moving the laser upwards somewhat reduces the problem of the step rise. The downside is that it reduces the maximum strain that can be measured. A linear approximation based on the user estimating the curve shape is tested thoroughly to see in what extent the subjective assessment affected the end results. Two test subjects familiar with the project are given the same 40 raw data files, they then extract the impact curves from the raw data files using the linear approximation when so is needed.

The results show that the level of subjectivity affects the end result in general and the damping in particular. The damping is very sensitive to if the right starting point is found. The degree of subjectivity of the linear approximation results in negative damping in some tests, that is impossible since damping is a measurement of energy loss. Energy cannot be generated during the impact, therefore the damping must be positive.

For materials with high stiffness a greater portion of the compression curve is lost due to the step rise. A high shore value means a high equivalent frequency and a fast impact. A faster impact uses less data points hence the relative increase in data loss. The damping cannot be measured with enough accuracy

5.1.4 High speed filming

The high speed filming showed that no or very small barreling is detected in the tests. This is easiest seen in Image 2 on the left side of the specimen. The shape stays cylindrical during the whole impact even with strain levels around 50%.

The edge tracking of the high speed filming also shows a difference in the laser sensor and the tracking curves from the films. This clearly shows the step rise error received from the laser sensor.

5.1.5 Results comparison

Comparing the result between the impact tests and the harmonic tests show that the dynamic modulus of the impact tests are higher than that of the harmonic tests.

Figure 19 and Figure 20 shows that the dynamic modulus of the impact tests is approximately a factor two higher.

Figure 23 show the dynamic modulus of the harmonic tests compared to the dynamic modulus of the impact method divided by a factor two.

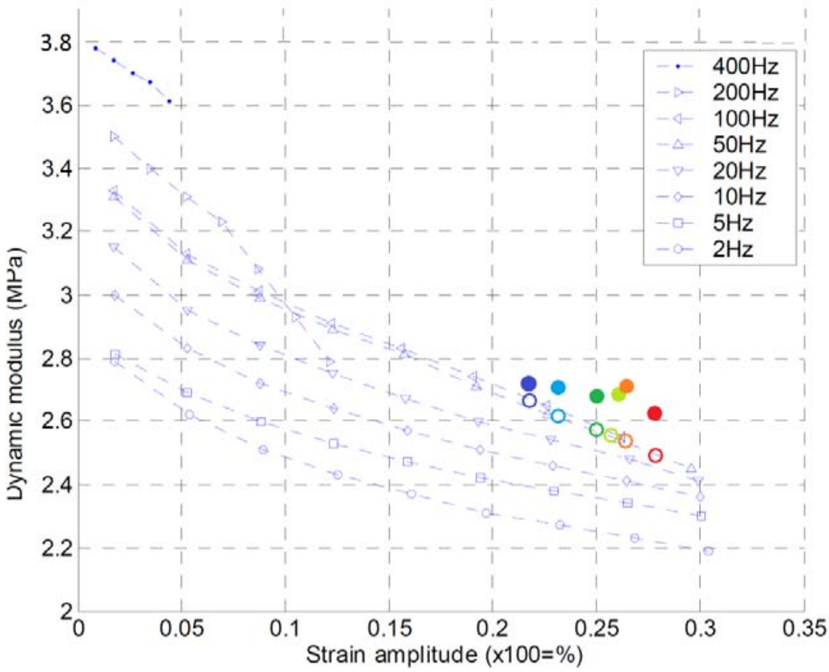


Figure 23: Comparison of 50% of the dynamic modulus vs. reference tests

The reason for this factor difference between the two test methods is unknown. Test of the sensors and a close examination of the code in the software used show that the test data returned is correct with minor deviation.

5.2 Material

5.2.1 Youngs modulus and Mullins effect in material

The Young's modulus for the rubber specimen is determined via different tests. It is also tested if Mullins effect can explain why the dynamic modulus is higher than in the reference tests.

The specimen is placed in a test machine that compresses it to 20% compression. The force needed is registered and used to calculate the Young's modulus using $E = \frac{\sigma_{\max}}{\varepsilon_{\max}}$

The following tests are made:

- Test the material in "virgin condition", it is rested and has not bed subjected to any forces
- Cycle the material 10 times at 1 Hz and 20% compression, then test the material
- Cycle the material 100 times at 1 Hz and 20 % compression, then test the material
- Finally the material is compressed and then left for 2-3 s. The force is then measured.

Table 4: Measured Young's modulus for the test material

Condition	Compression %	Force N	Young's modulus MPa
Virgin material	20	1100	11.2
After 10 cycles	20	1060	10.8
After 110 cycles	20	950	9.67
After 110 cycles and left for 2-3 s	20	800	8.14

The tests show a significant drop in the force if the specimen is loaded and then left in a compressed state as seen in Figure 24. The rubber specimen also shows a 15% decrease in Young's modulus after 110 cycles.

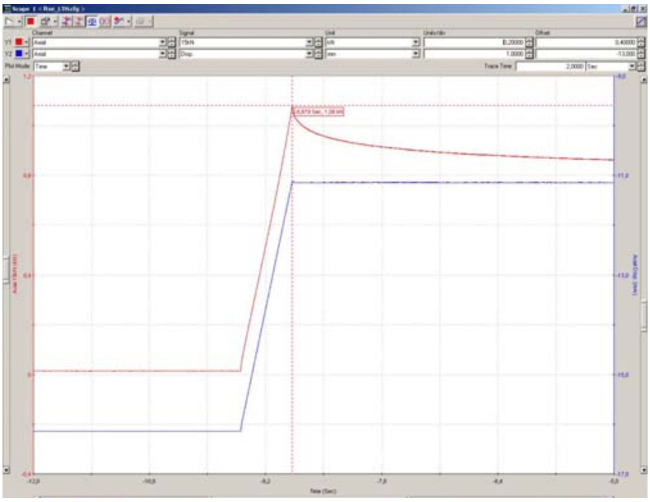


Figure 24: Compression test with relaxation

The red line in Figure 24 shows a drop right after the force is loaded, the material relaxes at the load level. The load is applied in about 0.5 s, much slower than in the drop tests.

A small Mullins effect is detected in the material. After about 100 cycles at 1 Hz the measured Young's modulus is decreased by roughly 15%. It is possible that a longer cycle would decrease the Young's modulus even more. This procedure cannot be performed using the drop test rig. Before each test cycle the material specimens have been exposed to a few drop tests to soften the material. It is however too time consuming to do more than a few test drops.

Before each test the rubber specimen to be tested is reconditioned. This is done by applying a force of 600-750 N to the material several times. By doing this cross links between the polymer chains in the rubber are broken and the dynamic modulus is thereby lowered. During the evaluation of the results it appears that the conditioning of the rubber specimen done before a test cycle is not sufficient. The measured dynamic modulus is higher than in the reference tests. The load applied should probably have been cycled more in order for the results to be more accurate.

5.3 Test method

It is very hard to achieve a wide frequency and compression range with the test method as the two variables are connected. The measured values appear to stack at moderate frequencies. The theory can be used to predict what drop heights and weights corresponds to frequencies and strain amplitudes. Harder materials have difficulties reaching low frequencies and high strains. Soft materials have difficulties reaching high frequencies, they quickly reach the maximum strain level allowed.

A mayor disadvantage compared to the harmonic test is that the compression cannot be held constant while the frequency is varied. This makes it hard to get a good frequency span. The same goes for the amplitude span, the frequency cannot be held constant while the strain is varied.

5.4 Equipment

The step rise in the laser limits what materials can be investigated as it rules out the harder materials. The laser is not accurate enough to measure damping or dynamic modules for harder materials. For softer materials the method provides good data.

As the specimen is not held in place it moves after impact. Only one impact can therefore be investigated per drop. If the specimen is fixed the weights can bounce several times and several impacts can be generated from one drop.

The force sensor provides good values and seems very reliable. No disturbing natural frequencies are observed in the test rig during impact.

The measuring equipment and sensors all work without problems, apart from the laser. Tests with the accelerometer attached to the weights provided relatively good data from the impact acceleration. The data could not be used to accurately describe the velocity or displacement as the small errors are amplified in the integration steps.

Chapter 6

6 Discussion

The testing and post processing of the data file is time consuming as it is done one test at a time. With a more automated test method it should be possible to get the impact data directly from the test instead of having to cut it from the raw data files.

The test method limits the spread of data in terms of frequency and strain levels compared to harmonic testing. This is a limitation of the impact test method.

The tests are done by starting with the lowest weight and adding more weights until the maximum possible weight or allowed strain is reached. The test cycle starts with a low impact force, as weights are added the force rises.

It is better if the tests start with the largest impact force. By increasing the force the maximum load level is constantly raised and any previous reconditioning is undone. If the force is decreased for each test only the first tests should be experiencing Mullins effect. If the tests are made with the largest weight first then the first calculated dynamic modulus could be wrong, but since the following test would have been made with a smaller force these would be closer to the real value.

The filled dots in Figure 23 are the measured dynamic modulus values divided by two, the hollow dots are the values from the reference tests. Comparison shows that the measured values divided by two corresponds well to the reference test values.

The test cycle should be started at the maximum drop weight instead of the minimum. This minimizes the Mullins effect that insufficient reconditioning can cause. Tests where the Young's modulus is measured before and after reconditioning shows a decrease around 15% after the reconditioning.

If the rubber specimen have been tested while insufficiently reconditioned, the measured dynamic modulus should be too high. This can somewhat explain why the tests result in high dynamic values compared to the harmonic test. However it cannot explain why the measured values are almost a factor two higher.

The tests of the measuring equipment resulted in similar force and displacement values for both the static and dynamic tests. This indicates that the sensors return correct values, apart from the step rise effect in the laser sensor.

The raw and unedited data files are used to manually calculate the dynamic modulus for a series of drop tests. The results correspond with the values calculated by the software. This shows that the software does not miscalculate and that the factor two does not originate from the software. Evaluations of the high speed films support this conclusion.

Tests show that the damping can be measured using the time difference between the maximum values of the force and displacement curves instead of the time difference at the end values. Figure 25 shows only a small difference between these methods of measuring the damping. This makes it easier to determine the damping since the displacement curve cannot describe the rubber's compression after the force returns a zero value. When the force is zero the rubber and weights are not in contact anymore. The laser measures the distance to the weight, not the height of the specimen.

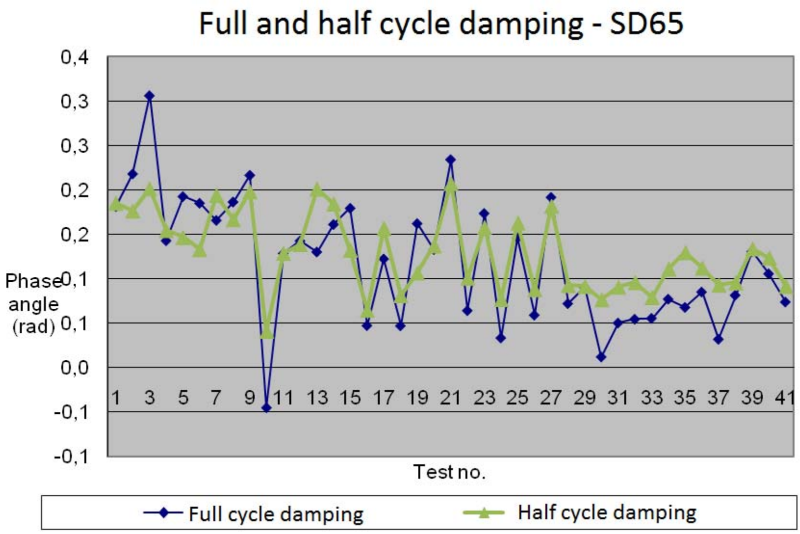


Figure 25: Full and half cycle damping plotted for different drops

The theory states that the maximum value of the displacement governs the dynamic modulus. The time difference between the force and displacement maximum values governs the damping.

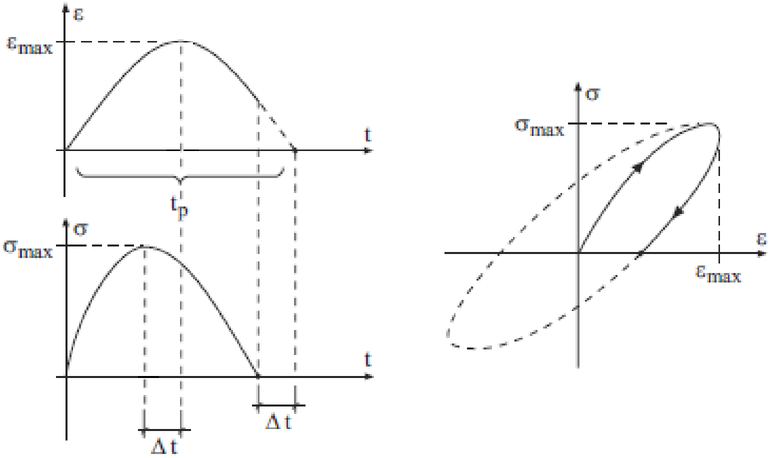


Figure 26: Dynamic modulus and damping

In Figure 26 the impact strain and stress histories are plotted together in a composed stress strain curve. Two ways of determining Δt are used. One by using the time difference of the maximum values between the curves, in the other the time difference between the endpoints of the curves are used.

The dashed line in the strain plot is where the mass loses contact with the specimen, hence σ = 0. By comparing the time difference for the maximum values no assumptions of the dashed line's gradient is made. However, a long rise time makes the strain curve's starting point unknown thereby affecting the size of Δt. The dynamic modulus is only affected by the size of the maximum value of the strain and stress. If the correct zero and the maximum values are measured the dynamic modulus can still be accurately evaluated.

Chapter 7

7 Proposals for future work

The following list consists of proposals for the future work, the ideas have been generated during the project but have for different reasons not been able to be tested in this project.

- ► Replace the laser

A laser without the step rise should provide better measurements. Lasers with equal sampling rate, longer visual range but with lower resolution exists. This would move the step rise farther from the interesting area.

- ► Combine with static test method to cover low frequencies

The test method is limited to frequencies above 30 Hz. In order to produce good material models test data from static tests could be combined with the test data from the impact test method.

- ► Fixate specimen

By fixating the test specimen and evaluating the first few impacts more test data could be generated during each test.

- ► Automate the tests

In order for the test method to compete with the harmonic test method extensive automation is required.

- ► Replace the falling weights

The use of falling weights limits the test method and may prove hindering in the process of automation.

- ► Add additional sensors

By adding additional sensors the data logger recording could be trigged producing data files only containing impact data. This would simplify the post processing.

► Test using pre tension

In many situations it is desirable to be able to include pre-strain in the rubber specimen.

Chapter 8

8. Bibliography

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[3] Olsson, Anders K. 2007. *Finite element procedures in modelling the dynamic properties of rubber.* Lund : Division of Structural Mechanics, LTH, Lund University, 2007.

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[5] Ciesielski, Andrew. 1999. *An introduction to rubber technology.* Trowbridge : Rapra Technology Limited, 1999.

Chapter 9

9. Table of images

Image 1: Tetra Classic®

http://www.tetrapak.com/media/globalimagebank/abouttetrapak/thecompany/Pictures/history_1940_v.2.jpg

Image 3: Kistler Type 9313AA1

http://www.kistler.com/medias/pMqWDjxMVdrGP85D8YwBEd-30.jpg

Image 4: NI-USB 6216

http://www.en-genius.net/includes/images/tmp_051908b.jpg

Image 5: Igus Drylin R and SKF LVCR flanged bearings

http://www.skf.com/files/877721.pdf page 38

http://www.igus.eu/wpck/default.aspx?pagename=drylin_r_fjum_01

Image 6: Igus OQA Quad Block with supported shaft

http://www.igus.eu/_wpck/images/global/thumbs/drylin_r_oqa_01_thumb.jpg
http://www.igus.co.uk/_wpck/images/global/1_2/drylin_r_swum_ewum_1.jpg

Image 7: Rail, housing, plate and carriage

http://img-europe.electrocomponents.com/largeimages/R7026725-01.jpg
http://t2.gstatic.com/images?q=tbn:ANd9GcTVl35eDRtxi39-YCRDL-yVZrwbYZlEttKWPdrsFj0k9IoUzME&t=1&usg=__NMn2DwBH7BAmj-ZrNyVH2IdEQoQ=

Figure 27: Item® system

http://www.solidcomponents.com/company/?SCCC=SCCNS20DW&Lang=46&VisualID=15425

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http://www.solidcomponents.com/files/company/SCCQS01MM/companyfiles/img/thumbnail/item_0041963.jpg

Figure 28: Different laser types

http://norkom.beta.qt.pl/www_dokumentacja/czujniki/e214e11_3z4m_datasheet.pdf

Appendix

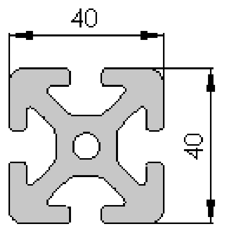
A. Components design loop 1

The following is illustrations of the chosen components in design loop 1.

1. Item® system

The Item system has been used successfully at other similar applications at Tetra Pak®.

Item profile 8



Item profile 8

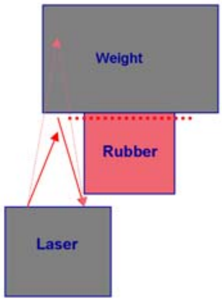
Connector

T-slot nut

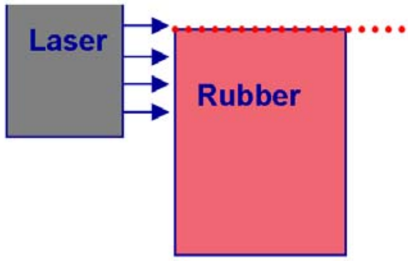
Figure 27: Item® system

2. Laser alternatives

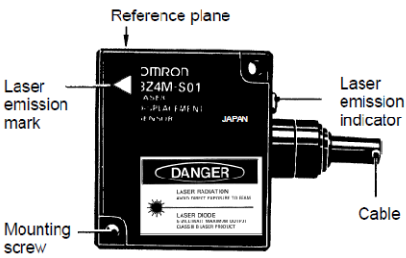
The Omron 3Z4M-S01 is used as it is unknown if the Sick Sensick AT20E can separate the rubber from the weight during impact.



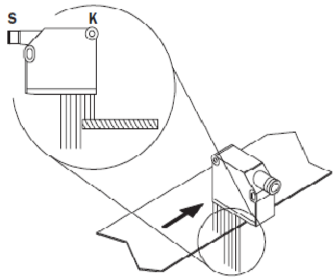
Omron laser



Sick array laser



Omron 3Z4M-S01



Sick Sensick AT20E Edge/Proximity

Figure 28: Different laser types

B. Components design loop 2

B Unit measuring the compression of the rubber specimen

The table shows some of the lasers from MEL, high values of linearity, resolution and suitable values of range are important. The M7L/10 is used in this project.

Table 5: M7L laser sensors.

	Sensor	M7L / 0.5	M7L / 2	M7L / 4	M7L / 10	M7L / 20	M7L / 50	M7L / 100	M7L / 200	M7L / 400
	Range [mm]	0.5	2	4	10	20	50	100	200	400
	Range begin [mm]	23.7	23	22	40	55	95	170	240	480
	Linearity* ± [µm]	1.0	4.0	8.0	20	40	100	200	400	700
	Resolution* [µm]	0.2	0.4	1.0	5.0	9.0	30	60	200	600

A. Unit measuring impact force

The Kistler Type 9313AA1 is used in this project.

Image 3: Kistler Type 9313AA1

B. Data recorder

The Logger – National Instruments USB 6216 is an isolated, USB bus powered, multi in and out, data acquisition device is used.

Image 4: NI-USB 6216

C. Linear transportation

The different design alternatives are presented in more detail than in the report.

Since one of the goals was to minimize the weight, plastic sliding components are investigated as well as metal roller or ball bearing components. The following components illustrate the general design ideas; they are available with both plastic sliding bearings and metal bearings with balls or rollers.

Alternative 1. Linear bearings

The linear slide bearing with flange is represented by the Drylin R linear slide bearing from the manufacturer Igus. The bearing is made of aluminum and the slide film is made of plastic. The SKF LVCR is a flanged linear ball bearing unit made from cast iron.

Image 5: Igus Drylin R and SKF LVCR flanged bearings

Alternative 2. Supported shafts

Instead of using separate bearings, shafts and connectors a combined solution can be used. A supported shaft has the advantage that it has support along its whole length.

The Drylin OQA quadblock or SKF Quadro unit LQCR are open and closed types of carriages where the bearings are inserted into and fixated to the block.

The OQA is an open type bearing. The carriage that holds the four bearings is made of aluminum and the supported shaft is made of either stainless steel or hard anodized aluminum. The LQCR is a closed type aluminum carriage using four self adjusting roller bearings.

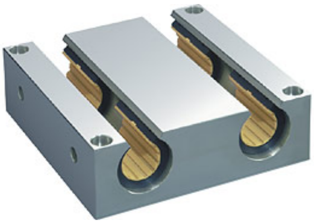


Image 6: Igus OQA Quad Block with supported shaft

Alternative 3. Rails

Instead of using a single four bearing carriage, e.g. OQA or LQCR, smaller one bearing housings are available. The Drylin W is a series of modular linear guides. The bearing blocks can be bolted to each other using an aluminum plate. The rail is available in several different widths and the user chooses the length of the plate. The housing is made of die cast Zink using a plastic slide film.

Image 7: Rail, housing, plate and carriage

Design illustrations

Illustration 1 Alternative 1

The second option is to use two parallel vertical shafts, two closed linear bearings and a plate. The plate has three countersunk holes, two for the bearings and one for the weights. The countersunk hole together with a hole for the threaded rod fixates the weight package.

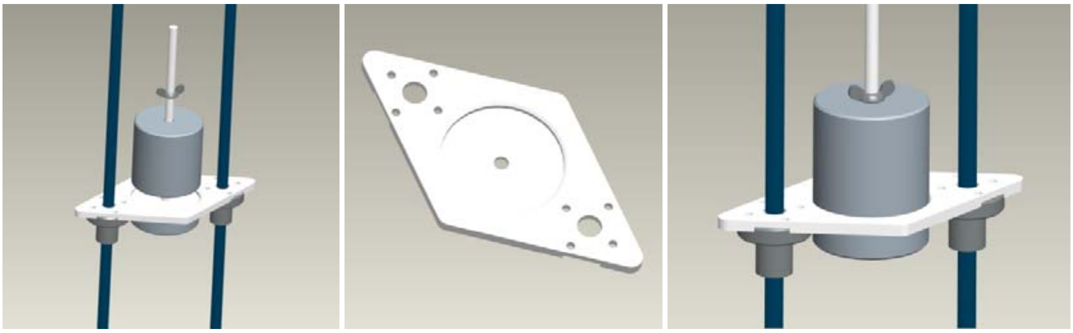


Figure 29: Alternative 1

Illustration 2 Alternative 2

The first option uses two supported shafts and a carriage. The metal plate that holds the weights is attached to the bearings or carriage by screws. A counter-sink in the plate matching the outer diameter of the weight together with a hole for the threaded rod fixates the weight package.

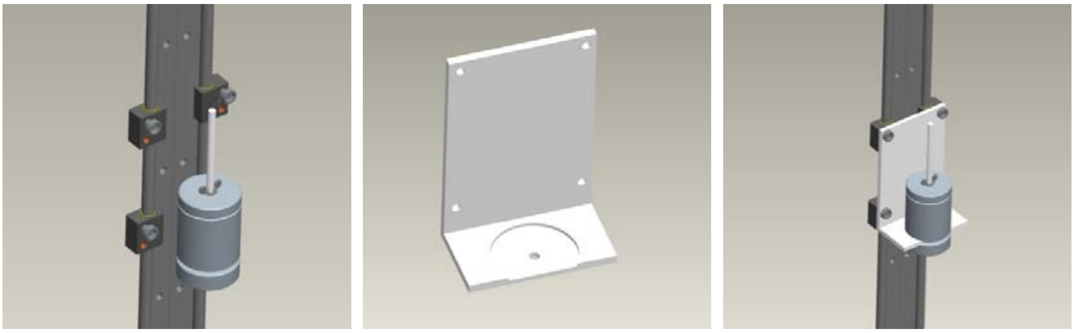


Figure 30: Alternative 2

Illustration 3 Alternative 3

The third option is to use the existing configuration using an extruded aluminum profile.

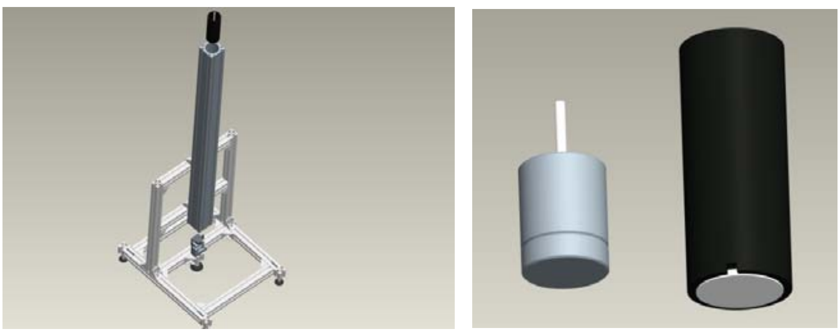


Figure 31: Alternative 3