ABRASIVE WEAR OF LINK CHAINS

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Abstract Link chains are widely used in many different sectors of industry, for example in hoist applications, marine applications, manure chains in agricultural applications, snow chains for cars or even as a bicycle lock. A more specific application is the tickler chain, where the link chain is used to drag over the seabed in order to increase the catch rate. In this case the link chain is subjected to extreme abrasive wear due to the sand and seawater environment. Fracture of these chains causes serious economical damage due to downtime and especially production loss. The main objective of this research is to quantify the most important wear mechanisms that act on a link chain, and with that knowledge to try to design and build a reliable test rig that simulates abrasive wear of tickler chains. With these simulation results the chain parameters, such as geometry and material, can be improved in order to decrease the wear rate.

Keywords link chain, tickler chain, three-body abrasive wear, sand and seawater environment

1 INTRODUCTION

Chains are extensively used in many different sectors of industry. According to their intended use there exist two major chain types. The first type is designed for transferring power in machines, so the links need to mesh with the teeth of the sprockets. A well known example is the roller chain, which is used to drive the wheels in a bicycle. The second major type is designed for lifting, pulling or securing. Such link chains consist of a moving series of interconnected links or shackles, which are often torus-shaped and usually made of metal. These chains are used in bicycle locks, anchor chains, hoists, etc.

It is a well-known problem that link chains are susceptible to wear. Due to the applied normal force and the relative movement between the shackles the chain wears out. This wear leads to thickness reduction of the shackles, resulting in a loss of strength. This can cause chain fracture, to detrimental effect. For example, if the lifting chains of a hoist break dangerous situations could occur. For this reason they should be inspected thoroughly.

In marine industries the wear is not only caused by the relative movement of the shackles. Foreign particles from the general environment, like sand and small fragments of rocks, accelerate the wear mechanism. An example of the extreme wear on marine chains is shown in Figure 1. This chain was employed as a tickler chain in beam trawling, as shown in Figure 2. Several tickler chains and a fishing net are attached to a beam which drags over the seabed pulled by a fishing vessel. The chains plough through the seabed in order to scare the flatfish and drag them into the fishing net. Fracture of these chains causes serious economical damage due to downtime and production loss.

Figure 1: abrasive wear of link chains [1]

Figure 2: small model of a beam equipped with tickler chains [1]

In order to investigate abrasive wear some test rigs have been developed [2-4]. As these test rigs do not include the geometry of the wear contact, a reliable test rig to measure the wear of link chains doesn’t exist yet. Furthermore there are no norms available. The main objective of this master thesis is to quantify the most important wear mechanisms that act on a link chain, and with those results try to design and build a reliable test rig that simulates abrasive wear of tickler chains. With these simulation results the chain parameters, such as geometry and material, can be improved in order to decrease the wear rate.

2 ANALYSIS OF WEAR ON LINK CHAINS

2.1 Chain wear mechanisms

To get a clear view of the different kinds of wear that can occur on a shackle, the most important wear mechanisms are shown in Figure 3. These wear mechanisms that act on the shackles can be divided in one-body, two-body and three-body wear, depending on the number of working bodies in the mechanism [5].

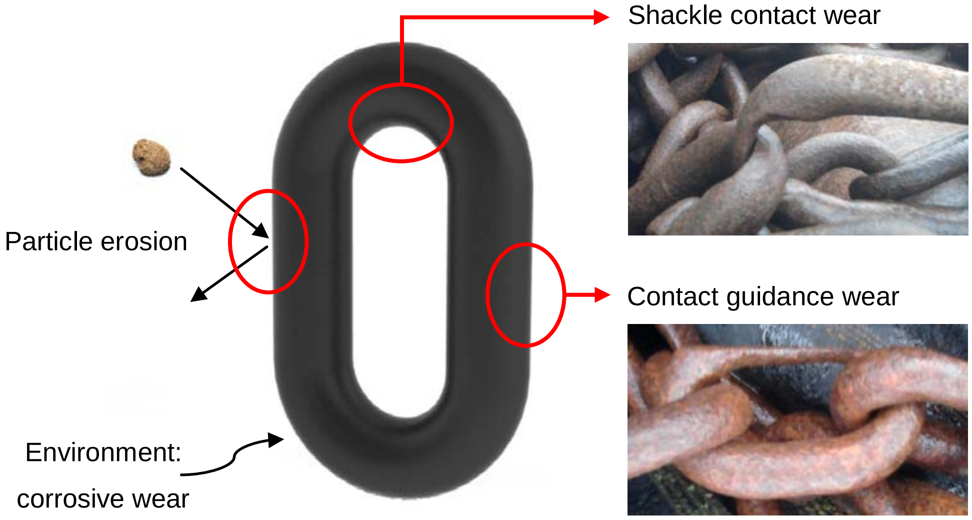

Figure 3: chain wear mechanisms

The most important one-body wear mechanism is particle erosion. In this wear mechanism little particles collide against the shackle itself. Because of the high amount of collisions, wear occurs. This kind of wear depends on several factors, such as the shackle hardness and the impact velocity of the colliding particles. A better known example is sandblasting, which is in fact controlled particle erosion.

For two-body wear there is a difference between abrasive and adhesive wear. Abrasive two-body wear occurs when a hard object ploughs through a softer object, due to an applied normal force and the relative movement of these objects. For chains in the marine industry this wear mechanism occurs as contact guidance wear, when the chains rub over the seabed. Adhesive two-body wear occurs between similar materials when there is a high contact load combined with a small contact surface. Because of the very high contact pressures micro-welding of the roughness peaks is possible. This in combination with the relative movement will cause surface degradation. For link chains this wear mechanism can take place in the shackle contact.

During three-body abrasive wear, a hard particle comes in between two objects. Due to the relative movement of these objects and an applied normal force the hard particle acts as a cutting material. For link chains this wear mechanism occurs in the shackle contact, when sand and fragments of rocks get lodged in between the two shackles. When this foreign particle is harder than the shackles the wear rate increases significantly.

Another wear mechanism that can occur is corrosive wear due to the environment. For marine applications the chains are in seawater, which causes corrosive wear. This corrosive wear in combination with one of the other chain wear mechanisms creates excessive chain wear, which reduces the chain life significantly.

2.2 Environmental influences

Previous work on three-body abrasive wear of ductile metals concluded that the influence of the environment is very important, especially if the wear takes place under wet circumstances [2]. These three-body wear tests were carried out on a commercial lapping and polishing machine with different particle sizes and under wet or dry conditions.

Table 1 shows the difference in wear rate under different test conditions. Examination of the wear surfaces after dry tests suggested that the dominant wear type was three-body abrasive wear. For a particle size of 7µm under wet circumstances the three-body abrasive wear was considerably reduced. In this case the particles are no longer cutting in the surface, but they are rolling due to the hydrodynamic lift of the water. For the same wet test conditions with the larger particles of 60µm, the main observed damage mode was three-body abrasive wear. In this case the water acts as a lubricant, so the abrasive particles can cut very easily in the soft metal. This phenomenon increases the wear rate significantly compared to the dry circumstances. It can be compared with a milling process where some cutting oil is added in order to increase machinability.

Table 1: difference in wear rate under wet and dry three-body conditions [2]

	Dry circumstances	**Wet circumstances Particle size: 7µm**	**Wet circumstances Particle size: 60µm**
Three- body abrasive wear: sliding and cutting of the particles	Dominant wear type	Rolling of particles due to hydrodynamic lift	Dominant wear type
Friction	High	Reduced by water	Reduced by water
Wear rate	Medium	Low	High

Figure 4 shows the difference in wear rate for three-body abrasive wear of mild steel and particles of 60 µm under wet and dry conditions. It has been observed that the wear rate in the wet condition is much higher than in the dry condition for a high specific load. For marine applications the chains are embedded in a sandy environment (particle size +/- 60µm) and surrounded with seawater, so this observed phenomenon could explain why the link chains in the marine industry wear out extremely fast.

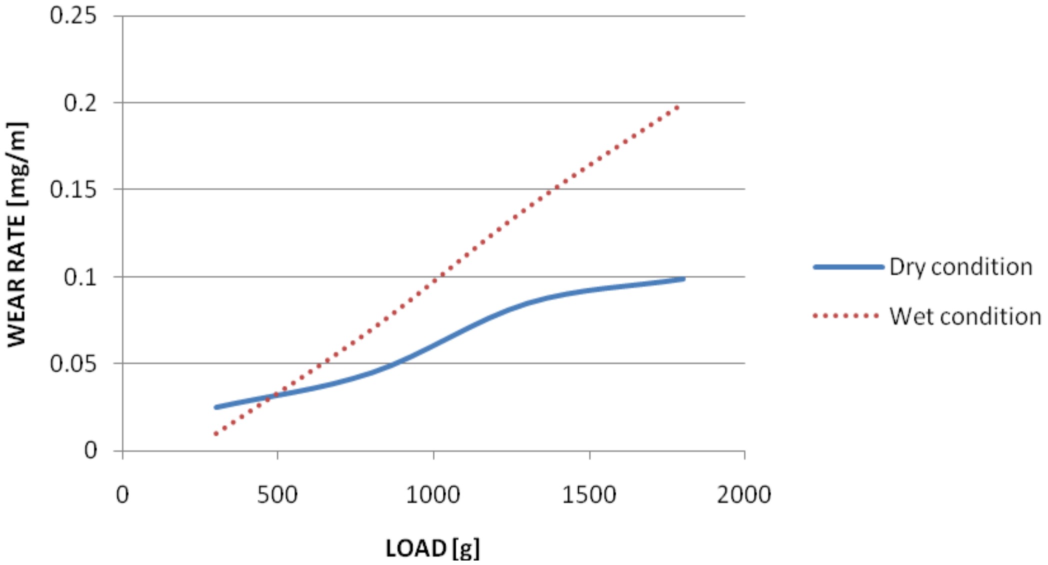

Figure 4: Difference in wear rate of mild steel under wet and dry conditions with particle size 60µm [2]

3 TEST RIG

3.1 Existing wear tests

Figure 5 shows a well known pin on disk test. The pin on disc tester consists of a pin which is pressed against a rotating disc that contains the test material. The pin can be stationary or moved forward and backward, in order to create a spiral path. The normal load, rotational speed, and the wear track diameter can be set by the user in order to examine different test conditions. This standard test can be used to examine the two-body contact guidance wear on the outside of a shackle. The shackle should be mounted on the pin and then be pressed against the rotating disc that contains the sand particles. This would then be an easily set up extended application of the standard pin on disk tester in order to observe the two-body contact guidance wear. When the wear rate of a rougher surface needs to be quantified, for example a seabed full of stones, a variant of the pin on disk tester can be used. This type of tester is shown in Figure 6, where a metal sample is pressed against a rotating container which holds gravel or rocks.

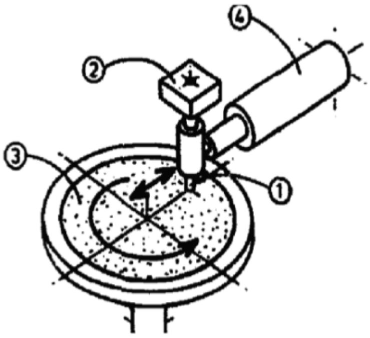

Figure 5: metal pin rubbed along spiral path across silicon carbide paper [4]

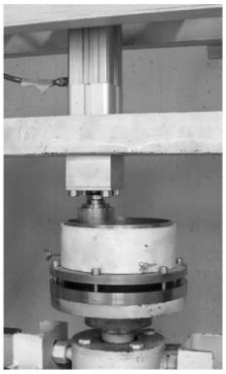

Figure 6: metal pin pressed against different kinds of gravel [3]

In recent years some small scale test rigs were designed at Laboratory Soete [6-9]. Four groups of four students were asked to build a test rig that simulated the wear of a tickler chain. Three test rigs used a closed chain cycle, as shown in Figure 7. In this case the chain is closed and is placed around a set of rotating wheels. One wheel is driven by a motor which lets the chain drag through a container filled with sand. With this type of test both two-body contact guidance and three-body shackle contact wear can be inspected. Another test rig used an open chain cycle, as shown in Figure 8. Three shackles are tensioned by a dead weight and eccentrically connected by a rod to a rotating disk. This ensures that the shackles move continuously up and down into a sand and seawater environment. This type of test rig focuses on three-body shackle contact wear, contact guidance wear cannot be evaluated.

Figure 7: closed chain cycle test rig developed at Laboratory Soete [7]

Figure 8: open chain cycle test rig developed at Laboratory Soete [8]

The main advantages and disadvantages of these two types of test rigs are summarized in Table 2. The main drawback of the closed chain cycle is the non-universality. Each different chain type and/or chain size requires a different set of rotating wheels, driving wheel and a connecting link. These test rigs are also heavily subjected to wear, which is not intended with a test rig. Despite these disadvantages both contact guidance and shackle contact wear can be evaluated in one single test rig, which is a great advantage. The biggest advantage of the open chain cycle test rig is the universality. The setup makes it possible to easily mount a different chain type and/or size. The test rig is also less subjected to wear and quite simple to construct.

Table 2: main advantages and disadvantages of test rigs designed at Laboratory Soete

	Closed chain cycle	**Open chain cycle**
Pro	- Both contact guidance and shackle contact wear	- Universal: easily mount different chain type and/or size - Simple - Test bench less subjected to wear
Contra	- Not universal: different chain types and/or sizes need different rotating wheels - High wear rate of rotating wheels - Connecting link not always available	- Only shackle contact wear - Reality?

3.2 Concepts

An important requirement of the test rig is that different parameters like shackle size, applied force, abrasive medium, etc. can easily be changed. For this reason the closed chain cycle test rig, as mentioned in paragraph 3.1, does not meet the requirements. The open chain cycle is a universal test rig concept, so it is quite obvious that this setup was chosen as a starting point. Because the two-body contact guidance wear can be examined with a simple pin on disk tester, the new test rig needs to focus on the three-body shackle contact wear. With this knowledge several test rig concepts were developed.

3.2.1 Generation of a running wave

The first concept was to generate a running wave in the chain, as shown in Figure 9. A running wave introduces relative movement of the shackles, which causes the three-body shackle contact wear in combination with a sand- and seawater environment. The wave is generated with a common crankshaft mechanism, while the required abrasive medium is transported by a screw of Archimedes.

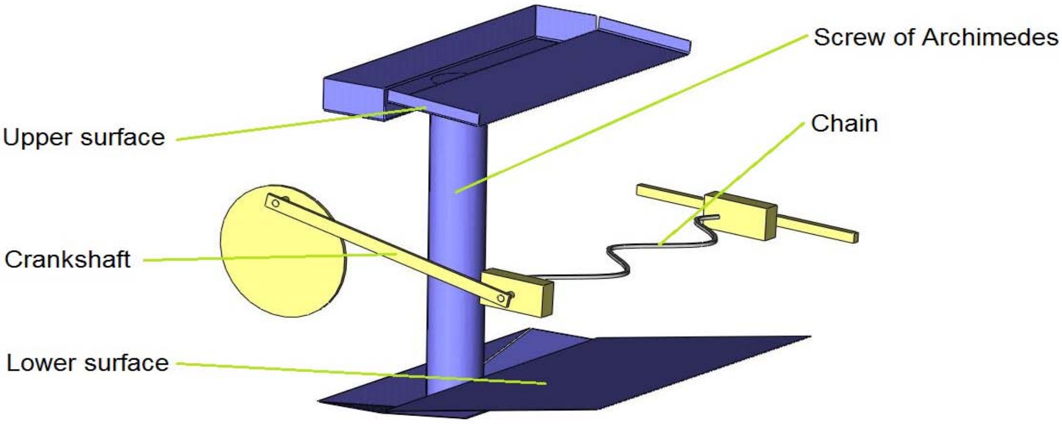

Figure 9: generation of a running wave

A big advantage of this concept is the good shackle movement that is introduced by the wave. Also the contact guidance wear can be inspected when the wave is generated on a plate. The main disadvantage is that the control of the different parameters is very difficult. For example, the applied force in the chain depends on the acceleration of the chain caused by the running wave, which is different for each shackle. Continuous wear measurement is also nearly impossible.

3.2.2 Torsional motion in shackles

Figure 10 shows the second concept which introduces a torsional motion in the chain. Three shackles of a link chain are clamped in between a fixed and a pulling axle. A rotating shaft is connected by two crankshaft mechanisms to these axles, which are pivoting. Because these axles are pivoting in the opposite direction, torsional motion is generated between the clamped shackles.

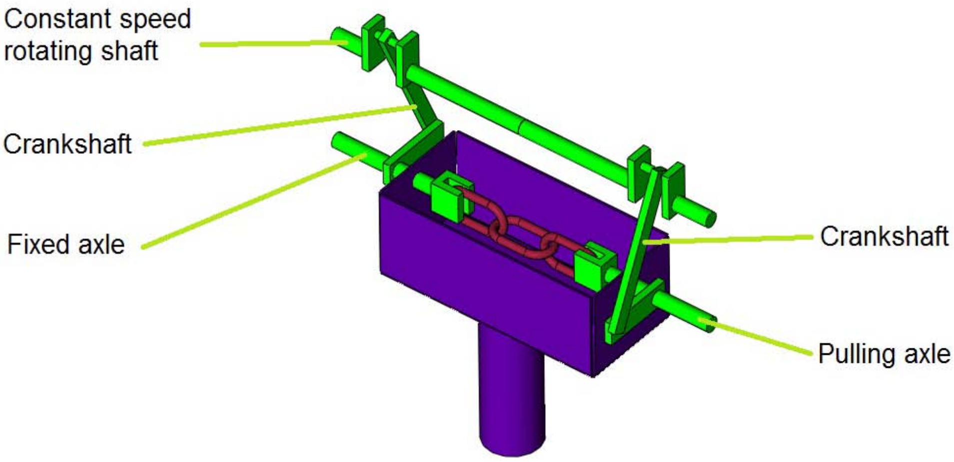

Figure 10: torsion in shackles

The main drawback of this test rig would be the introduced movement of the shackles, which is for small displacements of the crankshaft a pure micro-slip motion. Continuous wear measurement is possible by placing an LVDT on the pulling axle, which will move when the chain wears out.

3.2.3 Focus on shackle contact

The third concept consists of only two shackles that are tensioned by a dead weight, as shown in Figure 11. One shackle is connected to a rotating disk by a ball-joint, while the other one is fixed. This fixed shackle is prevented from rotating, so that it can only move in the direction of the applied force. For this type of test rig there are two possibilities: a vertical or a horizontal setup. In the vertical position (Figure 11, left) both shackles could be immersed in a sand and seawater environment. For the horizontal position (Figure 11, right) an external sand supply must be provided.

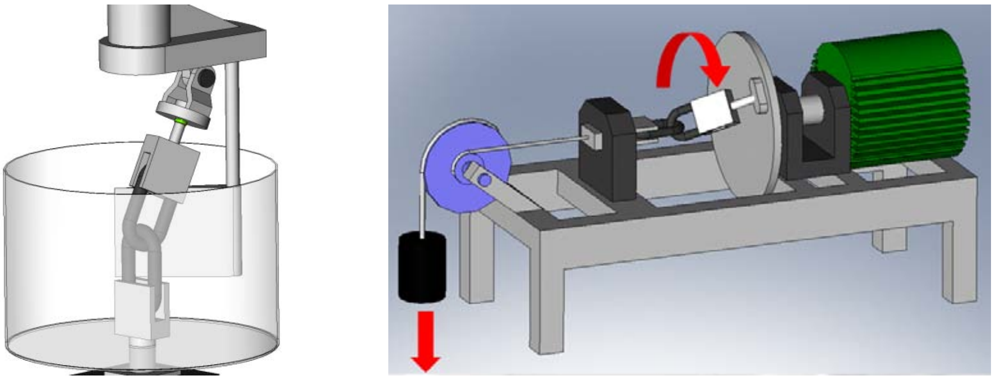

Figure 11: focus on shackle contact wear

The greatest advantage of this test rig concept is the probable high wear rate caused by the introduced rotating shackle motion. In this case continuous wear measurement is possible by placing an LVDT on the fixed shackle, which will pick up the displacement caused by the chain wear. For the vertical setup the abrasive medium can be held in a container. The main drawback of this solution is that the sand and seawater will not be continuously refreshed. In the case of the horizontal setup an external sand supply is necessary.

3.3 Link chain test rig developed at Laboratory Soete

The final test rig that was developed at Laboratory Soete is based on the concept from paragraph 3.2.3. This setup focuses on the three-body shackle contact wear, as the two-body contact guidance wear can be tested on a standard pin on disk tester. A detailed Solidworks-model of the complete test rig is shown in Figure 12. A horizontal setup was chosen (also shown in Figure 11), so an external sand supply is necessary.

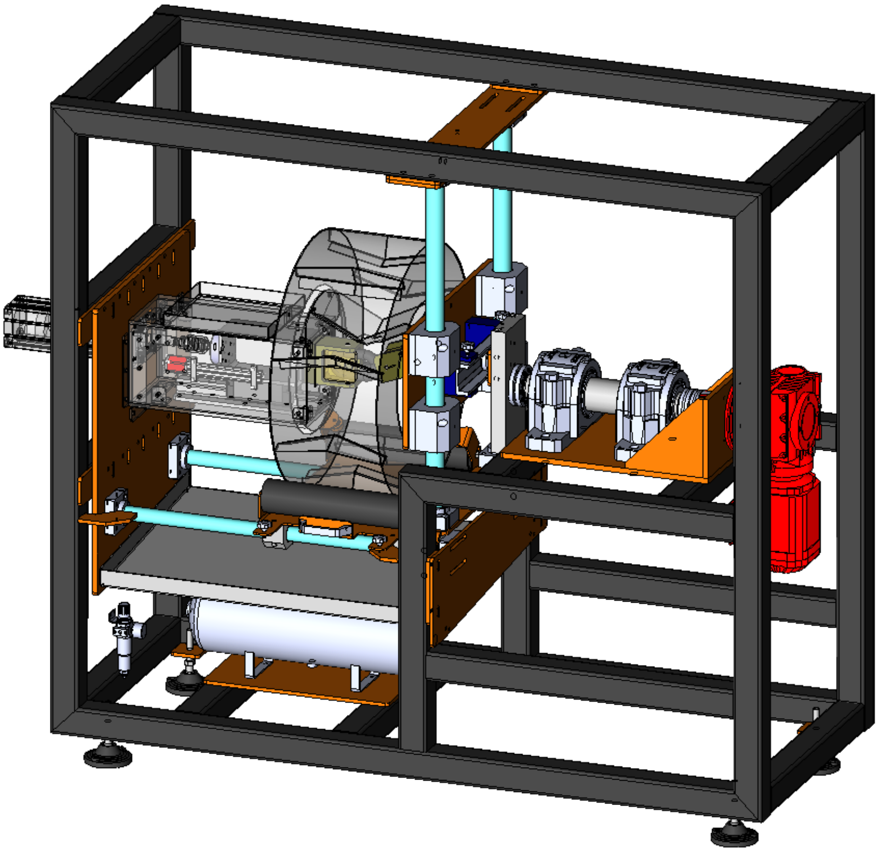

Figure 12: Solidworks-model of the test rig for link chains

The test setup can apply two different shackle motions, so that two different three-body shackle contact wear cases can be investigated. In the first case a circular shackle motion is introduced. One shackle of the link chain is fixed, while the other one makes a circular motion at contact speed. With a little modification a second type of motion, the plane motion, can be executed. In this case the motion-free shackle moves in a plane, so another wear surface is introduced. The additional effect of shackle-to-shackle impact on the three-body wear of the shackles can also be investigated. In this case the force is continuously applied and removed, so the shackles will impact with each other while they are in an abrasive environment. The design specifications of the test rig are summarized in Table 3. In the next paragraphs these different setups will be explained more in detail.

Table 3: design specifications of the test rig

Test rig for link chains: design specifications
Three-body shackle contact wear: - circular motion - plane motion - impact on shackle contact
Shackle sizes: d11-s33, d16-s45, d18-s64, d26-s92 (d=diameter, s=pitch)
Maximum tensioning force: 10kN
Continuous sand and seawater supply
Continuous measurement: - applied force - displacement of the fixed shackle: wear investigation

3.3.1 *Circular motion*

Figure 13 shows a detail of the test rig set up for investigating circular motion. The fixed shackle is placed in a holder which is mounted on a linear guidance rail. This prevents the shackle from rotating, but allows a certain movement in the direction of the applied force. This tensional force is established by a high force pneumatic cylinder, which is connected to the fixed shackle by the linear guidance rail. On this linear guidance rail a load cell and an LVDT are mounted, so both the force and the displacement of the fixed shackle can be continuously measured. On the other side the rotating shackle is placed in a holder, which is eccentrically connected by a thrust bearing to a rotating shaft. This shaft is driven by a worm-wormgear motor reductor.

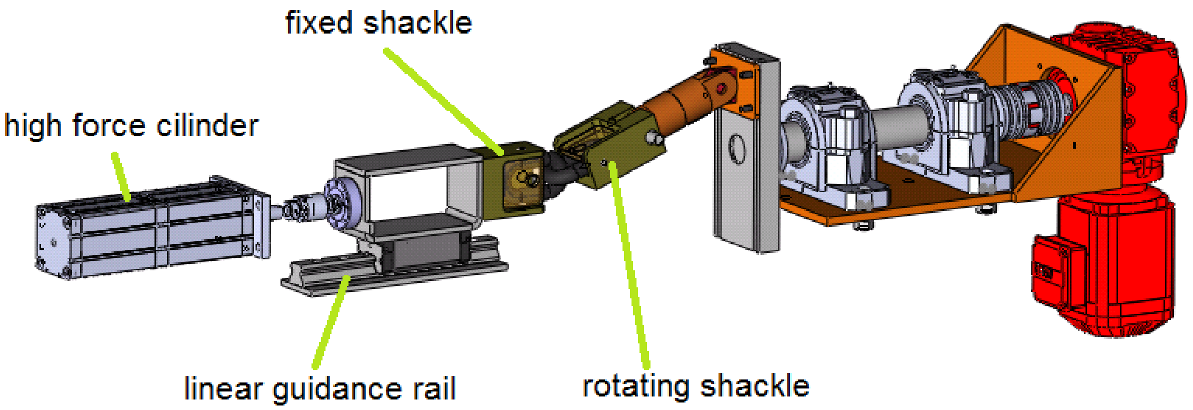

Figure 13: circular motion

3.3.2 *Plane motion*

For the second type of motion, the plane motion, a detail of the test rig is shown in Figure 14. The fixed shackle is connected to the pneumatic cylinder in exactly the same way as in the case of the circular motion. The only difference is the connection of the motion-free shackle to the motor. This shackle is now connected to a plate, which is placed on a linear guidance system. This plate performs a linear back and forth motion by an eccentric mechanism, which is driven by the motor reductor.

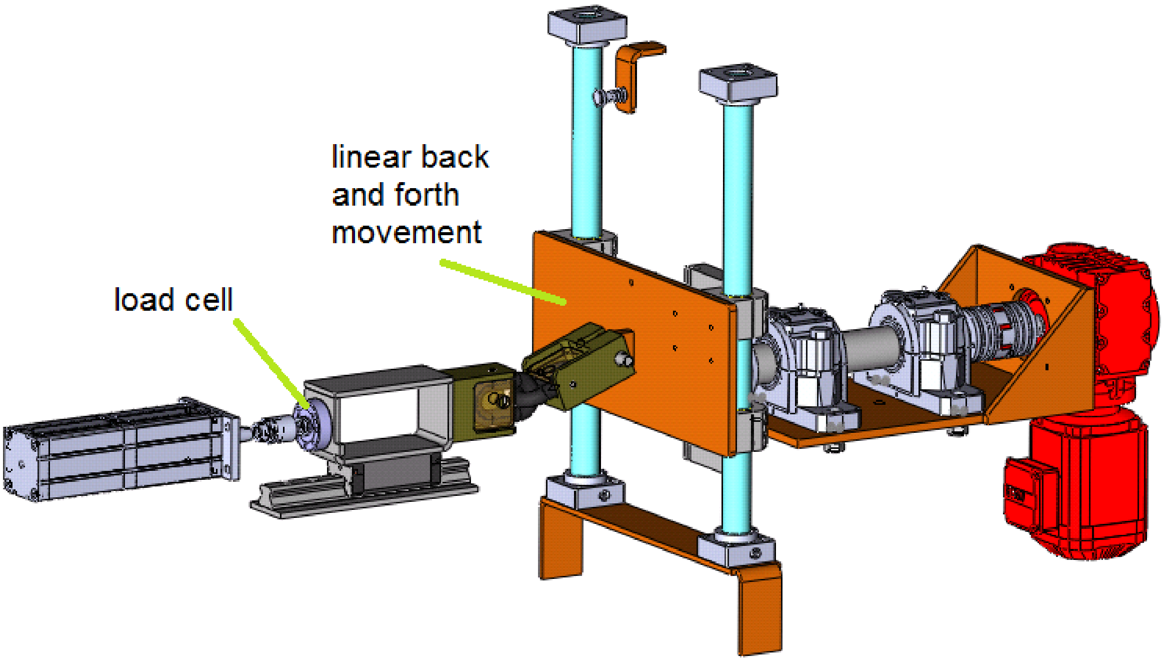

Figure 14: plane movement

3.3.3 Sand supply

As already mentioned in paragraph 3.3, an external sand and seawater supply is necessary to provide an abrasive environment around the mounted shackles. This is provided by a 'sand mill', from which the design is based on a concrete mixer. Figure 15 shows the 'sand mill' more in detail. The mixer, which is placed on a linear guidance system, is driven by a drum motor so it could rotate around its center. After it is filled with sand and seawater a homogeneous mixture is transported to the top, where it falls down into a funnel (not shown in Figure 15). This funnel guides the mixture to the desired location, so a continuous sand and seawater supply around the shackle contact is established.

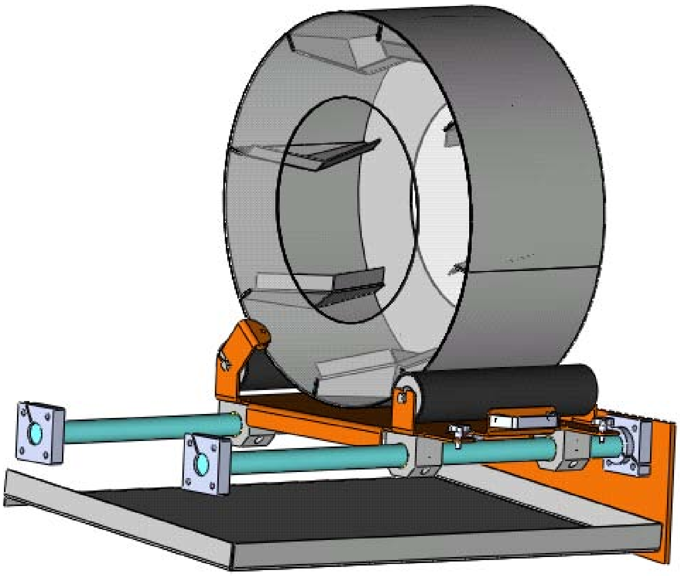

Figure 15: sand supply

4 CONCLUSIONS

The most important link chain wear mechanisms were identified and compared, showing that the two-body contact guidance wear and the three-body shackle contact wear are the most important ones for the link chain. Because the contact guidance wear can be easily investigated with a standard pin on disk tester, the new test rig should focus on the abrasive three-body shackle contact wear. With this knowledge a new test rig has been developed, in order to simulate the wear of a link chain. In the near future the test rig will be constructed so that multiple tests on link chains can be performed. With these simulation results the chain parameters, such as geometry and material, could potentially be improved in order to decrease the wear rate.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

1. Plasschaert, S. and D. Van Steenkiste, *Visit ILVO Oostende.* 2010.
2. Bingley, M.S. and S. Schnee, *A study of the mechanisms of abrasive wear for ductile metals under wet and dry three-body conditions.* Wear, 2005. **258**(1-4): p. 50-61.
3. Terva, J., et al., *Abrasive wear of steel against gravel with different rock-steel combinations.* Wear, 2009. **267**(11): p. 1821-1831.
4. Torrance, A.A. and T.R. Buckley, *A slip-line field model of abrasive wear.* Wear, 1996. **196**(1-2): p. 35-45.
5. van Beek, A., *Advanced Engineering Design*. 2009. 517.
6. Byltiauw, M., et al., *Simulatie Kettingslijtage.* Vakoverschrijdend project 2008-2009.
7. De Witte, T., et al., *Simulatieopstelling voor kettingslijtage.* Vakoverschrijdend project, 2008-2009.
8. Maselyne, J., et al., *Simulatie van slijtage van kettingen in abrasieve omstandigheden.* Vakoverschrijdend project, 2008-2009.
9. Vanhulsel, P., et al., *Simulatie slijtage van kettingen.* Vakoverschrijdend project, 2008-2009.