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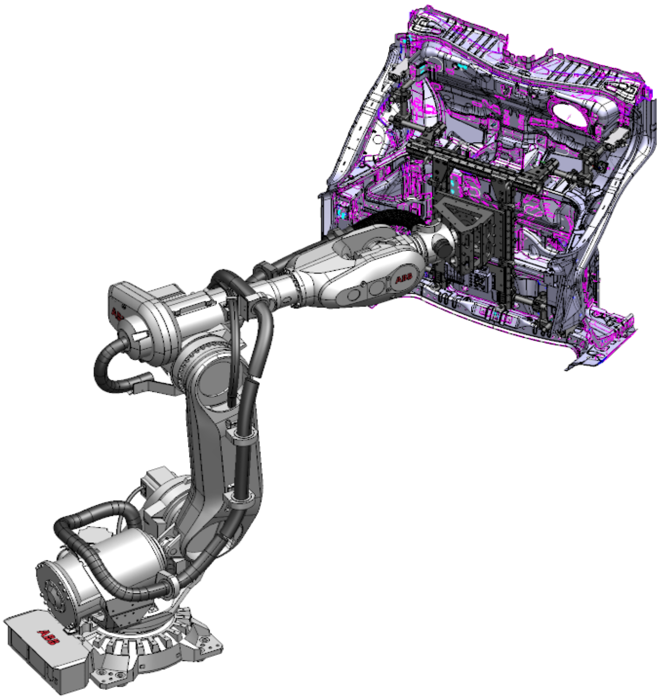

Optimizing robot programs for longer gripper lifetime

Method for acceleration measuring

Bachelor's thesis in Mechanical Engineering

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PREFACE

Following thesis work was done as a part of Mechanical Engineering program at Chalmers University of Technology. The program includes 180hp, out of which 15hp comes from thesis work.
Volvo Cars was the provider of the thesis work, and all the work was done in collaboration with Volvo Cars at the company's facilities in Gothenburg, Sweden.
Thanks to Manufacturing Engineering department at Volvo Cars for giving support during the project. Special thanks to Daniel Thomson, supervisor for this thesis work and Peter Hammersberg, examiner of this thesis work for helping throughout the whole project.

ABSTRACT

Modern production is challenging in many ways. Competition is high and the costs need to be reduced continuously to be competitive. This is often achieved with a production system that runs smoothly and is in balance. However, the unforeseen breakdowns of machines and processes stops the production and impose big costs to the company.

Company Volvo Cars is having issues with robots' gripping mechanisms in welding and assembly processes at their factories. The robots' gripping mechanisms get fatigued and fail, which stops the processes until the grippers are fixed and this is bad for the company's productivity.

This project investigated the possibility of measuring vibrations and accelerations occurring on robot grippers in order to minimize cyclic stress occurring.

The study is limited to one failure mode and is based on the data generated by one robot at one department. It gives enough data to explore and test the fundamental concepts of a method that can be applied and verified on other robots.

Project resulted in a method for measuring accelerations on robot grippers. The method helps to find imbalances in robot movements due to unideal programming of the robot.

Further, lowered cyclic stresses on gripper were achieved using the developed method.

Reduced stresses in grippers prolong gripper lifetime and reduces production stops.

Volvo Cars want to use the method for verifying all new robot programs before putting them into production. The company also considers using the method for doing controls on existing grippers in production to find and eliminate imbalances in robot processes.

SAMMANFATTNING

Modern produktion är utmanande på många sätt. Konkurrensen är hög och kostnaderna behöver minskas kontinuerligt för att vara konkurrenskraftiga. Detta uppnås ofta med ett produktionssystem som går smidigt och är i balans. De oförutsedda haverierna av maskiner och processer stoppar dock produktionen och medför stora kostnader för företaget.
Företaget Volvo Cars har problem med robotars gripmekanismer i svets- och monteringsprocesser på sina fabriker. Robotarnas gripmekanismer blir utmattade och brister, vilket stoppar processerna tills gripdonen är reparerade och det är dåligt för företagets produktivitet.
Detta projekt undersökte möjligheten att mäta vibrationer och accelerationer som uppstår på robotgriprar för att minimera cyklisk stress.
Projektet resulterade i en metod för att mäta accelerationer på robotgripdon. Metoden hjälper till att hitta obalanser i robotrörelser på grund av dålig programmering av roboten.
Vidare uppnåddes sänkta cykliska spänningar på gripdon med den utvecklade metoden.
Minskad spänning i gripdon förlänger griprars livslängd och minskar produktionsstopp.
Volvo Cars vill använda metoden för att verifiera alla nya robotprogram innan de sätts i produktion. Företaget överväger också att använda metoden för att göra kontroller på befintliga gripdon i produktionen för att hitta och eliminera obalanser i robotprocesser.

Table of Contents

INTRODUCTION

In today's car manufacturing, a lot of processes are being automated by usage of robots for doing different tasks in factories. Volvo Cars uses robots in many of its processes. The scope of this project assesses pick and place robots in the car body factory.
The company is having issues with robots gripping mechanisms where fatigue in material is causing the mechanisms to fail. Fatigue in materials is often caused by cyclic loading, eventually causing the mechanism to fail. A gripper is a part of the robot and as such, it is subjected to the accelerations from the robot. We want to lower the accelerations in order to prolong the lifetime of grippers.

In car manufacturing, there is small room for errors. Every breakdown in the production imposes big losses for car manufacturers. That is why preventive maintenance is playing a big role. In car industry, most processes are aligned in a line flow. When one process stops, all processes come to a stop until the issue is fixed. We want to minimize those stops and that is where condition-based maintenance plays a big role. With help of condition-based maintenance we can, based on several parameters predict when or where a breakdown is going to occur. This makes it much easier to do preventive maintenance repairs to equipment and in that way, save time and resources to the company by avoiding failures in machines/equipment. Condition based monitoring means that sensors are mounted on machines/equipment for measuring chosen parameters for the specific machine. Based on feedback from sensors, we can understand the state of a given machine. For example, if a bearing is about to fail, if there isn't enough lubrication in a machine and similar.

Condition monitoring is being widely implemented in Volvo Cars factories in Torslanda, Gothenburg, including Painting facilities and Assembly facilities. However, the condition monitoring hasn't yet been tested on robots and their gripping mechanisms. This is mostly because the method isn't as easy to implement in robot applications because of their movements in different axis. This project is aiming to explore possibilities of implementing condition-based monitoring on robot grippers using acceleration measuring equipment and that way finding imbalances in the system, which can be used to initiate preventive maintenance. The aim is both to initiate direct maintenance but also to build knowledge about grip design itself.

This study focuses on exploring peak-loads of one chosen gripper using acceleration measuring equipment. Also, study focuses on developing a method/routine for measuring of acceleration that can be used on all grippers. The developed method will not focus on maintenance routines, but mainly on peak-load detection and gripper system imbalance.

BACKGROUND

Modern production is challenging in many ways. Competition is high and the costs need to be reduced continuously to be competitive. This is often achieved with a production system that runs smoothly and is in balance. However, the unforeseen breakdowns of machines and processes stops the production and impose big costs to the company.
Therefore, new ways of doing preventive maintenance are needed. It makes maintenance a much less expensive task for the company, and it reduces repair costs, thus increasing overall profit of the production processes.

Company Volvo Cars is having issues with robots' gripping mechanisms in welding and assembly processes at their factories. The robots' gripping mechanisms get fatigued and fail, which stops the processes until the grippers are fixed and this is bad for the company's productivity. Therefore, the company is trying to find a solution that can help prevent stops as a result of fatigue in robot grippers and make a better-balanced robot process.

AIM

Aim of this project is to investigate if it is possible to use acceleration measuring for robot gripper applications. Project is to develop a method that can be used to find and eliminate imbalances in gripper systems on robots. The findings of the project will help reducing production downtimes due to fatigue failures in grippers.

LIMITATIONS

The study is limited to one failure mode and is based on the data generated by one robot at one department. It gives enough data to explore and test the fundamental concepts of a method that can be applied and verified on other robots.
Once verified, the developed method for finding imbalances in and preventing failures in gripper systems will provide new knowledge about cyclical stresses on robot grippers. It can be used to develop maintenance routines in later stages.

SPECIFICATION OF ISSUE UNDER INVESTIGATION

Questions to be answered during the project:

- Can passive vibration/acceleration monitoring be implemented for use on robot grippers?
- In what way are vibration/acceleration patterns correlated with fatigue failures?
- How can vibration/acceleration measurements be evaluated to give meaningful insights in state of the gripper system?
- Can the method be used as a part of maintenance routine work?
- (Optional) Can vibration/acceleration monitoring be used for condition-based maintenance?
- (Optional) Is it possible to send vibration/acceleration data directly to the cloud storage for live parameter monitoring?

2. THEORY

In this chapter, the theory needed for accomplishing project work is presented.

Since the vibration measuring is relatively new and hasn't been applied to robot grippers as much as with other types of equipment, there isn't much information about it. Therefore, an external search was done on different types of vibration measuring and condition-based maintenance.

2.1 VIBRATION MEASURING IN PRODUCTION

Using vibration measuring effectively means that we must know the vibrational behavior of a machine in its perfect condition, its basic vibration signature or fingerprint as well as knowing how vibrational behavior changes with a crack growth of a damaged (cracked) machine. When these parameters are known, then the vibration measuring can be used to see when the behavior of the machine is about to reach critical vibrations associated with a damaged machine. The vibration curves can be found out experimentally by taking measurements of a new component as well as of a damaged/worn one. Those can be used as references.
Every machine has its own characteristic vibrational behavior produced by different components in the machine e.g., bearings, pistons etc. All these components have specific vibrational signatures that are reflected on the machine's structure. Increased wear or imbalance within a machine will change the vibrational output [1].

2.2 VIBRATION MEASURING IN BEARINGS AND SHAFTS

Amplitude of the radial vibrations within a rotating shaft can be direct indicators of the overall mechanical condition of rotating machines. With vibration measuring on such machines, many malfunctions can be detected, such as rotor misalignment, unbalance, worn bearings and so on, using data analysis and signal processing. It is relatively easy to detect changes in vibrational output of a system and thus find imbalances in a system.
Such measuring of vibration indicates the health of a system and can show when the excessive wear or fatigue of a component is occurring [2].

2.3 ABOUT ROBOTIC GRIPPERS

When handling components, robots use gripping mechanisms, shortly called grippers. Robotic grippers sit at the end of a robot arm, and it is the gripper that robot handles components with. There are many different variants of robotic grippers. This project focuses on modular grippers from manufacturer Springer. Modular grippers are made to be easily adjustable to changing requirements and geometries. All gripping mechanisms use pipes with different cross-sections depending on the payload of the robot and weight of the processed component. The use of standard pipes, see Figure 1, reduces the amount of mounting and adjusting as all grippers use similar profiles and fastening methods [3]. This means that all robots in production can use same gripper supplier and be tailored to work with a given process and component.

The gripping mechanism investigated during the project is pneumatically driven and several sensors are attached to the gripper for right positioning. In this application the robot picks the whole underbody of the chassis and places it in different positions for spot-welding depending on car model that is being processed. After the welding, the part is placed on a material rack for processing in next cell.

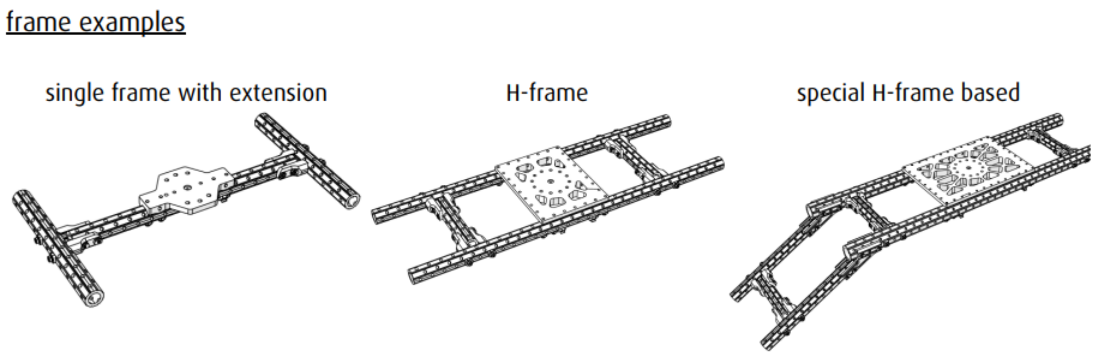


Figure 1: Examples of different frames that can be used when designing a gripper

2.4 VIBRATION/ACCELERATION MEASURING IN ROBOT GRIPPERS

Although vibration measuring has a relatively long history of use in industry, there haven't been studies about using vibration measurements on robotic grippers. Measuring vibrations in grippers isn't as easy as measuring vibrations on a simple machine. Robots move their grippers in several axles, they rotate, and they follow a programmed path for millions of cycles. All these factors make it hard to evaluate vibration data and to bring some meaning to the data that is extracted. In conventional machines we will get vibration changes when a bearing is worn out or a shaft is out of balance. With robotic grippers, the change in vibrational behavior can depend on many different factors, such as badly programmed paths and speeds in robot program, misalignment of gripper, badly constructed grippers and so on. A better way of checking the state of gripper and robot system is by using accelerometer, a sensor that measures acceleration of machines. The named equipment will be used in this study.
When studying accelerations that a gripper is subjected to, measuring results will be compared to dimensioning requirements to see if a robot is working within the given standards.

2.5 CYCLICAL STRESS AND FATIGUE

Fatigue in a material is occurring due to cyclical stress variations within a material. All materials have their fatigue lifespan, and the higher the stress amplitudes are the shorter the lifespan of a material will be before it experiences fatigue crack growth and catastrophic failure. Some materials like low alloy steels and carbon steels have a fatigue limit, below which the material will unlikely fail by fatigue, regardless of number of cycles [4]. Grippers that are investigated in this project are made of aluminum, which is a material that will eventually experience fatigue even at lower levels of cyclic stress.
To make a material last longer within a mechanism, it is desirable to make stress variations (amplitudes) as small as possible. This can be done by planning for cyclical loads in initial design reducing the risk of stress concentrations due to geometry variations (that is small radius in heavy loaded parts) or changing the state of the surface by grinding or hardening.

3. METHODOLOGY

In this chapter the methods for accomplishing the project goal are brought up and evaluated.

3.1 COLLECTING OF HISTORICAL DATA

First part of project was to find out if there is any data available on gripper failures occurring in the past. Investigation in this part showed that there isn't enough data to gather from past gripper failures for further investigation. Not finding any data meant that data collection needed to be done during the project. Data collection was done by mounting a vibration sensor to the gripping mechanism of a chosen robot. The robot is always doing the same cycle which means that only a few measurements are needed to get an insight in overall performance of the gripper. Thus, a sample of approximately 20 measurements were done on the gripper, giving similar vibration values throughout the measuring samples.

3.2 DECIDING OF A SUITABLE GRIPPER FOR MEASURING

Deciding what gripper to do acceleration measuring on was an important part of the project. The chosen gripper needed to be big enough to have room for the acceleration sensor, the process needed to have records of failing in the past and be accessible for filming. Decision was made by interviewing people that work with grippers (designing or repairing grippers). Gripper that was most suitable for this project showed to be the TA-136050RGP09 robot gripper. It is a gripper that handles whole underbody of a car chassis and takes it through various points for welding. It starts the cycle by taking the chassis from a fixture there the part already has been processed by other robots. The chassis is then taken through various stationary welding stations for further processing and finally, the chassis is deposited on a fixture for further transportation of the part.
Figure 2 shows TA-136050RGP09 gripper attached to a robot and holding underbody of a car. Gripper is holding the part with 4 clamps in each corner of the part.
Figure 3 gives a close up view of the same gripper.

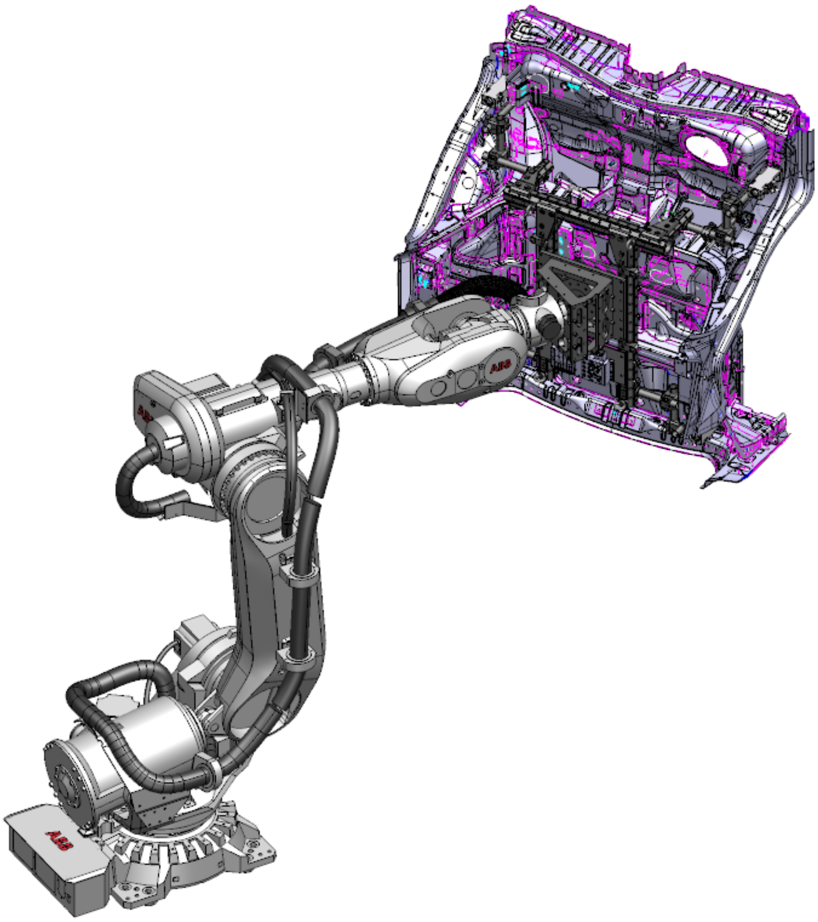


Figure 2:Robot with TA-136050RGP09 gripper and chassis attached

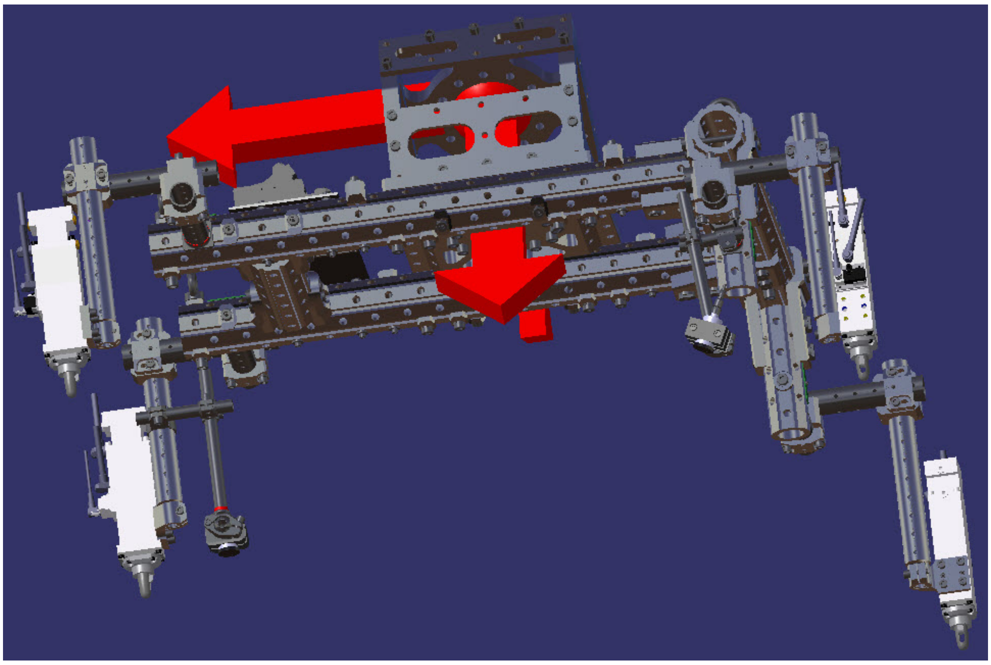


Figure 3: Close-up picture of TA-136050RGP09 gripper CAD model

3.3 MEASURING SOFTWARE

Today there are many different options to choose from when doing vibration measuring in production. Big part of those sensors is built for measuring vibrations in simple, common machines in production such as motors or transmissions for production line drive.
There aren't many options of sensors dedicated to use on grippers. The sensor that company decided to use for this project was the TREC 16-G acceleration sensor provided by gripper manufacturer TÜNKERS. This sensor measures acceleration of the gripper and stores data on an SD-card. Sensor is mounted directly on the gripper and is battery powered. Measuring data is sent to computer device via Wi-Fi.
The unit is mounted directly on a gripper in production area and measures acceleration in X-, Y- and Z- axles, directions shown on the sensor housing.

Figure 4: TREC 16-G measuring equipment

3.4 INSTALLATION ON GRIPPER

The sensor is mounted at a defined position on gripper. Defining the position is done according to the gripper's path in the cell. The sensor needs to be mounted so it doesn't collide with other objects in the robot cell.
Testing the position of the sensor by manually operating the robot to target points and checking that the sensor doesn't collide with other objects in the path is done to ensure safe positioning of the sensor.
Bottom side of the sensor needs to be firmly attached to gripper, so no movement occurs between the gripper and the sensor, otherwise wrong measurements will occur.
Noting the X-, Y- and Z- axis is done when mounting the sensor on gripper. This way the measurement results can be taken in relationship to the gripper movement.

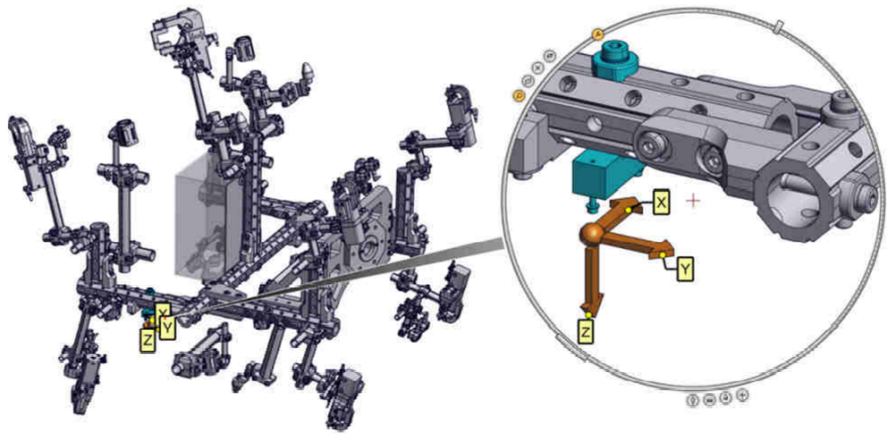


Figure 5: Mounting the sensor on gripper

3.5 ANALYSIS PROCEDURE / CONNECTING AND SETTING UP MEASURING SOFTWARE

The sensor has an indicating light on the top side. When pressed one time, the light will turn green, meaning that the sensor is on. Now the sensor Wi-Fi is on, and we can connect to it from a laptop or mobile phone. Wi-Fi name, password and IP-address can be found on the topside of sensor.
When connected to the sensor's Wi-Fi, we need to start the program "TREC-16G Launcher" provided on the USB-dongle found in the sensor package. Press connect and the sensor should be connected to the software showing the measuring screen. Now the indicating light should change color to blue, meaning that the sensor is ready for measuring.
Start the measuring by clicking on "Start" in the program and stop it by clicking on "Stop". The device sends measurement data via Wi-Fi, which means that the computer that is connected to the device needs to be close by, otherwise the connection will be lost.

Start the measuring at the start of a robot cycle and stop it in the end of a cycle. That way the comparisons can be done on few different measurements. A video can also be recorded with help of an event camera so that the values in the measurements can be assigned to movements on video.
When the measuring is done, data can be downloaded by going into "Measurements" tab in the program, choosing a wanted measurement and download it. Measurement data can be opened and analyzed in the "TREC-16G Viewer" program. The viewer shows a graph with accelerations in X-, Y- and Z- axis as well as a vector of the three accelerations based on a time axis.
It is also possible to evaluate few different measuring results in same graph. Preview of the measuring data can be seen in Figure 6 below.

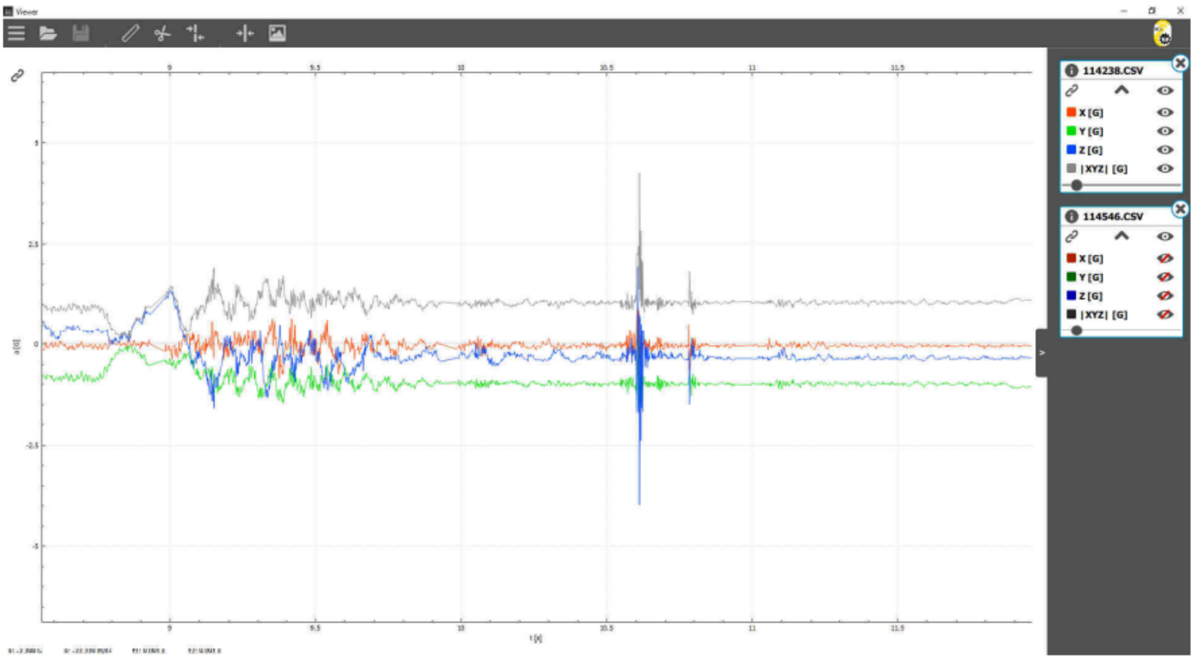
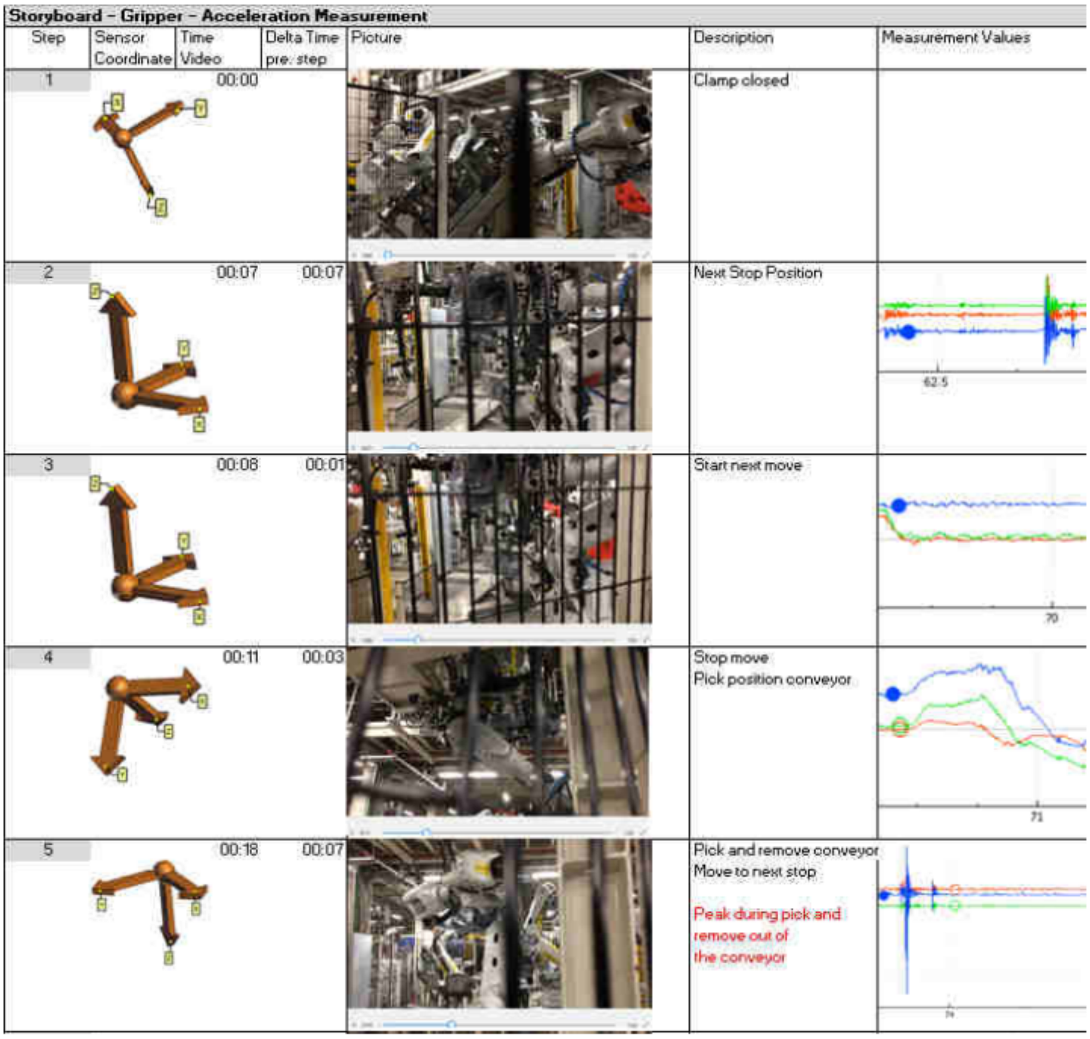


Figure 6: TREC 16-G Viewer software showing acceleration curves in X, Y and Z axis

3.6 EVALUATING MEASUREMENT DATA

When evaluating measurement data, following method can be used.
Comparing measurement data from the viewer software with a video timeline. This is the best way to see what has happened to the gripper at a point that got an abnormal peak in the measurement.
In the example below we can see unusually high peak in the measured acceleration, and it can be located with help of the timestamp on the video to see what has caused the peak. This makes for an easy locating of the stress in grippers.


Storyboard – Gripper – Acceleration Measurement

Step	Sensor Coordinate	Time Video	Delta Time pre. step	Picture	Description	Measurement Values
1		00:00			Clamp closed	
2		00:07	00:07		Next Stop Position	
3		00:08	00:01		Start next move	
4		00:11	00:03		Stop move Pick position conveyor	
5		00:18	00:07		Pick and remove conveyor Move to next stop Peak during pick and remove out of the conveyor	

Figure 7: Synchronizing video and measurement timestamps

After the stress has been located to a certain movement, it needs to be investigated and a solution is to be found. Possible solutions can be to change movement speed in the critical spots, changing worn out equipment with new parts, recalibrate the gripper positioning.
A new measurement is to be taken after every change of the gripper to document what impact different changes make on vibration and acceleration output.

3.7 REDUCING ACCELERATIONS/VIBRATIONS IN THE GRIPPER

At this stage, the accelerations of the gripper are known and can be assessed.
A systematical way to do this is to compare video timestamp to the acceleration curve timestamp. A way of doing this comparison can be seen in Figure 7 and Figure 8.

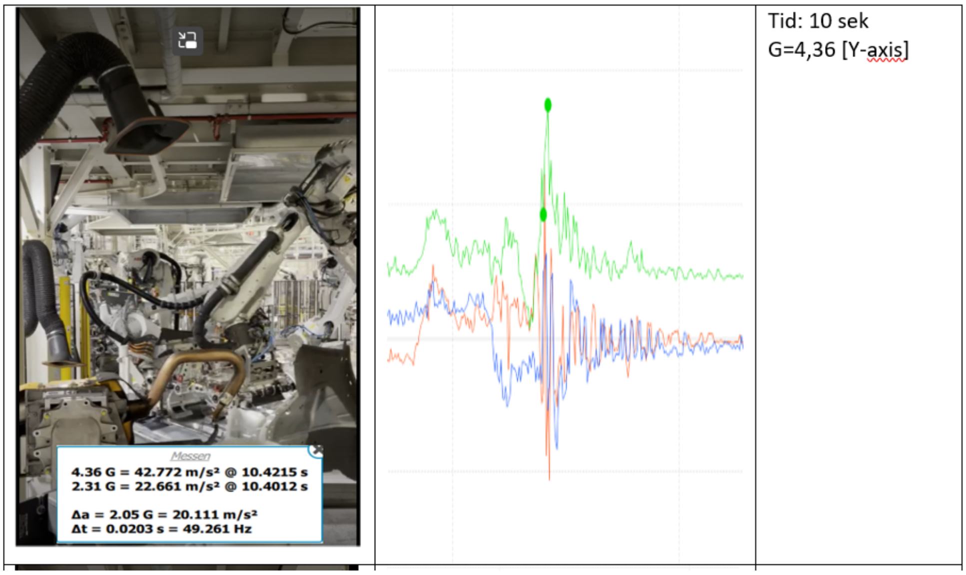


Figure 8: Robot position and acceleration curve at 10 seconds cycle duration

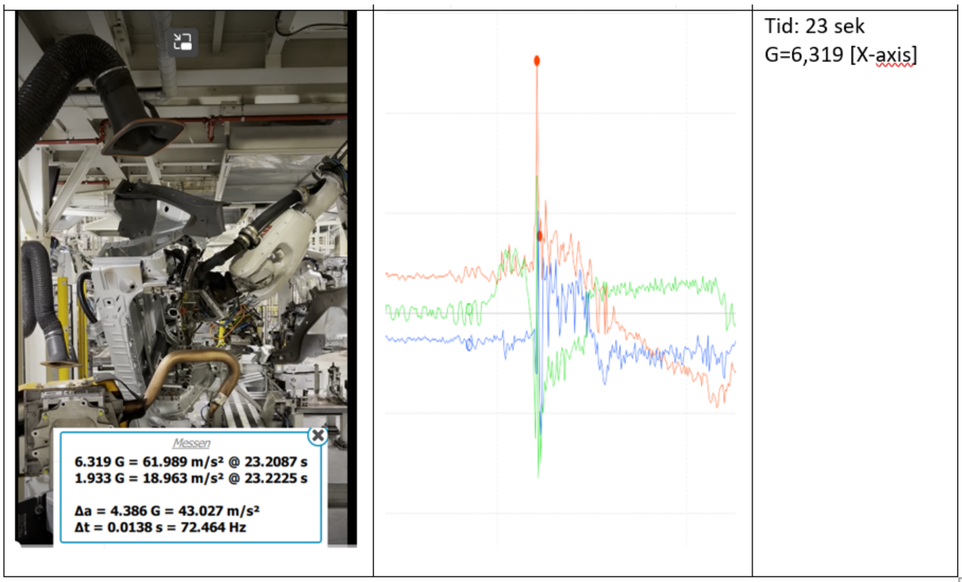


Figure 9: Robot position and acceleration curve at 23 seconds cycle duration

Dimensioning requirements of grippers at Volvo Cars state that the gripper must withstand accelerations of 3G above the axis or totally 3G amplitude change across different sides of an axis. When looking at vibration measuring data, at timestamps of 10 respectively 23 seconds in the cycle time, peaks bigger than 3G occur. Investigation of these points is necessary.

3.8 INVESTIGATION OF PEAKS AND TAKING MEASURES

As the vibration data indicates, peaks of too big amplitudes are occurring at timestamps of 10 and 23 seconds. When investigating those points in the robot cycle, both peaks occur when robot arrives at a given position and makes a sudden stop.
Looking into robot code reveals that the movement speed is set to 1500mm/s and there is no buffer for slowing the robot down before it makes complete stop. First measure was to change speeds of approaching these points.
Movement speed towards first stopping point at 10 seconds was brought down to 500mm/s and the second stopping point at 23 seconds was also slowed down to 500mm/s.
Taking these measures made a big improvement in vibration data of this gripper.

4 RESULTS AND FINDINGS

In this chapter, most important findings and results of the project are presented.

4.1 REDUCING VIBRATIONS IN THE GRIPPER

By taking measures that were presented in *Chapter 3.8*, accelerations could be brought down to a level that is significantly lower and thus much better for the health of gripper. Bringing down the movement speeds and making the robot movements smoother meant that acceleration and vibration curve of the process also became much smoother. At the timestamp of 10 seconds, vibrations were brought down from 4,36G to 2,673G which lowered the stresses to the acceptable levels as stated in dimensioning requirements. At timestamp of 23 seconds, vibrations were lowered from 6,319G to 1,721G which is an even better improvement compared to the first point.
After taking these measures, the gripper accelerations and vibrations are now within acceptable guidelines and the process is smoother which will result in gripper construction lasting longer.

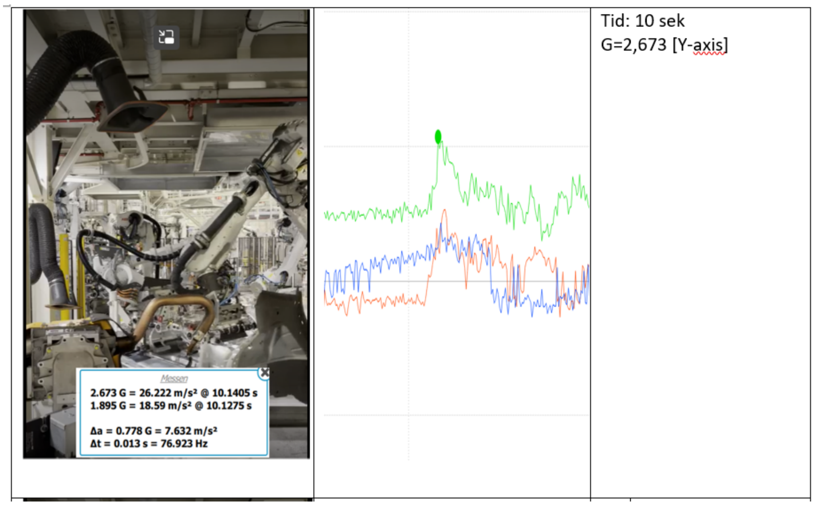


Figure 10: Acceleration lowered from 4,36G in this spot to 2,673G due to smoother movements of the robot.

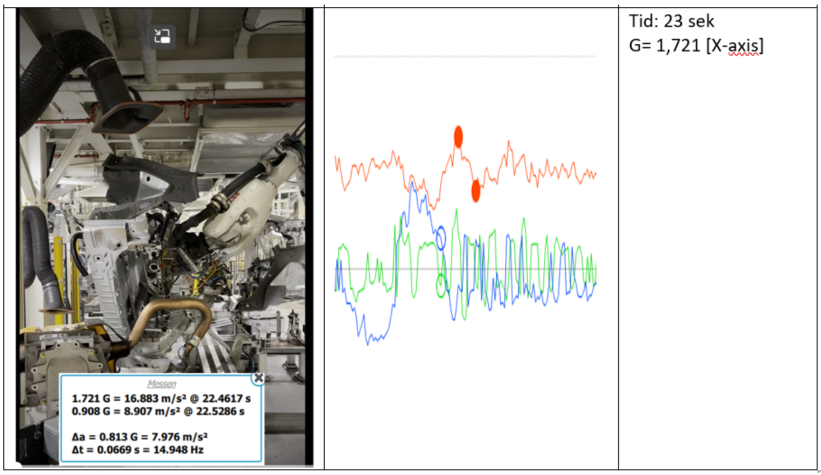


Figure 11:Acceleration lowered from 6,319G to 1,721G by making the robot movement smoother in this point.

4.2 USING OF VIBRATION AND ACCELERATION MEASURING

An important part of this project was to find out if the vibration and acceleration measuring can be used in robotic grippers and to present a method for doing it.
Usage of vibration and acceleration measuring on robotic grippers is possible using the method presented in this project. Presented method can't be used for continuous vibration monitoring because this sensor sends data via Wi-Fi and requires that a person is standing nearby and collecting data.
A permanent way of doing vibration measuring continuously is by using sensors that are mounted on the gripper and use gripper's power supply, storing the data on a server.
That way wanted parameters can be set, and we can get alarms when the vibration/acceleration values exceed a certain value.

4.3 IMPROVING LIFETIME OF THE GRIPPER

As explained in *Chapter 2.5*, vibration causes fatigue failures in materials. By lowering the vibrations or accelerations that a mechanism experiences during its operating, the lifetime will be improved. Lowered vibrations and accelerations mean that the process becomes much smoother and that also gives smaller wear of supporting parts of mechanism such as clamps found on grippers.
Energy usage lowers by eliminating the extreme accelerations and decelerations that robot used to make. This may not sound important as it gives a small percentage of decrease in energy usage, but it adds up over hundreds of robots and gives a good overall improvement.

5. DISCUSSION

Chapter 5 discusses and evaluates results presented in Chapter 4 Results based on the posted research questions.

5.1 EVALUATION OF DEVELOPED METHOD

The method that was developed for vibration and acceleration measuring on grippers followed all the guidelines of the project and was presented in previous chapters. An instruction was made for use at Volvo Cars there every step was thoroughly presented and can be followed easily.

Method is made easy to use on different robotic grippers without major modifications.

The developed method is mainly for verification use and isn't suitable for constant monitoring of gripper's vibration state. Verification means that when a new gripper is installed or when a change is made in the process, this method can be used to verify that the process has been tuned according to the company specifications.

Volvo Cars see potential in this method and the company wants to use it for verifying all new gripper installations. This way it can be made sure that every robot process is developed according to requirements for gripper accelerations.

5.2 IDENTIFIED UNCERTAINTIES WITH DEVELOPED METHOD

Following uncertainties could be identified with the developed method:

- **Availability of the equipment:** There can be difficulties when trying to implement this method on a larger scale. Measuring equipment that has been used in this project isn't highly available on the market. The manufacturer hasn't produced a large amount of these measuring devices as there wasn't a simple way for implementing the measurement device at customer companies.
- **Price:** The price for doing this type of measuring is unknown. It will probably be done by the employees at the company but indirect costs of doing measurements using this method haven't been evaluated. Indirect costs can be stopping robot cycles in order to install measuring equipment, costs for destroying the equipment in case of faulty installation on the gripper and similar.
- **Safety:** Installing equipment on grippers can be a dangerous process if the safety instructions of the factory aren't followed when entering a robot cage. Safety instructions must therefore always be followed when entering robot cages for installing equipment to avoid injuries.

5.3 SUGGESTIONS FOR FUTURE WORK

This section aims at giving Volvo Cars suggestions for future work and how they can move on with vibration measuring on robotic grippers.

As said earlier, the developed method focused mostly on identifying vibration peaks in grippers and could only be used for controlling the state of gripper at the time of measurement.

One area that can be developed further is testing another equipment that will sit on grippers permanently and send data to a PLC or a computer. This makes it easier to constantly monitor the vibrations with a possibility to create alarms when a certain value is exceeded. Equipment that can be used for this kind of monitoring are vibration sensors from a company like ifm. Further, sending and storing vibration data on a cloud server could be of interest for the company. This can be done if the sensors are connected to an interface that sends data to a dedicated cloud server. This makes the data accessible from all around the world, with Internet connection. It also makes for easier monitoring of breakdowns as data will be stored in the cloud and wanted vibration values at a certain point in time can then be found and investigated.

When doing this type of work in the future, it would be good to make cost estimation of the project in the beginning. Sometimes, the project isn't worth doing for the company if the cost of implementing a solution is too high compared to the benefits that the solution offers.

6. CONCLUSIONS

Chapter 6 presents conclusions of this study on applying vibration measuring on robotic grippers.

The aim of this study was to perform an analysis of whether it is possible to apply vibration measuring as a method for finding irregularities in a robot process in factory and with help of this method, eliminate irregularities and make lifetime of grippers longer.
With the presented method in *Chapter 3 Methodology,* Volvo Cars has been presented a solution for using vibration measuring on robotic grippers. From this method, the company can gain experience and further develop the method to fit company's needs closer and can also investigate similar methods for applying vibration measuring in their work.

Answering the research questions:

Can acceleration measuring be used on robotic grippers?

Method presented in *Chapter 3 Methodology* can be used for acceleration measuring on grippers. The insights about the whole process can be gathered from using the method and the process can be evaluated and modified according to data that acceleration measuring provides. Results of using this method is shown in *Chapter 4 Results* and presents benefits of using the method. Much lower levels of stresses were achieved, and those changes increase the lifetime of the gripper.

How can acceleration measurements be evaluated to give meaningful insights in state of the gripper system?

Method for evaluation of data was presented in *Chapter 3 Methodology.* By using this method, the acceleration peaks (critical points) can be found and evaluated. The method was developed to be simple and easy to use for all employees at the department.

Can the method be used as a part of maintenance routine work?

Yes, it can be used as a part of maintenance routine work. The presented method uses a battery powered device that sends data via Wi-Fi, which means that the installation of this device is very simple, and the location of device can be changed to different grippers very quickly. This makes for simple assessment of vibrations on different grippers that maintenance personal can use in their everyday work as a check.

In what way are acceleration patterns correlated with fatigue failures?

A higher acceleration will give greater cyclical loads within a material. Change in directions (acceleration and deceleration) means that the material will experience high load and bending. Higher cyclical loads lead to shorter time to failure, and if the cyclical loads can be lowered than the material can withstand higher number of cycles before it experiences fatigue.

REFERENCES

[1] Südmersen, U.: Vibration Monitoring for Process Control and Optimization in Production Lines, FORTEC- Forschungstechnik GmbH, Germany, 2006

[2] Website: Shaft and bearing monitoring, mc-monitoring, https://mc-monitoring.com/products-service/products-service-monitoring-solutions-2/shaft-bearing-vibration-monitoring/

[3] Website: Handling systems for the body shop automation, Springer GmbH, https://www.springer.group/en/products/gripping-systems/handling-systems-for-body-construction/

[4] Website: Overview of vibration-induced fatigue, Inspectioneering.com, Vibration Fatigue | Inspectioneering | Inspectioneering

[5] Website: Vibration Technical Guide, IMV Japan, All about Vibration Measuring Systems - IMV CORPORATION

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