Sensor-monitored wear of the mechanically stressed screw in a screw compactor

A. Podolka, A. Knoblauch, V. Fiala

Department of Materials and Production, Aalborg University
Fibigerstraede 16, DK-9220 Aalborg East, Denmark
Email: {vfiala22; aknobl22; apodol22}@student.aau.dk,
Web page: http://www.mechman.mp.aau.dk/

Abstract
The article deals with the sensor-monitored wear of the screw in a screw compactor from the company RUNI A/S. In order to realise this project, a concept was developed that reflects the measurement of the screw in new and worn condition. The concept is based on the inductance of the screw at different material thicknesses.
In the first part of the report, the possibilities offered to RUNI by such monitoring are described and the functionalities of the sensors used are explained. Also the choice of sensors is discussed.
The second part describes the practical implementation of the sensors on a test bench and discusses the measured results. Finally, a look into the future and a conclusion from the tests are given.

Keywords: Sensors, Inductive, Capacitve, preventive maintenance, PLC,

1. General Introduction

The submitted article will be used as a part of the student symposium MechMan.
RUNI A/S is a Danish company specializing equipment for processing and handling waste.
From 1996 RUNIs main product is the screw compactor (**Fig. 1**) which they called "omnivorous" since they supplied more than 2000 screw compactors worldwide for various purposes. Because of their history the compactors are robust, solid machines build out of thick steel plates. [1]

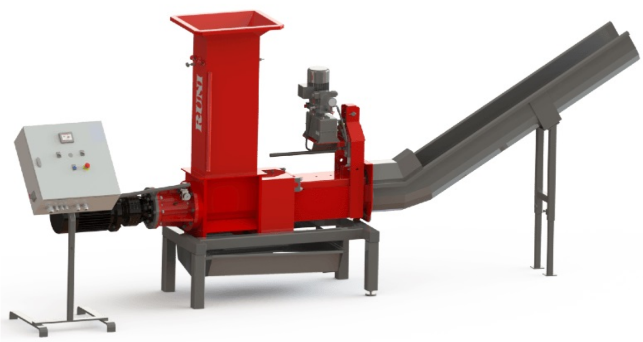

Fig. 1 RUNI screw compactor SK240 [2]

The problem that RUNI is facing with its compacting machines and their design is that the screw is getting worn out after an unknown amount of time of the machine operation. Since the customers who are using these machines from RUNI are compacting various materials (plastic bottles, beer or soda cans, polystyrene, ...) the speed at which the screw is wearing out differs depending on the customer and the size of the machine and subsequently the size of the screw they are using.
Every screw has a given wear tolerance to determine if the screw can be repaired. If the screw is worn out beyond a given tolerance it cannot be repaired and it has to be replaced by a new one, which is a costly option compared to the repair.

1.1 Usecases for compactors

The solutions and usecases for the screw compactors from RUNI are very different. The first compactors they build was for EPS (Expanded PolyStyrene). It was specifically build to compact fish boxes from the fishing industry. The main focus of RUNI is still in compacting plastics and especially Polystyrene but they also provide customers with solutions to compact other materials like metals. RUNI can provide different machines for preshredding material and compact it and also if needed they can dewater the waste to make it lighter. The materials they have experience with are:

- Foam Plastic
- Plastic Containers
- Dust
- Metal Containers

But still they offer test machines for customers to try other and new materials to expand their knowledge. [3]

2. Vision of the solution

The vision is to create a solution which would mainly be able to correctly measure the wear of the screw, while the machine is operating and be able to collect and display the data to not only the user but also RUNI and their servicemen. The system to measure the wear should be cost effective, precise, measure during the operation of the machine and most importantly should be able to be retrofitted into already existing machines.

3. Screw wear measurements

The first approach is to research direct measuring methods. Capacitive, Inductive, Ultrasound, and Laser measurement methods can be included in this group. This approach does not require complex calculations to obtain the thickness of the screw, as the output values from the sensor can be directly assigned to the wear value. This makes this approach very attractive in terms of implementation and data evaluation. [4]

3.1 Capacitive

This approach uses capacitive proximity sensors to accurately measure the thickness of the screw. Individual sensors must be positioned to measure the end of the screw (90 degrees to the plane of the screw) where wear is the highest. Capacitive sensors measure changes in the dielectric properties of the material being measured (**Fig. 2**).

The sensors can sense whenever there is material in the sensing area of the sensor, or not. Capacitive sensors can also detect non-ferromagnetic materials, this can be an advantage or disadvantage depending on the application. With capacitive sensors, it is possible to get information about how long the sensor has sensed something, from the time value,the thickness of the screw can directly be evaluated. [4] [5] [6] [7]

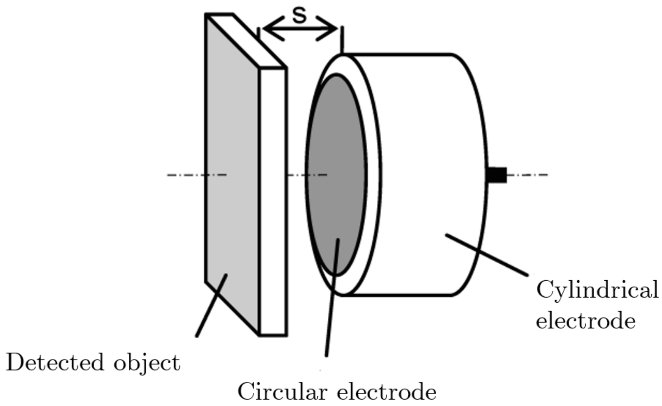

Fig. 2 The principle of non-contact Capacitive sensor [7]

3.2 Inductive

Inductive sensors (**Fig. 3**) use electromagnetic fields to measure changes in the electrical conductivity of a material. Like capacitive sensors, inductive sensors can sense if there is a component in front of them in the sensing area. The main difference to capacitive sensors is the ability to sense only ferromagnetic materials. This feature of inductive sensors can be of great benefit for screw measurements because the compacted material does not interfere with the data. By relating the amount of time the sensor has sensed the part to the exact thickness value, a system can be obtained that outputs an accurate wear value. Like Capacitive sensors, Inductive sensors must be installed to measure the end of the bolt (90 degrees to the plane of the screw). [4] [8] [9] [10]

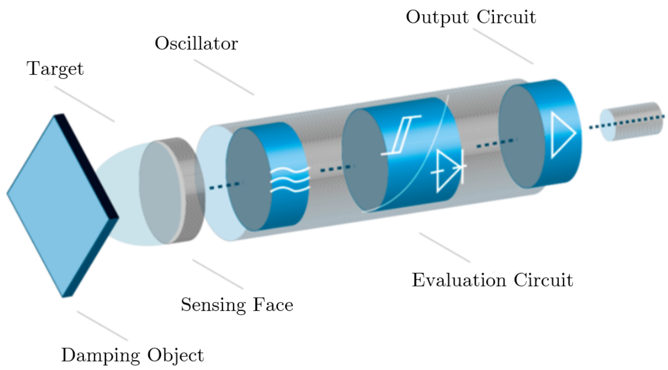

Fig. 3 Inside of a conventional cylindrical sensor [11]

3.3 Ultrasound

Using high-frequency sound waves, it is possible to evaluate how much material has been removed from the screw walls due to frictional wear. When the sound waves hit the object, part of the waves are reflected back into the sensor. The transducer detects these echoes and measures the time it takes for them to return. By knowing the speed of sound in the environment, the sensor can calculate the distance to the object. From this data, a change in distance can be created over the time the machine is used. The ultrasonic sensors would be installed in the plane of the screw, where the concept of ultrasonic sensors would be used the most. [4] [12]

3.4 Laser

Laser sensors work by emitting a focused beam of light, usually a laser beam, and then detecting how that light reflects or scatters off the object. This can be used in the same way as ultrasonic sensors. However, the advantage of laser sensors is their variability, as the first method mentioned is not the only way to use laser sensors. If two sensors were installed opposite each other, at the end of a screw, the thickness could be related to the time when the opposite sensor does not receive the signal because the beam is blocked by the flights of the screw. In this arrangement, the sensors would be mounted at 90 degrees to the plane of the screw. [4]

4. Data collection

To read out the sensors and process the values RUNI provided a "Mobile Data Logger" also called briefcase. It contains different components as followed:

- 230V input
- Power supply unit
- Schneider Electric PLC "Modicon M251MESE"
- Schneider Electric analog module "TM3TI4/G"
- Schneider Electric digital module "TM3DM8RG"
- WAGO Triple-deck terminal blocks
- WIENET IP-SWITCH UMS 6-L
- Secomedia "SiteManager" IoT gateway

With the briefcase, it is possible to read out data from the sensors independently of the machine, as the briefcase is powered autonomously and it is not connected to the power of the machine. The PLC in there gives the possibility to connect all sensors at the same time in a real industrial environment. At the same time because of the flexibility with the connectors it is possible to make fast changes.
The software to program the PLC is "Machine Expert logic builder" from Schneider Electric. The software gives access to the PLC, to program it in a "CODESYS" environment.

5. Sensor decision

After evaluating the problem, the look at the solution approach and the sensor overview, one main approach with two different sensor types was selected. Among these sensors are Capacitive and Inductive sensors.

5.1 Style of use

Both types of sensors have a Boolean output, and in this particular case both will be used for proximity detection and for high precision measurements, where both sensors will measure the amount of time that a spinning screw is in front of them. This approach was assessed as the most feasible for obtaining the required data compared to other approaches and ideas.

5.2 Setup

In terms of setup, it is not difficult to implement these two sensors in a real machine without major changes to the original design. Moreover, they are set up almost identically, which speeds up the whole testing and implementation process. If the the setup of a Capacitive and Inductive sensor is compared with a Laser sensor, the whole setup process is significantly simpler and the acquisition of a feasible setup is significantly higher.

5.3 Evaluation

Using Capacitive and Inductive sensors, a direct relation can be established between the time for which the sensors indicate the true value and the thickness of the screw. This connection can be made very quickly and can give an accurate idea of the wear on the screw at any point in time.

5.4 Research

Both of the selected sensor types are well researched and widely used. This is beneficial for a more thorough investigation of what can be achieved with these sensors. At the same time, the exact solution to the described problem is not publicly available. Therefore, the selected sensor types are unique in this compacting industry and their implementation is interesting, but they are also well developed in other industries.

5.5 Price

This reason is usually the main concern of a company that wants to implement and improve its machines. Since both types of sensors are widely used, their price is affordable and the whole setup for data output and implementation in the machine design is minimal compared to other alternatives (Laser, Complex in-direct measurement methods).

5.6 Comparison

As indicated above, both Capacitive and Inductive sensors are very similar in terms of design, output and price, for better data coverage not only one of them was chosen but both were used in the feasibility test. This approach does not change the design of how to implement and receive data from sensors, but more data is obtained and comparisons can be made between these types of sensors.

6. PLC program

As mentioned the PLC is programmed in a CODESYS version of Schneider Electric. In CODESYS different environments of programming are possible to use:

- Continuous Function Chart (CFC)
- Continuous Function Chart (CFC) page oriented
- Function Block Diagram (FBD)
- Ladder Logic Diagram (LD)
- Sequential Function Diagram (SFC)
- Structured Text (ST)

Depending on the environments the program is created by a floating text of function blocks which are connected. In this project only LD programs are written and explained. A program in in the PLC is called POU (Program Organization Unit). Those POUs are are executed by the PLC from top to bottom according to the order how they are stored in the PLC. The time the PLC needs to execute every POU one time is called cycle time.
Each POU consists of different networks which are processed by the PLC from top to bottom like the POUs. This means that a value or an operation from POU 10 cannot be called up in POU 5 or has the wrong value. LD FBD programs are graphically written programs with different function blocks. Those function blocks are representing the wiring of relays. This means that every block stands for a function which is provides by the language and then processed by the PLC. As example the SUB (subtract) function block (**Fig. 4**) is described. [13]

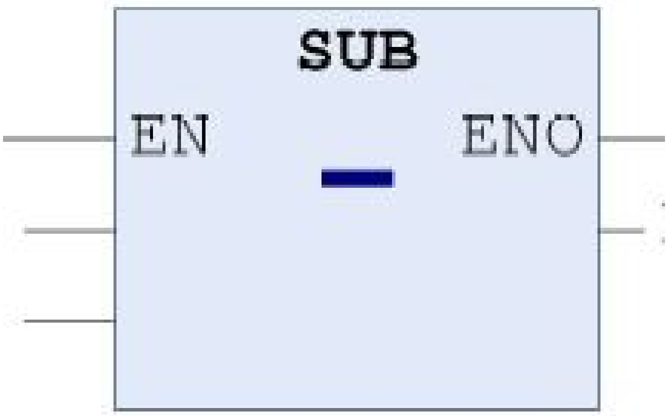

Fig. 4 LD subtract function block

The block shows a total of three connections situated on its left side, representing the inputs, while two connections on the right side symbolize outputs. The first input on the left side, positioned at the top position, pertains to a boolean-controlled enable input. This particular input serves the purpose of activating the block in response to distinct events. If it detects a true signal at this input, the block triggers the subsequent subtraction operation. This subtract is defined by the other two inputs. The PLC reads the inputs always from top to bottom and subtract the values in this order. The upper output is only to transfer the boolean signal from the first input. The second output gives the value from the mathematical operation out.

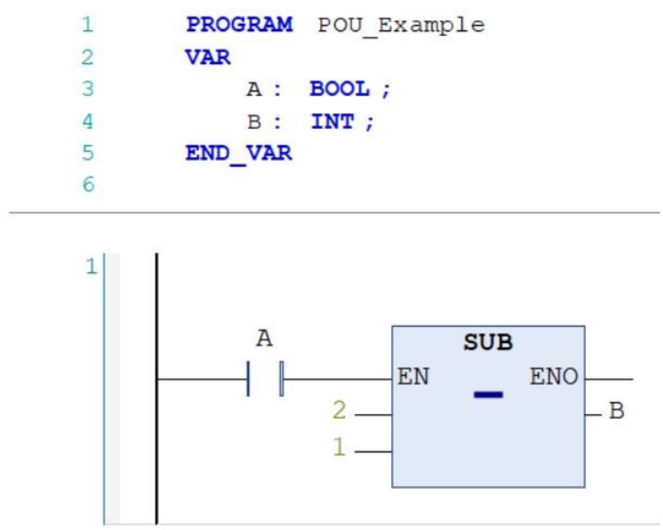

Fig. 5 Example POU

In the shown example POU (**Fig. 5**) does a controllable subtract operation. When the variable "A", above the contact is true, the contact which is assigned to "A" is closed. The SUB block executes then because the input which triggers the operation is true. The block then subtracts "1" from "2" and stores the result in value "B". The function block and the contact are stored in Network 1. Above the network CODESYS defines the variable with the data type of the variable. Because a contact can only be operated by a boolean variable, the variable "A" is defined as boolean. The result of the mathematical operation returns an integer value, which is a whole number without decimals or fractional parts. This means variable "B" has to be defined as a integer. The variables "A" and "B" used in this example are not global. This means they are only accessible in this specific POU and a different POU can use the same variables but they are independent from each other. An other possibility to store variables is to store them global. Global variables are usable in all POUs in one program. Global variables are indicated by the prefix GVL. Variables can be assigned to a digital or analog input or output from the PLC.

7. Measured data

7.1 Raw data and data visualization

The raw data from the sensors are stored in a text files. For comparability and analysis of the data, three measurements of five minutes each were taken. From the text file the the data is converted into excel to evaluate and compare them.
The following statistical values were selected for comparison.

- Average: The average value shows the distribution of the values for each run. This give insights about how big the impact of rounding is.
- Median: The Median provides information about the direction in which the values tend to move.
- Minimum: Shows the minimum value for each run.
- Maximum: Shows the maximum value for each run.
- Range: The range is important to validate the accuracy of a sensor.
- Average difference: The average difference compares the run with reinforcement and without reinforcement. With this it is possible to proof that the values are significant different between the screw thickness.
- Standard deviation: The standard deviation provides information about the scatter range of the values and is used to decide which sensor is useful for further measurements.
- Value distribution: Shows how the values are distributed during the 213 points
- Percentage each value: Shows the distribution in percentage

In addition, an analysis of the percentage distribution of values was conducted to illustrate the impact of rounding errors and to assess the appropriateness of a higher resolution measurement.
First the value distribution for all runs and all sensors are visualized in graphs. Additional the distribution for all values of each sensor from all runs are visualized to see if there is a difference between the worn screw and the reinforced screw.

7.2 Data evaluation

Based on the evaluated data, a clear difference can be seen in the accuracy and usability of the sensors. The two capacitive sensors produce worse results than the two inductive sensors. For ongoing tests the inductive sensors should be chosen.
In addition to the poor measurement results, the capacitive sensors are not an option, as they cannot distinguish the difference between EPS and the screw when they are used with material in the machine.

8. Recommendations

For ongoing investigations how the wear of the screw can be detected during the workflow and also how to improve the current setup the there are various points suggested.

- More detailed analyse for real world application
- Investigate the cycle time from the PLC
- Possible theoretical solutions with a numerical model and simulations
- Cloud based data transfer between the machines, customers and RUNI
- Defining the time threshold of a worn screw

9. Conclusion

Firstly the problem was analysed and then brainstorming ideas for potential solutions. A research has then been conducted in order to determine which solution is the most suitable for such application. The solutions which was chosen based on the conducted research were two types of proximity sensors (Capacitive and Inductive), which are inexpensive, compact and precise sensors.

These sensors were then purchased in two variants based on their properties such as output, price, connectivity to the Mobile data logger and setup, an 18 mm and a 30 mm capacitive and inductive sensors, giving four total sensors to conduct testing with. The measuring process consisted of doing three times a 5 minute cycle for both thicknesses of the compacting screw, with all of the sensors mounted at the same time. The results were then plotted and evaluated in Excel. It can be said on the basis of the measurements that the developed concept works and that a clear distinction between the new and the worn screw can be measured with inductive sensors. This serves to demonstrate the proposed concept and proves its feasibility and potential effectiveness. Based on the results, the most suitable sensor is the 30 mm Inductive, which provided the best results out of the four different sensors that have been tested.

Acknowledgement

The authors of this work gratefully acknowledge Grundfos for sponsoring the 11th MechMan symposium.

Also the authors want to thank Poul Kyvsgaard Hansen, Civ.Ing. Ph.D. for supervising and reviewing the project.

Special thanks go to the company Runi A/S and Lasse Wolkers Jepsen, Cand. Polyt. industrial design for his willingness to provide information, for his interesting contributions and answers to our questions, and for making the machine available for our testing purposes.

Finally the authors want to thank all the staff at Aalborg University, assistant engineer Henrik Wiberg and Mr Helge Glinvad Grøn, PhD fellow for their support in the practical implementation of our project.

References

[1] "RUNI's history," Online avalible: https://www.compactor-runi.com/about-us/history, RUNI A/S, access April, 2023 2023.

[2] "RUNI's sk240 screw compactor," Online avalible: https://www.compactor-runi.com/screw-compactors/runi-sk-240, RUNI A/S, access April 28th, 2023 2023.

[3] "RUNI compacting usecases," Online avalible: https://www.compactor-runi.com/compacting, RUNI A/S, access April 28th, 2023 2023.

[4] T. A. Kinney, "An overview of proximity sensors," Online avalible: https://www.machinedesign.com/automation-iiot/sensors/article/21831577/baumer-electric-an-overview-of-proximity-sensors, MachineDesign, 2023-05-20 2022.

[5] Y. Ye, C. Zhang, C. He, X. Wang, J. Huang, and J. Deng, "A review on applications of capacitive displacement sensing for capacitive proximity sensor," Online avalible: 10.1109/ACCESS.2020.2977716, vol. 8, pp. 45325–45342, 2020.

[6] Y. Ma, X. Wang, H. Li, X. Dong, and Y. Kang, "A new capacitive sensing system for roundness measurement," Online avalible: 10.4028/www.scientific.net/AMR.662.754, vol. 662, pp. 754–757, 04 2013.

[7] A. Vojáček, "Non-contact capacitive proximity sensors - general description," Online avalible: https://automatizace.hw.cz/komponenty-mereni-a-regulace/bezkontaktni-kapacitni-senzory-priblizeni-obecny- popis.html, Automatizace.HW, access May 17th, 2023 2014.

[8] A. Vojáček, "Non-contact inductive proximity sensors - general description," Online avalible: https://automatizace.hw.cz/komponenty-mereni-a-regulace/indukcni-snimace-priblizeni-obecny-popis.html, Automatizace.HW, 2023-05-17 2014.

[9] A. Stykemain, "Inductive sensor | different types and applications," Online avalible: https://realpars.com/inductive-sensor/, REAL PARTS, 2023-05-20 2021.

[10] J. R. Salas Avila, M. Lu, R. Huang, Z. Chen, S. Zhu, and W. Yin, "Accurate measurements of plate thickness with variable lift-off using a combined inductive and capacitive sensor," Online avalible: https://doi.org/10.1016/j.ndteint.2019.102202, vol. 110, p. 102202, 2020.

[11] "Inductive proximity switches," Online avalible: https://www.baumer.com/us/en/product-overview/object-detection/inductive-proximity-switches-/c/278, Baumer, access May 17th, 2023 2023.

[12] "Injection molding: Determine barrier screw condition without screw removal," Online avalible: https://www.ptonline.com/products/injection-molding-determine-barrier-screw-condition-without-screw-removal, PlasticsTechnology, 2023-05-20 2020.

[13] "Codesys ld fbd," Online avalible: https://content.helpme-codesys.com/en/CODESYS%20LD%20FBD/_ldfbd_start_page.html, CODESYS Online Help, access May 17th, 2023 2022.