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Condition-Based Lubrication of Roller Chains

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Lubrication of roller chains is an important maintenance aspect to reduce wear progress as well as noise emissions and friction losses. Supplying the right amount of lubricant to the chain joints without risking dry operation or wasting large amounts of lubricant requires knowledge of the current lubrication state of the chain. This paper presents two methods to detect the lubrication state of a roller chain during operation and use this data to control an automatic chain lubrication system. The results show that condition-based lubrication can reduce chain wear and lubricant consumption in comparison to manual or time-based lubrication.

[Keywords: roller chains, condition monitoring, lubrication monitoring, temperatur analysis, sound analysis]

Die Schmierung von Rollenketten stellt einen wichtigen Instandhaltungsapekt dar, um sowohl Verschleißfortschritt als auch Geräuschentwicklung und Reibungsverluste zu reduzieren. Die richtige Schmierstoffmenge bereitzustellen, ohne dabei Trockenlauf oder übermäßigen Schmierstoffverbrauch zu riskieren, bedarf Informationen über den aktuellen Schmierzustand der Kette. In diesem Beitrag werden zwei Methoden präsentiert, um den Schmierzustand einer Rollenkette im laufenden Betrieb zu erfassen und zur Steuerung eines automatischen Kettenschmiersystems zu verwenden. Die Ergebnisse zeigen, dass zustandsbasierte Schmierung sowohl den Verschleiß der Kette als auch den Schmierstoffverbrauch im Vergleich zu manuellem oder zeitgesteuertem Schmieren reduzieren kann.

[Schlagwörter: Rollenketten, Zustandsüberwachung, Schmierüberwachung, Temperaturanalyse, Geräuschanalyse]

1 INTRODUCTION

Roller chains are common machine elements to transmit power between distant shafts, but also as conveyor elements. Lubrication of roller chains helps to slow down wear progress, reduces noise emission and improves the efficiency of the chain drive. This has been demonstrated by Coenen in his dissertation, in which he investigated lubrication conditions of roller chain drives and their influence on wear progress in extensive experiments [1]. The results of operating a roller chain without lubrication is illustrated in Figure 1, with rust powder appearing on the edge of the dry joints, followed by excessive wear after prolonged time. Key aspects of roller chain lubrication are delivering the

Figure 1: Results of dry operation of a roller chain. Tribocorrosion with rust powder on the left, excessive wear on the right

right amount at the right time to the right part of the chain. Simply draining the chain in large amounts of oil is in most cases not helpful and rather causes a waste of resources and financial assets, depending on the application even an environmental or fire hazard. Ideally, new lubricant only gets applied to the chain when it actually shows a lack of lubricant. This requires the ability to measure the current lubri-

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cation state of the chain and a means to apply new lubricant based on the result of this measurement. While there are publications concerning the detection of the lubrication state of bearings [2, 3], there is to the knowledge of the authors no work published about detecting the lubrication state of a roller chain. In this paper, two methods to detect the current chain lubrication state during operation are presented, chain temperature and sound emissions, followed by a series of validation experiments in which the measurements are used to control an automatic lubrication system.

2 LUBRICATION MONITORING

All presented experiments were conducted on the chain test rig of the Institute for Mechanical Handling and Logistics at the University of Stuttgart. This machine, shown in Figure 2, consists of two drive trains featuring the driving sprocket and the driven sprocket, respectively. The driving motor together with transmission, bearings and driving sprocket is mounted on linear guide rails, offering a variable shaft distance. The chain can be pre-loaded via a pneumatic cylinder, moving the two shafts apart. The motor of the driven sprocket is switched to generate a braking torque, simulating power transmission with the tested roller chain.

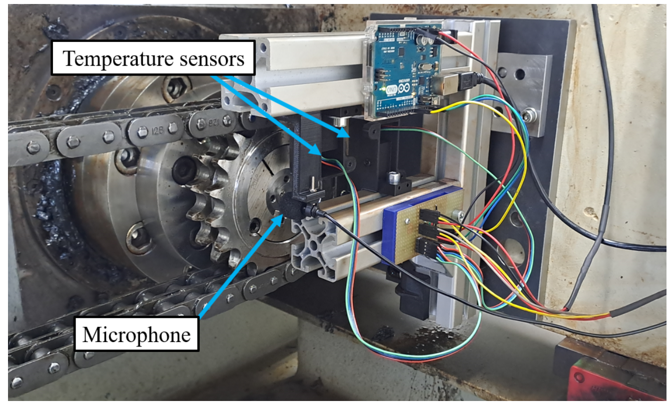

Figure 3: Measurement setup on the chain drive. The two contactless temperature sensors measure the chain temperature, with two additional contact temperature sensors (not shown) measuring the ambient temperature in the room of the chain test rig. The image also shows the microphone for the sound-based lubrication monitoring (see 2.2)

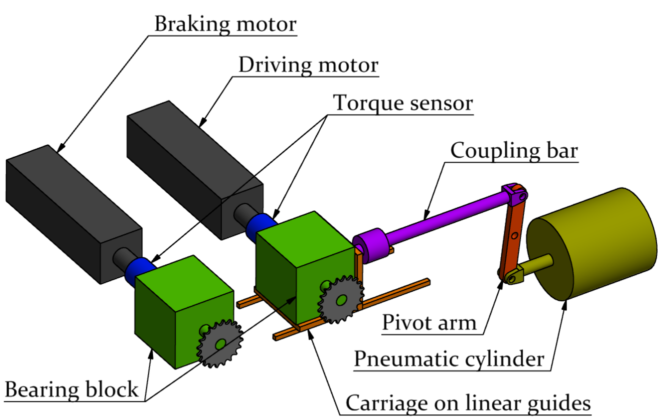

Figure 2: Schematic view of the chain test rig at IFT, see [4]

2.1 TEMPERATURE-BASED LUBRICATION MONITORING

Measuring the lubrication state based on the chain temperature was already presented by the authors in [4]. Two contactless infrared thermometers measure the chain temperature during operation, for reference the ambient temperature around the chain test rig is also measured. The sensor setup for both temperature as well as sound measurement is shown in Figure 3. Three 12B-2 roller chains with different wear levels, 0% elongated, 1.8% elongated and 3.8% elongated are tested at four different lubrication levels, respectively. The lubrication levels are created by submerging the chains in a high-performance high-temperature chain oil and gradually removing some oil after each test. For the fourth lubrication level, the chains are submerged in a degreasing agent to simulate a dry operation of the chain. In [4], the chain temperature is observed for only 15 minutes, whereas in the experiments presented here, the chain is operated for 45 minutes to let the chain drive get closer to a thermal equilibrium. Besides the increased operation time, the experiments are equivalent to those presented in [4]. Some of the results are presented below. Figure 4 shows the difference between chain and ambient temperature for the three different chains at sufficient lubrication level. The difference in chain temperature is minimal, such that an influence of the wear on the chain temperature can be neglected from this data. The general dynamic of the temperature over the course of the test duration is nearly the same for all three chains. Figure 5 shows the temperature dynamics for the new chain with 0% elongation at the four different lubrication levels. Notably, the difference between sufficient lubrication and the two intermediate lubrication levels is minimal, only the dry operation shows a significantly different chain temperature. Generally, the chain temperature is a suitable indicator to observe the lubrication state of the chain, although the experiments suggest that only a dry operation can be detected. The very low influence of the wear on chain temperature is beneficial for condition-based lubrication, as an increase of chain temperature is more likely to be due to lubrication issues instead of e.g. due to progressing elongation.

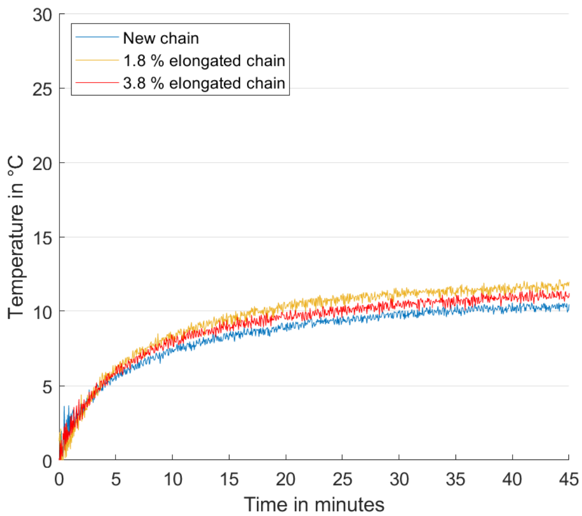

Figure 4: Difference between chain temperature and ambient temperature for 3 different chains at sufficient lubrication level

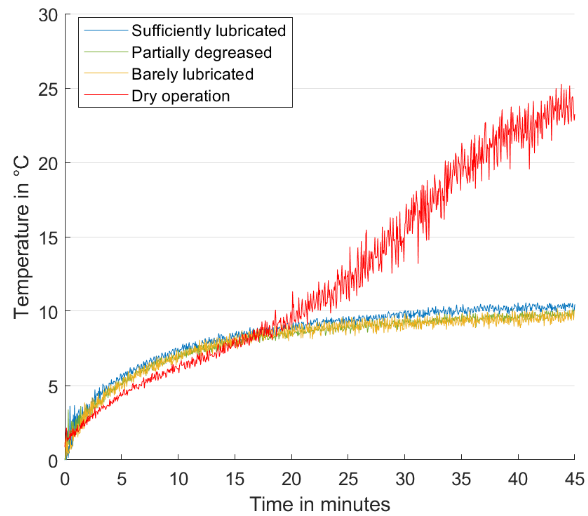

Figure 5: Difference between chain temperature and ambient temperature for a new chain with different amounts of lubrication

2.2 SOUND-BASED LUBRICATION MONITORING

The second approach uses a microphone to record the sound of the chain drive at the driving sprocket in regular intervals and derive the lubrication state from this. The experimental approach is mostly equivalent to the temperature measurements in 2.1. Four 12B-2 roller chains with different wear levels (0%, 0.2%, 1.8% and 3.8%) are tested at four different lubrication levels, which are created equivalently to the temperature tests. A microphone records 30 seconds of the sound created by the chain engaging with the driving sprocket at different speed and load conditions. There are many different possibilities to process the resulting sound data, in the approach presented here, a Fourier analysis is followed by integrating the resulting amplitude spectrum. This integral shows a good correlation with the lubrication state in all the experiments while only showing very little correlation with the chain wear. The integral indicator for all four chains at different lubrication levels is shown in Figure 6. Observing the integral indicator with respect to the chain wear level for the cases of sufficient lubrication and dry operation shows a significantly smaller dependency (Figure 7). The integral of the amplitude spectrum is accordingly used as second indicator to monitor the lubrication state of the chain and control the automatic lubrication system.

3 CONDITION-BASED LUBRICATION

During the validation tests for condition-based lubrication, an automatic chain lubrication system is used [5]. This system features a lubrication sprocket (see Figure 8) that engages with the free span of the chain drive in addition to the driving and driven sprocket and gets supplied with a mixture of lubricant and pressured air. Bores in the sprocket hub align with the joints of the chain and allow the lubricant-air mixture to get propelled directly at the chain joints between inner and outer link plate. The lubricant-air mixture is provided by a pump and a mixing unit that can be switched on and off at will, for example to lubricate the chain in certain time intervals. The complete setup is illustrated as a block diagram in Figure 9.

3.1 CONDITION-BASED LUBRICATION DECISION

In regular intervals of 30 minutes, the lubrication state of the chain is measured and its numerical value compared to a threshold to decide whether to lubricate the chain. The sensor value acts as a measurement of the degree of lack of lubrication, so if the value is higher than the threshold, the lubrication pump is switched on for 30 seconds. If the value is lower than the threshold, the chain does not get lubricated. The choice of this threshold has a large influence on the performance of the condition-based lubrication, however, choosing this threshold is not trivial. While typical measurements in a well-lubricated state can provide a basis for the threshold, choosing it too low risks triggering lubrication every single cycle, even if the chain might not require additional lubricant. On the other hand, a too high threshold risks rarely or never lubricating the chain, even if lubrication is needed. Thus, the threshold choice makes the difference between an unnecessarily high lubricant consumption or accelerated chain wear due to dry operation. For this reason, a second approach is tested with the intention to lower the

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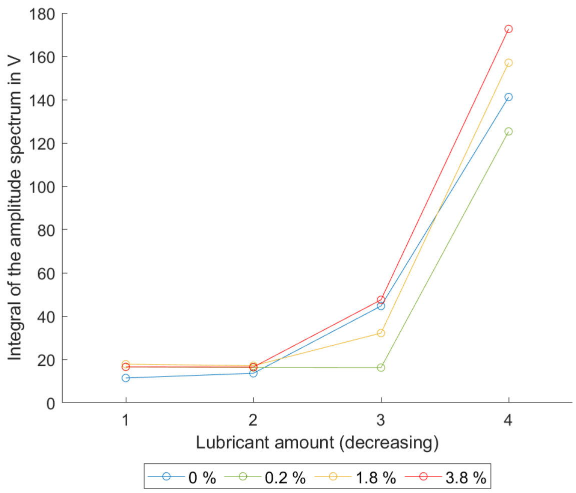

Figure 6: Integral of the amplitude spectrum with respect to the lubrication level of four different chains at four different lubrication levels. 1: Sufficiently lubricated. 2: Partially degreased. 3: Barely lubricated. 4: Dry operation.

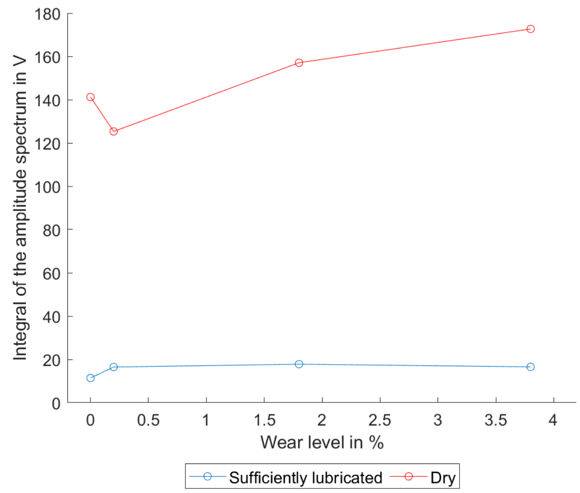

Figure 7: Integral of the amplitude spectrum with respect to the wear level of four different chains at two different lubrication levels.

influence of the threshold. Instead of directly triggering lubrication, the relation between sensor value and threshold only changes the remaining time until the next lubrication. Every time the measured sensor value is above the threshold, the time until the next lubrication is reduced by one hour, if it is below, the time until the next lubrication is increased by one hour. If the measurement is very close to the threshold, the remaining time does not get changed. The lubrication interval is limited to a minimum of one hour and a maximum of eight hours, between which the algorithm may set the interval based on the sensor data. An overview of the lubrication decision is shown in Table 1. Hence, even when the measurement never exceeds the threshold, the chain will get lubricated every eight hours. If the measurement stays repeatedly under the threshold, the chain will only get lubricated once every hour instead of every single measurement cycle. With this technique, the influence of the threshold is reduced while at the same time enabling an adaptive approach to settle on the ideal lubrication interval.

Sensor value w.r.t. threshold	Lubrication decision
$>$	Shorten lubrication interval by 1 hour
$\approx$	Do not change lubrication interval
$<$	Increase lubrication interval by 1 hour

Table 1: Summary of the lubrication decision for the combination of lubrication state and time

3.2 Validation Experiments

The performance of condition-based lubrication is tested on six 16B-1 chains for 200 hours each. In the first test, the chain gets lubricated manually by applying oil with a brush. In the second test, the chain gets lubricated by the automatic lubrication system in a time-based fashion every 120 minutes. Chain 3 and 4 are lubricated based on temperature and sound, respectively, considering only whether the threshold value is exceeded. Chain 5 and 6 are lubricated based on temperature and sound as well, but the threshold is used to adapt the time interval until the next lubrication. The different experiments are summarized in Table 2 with respect to the basis for the lubrication decision and the way that lubricant is applied to the chain. The amount of lubricant and the lubrication times as well as the wear progression are regularly monitored.

4 Results and Discussion

The first two experiments, with manual lubrication and time-based lubrication, confirm intuitive assumptions as well as the results of [1]; lubricating often and with larger amounts of oil significantly reduces the wear progression of the chain, naturally at the cost of a high lubricant consumption, which may not be desired. The wear progress of all six chains is shown in Figure 10, the lubricant consumption in Figure 11, the values at the end of the tests can be found in Table 3. The wear of the manually lubricated

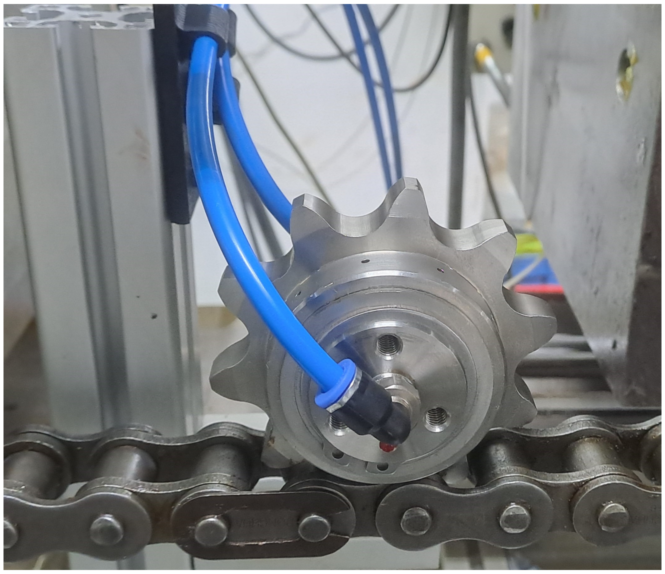

Figure 8: Applicator sprocket of the automatic lubrication system. The blue tubes supply the sprocket hub with lubricant-air mixture from the pump.

No.	Basis for lubrication decision	Lubricant application
1	Time	Manually
2	Time	Automated
3	Sound	Automated
4	Temperature	Automated
5	Time + Sound	Automated
6	Time + Temperature	Automated

Table 2: Overview over the validation experiments

chain increases particularly after 72 hours with the effect of the initial lubrication decreasing. The sound-based and temperature-based lubrication results illustrate the difficulty of choosing a suitable threshold, with both chains exceeding the wear of the manually lubricated chain despite consuming more lubricant. Notably, this chain does not only show the highest wear of all four condition-based lubricated chains, but at the same time the highest lubricant consumption among them. Among these four, it is the only chain that does not get lubricated during the first 24 hours of the test due to not exceeding its threshold, this is likely the reason for the high elongation over the course of the test. Figure 11 shows that the other three condition-based lubricated chains get supplied with lubricant already earlier in the experiment.

In the last two experiments, with the chain condition only adapting the lubrication interval, the chain elongation is lower than with the two purely condition-based approaches. Whether this is specifically due to the adapted lubrication decision can not be determined with certainty,

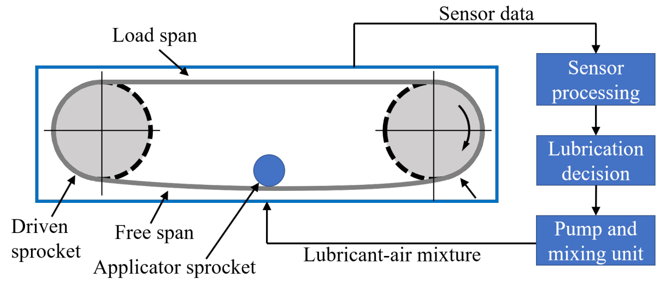

Figure 9: Condition-based lubrication setup. The sensor data gets processed to retrieve the current lubrication state of the chain, which is used for the lubrication decision. In case the chain should get lubricated, the pump and mixing unit are switched on for 30 seconds to supply the applicator sprocket with a lubricant-air mixture

No.	Elongation	Lubricant
1	0.22 %	76 g
2	0.02 %	327 g
3	0.28 %	117 g
4	0.33 %	132 g
5	0.16 %	114 g
6	0.1 %	114 g

Table 3: Result summary of the validation experiments: elongation at the end of the test and total lubricant consumption

however, the results still illustrate the benefit of the reduced influence of the difficult threshold choice. Even if the threshold gets chosen unnecessarily high, the chains would get lubricated three times in the first 24 hours.

The results of the sound analysis during the manually lubricated test (Figure 12), illustrate the good correlation of lubrication state and the integral of the amplitude spectrum. After all three lubrication points, the integral drops significantly to the value of the beginning of the experiment.

5 Summary

The presented experiments show two methods to measure the lubrication state of a roller chain during operation. Measuring the chain temperature only detects dry operation of the chain, whereas the sound analysis of the sprocket engagement can also differentiate the extent of the lack of lubricant. With this data, the lubrication of the chain can be controlled, however, the algorithm for the lubrication decision has a large influence on the result. One of the investigated approaches, comparing the measurement results directly to a threshold, is highly dependent on the exact choice of threshold. This can lead to under- or overlubricating the

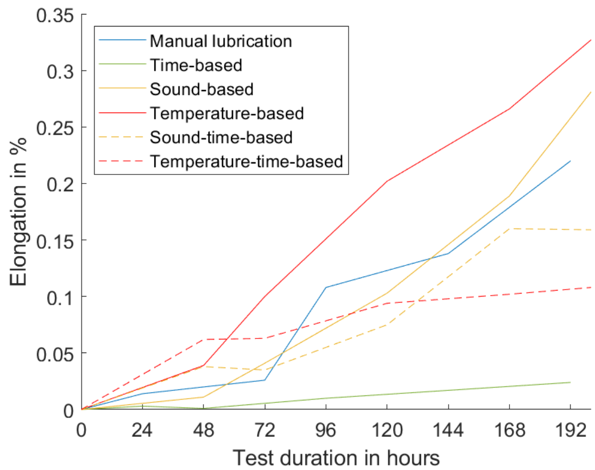

Figure 10: Wear progression of the chains over a test duration of 200 hours

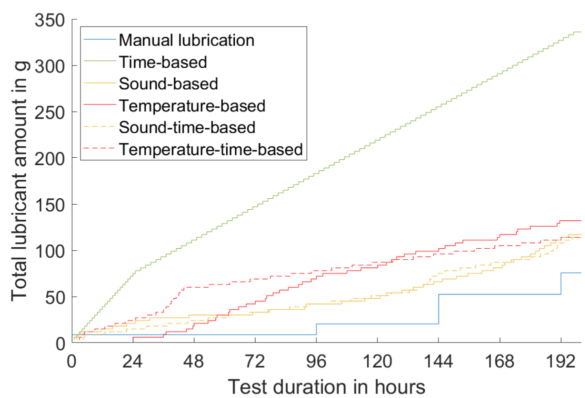

Figure 11: Accumulated lubricant consumption over a test duration of 200 hours

chain in case of a poorly chosen threshold. The second approach, adapting the lubrication interval based on the measurement data, lowers the influence of the threshold and improves the results concerning chain wear and lubricant consumption. Generally, the experiments confirm the benefits of lubricating roller chains for their wear behavior. Next to the amount of lubricant, the timing of application also matters for roller chain performance. The usage of condition-based automatic chain lubrication can improve both these aspects and increase chain life time while also limiting lubricant consumption.

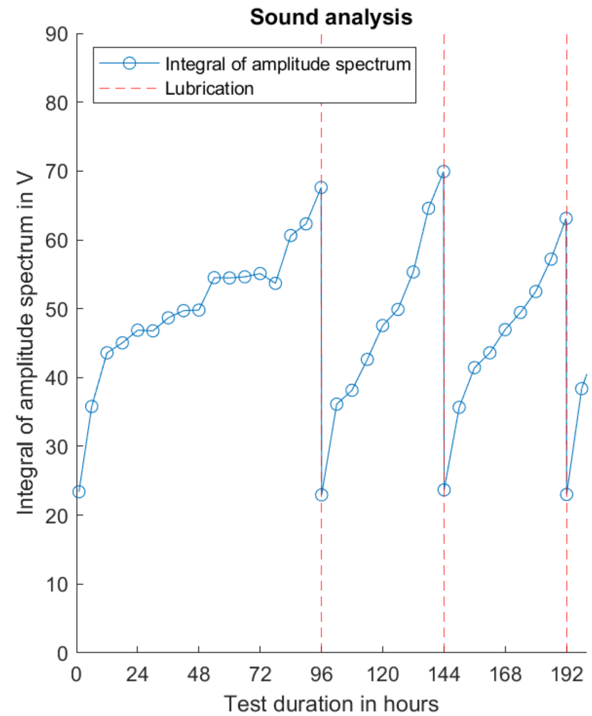

Figure 12: Integral of the amplitude spectrum during the manually lubricated test.

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