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**FEASIBILITY ANALYSIS OF QUANTITATIVE THERMOGRAPHY FOR
FAILURES AND THE LACK OF LUBRICATION DETECTION IN
CYLINDRICAL SPUR GEARS**

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Abstract. *Gear failures generally result from contact fatigue caused by cyclical stresses originated by tooth contact. Additionally, the lack of gear lubrication increases the temperature of the arrangement, which may cause gear failure. In this framework, this paper aims to verify the feasibility of using quantitative thermography in its active and passive modes to analyze these anomalies. The experiments were performed in a controlled environment to detect the lack of lubrication and faults in the pinion teeth surfaces of a spur gear transmission. Although thermography detected the lack of lubrication, our data indicate that this technique was not able to detect pinion defects. This work reveals that quantitative thermography is not efficient in identifying small flaws in the teeth surfaces of cylindrical spur gears. Although the temperature gradient associated with the lubricated and non-lubricated pinion was obtained, it was not expressive enough to distinguish the difference between a small flaw and an environmental temperature change (operation of a heat-generating source, such as an oven) or instabilities in the mechanical system (misalignments, imbalances, and clearances). We conclude that thermography is not a practical technique to determine the deficiency of the system's lubrication.*

Keywords: *active thermography, passive thermography, spur gears, contact fatigue, tooth flaws and lubrication.*

1. INTRODUCTION

Gears are machine elements used for torque transmission and speed reduction via contact between teeth. Although these elements have been used for a long time, they still are effective alternatives to the operation of industrial machinery and equipment.

Machines, their components, and subcomponents tend to fail due to misuse or lack of maintenance. One of the most common wears on mechanical elements is contact fatigue, which is enhanced by poor working conditions, such as misalignments, imbalances, lack of lubrication, and overload. In this regard, the main gear surface defects are micro-pitting, pitting, spalling, and scuffing. In order to mitigate this problem, predictive maintenance practices are extensively used in industry aiming to reduce downtime costs and improve production.

Predictive maintenance aims to determine the service life and the operating conditions of machines and equipment. This technique allows to determine when maintenance should be performed based on data acquired by non-destructive analysis. The most applied techniques in rotating machines are vibration, oil, ultrasound, and thermographic analyses.

Thermography is a non-destructive testing method that may be used to detect anomalies in machine structure (Olanda, 2018). The excess thermal radiation during machine operation may result from increased load in the working cycle or damage in the gears, providing different temperature patterns in the analyzed component. In this context, Waqar and Demetgul (2016) detected considerable temperature differences in a helical gearbox between healthy operating conditions and teeth-induced failures, employing quantitative infrared thermography.

Infrared thermography was able to identify the temperature distribution on the teeth surface of hypoid gears, emphasizing the area with high contact pressure in the tooth contact (Nagata *et al.* 2010 and Hirogaki *et al.*, 2013). Passive thermography was able to detect wear points on teeth surfaces of helical gears after heating caused by joule effect. In this

situation, the damaged areas have a slower cooling rate because of the heterogeneous character of the surface, enabling the identification of these regions via thermal images (Tian *et al.* 2014). Therefore, fault introduction in the teeth of helical gears was not effective to identify poor working conditions because of the temperature increment on the surface of the gear housing (Wagar and Demetgul 2016).

Blazej *et al.* (2016) and Kuzin *et al.* (2017) used active thermography to determine the temperature conditions in the operation of a belt conveyor gear set, located in an underground mine. The measurements carried out as part of the experiment did not enable the detection of significant changes in the technical conditions of the gear system. However, they have allowed the identification of the components' features and the specification of their temperatures during constant work. Thus, thermography may be used as a predictive technique for analyzing anomalies in equipment.

In this paper we propose to evaluate the feasibility of using active and passive thermography techniques in a controlled environment to detect the lack of lubrication and the presence of artificial flaws inserted in the surface of the pinion teeth of a pair of cylindrical spur gears operating under constant rotation. The lack of lubricating elements and the presence of anomalies on the surfaces of the gear's teeth are directly related to the friction between them, which may cause temperature variation of the disks. In this research, it is assessed if the quantitative evaluation is enough to confirm the abnormal working condition of the gears.

1.1 Gear failures and running-in

For mechanical contact elements such as gears, wear is the first indication that failure will occur. In the most general sense, wear is classified as moderate or severe.

According to Silva (2016), moderate wear occurs in the outer surface layers, where the surfaces remain smooth and covered by oxide surfaces generated by friction. On the other hand, in severe wear, the surfaces are strongly deformed and the wear debris consist of particles up to a few hundred micrometers in size.

According with Waqar and Demetgul (2016), normal gear faults consist of root cracks, scoring, pitting, scratches, and distributed failures, such as adhesive wear, abrasive wear, surface inaccuracy, and misalignment. Most gear failures are caused by assembly, deficient lubrication and overload, classified into four general classes: wear, fatigue, plastic deformation, and breaks. The occurrence of these anomalies results in energy dissipation in various modes, one of which is heat, detected as increased emission of infrared thermal radiation by the surfaces of the element.

Inefficient or inexistent maintenance procedures result in progressive wear, which disables industrial machinery and equipment. Thus, in order to prevent failure, verification of the proper components assembly and lubrication procedures must be performed (Silva and Maribondo, 2018).

Contact fatigue is one of the main causes of gear failure in which cracks are originated either from tangential stresses caused by friction or by a high concentration of stresses on the surface, where roughness is significant.

Pittings, formed in the region near the primitive line, defined by the primitive diameter, is one of the main consequences of fatigue contact. Amaro (2001) defines pitting as wear caused by high localized stress, which may appear because of surface roughness, geometric defects on these surfaces, or the absence of an appropriate lubricating film.

In general, in assembled components, there will be contact between the parts, and in some regions, it will be more intense contact than in others (Koda 2009). Running-in (softening) consists of wearing out the roughness to provide a better adaptation of the contact surfaces, increasing the contact area by removing the peaks.

1.2 Thermography as an inspection technique

Waqar and Demetgul (2016) state that Thermography may be used to identify and analyze thermal anomalies. This technique is based on the measurement of the radiant thermal energy (heat) distribution emitted from the target surface. In order to obtain sound measurements, surface emitted heat is converted to a surface thermogram, which requires knowledge of its emissivity.

Thermographic studies use qualitative and quantitative assessments. In qualitative analysis, an examination of thermal anomalies in the bodies is performed. On the other hand, the quantitative study specifies temperature values. Therefore, both Thermographic techniques seek to find differences in surface temperatures, but only the quantitative analysis specifies temperature values of the surface (Olinda 2018).

Thus, in active thermography, forced heating or cooling of the material is investigated and, in passive thermography, the natural heating or cooling in the element is monitored. Both methods can reveal the presence of damage or defects.

Under operating conditions, anomalies in mechanical components (wear, for instance) are commonly followed by abnormal heating. Therefore, during operation, it is expected that a flawed surface will have a higher temperature.

2. MATERIALS AND METHODS

In order to evaluate the feasibility of thermography to detect gears' anomalies, we reproduced the operation of a pair of cylindrical spur gears, as shown in Fig. 1. The tests were conducted in the Laboratory of Ergonomics and Safety Engineering at the Federal University of Campina Grande (LEEST / UFCG). Some additional experimental data were set

as follows: room temperature at 23°C, lamps turned off, and the windows and doors closed during the tests, which minimizes the influence of thermal exchanges with the external environment and artificial sources of heat generation. Also, room temperature was stabilized by turning on the refrigeration system 50 minutes prior to the experiments.

The experimental setup components highlighted in Fig. 1 are:

1. Thermal insulation cabin;
2. WEG W22 engine - 0.5 CV;
3. Frequency inverter WEG - CFW 08;
4. Bearing ($\varnothing = 20$ mm);
5. Bearing support;
6. Pinion shaft;
7. Pinion;
8. Screw and washer to attach the gears;
9. Gear;
10. Gear shaft;
11. Shock absorbers.

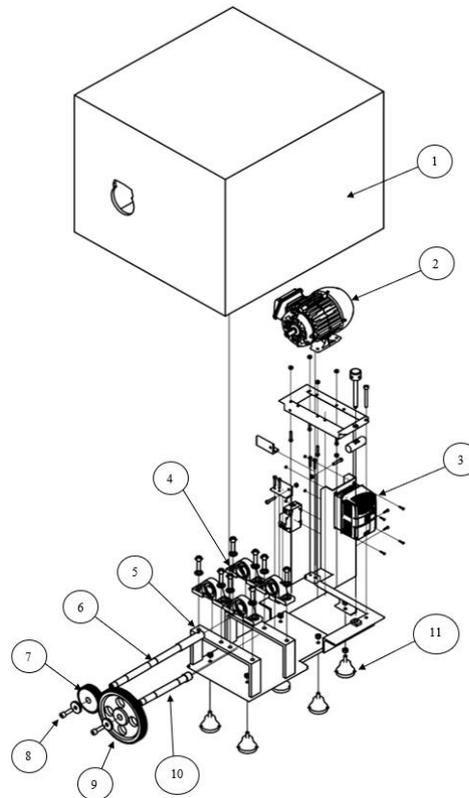


Figure 1. Experimental setup.

The thermal insulation cabin consists of laminated aluminum sheets with 0.1 mm thickness to reflect the heat from the environment and not interfere with the results. The engine worked at 1200 rpm with a frequency inverter. As support elements, we used the P204 bearing model with self-aligning ball bearings. Also, the shafts and gears are made of SAE 1020 and SAE 1045 steel, respectively. To set the gears, we used hexagonal screws with a nominal diameter of 10 mm, tightened before starting each test to avoid clearances to interfere in the system temperature. Regarding vibration control, we applied rubber dampers at the bench base to mitigate its causes.

Before performing each experiment, we manually lubricated the gears by brushing the moving parts with Texaco's marfak multipurpose grease 2. This grease was chosen because of its intense use in situations of industrial lubrication for spur gears operating at low speed. Table 1 shows the characteristics of the main gears' parameters.

Table 1. Technical Information of the Gears.

Parameters	Unit	Pinion	Gear
Reduction	-		2:1
Number of teeth	-		42 87
Center distance (a)	mm		126.22
Module	mm		1.95
Pressure angle	°		20
Face width	mm		23
Gear coefficient (ratio of number of teeth)	-		2.071428
Diameter	mm	85.788	174.438

The gears had their surfaces painted with matte black paint which, according to the manufacturer, has 0.98 emissivity. Thermograms were measured according to the Brazilian Standards on Thermography NBR 16292:2014 [8,11,12].

The reflective method of NBR 16292 (2014) provides instructions to neutralize the influence of thermal radiation from neighboring surfaces on Thermography readings and this standard was followed to measure the reflected temperature. In the setup, a 0.1 mm thick aluminum (reflectivity $\rho \approx 0.9$) is placed in front of the region analyzed for reflected temperature measurements. The thermal camera emissivity is set at 1 and average values of ten mapped points

of five thermograms recorded to configure the thermal camera before testing. Experiments were conducted in a controlled room with stabilized temperature as described previously.

In order to perform the experiment, thermograms (photos) were taken at 5 minutes intervals from its stationary condition until the last minute of the gears operation. The total experimental time was 60 minutes, leading to 13 thermograms per experiment. Two quantitative analysis techniques were used in these tests: a) active thermography (60 minutes of the gears operation) and b) passive thermography (60 minutes of the gears cooling) right after the machine stopped, as shown in Fig. 3.

The test was repeated 10 times for each operating condition established for the gears which included: a) no lubrication and pinion with no faults; b) lubricated and pinion with no flaws; c) no lubrication and with flaws in the pinion teeth surfaces; and d) lubricated and with flaws on the pinion teeth surface.

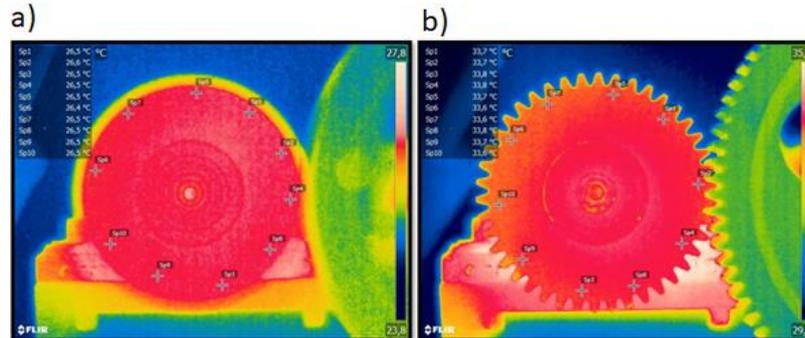


Figure 2. a) Thermograms taken with the operating pinion using active thermography, and (b) Using passive thermography in its cooling state.

The pinion surface was chosen for analysis because it is the element most susceptible to failure events, and, consequently, the component of higher thermal radiation emission as it is subjected to a greater number of cycles. Thus, ten points were mapped at the ends of the frontal surface for temperature data acquisition, as shown in Fig. 3. The points were chosen at the ends because they were closer to the friction region between the teeth.

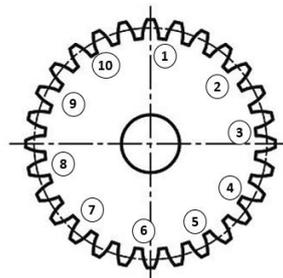


Figure 3. Temperature Mapping of measurement points.

For the quantitative thermography evaluation, the following parameters were measured: reflected temperature (T_{ref}), room temperature (T_{room}), relative humidity (RU%), and wind speed (WS). This step was performed by using the AMI 300 probe from Instrutemp, positioned close to the pinion, as shown in Fig. 4.

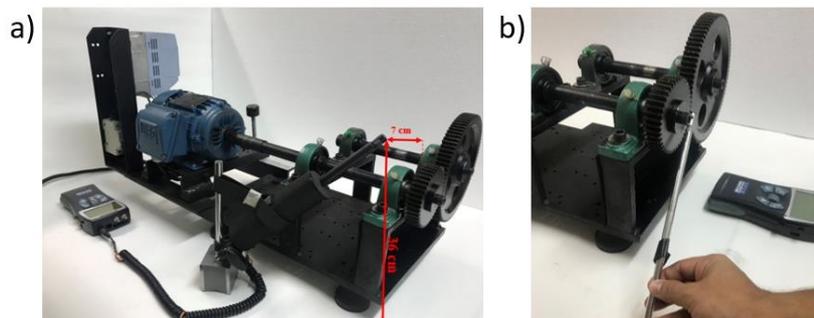


Figure 4. Instruments positioning for (a) room temperature and relative humidity measurement, and (b) wind speed.

We positioned the probe as near the pinion as possible to measure the room temperature and relative humidity. Table 2 shows the average values obtained for each test condition.

Table 2. Average values of reflected temperature, room temperature, and relative humidity for each operating condition.

Operating Condition / Employed Technique	T_{ref} (°C)	T_{room} (°C)	RU%
No lubrication and no faults / Active Thermography	25.78	27.51	64.31
With lubrication and no faults / Active Thermography	26.22	27.50	60.54
No lubrication and with faults / Active Thermography	26.73	28.20	53.51
With lubrication and faults / Active Thermography	26.79	27.81	49.88
No lubrication and no faults / Passive Thermography	25.78	27.68	62.01
With lubrication and no faults / Passive Thermography	26.22	27.95	58.81
No lubrication and with faults / Passive Thermography	26.73	27.93	54.16
With lubrication and faults / Passive Thermography	26.79	27.61	51.20

In addition to the temperatures measured in the mapped points, we also measured the wind speed on the pinion surface, as shown in Fig. 5. Table 3 presents the values obtained for the wind speed for the four operating conditions of the gears located in point 5, which was characterized as the point with highest speed, since it was the nearest point to the contact region between the gears' teeth. The wind speed was only recorded in active thermography since a wind vortex is generated by the gear bearings. The wind speed at the points shown in Fig. 5 was 0 m/s in passive thermography.

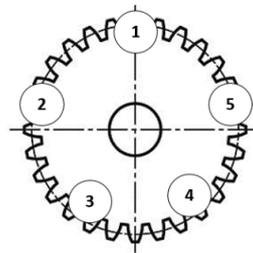


Figure 5. Wind speed measurement points.

Table 3. Average wind speed at point 5 for the four pinion operating conditions.

Operation Condition	Average wind speed at point 5 (m/s)
No lubrication and no faults	0.63
With lubrication and no faults	0.57
No lubrication and with faults	0.68
With lubrication and faults	0.66

Lower wind speeds are expected for lubricated gears because of the damping properties of the lubricant. In order to acquire the thermograms of the pinion surface, we used a T620 thermal imaging system from Flir Systems with a resolution in the infrared mode of 640x480 pixels, operating in the spectral range of 7.5-14 μm , temperature range from -40 °C to 650 °C, and minimum focal length of 0.25 m. After acquisition, the thermal images were treated using the Flir Tools software to implement the data of relative humidity, reflected temperature, room temperature, and to adjust the position of the temperature measurement points, as shown in Figs. 2 and 3.

The thermal imager was positioned to acquire high quality images. Thermogram generation were performed according to the configuration shown in Fig.6. For the faulty pinions, flaws were introduced as follows: first, the primitive diameter region was defined and then hammering with a flat-tip tool was performed to generate the flaws that structurally approach pittings in five teeth.

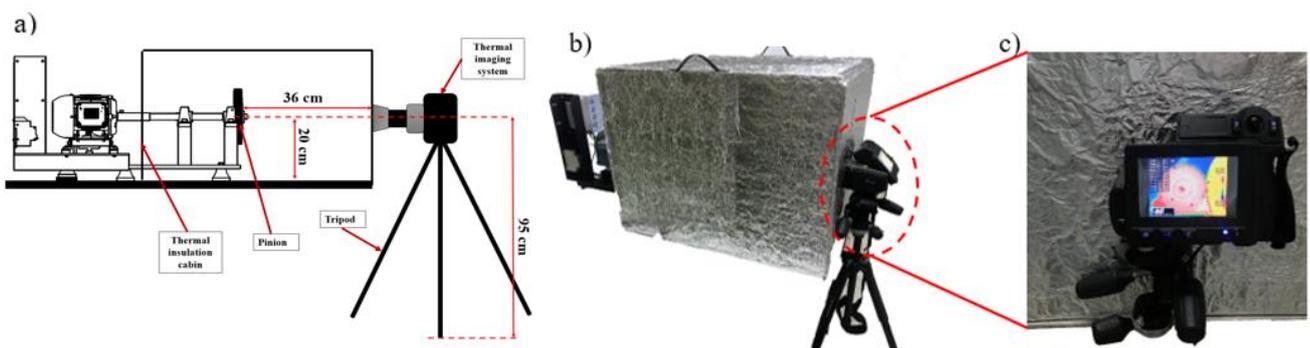


Figure 6. (a) Experimental setup of the thermal imaging system; (b) thermal imaging system position; (c) thermogram of the pinion surface.

3. RESULTS AND DISCUSSIONS

For the tests conducted by active and passive thermography, we performed ten experiments with non-lubricated gears and another ten experiments with lubricated gears. In total, we performed 40 experiments, including the conditions in which the system did not present flaws and the ones that presented them in the surfaces of the pinion teeth. When the gears were in operation, the active thermography was performed for 60 minutes. Then, right after the gears stopped working, the thermograms were taken via passive thermography. Repeat tests were performed after a 3 to 4 hours interval as this resting time was necessary for the system's temperature to stabilize.

For each experiment condition, we calculated the average temperature and the standard deviation at 5 minutes intervals for both active and passive techniques. Since the initial temperature was not exactly the same for each experiment, temperatures were normalized with respect to the initial temperature so that relative temperature changes could be determined at five minutes intervals for all experiments. Table 4 and Figure 7 show that an expressive increment in the temperature was observed for experiments without lubrication (tests 1 and 2). This temperature increase was attributed to running-in, where the gears' surface roughness is high, which causes a significant friction between teeth and contributes for heat generation as the gears were new. The first 120 minutes of tests were enough for the gears to overcome the running-in phase. Based on Tables 4 and 5, for active thermography with healthy gears, the use of lubricant resulted in a final operating temperature decrease from 32.69 °C (average) to 31.28 °C (average), as seen in Fig. 7. As expected, a decrease in pinion temperature levels was observed for experiments conducted with lubrication. A comparison between Tables 4 and 5 shows that gear lubrication led to average temperature drop of 1.41°C.

Table 4. Temperature data via active thermography for the gears without lubrication and faults.

		Time (min)												
		0	5	10	15	20	25	30	35	40	45	50	55	60
No Lubrication – Active Thermography (°C)	Experiment 1	24.51	26.10	28.19	29.34	30.16	30.98	31.49	31.80	32.22	32.64	33.09	33.53	33.72
	Experiment 2	25.22	27.09	28.86	29.83	30.85	31.20	31.91	32.31	32.74	32.96	33.44	33.68	33.66
	Experiment 3	24.62	26.19	27.78	28.90	29.79	30.55	30.90	31.43	31.83	32.04	32.44	32.68	32.96
	Experiment 4	25.20	26.79	27.95	28.97	29.91	30.60	30.88	31.45	31.88	32.18	32.39	32.41	32.98
	Experiment 5	24.07	25.65	27.03	28.12	28.98	29.72	30.26	30.85	31.09	31.57	31.81	32.06	32.40
	Experiment 6	24.38	25.91	27.30	28.30	29.06	29.89	30.38	30.88	31.41	31.73	32.14	32.27	32.53
	Experiment 7	24.35	25.57	26.90	27.91	28.80	29.55	30.01	30.51	31.11	31.53	31.74	31.92	32.25
	Experiment 8	24.14	26.58	27.79	28.73	29.43	30.07	30.50	30.84	31.13	31.55	31.81	31.86	32.38
	Experiment 9	24.75	26.41	27.65	28.67	29.47	30.05	30.50	31.02	31.34	31.56	31.92	32.18	32.39
	Experiment 10	23.97	25.68	26.81	27.97	28.82	29.40	29.85	30.38	30.71	31.07	31.27	31.61	31.67
	Average	24.52	26.20	27.63	28.67	29.53	30.20	30.67	31.15	31.55	31.88	32.21	32.42	32.69
Normalization	1.00	1.07	1.13	1.17	1.20	1.23	1.25	1.27	1.29	1.30	1.31	1.32	1.33	
Standard Deviation	0.41	0.49	0.60	0.59	0.63	0.58	0.61	0.57	0.58	0.54	0.62	0.66	0.61	
Standard Deviation (%)	41	49	60	59	63	58	61	57	58	54	62	66	61	

Table 5. Temperature data via active thermography for the lubricated gears and no faults.

		Time (min)												
		0	5	10	15	20	25	30	35	40	45	50	55	60
With Lubrication - Active Thermography (°C)	Experiment 1	24.82	25.89	26.53	27.50	28.17	28.67	29.15	29.58	29.96	30.31	30.42	30.76	31.04
	Experiment 2	24.73	25.76	26.80	27.53	28.18	28.71	29.32	29.62	30.16	30.59	30.61	30.80	31.00
	Experiment 3	24.59	25.63	26.50	27.4	28.26	28.81	29.14	29.66	30.10	30.33	30.64	31.03	31.39
	Experiment 4	25.15	25.85	26.89	27.68	28.38	28.84	29.49	29.94	30.13	30.5	30.64	31.09	31.34
	Experiment 5	24.90	25.64	26.55	27.77	28.22	28.82	29.24	29.67	30.12	30.51	30.45	30.82	31.11
	Experiment 6	25.01	25.84	26.80	27.69	28.32	28.92	29.52	29.80	30.15	30.62	30.85	31.14	31.29
	Experiment 7	25.34	26.12	26.98	27.88	28.73	29.19	29.67	30.25	30.42	30.82	31.26	31.49	31.84
	Experiment 8	25.16	26.14	27.13	28.01	28.69	29.12	29.69	30.30	30.64	30.78	31.14	31.43	31.72
	Experiment 9	25.29	26.22	27.01	27.76	28.48	29.01	29.48	29.85	30.25	30.47	30.70	30.87	31.15
	Experiment 10	24.63	25.47	26.59	27.38	28.02	28.62	28.99	29.58	29.86	30.21	30.42	30.78	30.94
	Average	24.96	25.86	26.78	27.66	28.35	28.87	29.37	29.83	30.18	30.51	30.71	31.02	31.28
Normalization	1.00	1.04	1.07	1.11	1.14	1.16	1.18	1.19	1.21	1.22	1.23	1.24	1.25	
Standard Deviation	0.26	0.23	0.21	0.20	0.22	0.18	0.23	0.25	0.21	0.19	0.28	0.25	0.29	
Standard Deviation (%)	26	23	21	20	22	18	23	25	21	19	28	25	29	

For the experiments performed using healthy pinion via passive thermography, the systems with and without lubrication had their temperature stabilized in about 60 minutes, as demonstrated in Tables 6 and 7, and Figs. 8 and 10. For these tests, the temperature averages and the normalized values in the final minutes indicated this equivalence. For the non-lubricated gear, the temperature decreased by 12% and, for the lubricated gear, the temperature decreased by 8%. As with the first experiments by active thermography, in average, the standard deviation for lubricated gears was smaller. In non-lubricated gears, this deviation decreases over time, as shown in Fig. 12.

For all tests carried out by passive thermography, a temperature peak appeared in about 5 minutes of the experiment, as demonstrated in Figs. 8 and 10. This phenomenon is attributed to pinion heat dissipation not being noticeable immediately after the system is stopped. As expected, for the lubricated geared pair, this peak was slightly less expressive as the grease acts as a thermal insulator, promoting an adhesive film of undefined thickness capable to generate greater thermal resistivity than the air. On the other hand, when the geared pair is not lubricated, air is the only fluid acting in heat transfer from the gear.

Table 6. Temperature data via passive thermography for the gears without lubrication and faults

		Time (min)												
		0	5	10	15	20	25	30	35	40	45	50	55	60
No Lubrication - Passive Thermography (°C)	Experiment 1	33.70	33.74	33.43	32.88	32.35	31.90	31.42	30.95	30.54	30.19	29.81	29.50	29.16
	Experiment 2	33.80	34.11	33.68	32.81	32.43	31.86	31.46	30.99	30.55	30.06	29.94	29.61	29.32
	Experiment 3	33.05	33.18	32.80	32.59	32.06	31.56	31.17	30.72	30.40	29.99	29.68	29.44	29.13
	Experiment 4	33.03	33.24	32.83	32.42	31.94	31.47	31.09	30.71	30.29	29.99	29.67	29.29	29.14
	Experiment 5	32.47	32.78	32.46	31.90	31.48	30.99	30.90	30.49	30.05	29.73	29.32	29.06	28.72
	Experiment 6	32.62	32.83	32.65	32.23	31.83	31.42	31.07	30.59	30.36	30.04	29.69	29.24	29.04
	Experiment 7	32.32	32.47	32.30	32.02	31.63	31.22	30.73	30.33	29.89	29.70	29.32	29.05	28.76
	Experiment 8	32.36	32.16	31.99	31.47	30.90	30.54	30.22	29.81	29.51	29.21	28.95	28.69	28.39
	Experiment 9	32.53	32.34	31.99	31.59	31.2	30.79	30.40	30.00	29.58	29.22	29.08	28.72	28.56
	Experiment 10	31.75	31.95	31.61	31.21	30.88	30.44	30.21	29.77	29.44	29.09	28.76	28.56	28.25
	Average	32.76	32.88	32.57	32.11	31.67	31.22	30.87	30.44	30.06	29.72	29.42	29.12	28.85
	Normalization	1.00	1.00	0.99	0.98	0.97	0.95	0.94	0.93	0.92	0.91	0.90	0.89	0.88
	Standard Deviation	0.60	0.66	0.61	0.54	0.53	0.49	0.44	0.42	0.41	0.39	0.38	0.35	0.35
	Standard Deviation (%)	60	66	61	54	53	49	44	42	41	39	38	35	35

Table 7. Temperature data via passive thermography for the lubricated gears with faults.

		Time (min)												
		0	5	10	15	20	25	30	35	40	45	50	55	60
With Lubrication - Passive Thermography (°C)	Experiment 1	31.09	31.25	31.09	30.94	30.65	30.23	29.90	29.66	29.37	29.03	28.89	28.56	28.41
	Experiment 2	31.23	31.46	31.60	31.28	30.80	30.70	30.18	30.05	29.81	29.56	29.22	28.92	28.65
	Experiment 3	31.46	31.61	31.48	31.32	30.98	30.62	30.31	30.03	29.77	29.42	29.14	28.93	28.77
	Experiment 4	31.31	31.73	31.48	31.20	30.98	30.68	30.43	29.95	29.64	29.34	29.03	28.71	28.57
	Experiment 5	31.21	31.46	31.24	31.06	30.76	30.41	30.08	29.82	29.51	29.19	28.97	28.84	28.28
	Experiment 6	31.44	31.67	31.71	31.39	31.13	30.74	30.38	30.12	29.49	29.48	29.19	28.89	28.75
	Experiment 7	31.66	32.00	31.92	31.69	31.34	30.98	30.56	30.41	30.19	29.84	29.56	29.42	29.05
	Experiment 8	31.74	32.14	32.02	31.67	31.39	30.95	30.69	30.33	29.98	29.55	29.44	29.04	28.94
	Experiment 9	31.23	31.53	31.43	31.23	30.87	30.63	30.30	29.95	29.64	29.27	29.14	28.83	28.69
	Experiment 10	31.10	31.31	31.28	30.96	30.71	30.44	30.08	29.71	29.30	29.05	28.78	28.56	28.30
	Average	31.35	31.62	31.53	31.27	30.96	30.64	30.29	30.00	29.67	29.37	29.14	28.87	28.64
	Normalization	1.00	1.01	1.01	1.00	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91
	Standard Deviation	0.21	0.27	0.28	0.25	0.24	0.22	0.23	0.23	0.26	0.24	0.23	0.24	0.24
	Standard Deviation (%)	21	27	28	25	24	22	23	23	26	24	23	24	24

After the experiments with healthy pinion, tests were performed with faulty pinions. In this condition, initial temperature values were approximately 1 °C higher than that of previous experiments due to difficulties in room temperature stabilization as one of the walls in the room was receiving significant solar energy. By normalizing the data with respect to the initial room temperature, we overcame this problem. After performing the tests, we verified that the temperature values for faulty and healthy pinions are similar and confirmed that a substantial thermal gradient is not achieved. This characteristic becomes more evident after 40 minutes of testing. Thus, we conclude that active thermography was not able to detect faulty pinions, as shown in Tables 8 and 9, and Fig. 7.

Normalized data indicates that a 28% increase in temperature was achieved in systems operated with no lubrication, while with lubricated gears the observed temperature increased by 24% temperature after 60 minutes of continuous operation as shown in Fig. 9. In the operating situation without lubrication, data standard deviation decreased with time, starting at approximately 3% and ending with values below 1%. During operation with lubricated gears, the standard deviation of the gear temperature (for the pinion in its healthy condition), was more homogeneous, remaining at approximately 1% of the average value throughout the experiments as observed in Fig. 11.

Table 8. Temperature data via active thermography for the gears without lubrication and faults.

		Time (min)												
		0	5	10	15	20	25	30	35	40	45	50	55	60
No Lubrication - Active	Experiment 1	27.19	28.11	29.05	29.83	30.52	31.07	31.40	31.73	31.99	32.16	32.42	32.69	32.77
	Experiment 2	26.07	27.05	28.28	29.12	29.89	30.61	31.04	31.51	31.91	32.18	32.61	32.84	32.89

Thermography (°C)	Experiment 3	26.00	27.15	28.15	29.13	29.66	30.43	30.85	31.37	31.67	32.05	32.36	32.60	32.78
	Experiment 4	24.41	25.74	27.24	28.25	29.04	29.72	30.42	30.87	31.34	31.68	31.98	32.24	32.52
Experiment 5	25.32	26.75	28.01	28.92	29.77	30.44	30.94	31.42	31.8	32.20	32.40	32.65	32.98	32.98
Experiment 6	25.94	27.50	28.59	29.40	29.70	30.77	31.23	31.73	31.81	32.24	32.52	32.73	32.99	32.99
Experiment 7	25.21	26.49	27.81	28.86	29.63	30.29	30.69	31.11	31.46	31.86	32.10	32.36	32.60	32.60
Experiment 8	25.47	26.92	28.11	29.14	29.80	30.28	30.86	31.22	31.64	31.95	32.22	32.36	32.67	32.67
Experiment 9	24.64	26.28	27.54	28.48	29.30	29.91	30.44	30.94	31.36	31.61	32.09	32.18	32.52	32.52
Experiment 10	25.46	27.03	27.95	28.98	29.66	30.26	30.80	31.24	31.54	31.86	32.03	32.32	32.51	32.51
Average	25.57	26.90	28.07	29.01	29.70	30.38	30.87	31.31	31.65	31.98	32.27	32.50	32.72	32.72
Normalization	1.00	1.05	1.10	1.13	1.16	1.19	1.21	1.22	1.24	1.25	1.26	1.27	1.28	1.28
Standard Deviation	0.75	0.62	0.48	0.42	0.36	0.37	0.29	0.28	0.21	0.21	0.21	0.22	0.18	0.18
Standard Deviation (%)	75	62	48	42	36	37	29	28	21	21	21	22	18	18

Table 9. Temperature data via Active thermography for the lubricated gears with faults.

		Time (min)												
		0	5	10	15	20	25	30	35	40	45	50	55	60
With Lubrication - Active Thermography (°C)	Experiment 1	25.50	26.21	27.14	28.24	28.73	29.38	29.77	30.40	30.56	30.82	31.04	31.41	31.56
	Experiment 2	25.60	26.52	27.50	28.14	28.90	29.47	30.01	30.24	30.54	30.86	31.16	31.39	31.55
	Experiment 3	25.80	26.66	27.64	28.26	29.07	29.34	29.91	30.31	30.69	30.93	31.19	31.38	31.57
	Experiment 4	25.58	26.26	27.37	28.32	28.95	29.31	29.75	30.16	30.53	30.75	31.17	31.35	31.44
	Experiment 5	25.19	27.00	27.57	28.38	29.11	29.54	29.90	30.16	30.52	30.81	31.00	31.12	31.25
	Experiment 6	25.43	26.27	27.21	28.09	28.71	29.28	29.78	30.09	30.24	30.70	30.84	31.25	31.30
	Experiment 7	25.18	26.25	27.23	28.15	28.62	29.21	29.45	29.94	30.32	30.62	30.88	31.03	31.35
	Experiment 8	25.24	26.03	27.00	27.83	28.45	28.92	29.32	29.69	29.98	30.21	30.48	30.61	30.79
	Experiment 9	24.91	25.89	26.96	27.84	28.42	29.11	29.84	29.84	30.33	30.70	30.86	31.22	31.28
	Experiment 10	24.89	25.71	26.78	27.69	28.30	28.92	29.36	29.69	29.85	30.32	30.54	30.84	31.03
	Average	25.33	26.28	27.24	28.09	28.73	29.25	29.71	30.05	30.36	30.67	30.92	31.16	31.31
	Normalization	1.00	1.04	1.08	1.11	1.13	1.15	1.17	1.19	1.20	1.21	1.22	1.23	1.24
	Standard Deviation	0.29	0.36	0.27	0.22	0.27	0.20	0.23	0.24	0.26	0.22	0.24	0.25	0.24
Standard Deviation (%)	29	36	27	22	27	20	23	24	26	22	24	25	24	

Similarly to what was observed with healthy pinions, passive thermography experiments with faulty pinions also showed no significant variation in temperature values that could characterize the presence of an anomaly, as may be seen in Tables 10 and 11, and Figs. 8 and 10. The normalized and standard deviation values were analogous to those obtained for the passive tests in lubricated gears with or without flaws, presented in Tables 6 and 7. However, for the non-lubricated geared pair, the behavior of the deviations was homogeneous and 1% lower than the previous condition, as demonstrated in Fig. 12.

Table 10. Temperature data via passive thermography for the non-lubricated gears with faults.

		Time (min)												
		0	5	10	15	20	25	30	35	40	45	50	55	60
No Lubrication - Passive Thermography (°C)	Experiment 1	32.8	33	32.58	32.2	31.69	31.15	30.8	30.38	30.04	29.75	29.34	28.99	28.77
	Experiment 2	32.93	33.01	32.77	32.38	31.99	31.49	31.13	30.65	30.31	29.97	29.61	29.2	28.98
	Experiment 3	32.86	32.88	32.64	32.25	31.86	31.36	30.99	30.54	30.18	29.81	29.53	29.22	28.94
	Experiment 4	32.58	32.64	32.4	31.84	31.32	30.86	30.54	30.03	29.67	29.35	28.95	28.8	28.49
	Experiment 5	32.99	33.17	32.87	32.4	32.01	31.46	30.99	30.68	30.29	29.81	29.67	29.29	28.93
	Experiment 6	33.09	33.23	32.83	32.44	31.98	31.47	30.99	30.62	30.31	29.9	29.65	29.36	28.98
	Experiment 7	32.61	32.9	32.39	31.9	31.51	31.14	30.73	30.35	29.88	29.45	29.18	28.99	28.76
	Experiment 8	32.63	32.82	32.59	32.17	31.56	31.2	30.71	30.41	30.01	29.46	29.16	28.91	28.72
	Experiment 9	32.57	32.74	32.24	31.86	31.39	31.06	30.63	30.24	29.71	29.56	29.24	29.03	28.7
	Experiment 10	32.55	32.63	32.29	31.86	31.54	31.04	30.6	30.09	29.64	29.5	29.08	28.87	28.44
	Average	32.76	32.90	32.56	32.13	31.69	31.22	30.81	30.40	30.00	29.66	29.34	29.07	28.77
	Normalization	1.00	1.00	0.99	0.98	0.97	0.95	0.94	0.93	0.92	0.91	0.90	0.89	0.88
	Standard Deviation	0.19	0.19	0.21	0.23	0.25	0.20	0.19	0.22	0.25	0.21	0.25	0.18	0.18
Standard Deviation (%)	19	19	21	23	25	20	19	22	25	21	25	18	18	

Table 11. Temperature data via passive thermography for the lubricated gears with faults.

		Time (min)												
		0	5	10	15	20	25	30	35	40	45	50	55	60
With Lubrication - Passive Thermography (°C)	Experiment 1	31.66	31.97	31.85	31.52	31.15	30.84	30.47	30	29.77	29.29	29.07	28.84	28.54
	Experiment 2	31.59	31.9	31.82	31.45	31.11	30.66	30.27	29.77	29.6	29.32	29.03	28.67	28.44
	Experiment 3	31.55	31.91	31.83	31.34	30.98	30.54	30.24	29.98	29.54	29.25	28.93	28.62	28.45
	Experiment 4	31.6	31.8	31.75	31.43	31.18	30.71	30.48	30.06	29.61	29.4	29.18	28.87	28.64
	Experiment 5	31.35	31.76	31.51	31.25	30.78	30.49	30.19	29.78	29.36	29.08	28.78	28.53	28.31

Experiment 6	31.43	31.8	31.81	31.4	31.02	30.63	30.34	29.83	29.55	29.27	28.95	28.74	28.45
Experiment 7	31.42	31.71	31.46	31.1	30.72	30.39	29.98	29.66	29.52	29.08	28.77	28.47	28.22
Experiment 8	30.95	31.33	31.09	30.8	30.39	30.09	29.77	29.46	29.12	28.71	28.68	28.44	28.2
Experiment 9	31.34	31.74	31.56	31.28	30.9	30.57	30.26	29.82	29.53	29.16	28.87	28.66	28.47
Experiment 10	31.1	31.31	31.19	30.86	30.49	30.16	29.86	29.48	29.14	28.83	28.52	28.31	27.97
Average	31.40	31.72	31.59	31.24	30.87	30.51	30.19	29.78	29.47	29.14	28.88	28.62	28.37
Normalization	1.00	1.01	1.01	1.00	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.90
Standard Deviation	0.22	0.22	0.26	0.24	0.26	0.22	0.23	0.19	0.20	0.21	0.19	0.17	0.19
Standard Deviation (%)	22	22	26	24	26	22	23	19	20	21	19	17	19

Figs. 7 and 10 illustrate the average temperature values that testify the proximity between the final values for experiments with healthy and faulty pinions, using active and passive thermography techniques. Figs. 9 and 10 illustrate this behavior with the normalized data for the same conditions. Figs. 11 and 12 illustrate the standard deviation behavior for tests performed via active and passive thermography, respectively, showing each operating condition of the geared pair.

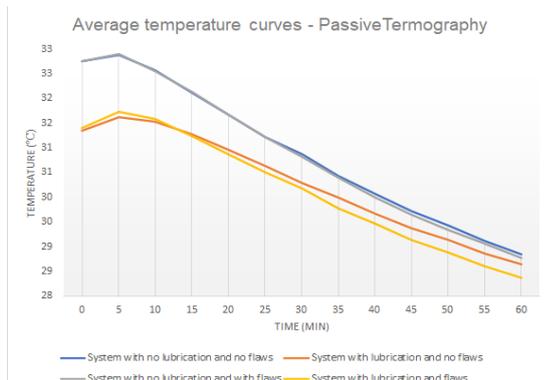


Figure 8. Average temperature curves by passive thermography for the four operating conditions.

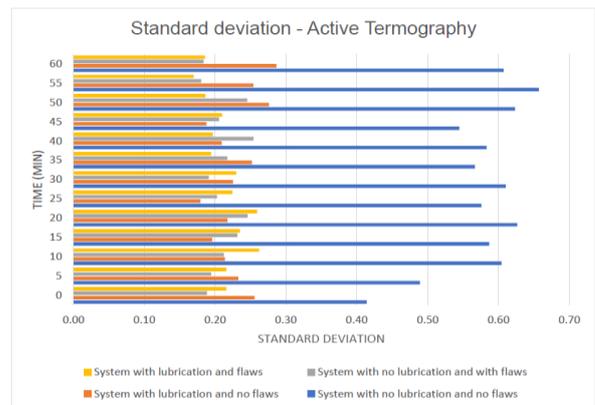


Figure 11. Average standard deviation via active thermography.

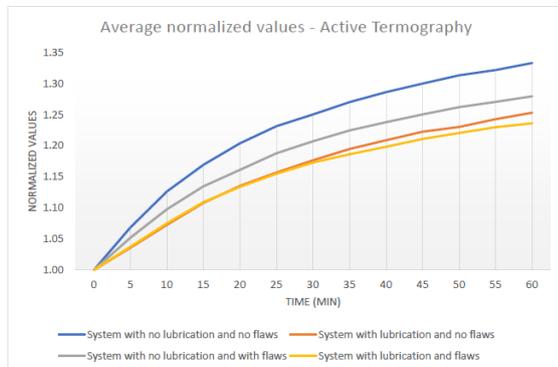


Figure 9. Average normalized values by active thermography for the four operating conditions.

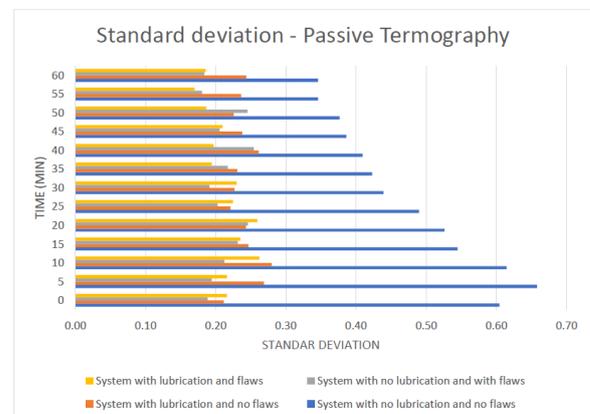


Figure 12. Average standard deviation via passive thermography.

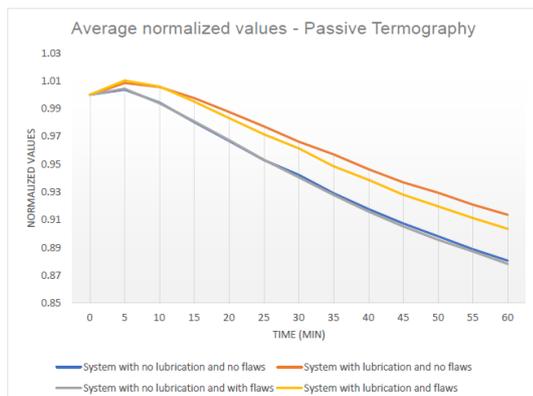


Figure 10. Average normalized values by passive thermography for the four operating conditions.

4. CONCLUSIONS

Our experimental results indicate that quantitative thermography is not effective to detect failures caused by fatigue when the lubricated pinion is working at constant rotation. However, this technique enabled us to identify an abnormal temperature increase in the pinions at running-in stage. Also, the standard deviation was higher in this phase, which proves the instability of the measured values in this situation.

When data was normalized with respect to the initial test temperature, a difference between the data obtained for lubricated gears and non-lubricated gears could be observed. Although these gradients were evident, thermography is deemed not efficient for industrial applications, since the temperature differences between the experiments are not high enough to allow us to diagnose the lack of lubrication or running-in. Additionally, an external heat source (an oven, for example), an overload, or a mechanical failure may increase the system temperature, which may lead to a misclassification of the heat source. For the lubricated gears, the standard deviation was homogeneous, attesting to the element higher thermal stability. Based on the results obtained, we conclude that quantitative thermography, in its active and passive methods, is not adequate to analyze the lack of lubrication and superficial flaws in the teeth of cylindrical spur gears.

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