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Determination of the mechanical thermostat electrical contacts switching quality with sound and vibration analysis [†]

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Abstract

A mechanical thermostat is a device that switches heating or cooling appliances on or off based on temperature. For this kind of use, electronic or mechanical switching concepts are applied. During the production of electrical contacts, several irregularities can occur leading to improper switching events of the thermostat electrical contacts. This paper presents a non-obstructive method based on the fact that when the switching event occurs it can be heard and felt by human senses. We performed several laboratory tests with two different methods. The first method includes thermostat switch sound signal analysis during the switching event. The second method is based on sampling of the accelerometer signal during the switching event. The results show that the sound analysis approach has great potential. The approach enables an accurate determination of the switching event even if the sampled signal carries also the switching event of the neighbour thermostat.

Keywords: Mechanical thermostat; Switch; Electrical contacts; Sound analysis; Accelerometer; IMU

1. Introduction

Electromechanical switches (EMS) as electromechanical devices are installed in a huge number of devices from everyday life and are very important for proper, safe and economic operation of home appliances [1]. The switching principle can base on force produced by current flowing through a coil (e.g. electromagnetic relays) acting on the electrical contact or as completely mechanical solution based on acting force of spring element. The basic task of EMS devices is to switch on or off communication or power electrical circuit. As EMS are very important, their performance should be reliable and operational life should be long [2].

Very important and present in our every day lives are electromechanical thermostats, used for switching on or off the (usually 230 V AC) electrical circuits at a certain temperature. Thermostats are installed in boilers, heaters, cooking stoves and many other appliances that need temperature regulation.

The mechanical thermostat can be split into the sensor and the electromechanical part (Fig. 1). The sensor part consists of three hollow components: sensing element, capillary tube and membrane. All three are welded together as one assembly. This assembly is filled with oil or gas that changes its volume when the sensing element temperature changes. When the volume of the oil or gas changes, the membrane stretches or extends and acts with force on the rocker and on the switch element. The spring rocker is designed to jump from one position to another when the force on it is high enough. This event locks the switch element into a steady position. The control shaft rotation is used to set the switching temperature. The thermostat housing can be made out of plastic or a combination of ceramic and metal.

Switches or devices for switching electrical circuits on or off can be generally split into Electromechanical (EM) and Solid state (SS). Each has advantages and disadvantages, but in terms of specific application requirements, one wins over the other [3].

When installed and used properly, SS devices last longer than devices in which they are installed. Their operation is silent and produce little electrical interference. The operational input voltages have a wide range and consume little power even at high voltages. One of the main advantages is that SS devices do not produce arc and for this reason are suitable for hazardous environments. Also, SS devices have no moving parts, so physical shocks or vibrations do not affect the performance.

On the other hand, the electromechanical switches have one or more moving parts, they usually fail due to the degradation effects of switching contacts due to arcing and fretting [4], though they are usually cheaper than SS devices. When the circuit must be completely on or off, the only choice is to

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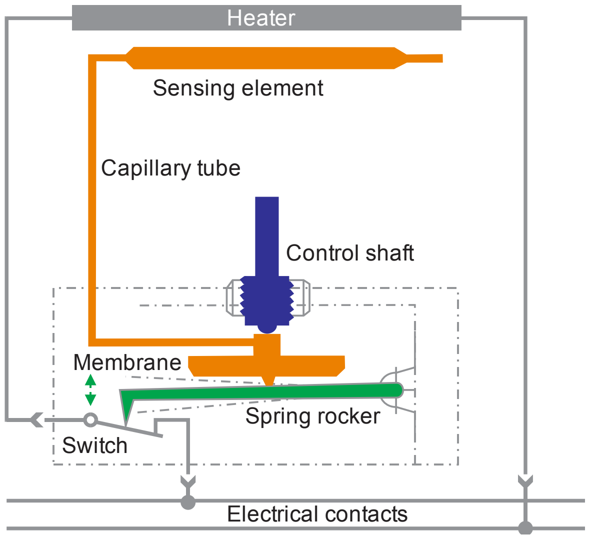

Fig. 1. Mechanical thermostat working principle.

choose an electromechanical switch with minimal on-state voltage drop and no danger of consequences originating from leakage current. EMSs are also better at heavy surge currents or spike voltages, usually present at mechanical thermostat applications, such as heaters.

The performance and lifespan of electromechanical switches and relays can be of a major concern in many power and communication applications [5]. The main reason for short lifetime and performance is too high applied voltage [6] or current, but also the vibrations acting on the assembly, the minimum force that pushes the electrical contacts together and also the shape of electrical contacts have a big influence on device quality [7]. Besides these reasons, the literature presents also failure after long-term storage when contact resistance increases [8].

The mechanical thermostat has an electrical switch triggered by a spring rocker (Fig. 1). As by all mechanical switches the electrical contacts can debounce in the switching phase for a few times before the contacts are fixed together. The debouncing effect is non-ideal behavior of the contacts that creates multiple electrical transitions and last around 0.3 s, declared as slow event. The duration of bouncing and the period can be different for each bounce, typical bounce frequency is from 200 Hz to 10 kHz. Because of the manufacturing assembly irregularities and false input materials the spring rocker does not jump instantly from one position to another, but moves slowly, pushing the switch also slowly into switching contacts state. If this happens, the switching contacts are electrically connected, but the switch force holding the switching contact together is not high enough, producing higher contact resistance. This means that the electrical contacts are ruined at higher current or even that the current flows over the thermostat assembly metal parts, which are not suitable for high current flow. For this reason it is impossible to test the switch operation only by verifying the electrical resistance. Our task was to find and test a suitable redundant and non-obstructive method that can be implemented into the production line.

When the mechanical thermostat electrical switch is properly switched the spring rocker produces a sound click when the rocker jumps from one position to another. This event produces also a gentle mechanical shock of the thermostat housing, felt by human fingers. In this article we evaluated two non-obstructive methods for testing if the spring rocker switched the electrical contacts of the thermostat properly or not. The first method is based on spring rocker sound analysis and the second is based on measuring vibrations of the thermostat housing as a consequence of the switching event. Besides checking the proposed solutions it was necessary to determine if several mechanical thermostats can be examined in parallel, positioned near one by one as are positioned in the production line where they are tested if the switching functions of the thermostat are operational.

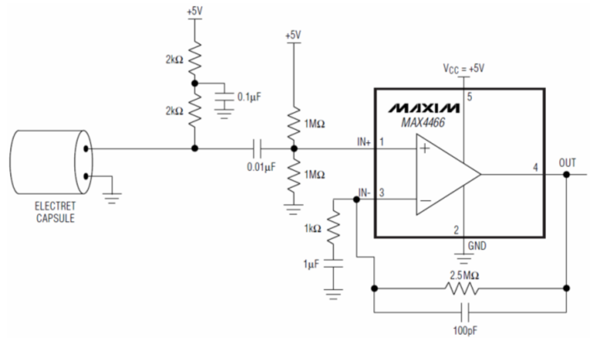

Fig. 2. Microphone amplifier.

2. Measurement equipment

For testing purposes three mechanical thermostats of the same type EGO 55.17062.460 were used. The thermostat family EGO 55.17x consists of 267 different thermostats with the same housing, switching element and rotational shaft, but differs in number of contacts and especially in sensing element parameters. For this reasons it is not necessary to perform experiments on different types of thermostats, because all have the same type and construction of the electrical switch.

All chosen thermostats have the nominal final switching temperature at 337 °C set by the control shaft at the maximum rotation position (clockwise). At minimum rotation position the switching temperature is at room temperature (defined 22 °C). The housing of this thermostat type is a combination of ceramic base and metal envelope.

For the evaluation of thermostat switching sound a dedicated one stage amplifier (Fig. 2) with total gain of cca. 2500 was developed. It is based on a MAX4466, a micropower op-amp optimized microphone preamplifier. Also, an omnidirectional electret microphone from Pro Signal company was used, type MCE-100 with a frequency range from 50 Hz to 10 kHz, sensitivity 5.6 mV/Pa/1 kHz, output impedance 2 kΩ, signal to noise ratio greater than 34 dB and allowed power supply

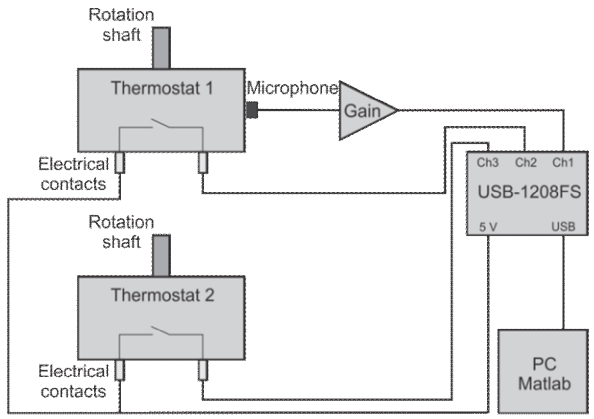

Fig. 3. Schematics for thermostat switching sound evaluation.

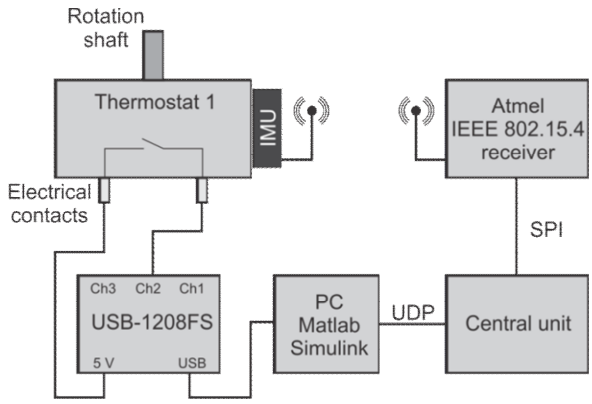

Fig. 4. Schematics for thermostat switching vibrations evaluation.

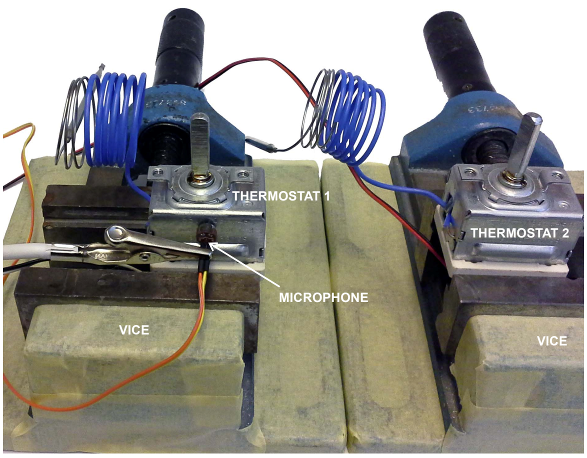

Fig. 5. Test bed for sound evaluation.

from 1.5 VDC to 10 VDC at 5 mA. For the power source for the audio amplifier we used 5 V output from USB-1208FS device from measurement computing company (Fig. 3).

The amplified signal from microphone (OUT on Fig. 2) was connected to an USB-1208FS device. It is an analog input and digital I/O data acquisition device that provides several features, among others also eight 12-bit (differential input) or 11-bit (single-ended) analog input channels at ±10 V input voltage. For signal capturing, Matlab running on a PC was used with in-built drivers as an interface with USB-1208FS device. The USB-1208FS device was also used as a 5 V power source to capture the switching event of the electrical contact of both thermostats (Fig. 3).

In addition to the evaluation of spring rocker switching sound we have tested also the possibility to measure the vibrations of the thermostat housing (Fig. 4) during spring rocker switching event. For this experiment an Inertial measurement unit (IMU) was used [9]. It consists of three digital sensors: an InvenSense 3-axis gyroscope IMU-3000, STmicroelectronics 3-axis accelerometer LIS331DLH and Honeywell 3-axis magnetometer HMC5883L.

During the experiment we have only sampled the data from the accelerometer. It enables a selectable range of ±2 g, ±4 g and ±8 g and has 16-bit output per axis. The highest possible sampling rate is 1 kHz and enables software selection of high-pass filters. During the experiment we have selected the accelerometer range of ±2 g and used all 16 bits to obtain 6 μs^{-2} resolution.

All sensors communicate via the I^2C bus with a maximum data transfer rate of 222 kbit/s. Each sensor provides 6 bytes of information (2 bytes per axis), total of 18 bytes. The theoretically attainable data transfer rate of the I^2C communication protocol is 1.2 kHz, but the maximum rate is fixed at 300 Hz due to limitations of the wireless 2.4 GHz IEEE 802.15.4 transceiver module that provides the connection to the Atmel IEEE 802.15.4 receiver, central unit via SPI and then via UDP to the PC and Matlab Simulink environment. Alongside the accelerometer data also the thermostat electrical switch contact state was sampled (Fig. 4).

3. Methodology

3.1 Sound analysis

In Fig. 5 the implementation of the experimental setup is shown. It can be seen that two mechanical thermostats are firmly positioned with two individual vices. The in-between space between the thermostats is 10 cm, the same as in the actual production line. The experiments were taking place in silent environment as can be realistically obtained also in the production environment. The thermostat on the left side, marked with number 1, has a microphone positioned around 1 mm from the thermostat housing. The amplified signal from the microphone is connected to the AD channel 1 of the USB-1208FS device. Both thermostats have one electrical contact pin connected to the 5 V power source of the USB device. The other contact pin of the thermostat 1 is connected to the AD channel 2 and electrical contact pin of the thermostat 2 is connected to the AD channel 3 of the USB device (Fig. 3). Which channel is sampled depends on the measuring protocol, described further in the text. All AD channels were sampled with 20 kHz (time resolution of 50 μs) as a single-ended (11-bit resolution + 1 sign bit) signal having a range from -5 V to 5 V. In Matlab several dedicated programs were written enabling capturing of the AD data into the workspace for further processing. All captured signals were additionally filtered with the use of high-pass 3rd order Butterworth filter with a cut-off frequency of 1 kHz to remove low frequencies, especially the power line frequency of 50 Hz.

3.1.1 One switching thermostat

Initial tests focused on capturing the switching sound signal from thermostat 1 on AD channel 1. Also, the electrical connection of the thermostat electrical switch was sampled on AD channel 2 to compare the properties of the sound and electrical signal. In Matlab the dedicated program was started to store traces of both signals. To enable quicker thermostat switching procedures two small containers with cold and hot water were used.

Before the start of the measuring and sampling procedure these two containers were used to set the thermostat shaft in the right position to set the switching temperature. First the temperature sensing element was put in the cold water container to cool the sensing element down. After a while the sensing element was put in the hot water container. If the thermostat switched during the change, the shaft was set in a proper position. If not, the procedure was repeated until the switching event occurred.

At the start of the measuring and signal sampling procedure the thermostat sensing element was first put in a cold water container to cool down the sensing element. After a while the thermostat sensing element was put into the hot water container until the thermostat electrical contact switched. Following this, the thermostat sensing element was put into the cold water to reverse the thermostat switch position. The procedure was repeated several times, each time with different thermostats numbered from 1 to 3, all causing cycling of several switching on and switching off events with adequate sampling time that lasted maximum 35 seconds as a preset time limit of a USB-1208FS sampling device.

3.1.2 Two switching thermostats

The methodology when two thermostats were switching was almost the same. Thermostat number 1 was equipped with a microphone whose amplified signal was connected to the AD channel 1 and its electrical contacts were connected to the AD channel 2. The second thermostat, marked with No. 2 in Fig. 5, did not have its own microphone, because we wanted to check if the switching sound from thermostat 2 can be heard on the microphone at thermostat 1. Thermostat 2 had also its electrical contacts connected to the AD channel 3. During analysis this signal was not important and could be left out. The temperature cycling procedure for both thermostats was the same as in previous experiment by using two chambers with cold and hot water.

Before the testing procedure began, both thermostats rotation shafts were set to switch at approximately the same time when sensing elements were moved from one water chamber to another.

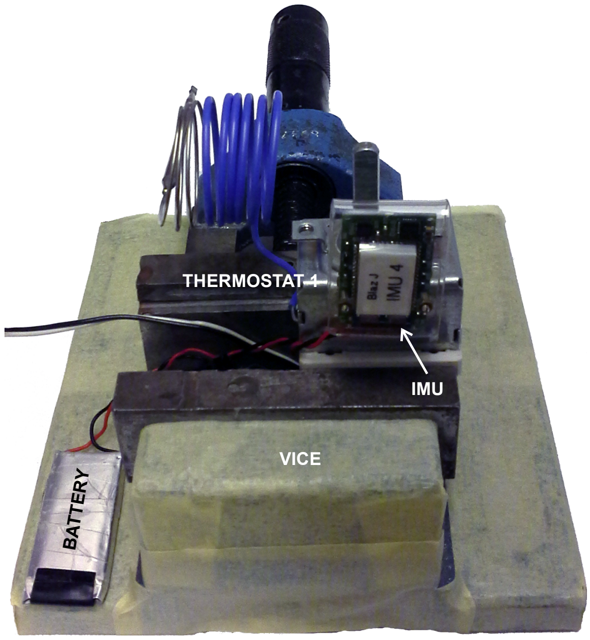

Fig. 6. Test bed for accelerations evaluation.

At the start of the measuring and signal sampling procedure, both sensing elements were first put in a cold water container to cool down the sensor. After a while, both thermostats sensing elements were put into hot water until both thermostat electrical contacts switched. Following this, both thermostat sensing elements were put into cold water to reverse the thermostat switch position. The procedure was repeated 3 times with the same combination of thermostats, causing cycling of several switching on and switching off events with adequate sampling time that lasted maximum 35 seconds as a preset time limit of a USB-1208FS sampling device. The whole procedure was repeated several times with repeatable results.

3.2 Vibrations analysis

For vibration analysis several trials were performed. The measuring approach during this experiment was almost the same as in the sound evaluation. The IMU unit was attached on one side of the thermostat housing in experiment 1 (Fig. 6), on control shaft in experiment 2 and on ceramic housing in experiment 3 with a thin two sided tape. With changing the position of the IMU unit we tested if its position can affect the sampling of the vibration signal.

At the beginning of the experiment the thermostat switch was off. In Matlab two programs were started, one as Matlab script and the other as a Simulink scheme. Matlab script sampled the data from AD channel 2 that captured the state of the electrical switch of the thermostat and the Simulink scheme captured the accelerometer data from the IMU unit. Matlab script was started first and Simulink as second. For this reason, the signals were not synchronised. This was not necessary, since the only information needed is approximate time when

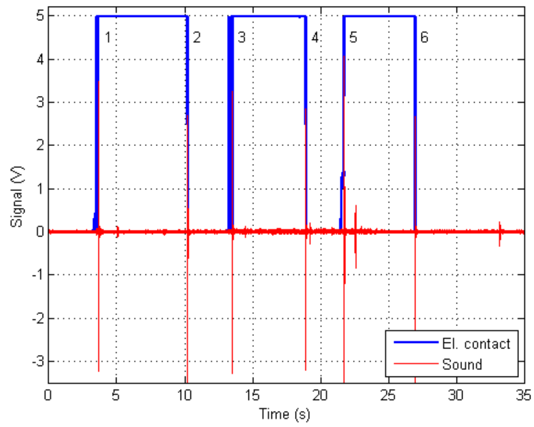

Fig. 7. Captured sound and electrical contact of thermostat 1.

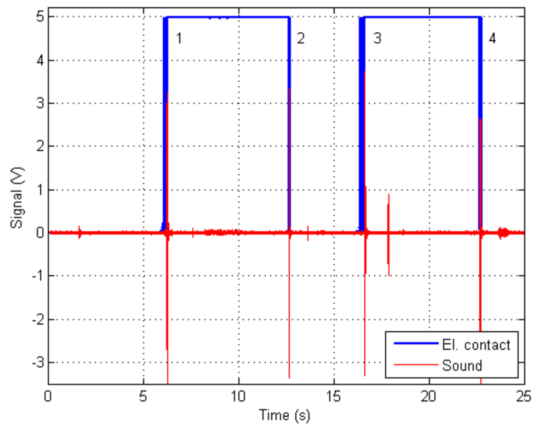

Fig. 8. Captured sound and electrical contact of thermostat 2.

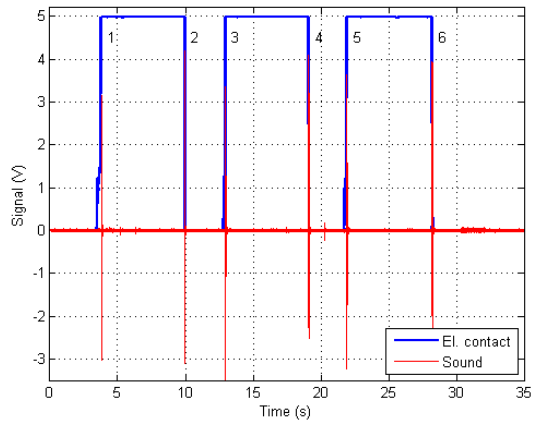

Fig. 9. Captured sound and electrical contact of thermostat 3.

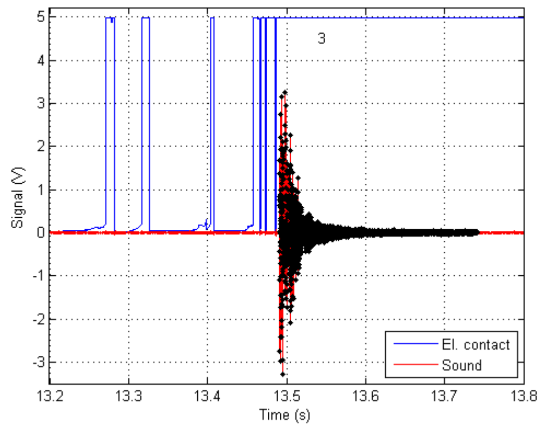

Fig. 10. Detail of switching on event for thermostat 1, marked with number 3 and area calculation.

the thermostat switch changes the state, to be able to compare with the accelerometer data. Sample frequency was 100 Hz.

Before the start of the measuring and sampling procedure it was necessary to set the thermostat shaft in the right position to set the switching temperature. This procedure was the same as in previous experiments.

The experimental procedure started by putting the thermostat sensing element from cold water into the chamber with hot water until the sound of the switch changed the state to on. Next, the sensing element was put into the chamber with cold water to flip the switch to off. The procedure and experiment was repeated several times. The whole experiment was repeated 3 times. During the second repetition the IMU unit was mounted on the rotational shaft and during the third repetition on the thermostat ceramic housing. The change of IMU location was needed to be able to distinguish if the change of location has an impact on the experimental results.

4. Results

4.1 Sound analysis

4.1.1 One switching thermostat

In Figs. 7-9 the captured sound signals are presented for all 3 test thermostats. The horizontal axis represents time in seconds, on the vertical axis is the captured voltage from ADC (USB-1208FS). In Figs. 7 and 9 can be seen that all three complete switching cycles were captured, marked with numbers from 1 to 6. With numbers 1, 3 and 5 the switch on events are marked, while numbers 2, 4 and 6 mark the switch off events. In Fig. 8 two complete switching cycles were captured, marked with numbers from 1 to 4. With numbers 1 and 3 the switch on events are marked, while numbers 2 and 4 mark the switch off events. The thin line represents sound signal and the thick line represents thermostat electrical contact voltage.

In Figs. 10 and 11 the details of switching events number 3 and 4 for thermostat 1 are displayed. Both of the figures clearly show that the mechanical switching is not suspended immediately, some debouncing events could not be overlooked. The debouncing occurs because the electrical contacts bounds to each other.

The same contacts debouncing behaviour occurred also at all thermostat 2 switching events. Two of them are displayed in Figs. 12 and 13. From Figs. 10 and 13 it can be clearly seen that the switch electrically changes the state at least 6 times in

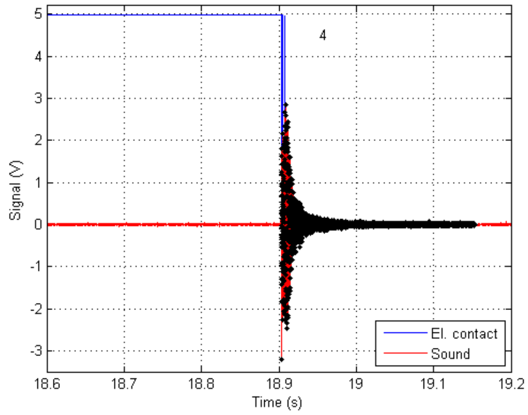

Fig. 11. Detail of switching off event for thermostat 1, marked with number 4 and area calculation.

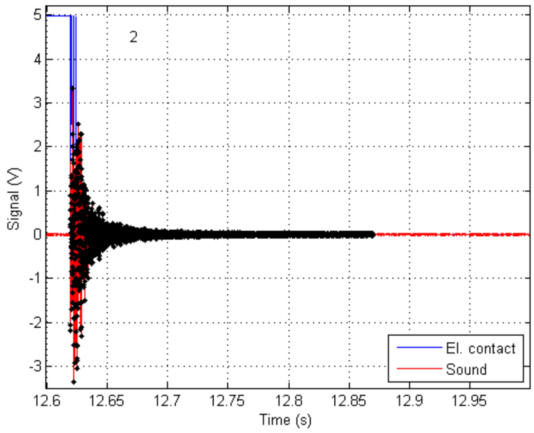

Fig. 12. Detail of switching off event for thermostat 2, marked with number 2 and area calculation.

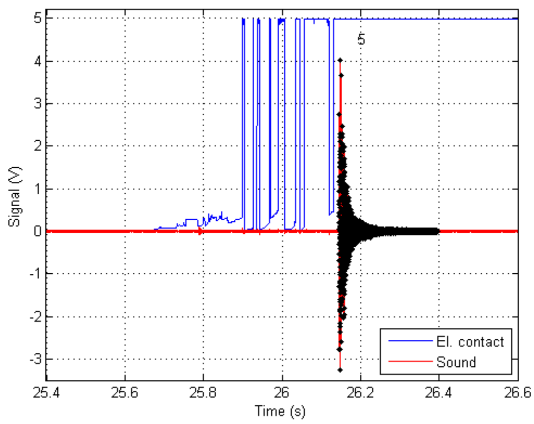

Fig. 13. Detail of switching on event for thermostat 2, marked with number 5 and area calculation.

the time window of 0.3 seconds before the spring rocker flips the switch into the steady state. At switching off events (Figs. 11 and 12) the number of mechanical debouncing events of the contacts is smaller because the contacts are moving away from each other.

Figs. 14 and 15 show the switch on events 1 and 3 for ther-

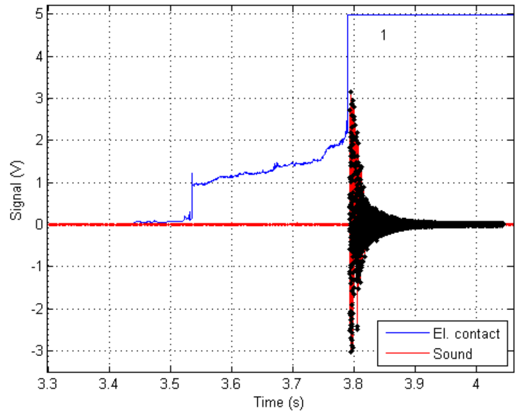

Fig. 14. Detail of switching on event for thermostat 3, marked with number 1 and area calculation.

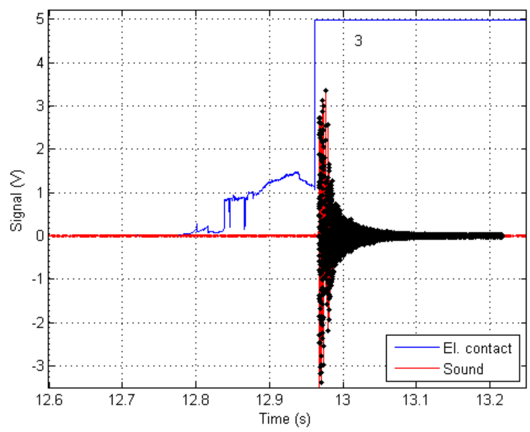

Fig. 15. Detail of switching on event for thermostat 3, marked with number 3 and area calculation.

mostat number 3. It can be clearly seen that no debouncing effect is present during switch on events, only the contact resistance changes following with the immediate fixation of the contacts. This kind of switching shows a possible problem with spring rocker or the switch itself. If there would be no instant change in sampled voltage and the contacts still conduct current, than the acting force between the contacts is not large enough. This means that there would be no sound at the time of switching event.

The traces show that detection of proper switching of the switch can be performed with sound evaluation, because the sampling of the sound on all detailed figures show the area where sound click is sampled.

Of a greater interest was the dilemma whether we could differentiate which thermostat switched in the case when switching sound from several thermostats are sampled. For this reason a method was developed that is able to define which thermostat switched, on the basis of sound amplitude. For this reason the presented data was used and is based on the sum of absolute values of the sound signal in the switching area as depicted in Figs. 10-15, marked with dots. The summation is started when the sound signal exceeds 1 V and lasts 0.25 s

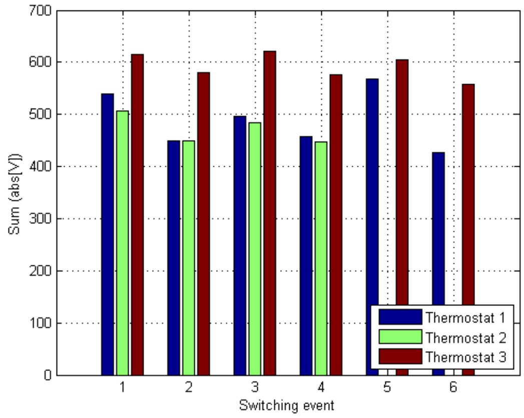

Fig. 16. Area sum for all switching events.

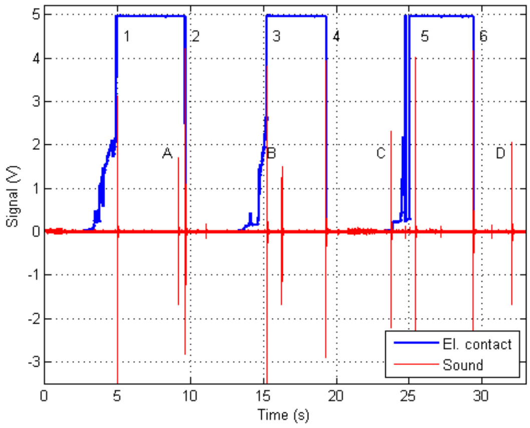

Fig. 17. Captured sound and electrical contacts for thermostat 1 and sound from thermostat 2; experiment 1.

(5000 samples).

In Fig. 16 the horizontal axis represents switching event number and the vertical axis the sum of absolute value of the sound signal from the microphone. The results are displayed for all three thermostats. It can be clearly seen that the sum of all switching areas of captured signals have value over 400, enabling statistical determination if the procedure is implemented in the production. Small value deviations can be also observed. For switching events numbered 1, 3 and 5 larger sums are present than by switching off events numbered 2, 4 and 6. This can be heard also by human ear and can be explained as the spring rocker flipping back without any obstacle, meaning that is not pushing the electrical switch of the mechanical thermostat.

4.1.2 Two switching thermostats

Figs. 17-19 show three experiments where it can be clearly seen that the microphone positioned near the thermostat 1 also picks up the switching sound from thermostat number 2. The switching events from thermostat 1 are marked with numbers and switching events for thermostat 2 are marked with letters.

The horizontal axis in Figs. 17-19 represents time in seconds and on the vertical axis is the captured voltage from

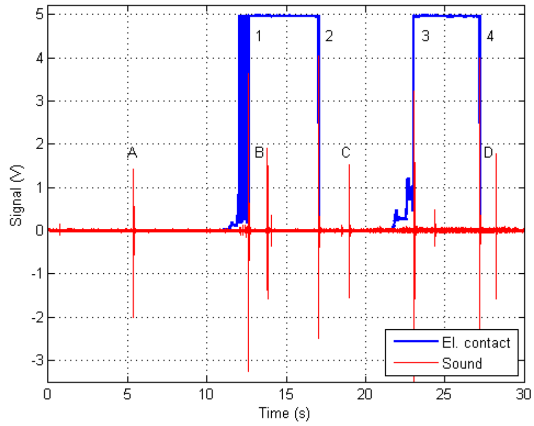

Fig. 18. Captured sound and electrical contacts for thermostat 1 and sound from thermostat 2; experiment 2.

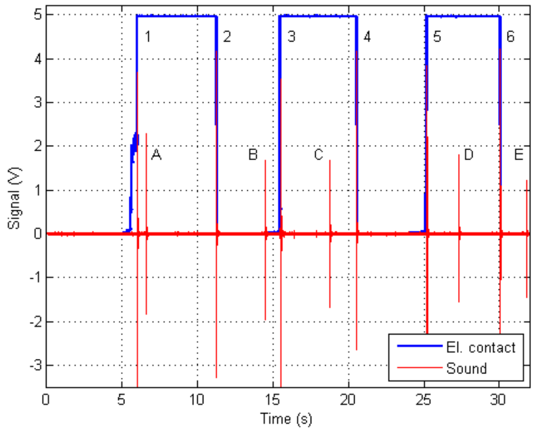

Fig. 19. Captured sound and electrical contacts for thermostat 1 and sound from thermostat 2; experiment 3.

ADC (USB-1208FS). The thin line represents sound signal and the thick line represents thermostat electrical contact voltage.

From Figs. 17-19 it is evident that the sound signal captured from thermostat 2 marked with letters has lower amplitude than the sound amplitude captured from thermostat 2.

To be able to distinguish which thermostat switched, the area sum method was used again with the result presented in Figs. 20-22. Based on previous observations (Fig. 16) it can be recognized that the area sum of switching events of thermostat 1 has again values larger than 400.

The same analysis for thermostat 2 show sums lower than 400, closer to 200. The switching events marked with numbers on horizontal axis belong to the switching events of thermostat 1, while the switching events marked with letters belong to thermostat 2. On the vertical axis the sums of absolute voltage values are presented.

Based on the results of this experiment we were able to set the threshold at value 350 to define the switching event for the thermostat equipped with the microphone. As can be seen in Fig. 23, marked with vertical black lines, the threshold approach defines the switching events properly.

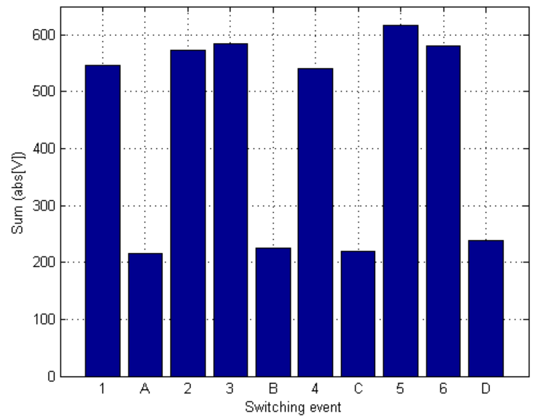

Fig. 20. Area sum for all switching events for both thermostats; experiment 1.

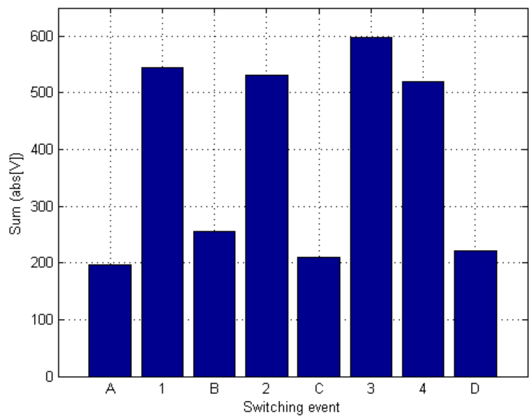

Fig. 21. Area sum for all switching events for both thermostats; experiment 2.

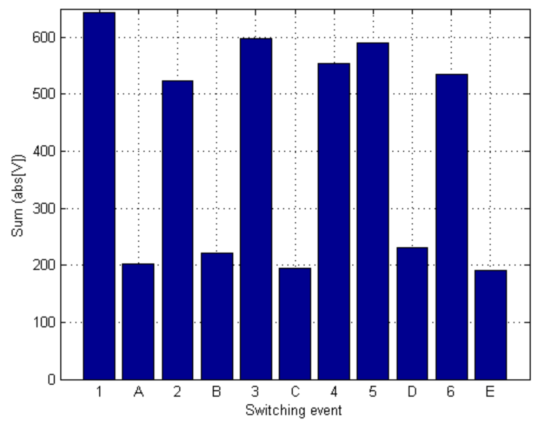

Fig. 22. Area sum for all switching events for both thermostats; experiment 3.

4.2 Vibrations analysis

The comparison results between sampling of the state of thermostat electrical switch and accelerometer data from IMU

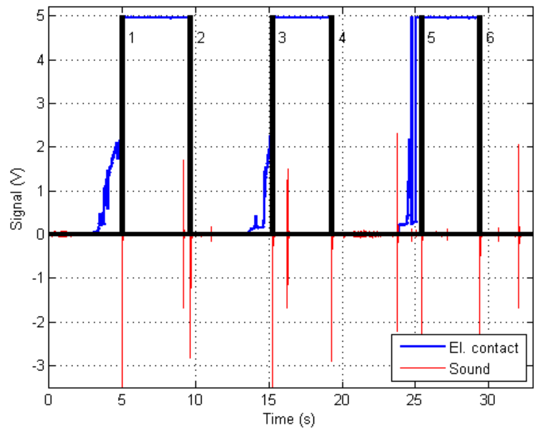

Fig. 23. Detecting switching events of the proper thermostat; experiment 1.

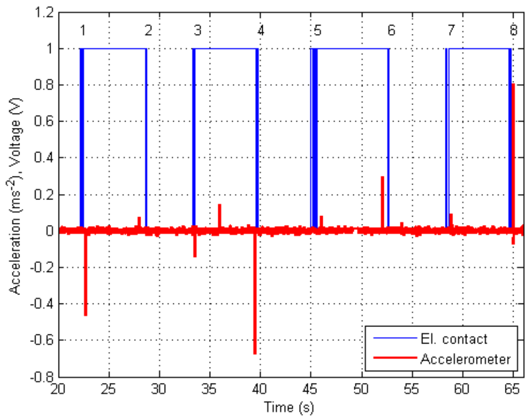

Fig. 24. Detecting switching events based on accelerometer data; IMU attached on metal housing.

unit is displayed in Figs. 24-26.

On the horizontal axis the time is displayed and on the vertical axis the acceleration in ms^{-2} is displayed, but multiplied by a factor 5 to be more evident on the chart. The data from AD channel 2 in volts was scaled also to fit best on the chart in regard to the accelerometer data values. The accelerometer returns 3 data values for X, Y and Z axis of the coordinate frame of the accelerometer. The individual accelerometer sampled values were combined in a vector and the length of this vector is displayed as the accelerometer data. The thin line on the chart represents the thermostat contact state data and the thick line represents the accelerometer data.

As can be evident from all figures, all switching events of the thermostat electrical switch were captured. This data is very helpful to determine if the accelerometer reading could determine when the thermostat electrical switch caused vibration of the housing.

During all experiments several accelerometer spikes are present. Some in positive and some in negative direction having different amplitudes. It would make sense that switching on would made a spike in one direction and switching off

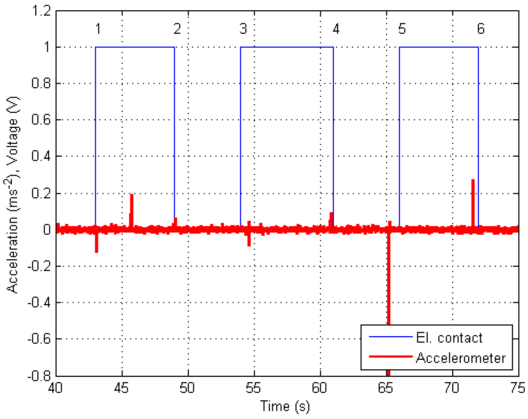

Fig. 25. Detecting switching events based on accelerometer data; IMU attached on control shaft.

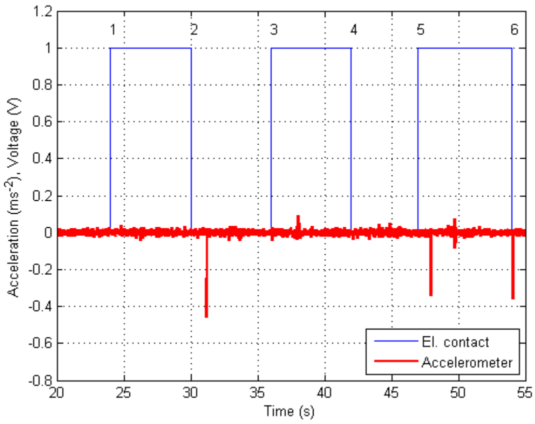

Fig. 26. Detecting switching events based on accelerometer data; IMU attached on cheramic housing.

event would made an accelerometers spike in the other direction. In Fig. 24 at the first switching event a negative spike is present with a quite large amplitude and at the second switching event a positive, but with a very small amplitude. At the third switching event again the negative acceleration spike is present, but before the fourth switching event two spikes are present, both in different directions. Just after the fifth switching event a small positive acceleration spike is present and just before the sixth switching event another one, but with a larger amplitude. At the last two switching events again two accelerometer spikes can be seen with quite small amplitudes. When all switching events passed, another spike was recorded. The same random events from the accelerometer were sampled also during both further experiments displayed in Figs. 25 and 26.

5. Discussion

The current testing method of electrical switching elements using only the electrical contact of the mechanical thermostat can be deemed unreliable. The protocol where only electrical

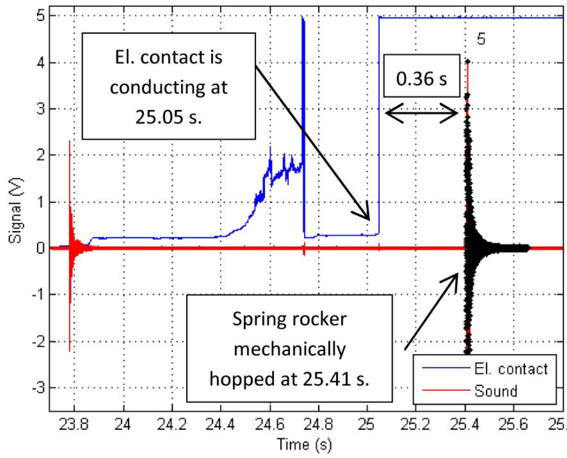

Fig. 27. Detail of switching event where the mechanical sound delays after electrical contact is present.

characteristics of the switch is checked can give false results when the spring rocker is false and does not push the electrical contacts together with proper force. When this happens the switch conducts current, but when appliances with a large power consumption are controlled with the thermostat, the electrical contacts overheat and are ruined permanently. During experiments (Fig. 17, event 5) an event was sampled (Fig. 27) where the electrical contacts were conducting current (at 25.05 s), but the spring rocker mechanically hopped the switch with a proper force after 0.36 s (at 25.41 s). If the spring rocker or some part of the electrical switch is false, the spring rocker hopping may never occur.

This drawback can be surpassed with thermostat spring rocker sound or vibrations evaluation as a redundant and non-obstructive method. When the membrane is expanded enough the spring rocker mechanically hops, pushing the electrical contacts firmly together. This hop can be heard and felt by human senses.

The first tested method was spring rocker sound evaluation in combination with the electrical properties of the switch. The results show that the method can be used to define when and if the spring rocker hops into the steady position. The drawback of this approach is not so easy implementation into the production facilities where a lot of other sounds and vibrations are present. The solution to this problem would be to sound isolate the testing area from other production facilities in combination with direction specialized microphones.

In the production test area several thermostats are tested at the same time. For this reason it is necessary to select the target thermostat sound from other sounds. The proposed method with detected signal of switching event being summed seems to be the right approach. This way the method detected the target thermostat switching event in all experiments. The sound signals from other thermostats have lower amplitudes and as a result also lower summed areas.

The second tested method is based on measuring the acceleration and deceleration of the thermostat housing during the switching events by using an accelerometer. These results are not so promising. It was impossible to define the exact time of the switching events on the basis of accelerometer data. Another drawback of this method is its limited implementation possibility in the production line environment. It might be close to impossible to filter out all the surrounding vibrations.

A very important aspect during the implementation of proposed sound method into the production facilities is also the fact that only one type of thermostat was tested. Several other thermostat types exist, differing in construction and assembly materials, but can be heard or felt by human senses in the same way as by the used type in presented experiments. Nevertheless, it is necessary to test also some other thermostat types to check for possible problems before implementation in the production line. Also, we did not have any thermostats available that would have a faulty spring rocker and do not produce sound and vibrations during the switching event. To demonstrate the problem the nearest situation is displayed in Fig. 27.

6. Conclusions

We tested two methods for checking the switching event of the mechanical thermostat switch as a parallel method to the current checking method in the production line. The first method is based on sound evaluation of the switching event. The second method involves measuring the acceleration of the thermostat housing due to the switching event. The first method proved to be very promising and can be developed further and tested on other thermostat types as well and also implemented into the production facilities. The second method did not give promising results and for this reason our opinion is that it can not be effectively used in the production line.

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