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Adaptive Temperature Control of a Household Refrigerator

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***Abstract*—Temperature control in household refrigerators and freezers is typically operated through simple on–off actuation devices, which limit the obtainable control performance and flexibility and determine a nonlinear behavior of the system. This manuscript describes an adaptive scheme that improves the characteristics of the induced temperature oscillations, without requiring modifications of the actuation hardware. The adaptive control scheme is then tested on a benchmark simulation model of a commercial refrigerator.**

I. Introduction

TEMPERATURE control in household refrigerators and freezers has been long investigated in the literature (see, *e.g.*, [1, 2, 3]). Recently, the subject has acquired new interest due to the increasing importance of environmental and energy–related issues, that call for more sophisticated control solutions [4]. The problem is interesting from the control perspective, since only low–end sensing and actuating devices are typically available on such appliances.

Proposed control solutions range from relay control techniques to systems based on fuzzy logic [5] or neural networks [6], etc. A discriminating factor in the design is also the availability of a variable–speed compressor (see, *e.g.*, [7, 8]), as opposed to a less expensive fixed–speed (*i.e.*, on–off) one [1]. The latter case is here addressed, employing standard on–off relay–based control enhanced with an adaptive scheme designed to increase the control performance and flexibility with a negligible cost increase.

The use of simple relays with hysteresis for control purposes is expected to drive the system temperature on a limit cycle [9, 10]. The period and amplitude of such cycle influence a number of relevant characteristics of the system. In particular, an excessive temperature swing may affect the food preservation properties [11], while too frequent compressor activations lead to excessive power consumption and mechanical components wear. Industry standards have been defined to assess the preservation and consumption behaviour of an appliance (see [12] and its bibliography).

Given the high content variability of the appliance, a fixed relay tuning may provide too conservative a solution if tight requirements on food preservation and energy consumption are to be met. This work presents a simple adaptive control scheme, designed to tune the characteristics of the temperature limit cycle, in order to minimize amplitude excursion, for apparent food preservation reasons, while maximising the period, to reduce the compressor upset. The presented scheme employs an additional linear filter in the control loop, and is sufficiently simple to be implemented on the standard microcontroller installed in the appliance.

Although the proposed method is quite general, in this work we will focus exclusively on household refrigerator appliances consisting of two cavities (one for the freezer and one for the refrigerator) and a single refrigerating source (a standard cooling circuit with a compressor).

The method has been tested on a detailed simulation model of a commercial refrigerator with the described structure, namely the Whirlpool® Marisienka Full No–Frost (MFNF) refrigerator (see Fig. 1), to demonstrate its applicability and performance. The presented results complement those of a previous experimental activity on a qualitatively different type of refrigerator [13]. In addition, a more detailed analysis on the feasibility of the presented adaptive algorithm on the given appliance is provided.

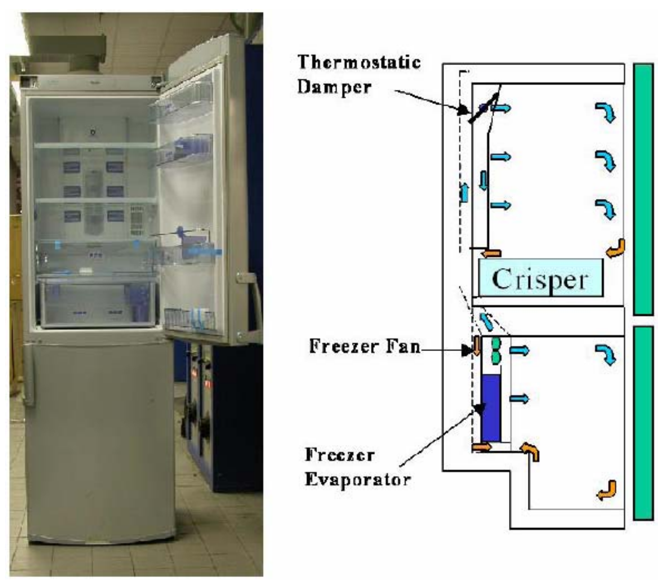

Fig. 1. The MFNF refrigerator (left) and the scheme showing the internal air flows (right).

II. The Marisienka Full No–frost Refrigerator

The MFNF refrigerator consists of two cavities: the freezer, which is cooled directly by the refrigerating system (compressor and cooling circuit), and the refrigerator cavity,

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which is not directly connected to the refrigerating system but is instead cooled by sliding open a damper connecting it to the freezer whenever it is necessary. A fan makes the air circulate inside the cavities as shown in the scheme of Fig. 1. The compressor, the damper and the fan have all on–off actuators.

Following standard test configurations, both cavities contain several packs with prescribed thermal characteristics. More precisely, the freezer and the refrigerator contain two food packs each (a cold one and a hot one), the packs in the refrigerator containing also an inner pack.

A lumped–parameter model has been derived for the refrigerator, greatly simplifying the convection dynamics, and describing only the fundamental heat exchange phenomena occurring in the device, which are relevant for the control design. As typical in the such cases, the model is actually composed of several ordinary differential equations of the type:

$$C_i\dot{T}_i = \sum_k G_k(T_k - T_i) - W_i,$$

that describe the thermal accumulation associated with the fundamental air cavities and the thermal exchange occurring between contiguous elements. In the previous expression C_i are the thermal capacities associated to air cavities, G_i represent equivalent conductances related to thermal exchange, T_i are the temperatures of air cavities or test packs, and W_i are external power terms. Further details on the model are omitted herein for reasons of intellectual property protection, in agreement with Whirlpool's policy.

The on–off actuation devices (evaporator, damper and fan), as well as the door openings, can be modeled by introducing suitable localized model variations. More specifically, the activation of the evaporator can be modeled by the introduction of an external power term. The switching of the other devices modifies the thermal convection properties of the system. For example, when activated, the fan and the damper increase air convection in the device.

The lumped–parameter model has been tested against an accurate simulation model and shown to yield sufficiently accurate results for the intended analysis.

III. The Adaptive Control Method

A. Relay–based control

Temperature control in refrigerators equipped with on–off compressors is typically achieved by means of the classical relay feedback loop (Figure 2).

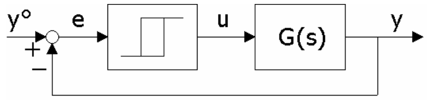

Fig. 2. Relay feedback loop.

Since the dynamics of the refrigerator are considerably slower than the freezer's, it is safe to neglect the coupling between the freezer and the refrigerator cavities. Therefore, the conceptual model adopted herein will consist of two loops of the type shown in Figure 2, operating in a decentralized fashion. A primary loop controls the freezer temperature acting on the compressor. The damper is actuated by a secondary loop having the refrigerator temperature as the set–point. The fan is simply activated when either the compressor is on or the damper is open (as is done on the commercial product), so that its state is determined by the previously explained control loops.

In general, a relay feedback loop is designed to drive the system to a permanent oscillatory condition around the set point. The describing function approach yields conditions for the occurrence of a permanent oscillation and to check the stability of the limit cycle (see, *e.g.*, [14, 15]). The two basic parameters of such oscillations (amplitude and frequency) for a given system depend on the relay's characteristic. The wider the relay's range, the slower the switching rate (this is rather obvious, since a wide range relay reacts more tolerantly towards fluctuations of the output). Conversely though, the slower the switching rate, the higher the oscillation amplitude. This is also quite intuitive because a low commutation rate of the control signal will grant more freedom to the error signal before changing the control signal. Therefore, typically, performance improvements for one parameter come at the expense of the other one.

The system's behavior also depends heavily on parameters that cannot be known beforehand (such as type and quantity of the objects stored within the refrigerator, room temperature, etc.). What is more, if the system is subject to variations, the performance of the system is likely to become sub–optimal over time.

B. A describing function interpretation of the introduction of a phase shifting filter in the feedback loop

The well known describing function approximation states that a linear system, subject to a nonlinear static feedback, will enter a permanent oscillation if the Nyquist curve $G(j\omega)$ of that linear system intersects the critical point locus associated to the static nonlinearity (see Figure 3).

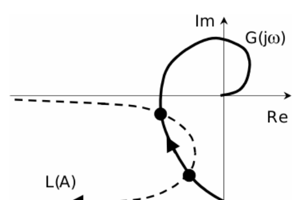

Fig. 3. Polar representation of the transfer function $G(s)$ and the critical point locus.

The intersection points determine the amplitude and frequency of the only possible permanent oscillations that are compatible with the feedback system. In particular, for a relay without hysteresis, the critical point locus coincides with the negative real axis, so that the limit cycle occurs at the frequency ω_u at which $arg(G(j\omega)) = -180°$.

By inserting a linear block $F(s)$ in the loop as in Figure 4, one can modify the frequency response of the linear dynamics seen by the relay to $F(j\omega)G(j\omega)$, thereby distorting the critical point locus. This can be used for identification purposes to find different points of $G(j\omega)$, by analysis of the resulting limit cycle characteristics [16, 17, 18, 19]. For example, if $F(s) = 1/s$ and the relay has no (or negligible) hysteresis, the point found on $G(j\omega)$ is the one with phase $-90°$, since the limit cycle yields the ultimate point of $F(j\omega)G(j\omega)$, and $arg(F(j\omega)) = -90°$.

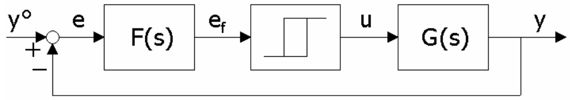

Fig. 4. Relay feedback with a phase shifting filter in the loop.

More in general the introduction of a phase shifting filter in the feedback loop has the effect of rotating the critical point locus associated to the nonlinear static feedback, as depicted in Figure 5. Notice that this rotation modifies the intersection points, thus changing the characteristics of the induced limit cycle (if any).

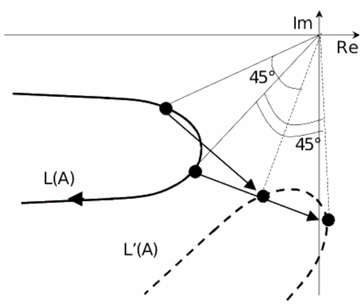

Fig. 5. Effect of adding a phase shift of 45° to the critical point locus.

C. The Adaptive On/Off Control Architecture

The same principle is here exploited for control purposes, rather than identification. By suitably designing $F(s)$ it is in fact possible to assign the characteristics of the induced oscillation, in the range of behaviors allowed by the given $G(j\omega)$. Furthermore, if $G(s)$ is time varying – as in the proposed setting – $F(s)$ can be adaptively tuned so that the limit cycle matches some specified criteria.

More precisely, the control system is equipped with a unitary gain filter, acting as a pure phase shifter, and a new component is developed that analyses the output of the system, computing the frequency and amplitude of each oscillation wave, and adjusts the filter by a given phase step until the performance is brought within acceptable thresholds. This control configuration (see Figure 6) is hereafter termed Adaptive On–Off Control (AOOC). The adaptive mechanism must closely monitor the oscillation characteristics, since phase shifting can impair the system's stability.

D. Phase shifting effects depending on the local characteristics of the system's frequency response

The modification of the oscillation properties induced by a phase shift depends on the characteristics of both the static nonlinearity and the controlled system. Focusing on the case of a single intersection point, for simplicity, the following two observations may be made:

ii) A positive phase shift will increase the oscillation frequency if $\left(\frac{d}{d\omega}\, arg(G(j\omega))\right) > 0$ in the vicinity of the intersection point.

ii) A positive phase shift will increase the oscillation amplitude if $\left(\frac{d}{d\omega}|G(j\omega)|\right)\cdot\left(\frac{d}{d\omega}\, arg(G(j\omega))\right) > 0$ in the vicinity of the intersection point.

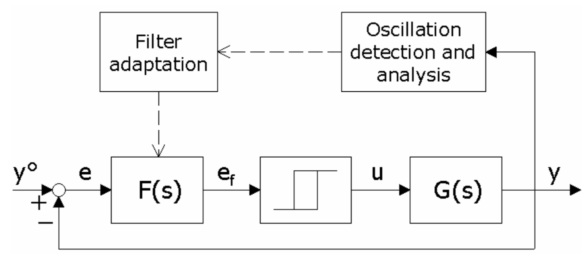

Fig. 6. Conceptual scheme of the AOOC system.

It is therefore important to determine the general characteristics of the controlled system, in order to be able to apply a phase shift with the correct sign.

The Bode diagrams represented in Figure 7 are obtained for the model of the MFNF refrigerator, for all possible combinations of the switching parameters (compressor, damper and fan, for a total of 2^3 model configurations).

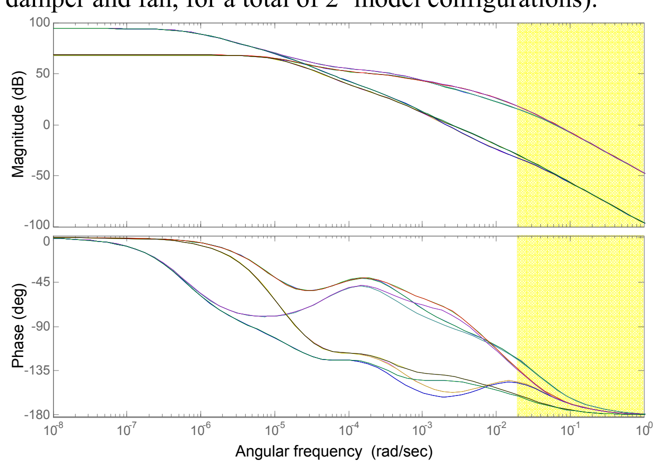

Fig. 7. Bode diagrams of the frequency response function associated to the MFNF refrigerator model for all possible combinations of the switching parameters.

Despite the considerable variability of the frequency response functions, one can observe that the system has reasonably low magnitude – in order to achieve suitably low amplitude oscillations – only in the last three represented decades. In that region, the magnitude is decreasing with frequency. A different reasoning applies to the phase: at the far right end of the diagram the phase is also decreasing with frequency for all cases, whereas in the two previous decades some combinations of the switching control signals result in a phase increasing with frequency. However, the working region is placed in the former frequency range (see highlighted part of Fig. 7), so that it is safe to assume that both the magnitude and the phase are decreasing for control purposes. As a result, if the filter provides a positive phase shift the oscillation period will increase, at the cost of an increase in the oscillation amplitude as well. A reasonable compromise needs to be found.

E. The adaptive algorithm's policy

The adaptive algorithm is set up to work as follows. The freezer temperature (the controlled variable) is continually monitored by a waveform detector to extract the waveform period and amplitude. A simple zero–crossing detection scheme that records set–point crossing instants is employed for this purpose. Since asymmetrical waveforms are typically generated, a complete period is measured by waiting for two consecutive set–point crossings from below. Once a complete waveform of the oscillating controlled signal has been recorded, its "amplitude" $\overline{A}$ (more precisely, the maximal signal excursion) and frequency $\overline{\omega}$ are obtained and used to adapt the filter.

More precisely, the current filter parameters will be modified so as to have a phase variation $\delta\varphi$ of fixed (small) entity and appropriate sign at the current oscillation frequency, according to the following scheme:

i) If the measured oscillation amplitude $\overline{A}$ is above the maximum limit A_{max}, the filter's phase is decreased by $\delta\varphi$, in order to reduce the oscillation amplitude (control of the temperature excursion around the set–point is the primary objective);

ii) If, on the other hand, $\overline{A} < A_{max}$ but the measured oscillation frequency $\overline{\omega}$ is higher than a desired threshold ω_{max}, the filter's phase is increased by $\delta\varphi$.

The value of the elementary phase variation $\delta\varphi$, which acts as the gain of the adaptive algorithm, must be chosen small enough to avoid endangering the system's stability, yet large enough to significantly affect performance. Given the nonlinear nature of the system, it is not easy (and in any case beyond the scope of this manuscript) to establish limits for $\delta\varphi$: the availability of a reliable model allows however to find suitable values for that parameter by trial and error in simulation, without the need of extensive and long testing on the real appliance.

To apply the intended phase in the control loop a unitary gain linear filter of the form

$$F(s) = \frac{1 + sT_z}{1 + sT_p}$$

is employed, which, by suitable setting of T_z and T_p, allows a phase range (–90°, 90°) at any frequency of interest. If the overall filter phase is negative (*i.e.*, if a lag is required), T_z is set to zero and only a pole is used. In the opposite case, a structure with a zero and high–frequency pole is used.

The adaptation scheme serves a double purpose. It primarily seeks to minimize the freezer's temperature excursion if the relay control by itself is not capable of achieving sufficient precision around the set–point. In this mode it increases the relay control performance. However, if the temperature has a sufficiently low excursion, there is room for oscillation frequency reduction, in order to diminish the device's switching activity, thereby increasing its lifetime.

IV. Simulation Results

The AOOC control scheme was tested against traditional relay control on the lumped–parameter model of the MFNF refrigerator. A simulation with a fixed phase–correction filter was also run, to show the benefits of phase correction alone.

Fig. 8 reports the simulation results obtained with the traditional relay feedback loop, where the relay's hysteresis zone has a global width of 2 degrees. As one can see, both the refrigerator and the freezer enter a qualitatively periodic sort of behavior, but in quite separate frequency bands (there is approximately a ratio of 1:4 between the frequency of the temperature in the refrigerator cavity and the one of the freezer). In particular, the freezer temperature "switching" frequency may be higher than necessary to obtain a comparable temperature amplitude swing.

Figure 9 shows the results of a simulation carried out with a suitable designed fixed phase–shifting in the feedback loop. The improvement in output "smoothness" (*i.e.*, the decrease in frequency) is apparent, showing the potential benefits of the AOOC scheme. Observe that the reduction of the commutation frequency of the compressor cannot be obtained without a cost in terms of a (small) increase of the temperature swing (recall that the oscillation characteristics are modulated by moving on the frequency response $G(j\omega)$, so that frequency and amplitude cannot be set independently).

As shown in Fig. 10, the AOOC scheme (operated with a maximum amplitude tolerance of ±1°C and a minimum period tolerance of 8 minutes) is actually capable of converging to the behavior envisaged in Figure 9. As time progresses the modulus of the (negative) phase of the filter increases (Fig. 10.d), leading the system's output to an increasingly smooth transition shape (at the expense of a higher oscillation amplitude). Notice also the expected decrease in the measured oscillation frequency resulting from the application of the AOOC.

The efficacy of the AOOC scheme can be further appreciated in a different functioning condition, *i.e.* with the refrigerator damper kept always open (Fig. 11). In this experiment, only the compressor on–off control command is active, and the progressive evolution of the freezer temperature oscillation towards a longer period is apparent.

V. Conclusions

An adaptive control scheme for temperature control in commercial refrigerators has been presented, which suitably tunes a phase–shifting filter in the feedback loop to affect the oscillatory properties of the standard relay control scheme. The method is designed to minimally perturb the hardware and software design of the device, using the same control architecture already available in commercial

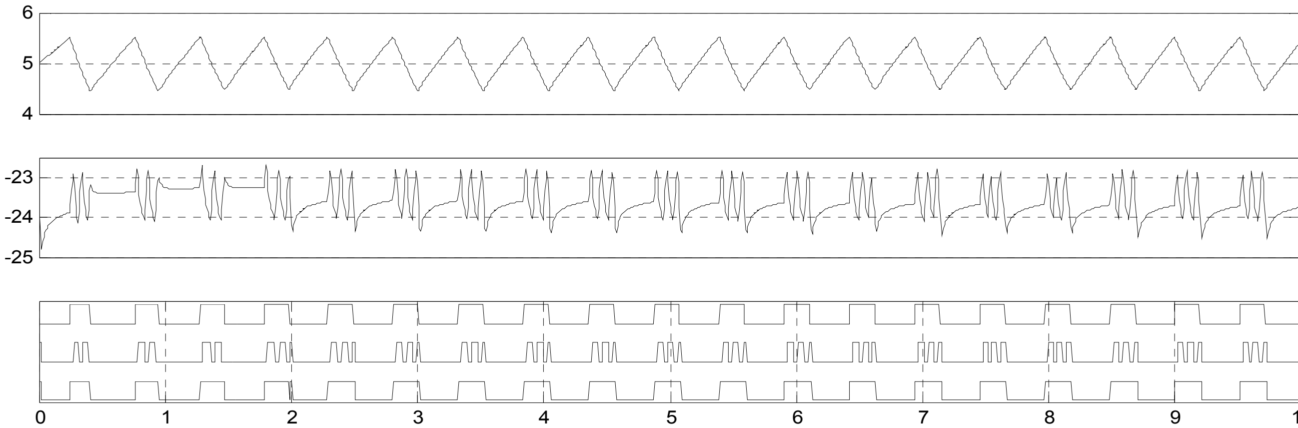

Fig. 8. Simulation results for the traditional relay–based control scheme. From top to bottom: a) refrigerator temperature, b) freezer temperature (middle), c) switching signals (top = damper, middle = compressor, bottom = fan).

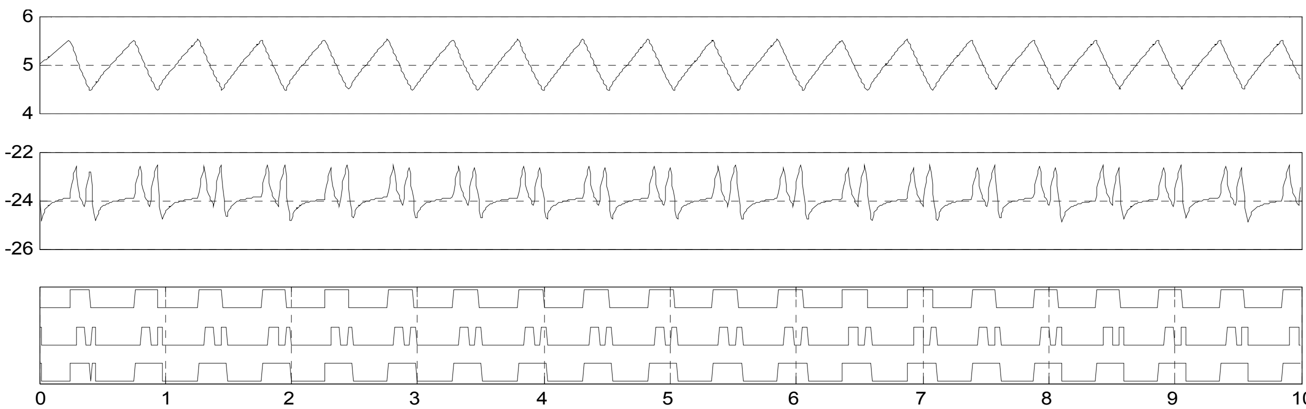

Fig. 9. Simulation results for the fixed filter control on the compressor, traditional control on the damper. From top to bottom: a) refrigerator temperature, b) freezer temperature (middle), c) switching signals (top = damper, middle = compressor, bottom = fan).

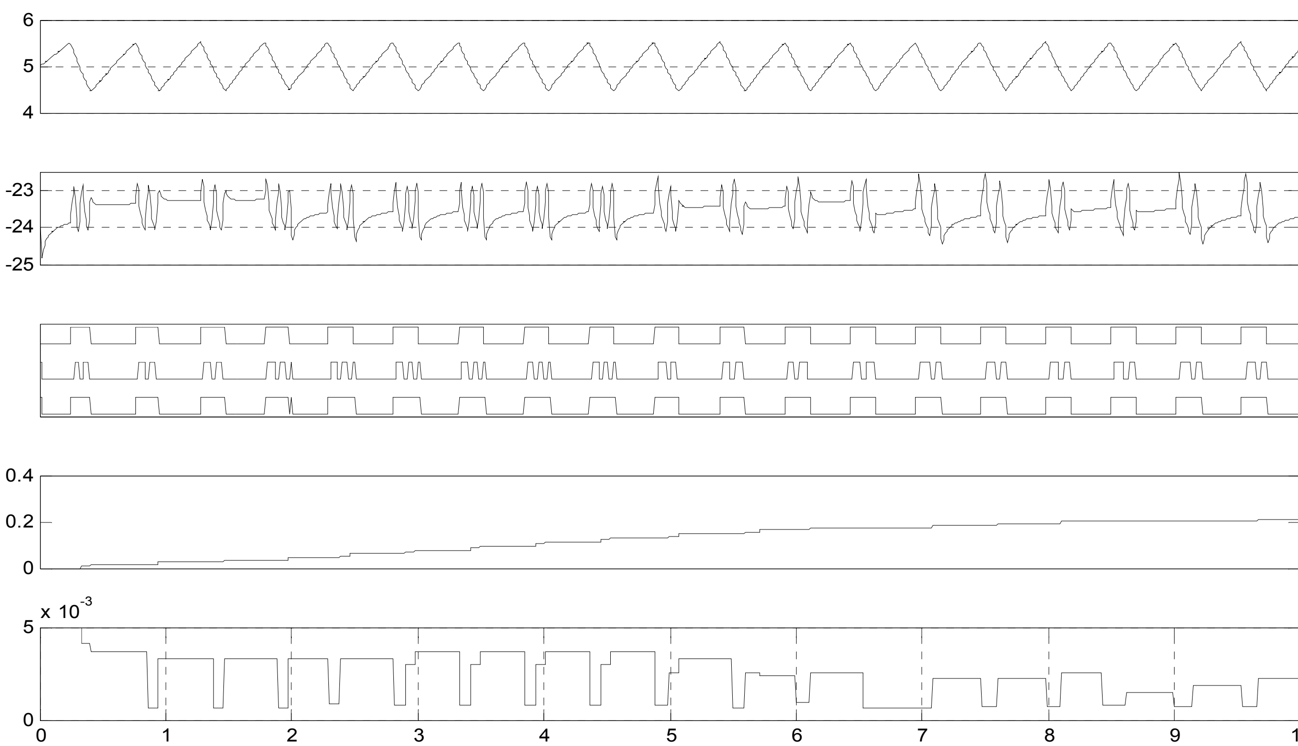

Fig. 10. Simulation results for the AOOC control on the compressor, traditional control on the damper. From top to bottom: a) refrigerator temperature, b) freezer temperature (middle), c) switching signals (top = damper, middle = compressor, bottom = fan), d) filter phase (radians), e) estimated waveform frequency (Hz).

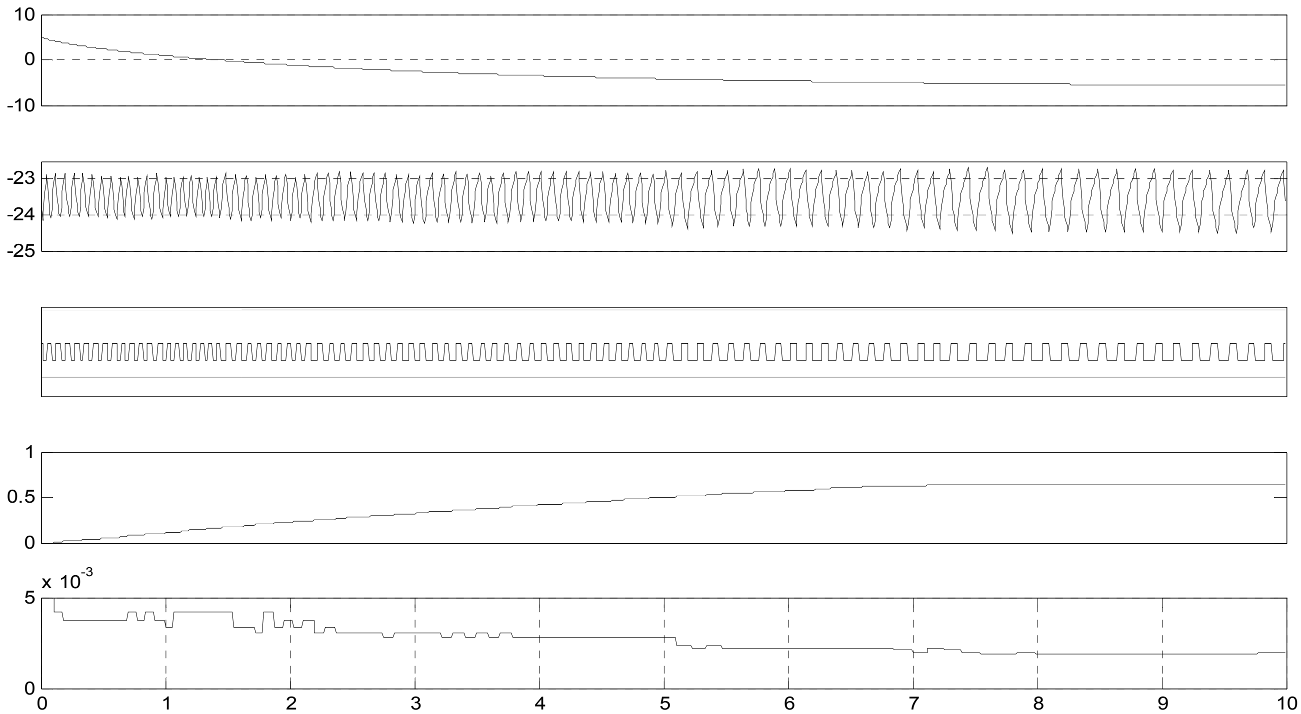

Fig. 11. Simulation results for the AOOC control on the compressor, with the damper always open. From top to bottom: a) refrigerator temperature, b) freezer temperature (middle), c) switching signals (top = damper, middle = compressor, bottom = fan), d) filter phase (radians), e) estimated waveform frequency (Hz).

refrigerators.

The activity was carried out with reference to the Whirlpool® Marisienka Full No–frost refrigerator, for which a lumped–parameter model was derived and used to evaluate the proposed scheme in simulation.

The focus is here restricted to the control of the freezer temperature. The presented scheme is already being extended to the control of both the freezer and refrigerator temperatures, and further extensions can be envisaged to multi–zone temperature control.

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