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Adaptive relay-based control of household freezers with on–off actuators

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ABSTRACT

This paper describes an adaptive scheme for temperature control in household freezers with low-end sensing and actuation equipment, like on–off compressors and dampers. The scheme is based on an auxiliary filter introduced in the relay loop to alter and improve the characteristics of the induced oscillation. The filter is tuned adaptively to cope with system variability and uncertainty. Some tests on detailed simulation models of a commercial appliance are reported to validate the approach and show its effectiveness with respect to both food preservation and energy consumption requirements.

1. Introduction and problem statement

Temperature control in household refrigerators and freezers has been the object of a long-lasting research effort, starting from pioneering works such as Jarrett (1972), and comprising industry-related researches like Knoop, Tershak, and Thieneman (1988), modelling and simulation works such as Ikegami, Nanayakkara, Nakashima, and Uehara (2001), and many other publications. In recent years, there has been a renaissance of the interest on the matter, owing to the increasing importance of environmental and energy-related issues, which both call for more sophisticated control solutions, see, e.g., Tanaka (2001). Indeed, by suitably exploiting results obtained in various domains, particularly process control, it is possible to improve the energy characteristics of an appliance at the sole cost of modifying the control strategy, not the device itself.

Besides the requirements introduced by food preservation and energy consumption considerations, temperature control is especially difficult if the refrigerator device is endowed with low-end sensing and actuating systems, as is typical for household appliances—a choice motivated by cost issues. Several control approaches have been attempted, ranging from traditional schemes based on relay control up to fuzzy logic, like, e.g., Becker, Oestreich, Hasse, and Litz (1994), and/or neural networks, such as Choi, Han, and Hong (1998). The developed applications can be roughly divided in two categories: those employing a variable-speed compressor (e.g., Buzelin, Amico, Vargas, & Parise, 2005; Liu, Chang, & Lin, 2004; Rasmussen & Ritchie, 1997; Tassou & Qureshi, 1994), and those with a fixed-speed (i.e., on–off) one, such as Jarrett (1972) and Lu and Ding (2006). It is worth noting that the on–off solution is less frequently investigated in the recent scientific literature, notwithstanding its usage in the overwhelming majority of household appliances. Comparisons of the two different types of actuation also exist, see, e.g., Wicks (2000), but when cost is an issue, the on–off solution is preferred over modulating actuators, even if it results in reduced performance and increases the complexity of the control analysis and assessment.

Relay control schemes operate by driving the controlled temperatures to eventually reach limit-cycle behaviours (Yu, 1984, 1999). In temperature control of refrigerator appliances, the period and amplitude of those limit cycles influence both food preservation and energy consumption: an excessive temperature swing may deteriorate the food (as explained in detail in Reid, 1999), 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 Harrington, 1994 and the references cited there).

Despite the apparent limitations of the on–off actuation solution, there is still room for some performance improvement by acting on the control policy. In particular, temperature oscillation characteristics can be partially modified, even with standard on–off actuation, to match specific requirements. This work, extending the preliminary results of Leva, Piroddi, and Boer (2008), presents a simple adaptive control scheme, designed to tune the characteristics of the temperature limit cycle, in order to

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minimise amplitude excursion, for food preservation reasons, while maximising the period, to reduce the compressor upset. The presented scheme inserts a linear filter in the relay control loop—an idea mutuated from relay-based identification techniques (Åström & Hägglund, 1991; Leva, 1993; Yu, 1999), where the filter is used to find a specific point of the process frequency response. Here, conversely, the filter is used for control purposes, i.e., to modify the characteristics of the induced temperature oscillations. Since the dynamics of the system are partially unknown and time varying (e.g., because of content variations or external temperature fluctuations), an adaptation mechanism is introduced to adjust the filter parameters on-line. A similar principle, albeit with a slightly more complex implementation scheme, was suggested in Rao and Atherton (1978) with reference to a satellite attitude control problem.

The presented scheme is sufficiently simple to be implemented on the microcontrollers typically installed in the considered appliances. The focus is here restricted to the control of a single temperature, namely that of the freezer, which poses the most stringent constraints (especially for preservation). The scheme is already being extended to the control of both the freezer and refrigerator temperatures, and further extensions can be envisaged to multi-zone control.

Some simulation tests referring to two different development stages of a single appliance are reported. Simulations were chosen so as to allow for reproducible test conditions, therefore leading to meaningful considerations and comparisons of the results. Also, the tests conform to those prescribed to verify the compatibility of an appliance with a certain energy consumption class. Correspondingly, the employed models are the same used by the manufacturer (Whirlpool) for the assessment of the control systems to be installed in the final products, which testifies the validity of the obtained results.

2. The considered appliance: model and control settings

The typical appliance considered in this work has two cavities (the freezer and the refrigerator) and a single refrigerating source, composed of a standard cooling circuit with an on–off compressor and a single evaporator, located in the freezer section (see Fig. 1).

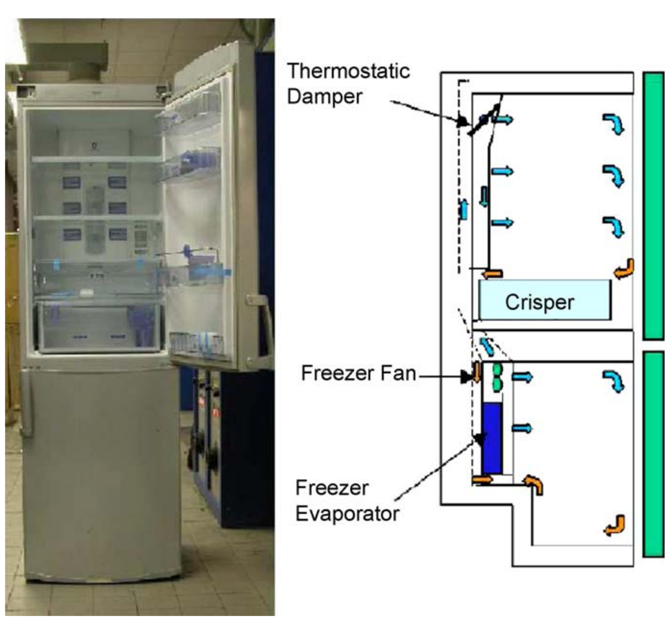

Fig. 1. (Left) Photograph of the considered appliance and (right) scheme showing the internal air flows.

Two simulation models are employed here, both referring to the "Marisienka full no-frost" refrigerator/freezer, manufactured by Whirlpool. Those models ("model 1" and "model 2") describe two different prototypes of the appliance: model 1 is an early realisation, while model 2 is relative to a more advanced version, very near to the final production one. The main difference between the two models is the internal air circulation system. Such simulation models are currently employed by Whirlpool for the assessment of commercial control systems, before final tuning is performed with a small number of physical tests on the *production* prototype. They are lumped models describing the fundamental heat exchanges in the appliance, and reproducing the test conditions prescribed by industry standards, including the fulfilment of energy consumption requirements (Harrington, 1994). In those models, the freezer and the refrigerator cavities are assumed to contain two "packs" each (a "cold" one and a "hot" one) with prescribed thermal characteristics, and each of the packs in the refrigerator contains also an "inner" pack, the aim of which is to represent the thermodynamic behaviour of the food. Detailed correlations involving power consumption, thermal losses, temperatures and so forth, plus the convenient physical parameters, allow to write the energy balance equations necessary to close the model. Such correlations, not publishable for intellectual/industrial property protection, were extensively tested by Whirlpool, and are considered fully reliable for the purpose of studies like this.

The freezer cavity is cooled directly by the refrigerating system, and is typically controlled by a relay loop having the freezer temperature as the set-point. The refrigerator cavity is instead cooled by sliding open a damper, that thermally connects it with the freezer whenever necessary. The damper is actuated by a secondary relay loop having the refrigerator temperature as the set-point. In addition, a fan is installed near the damper to facilitate air circulation, and is set on when either the compressor is on or the damper is open, and off otherwise. The dynamics of the refrigerator are generally slower than those of the freezer, so that it is safe to neglect the coupling between the two cavities for control purposes. A completely decentralised scheme is thus adopted in the following for the control of the two temperatures, the control action of each loop representing a disturbance for the other one. The on–off actuation devices (compressor, damper and fan), as well as the door openings, are modelled by introducing suitable localised model variations. More specifically, the compressor activation is modelled by the introduction of an external power term, whereas the switching of the other devices modifies the thermal convection properties of the system.

3. The proposed adaptive scheme

3.1. Design of on–off temperature control with the describing function approach

Temperature control in refrigerators is typically achieved by relay feedback, as shown in Fig. 2, so as to drive the system to a permanent oscillation around the set-point.

The well-known describing function approximation states that a closed loop system like that of Fig. 2 will enter a permanent oscillation if the frequency response $P(j\omega)$ of the linear part of the

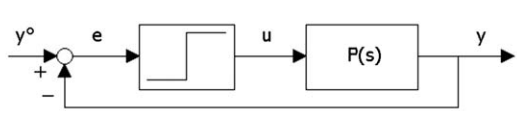

Fig. 2. Standard relay-based scheme for temperature control.