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Chen, Liang; Wisniewski, Rafal

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De-synchronization of the Distributed Refrigeration System

Liang CHEN[1,a], Rafael WISNIEWSKI[2,b]

[1]Engineering Research Center of Digitized Textile & Fashion Technology, Ministry of Education, Donghua University, Shanghai, China

[2]Dep. of Electronic Systems, Aalborg University, Aalborg, Denmark

[a]chenliang@dhu.edu.cn, [b]raf@es.aau.dk

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Abstract. The supermarket refrigeration system typically has a distributed control structure, which simple and flexible, however, neglects interactions between its subsystems. Practice shows that these interactions lead to a synchronous operation of the display cases. It causes excessive wear on the compressors and increased energy consumption. The paper focuses on the synchronization analysis and de-synchronization control. The supermarket refrigeration system is modeled as a piecewise-affine switched system. The system behavior is decomposed such that synchronization analysis can be completed by using the Poincare map. A new de-synchronization scheme is proposed, which includes two steps: the synchronization monitoring and the de-synchronization control. Thus, the early warning of the synchronization can be given and then the de-synchronization controller can be activated. The scheme achieves better control performance and can deal with the large scale refrigeration system with different system parameters in the display cases.

Introduction

A supermarket refrigeration system aims at preserving the foodstuffs usually stored in open display cases in the sales area of the supermarket. Each display case is typically equipped with a hysteresis controller which adjusts the expansion valve for refrigerant on/off such that the temperature in the display case is kept within tight bounds to ensure a high quality of the goods. A simple layout of the distributed supermarket refrigeration system is shown in Fig. 1.

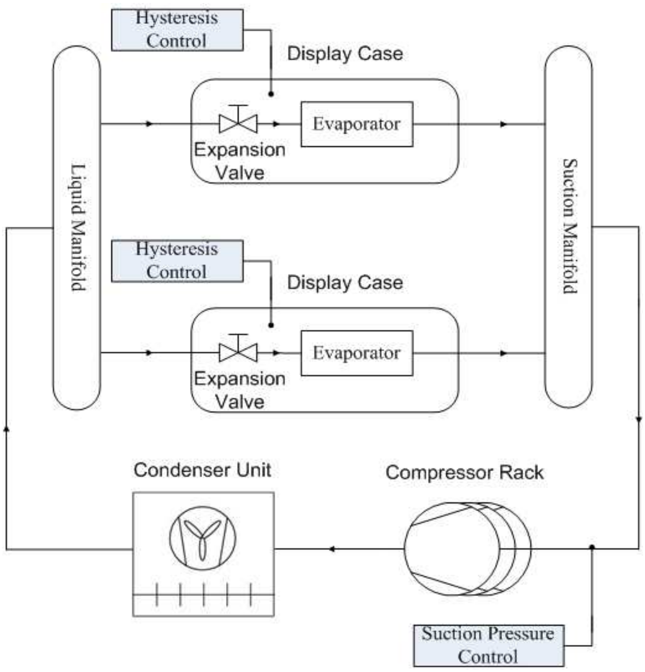

Fig. 1 Layout of the distributed refrigeration system

The supermarket refrigeration system has used such a distributed control system for many years, which is flexible and simple. However, it neglects cross-coupling negative effects between the subsystems, which are naturally inherited from the cyclic structure of the refrigeration process. Especially, practice shows that the temperatures in the display cases have the tendency to synchronize. The large fluctuation in the suction pressure is a consequence which then induces higher switch frequencies of the compressors. This subsequently leads to excessive wear on the compressors, and thus reducing lifetime of the compressors and increasing energy consumption. Based on our previous work [1-4], the paper further analyzes the synchronization dynamics when the supermarket refrigeration system has different display cases and develops a new de-synchronization scheme.

Synchronization Analysis

Because the emphasis of the paper is to examine the synchronization phenomenon, the paper considers the model only with the dynamics relevant to the hysteresis control in the display case and the suction pressure control in the compressors. The mathematical model presented here is a summary of the model developed in [1]. The supermarket refrigeration system with N display cases can be modeled as a piecewise-affine switched system with the general expression:

$$\dot{x}(t) = A_\delta x(t) + b_\delta , \tag{1}$$

where $x = [T_{air,1}, T_{air,2}, \ldots, T_{air,N}, P_{suc}]$ is the continuous state, $T_{air,i}$ is the air temperature of the ith display case, P_{suc} is the suction pressure. A_δ, b_δ are matrices depending on the discrete state $\delta = \{\delta_1, \delta_2, \ldots, \delta_N\}$. $\delta_i \in \{0,1\}$ indicates whether the expansion valve of the ith display case is open or closed. It is controlled by the hysteresis law: if $T_{air,i} \geq T_{air,i,up}$, $\delta_i = 1$; if $T_{air,i} \leq T_{air,i,low}$, $\delta_i = 0$; otherwise, δ_i makes no change. Here, $T_{air,\,i,\,up}$ is the upper temperature bound and $T_{air,\,i,\,low,}$ the lower bound.

The piecewise-affine switched model Eq. (1) is an important special class of hybrid systems where the state trajectory $x(t)$ is switched between many subsystems with different δ. Our previous paper [2] has shown how these subsystems living on polyhedra are glued together to form a single dynamical system defined on a coherent state space X_δ. A guard $G(\delta, \delta')$ is the set of transition states at which the system state is switched from (δ, x) to (δ', x'). Let $s = \{s_1, s_2, \ldots, s_i, \ldots\}$ be the sequence of discrete states associated with the continuous trajectory $x(t)$. The combination $w = (s, x(t))$ is referred to as a hybrid trajectory. Now we introduce the following definition of periodicity properties of hybrid systems:

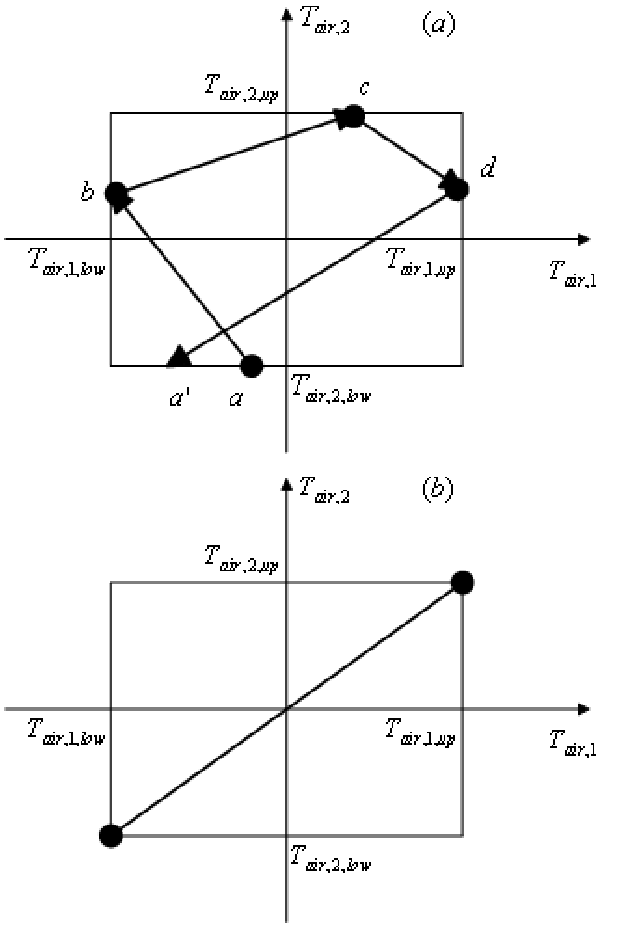

Fig. 2 Graph illustration of the switching process with two display cases: (a) an example, (b) synchronization.

Definition. For any integer $i > 0$, if there exists some integer constant $k > 0$ such that the symbolic sequence has the property $s_i = s_{i+k}$, then we say the system is traveling on a discrete period k orbit.

For simplicity we consider a refrigeration system with two display cases and one compressor unit. Thus the continuous states in Eq. (1) are $[T_{air,1}, T_{air,2}, P_{suc}]$; the discrete states are $(\delta_1, \delta_2) = \{(0, 0), (0, 1), (1, 0), (1, 1)\}$. A graph illustration of a typical switching process of the system is shown in Fig. 2a. The boundaries of the rectangle are the four guards of the system corresponding to the switching discrete states (δ_1, δ_2). Assume that the system starts from point $a(x_a, T_{air,2,low})$, then goes through point $b(T_{air,1,low}, y_b)$, point $c(x_c, T_{air,2,up})$ and point $d(T_{air,1,up}, y_d)$, back to point a'. If point a' coincides with point a, we say that the system is traveling on a discrete period-four orbit because the sequence of discrete states associated with the continuous trajectory is $s = \{(1, 0), (0, 0), (0, 1), (1, 1)\}$. Based on the above description, dynamic analysis of the synchronization can be completed by applying a Poincaré map, which is usually used to studying the switched system.

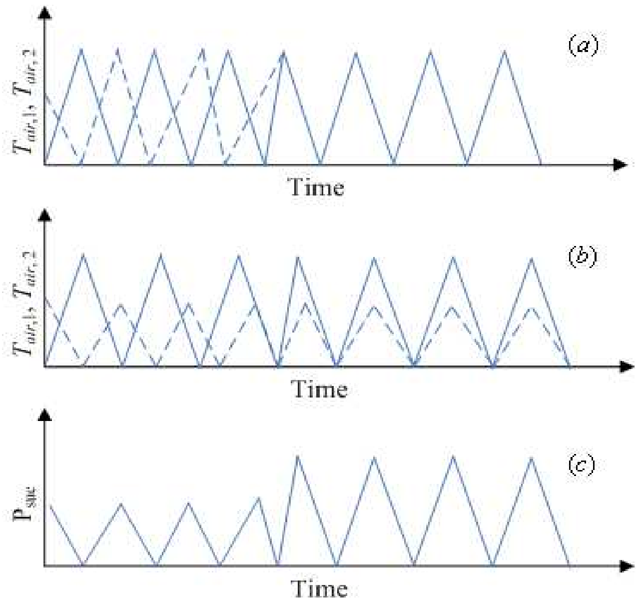

Fig. 3 Synchronization of two display cases with (a) same parameters, (b) different parameters, (c) the fluctuation hange of P_{suc}.

In a common supermarket the display cases are usually divided into several groups. Within the group, the display cases are alike in design and working under the same conditions. But different groups have different system parameters. Practice has found that the synchronization can happen in both situation, but with different temperature agreements (see Fig. 3a, b). The temperature in each display case is typically controlled by a hysteresis controller that opens and closes the expansion valve, i.e. the valve closes when the air temperature T_{air} (close to the goods) reaches a predefined upper temperature bound $T_{air,i,up}$ and stays close until T_{air} decreases to the lower temperature bound $T_{air\ i\ low}$ and the valve opens again. Therefore, both synchronization phenomena in Fig. 3 can be interpreted as that T_{air} in different display cases tend to reach the temperature bounds at the same time, which results in coinciding opening and closing of expansion valves. It is the key factor that leads to large fluctuation of the suction pressure P_{suc} (see Fig. 3c) which then induces higher switching frequencies of the compressors, and thus excessive wear on them. In addition, both synchronization behaviors also can be seen as a discrete period-two orbit (see Fig. 2b).

De-synchronization Scheme

The de-synchronization scheme to be developed should be able to extend to a real plant with N display cases operating in different system parameters. Moreover, the scheme should not be too restricted to the mathematical model. A hybrid model predictive control approach has been developed in [3]. However, the approach relies on the system model and leads to highly complex solutions, which makes the implementation of the solution somewhat impractical on a typical supermarket system. In addition, we also have suggested a de-synchronization scheme from the point of view of chaos theory. The algorithm and results have been shown in [4]. In this scheme, we proposed a concept that the system may be de-synchronized by making it chaotic, i.e. chaotification. Chaotification has been successfully applied in many continuous-time systems. Unfortunately, few literatures have been available on a simple and practical chaotifying method for the hybrid system.

We notice that whether the N display cases have the same system parameters or not, the essence of the synchronization is that operations of the expansion valves in different display cases coincide with each other. Based on this, we develop a new de-synchronization scheme in the paper. The scheme is divided into two steps: first, to monitor the system behavior and give early warnings of the synchronization; second, to activate the de-synchronization controller once the system is approaching the synchronization. Basic steps of the algorithm are given for the supermarket refrigeration system with N display cases as follows:

Step 1: Initialization

normalize the air temperature of the ith display case as: $T_i = (T_{air,i} - T_{air,i,low}) / (T_{air,i,up} - T_{air,i,low})$

introduce the critical temperature value of the ith display case as: $T_{c,i} = i/N \times (T_{air,i,up} - T_{air,i,low})$

introduce a parameter *count* to judge the approaching synchronization, initially *count* = 0

Step2: Monitoring the synchronization behavior

If $|T_i - T_j| < 0.1$, $count = count + 1$;

If $count \geqslant num$, the synchronization is approaching. Then, go to step 3. Otherwise, wait. Here, num is a constant decided by the trial and error.

Step3: Starting up the de-synchronization control

If the expansion valve in the ith display case is open, that is, $\delta_i = 0$, and T_i is approximated to $T_{c,i}$, then let $\delta_i = 1$, that is, close the ith expansion valve.

Numerical simulations are performed on the supermarket refrigeration system with two display cases. The system parameters are used as in [1]. Simulation results are shown in Fig. 4 with the de-synchronization of the air temperatures T_{air} and the smaller fluctuation of the suction pressure P_{suc}. As stated before, the larger fluctuation of P_{suc} in the synchronization situation induces higher switch frequencies of the compressors, thus leads to reducing lifetime of the compressors and increasing energy consumption. The de-synchronization scheme developed in the paper reduces the fluctuation of P_{suc} to a large extent. To be noticed, it is not necessary to reduce the fluctuation amplitude of P_{suc} as small as possible. Because in a typical supermarket refrigeration system, P_{suc} is normally controlled by using a PI controller with a dead band around the reference. This control strategy prevents a moderate change in P_{suc} from initiating compressor switch.

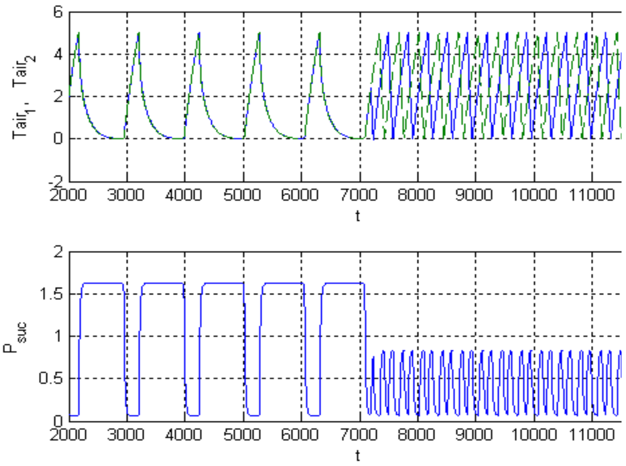

Fig. 4 Simulation with the desychronization scheme

Summary

The main object of the paper is to investigate and solve the synchronization phenomenon happened in the supermarket refrigeration system with a distributed control structure. The system behavior is studied based on a piecewise-affine switched model and a new de-synchronization scheme is proposed from the operation of the expansion valves. The scheme is easy to implement and achieves better control performance. Although the simulation is performed on a small refrigeration system consisting of two display cases. Nonetheless, it can be extended to large scale systems with different parameters in the display cases.

Acknowledgments

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