MULTIVARIABLE CONTROL FOR MULTI INPUT - MULTI OUTPUT COOLING MACHINES BASED ON VAPOR COMPRESSION

José Maria Gálvez, Ph.D.
Agostinho Gomes da Silva, M.Sc.
Department of Mechanical Engineering, Federal University of Minas Gerais, Brazil.
Av. Antônio Carlos 6627, Pampulha, 31.270-901 Belo Horizonte, MG, Brazil.
Phone: +55 31 499-5236. Fax: +55 31 443-3783. E-mail: jmgm@dedalus.lcc.ufmg.br.

Abstract

Traditionally, cooling machines are usually operated as open loop systems. With the just arrived world-wide energy crisis, the search for new energy-saving cooling systems has been intensified. Recently, several improvements have been proposed by the technical community but most of these new techniques are related with new device technology. Variable speed compressors and electronic expansion valves are among the most successful device improvements. The researcher's expectancy points to new automatic control schemes for the next generation of cooling machines, however, some difficulties must be solved before new schemes can be used in practice. The feedback control design is a difficult task due to the cross coupling among the process variables. This paper presents a new control scheme that allows to control the freezing power and the superheating in an independent way. It explains a control design procedure performed in the frequency domain. Finally, it shows simulation results, which validate the design procedure.

Keywords: Cooling Systems, Multivariable Control, Frequency Domain.

1. INTRODUCTION

The improvement of power consumption efficiency of industrial devices is one of the main issues for the incoming century. In the first century of the industrial age, the world population has virtually exploded, nature has been almost destroyed and energy resources have been almost depleted. In spite of that, the human living comfort has become a necessity for most of the whole world population even for the third world people. It is a fact that the next decades are going to testify a continuous and strenuous search for new devices and technologies to save energy resources.

The energy consumption by heating and cooling systems in commercial and industrial buildings corresponds to 50% of the world energy consumption (Imbabi, 1990). The operation of heating and cooling systems in commercial and industrial buildings still is an inefficient and high-energy consumption process (Shoureshi, 1993).

It is already known that the solution for the poor operation of heating and cooling systems relies on the proper choice and design of automatic controllers. Low cost controllers such as On/Off control and PID control are currently used as the standard controllers in the heating, ventilation and air conditioning (HVAC) industry. However, their low energy efficiency causes an extra undesired energy burning.

An important fact that causes the control low energy efficiency is that most designs are only capable of dealing with constant thermal loads, which is not the general case. In practice, thermal loads are time varying. The temperature sensor location is another difficult in the control field of heating and cooling devices. The natural position for the temperature sensor is close to, or even inside, the target environment. In practice, to avoid the inclusion of time delays in the control loop, the temperature sensor is usually located close to the heat source (sink). Furthermore, conventional single-input single-output (SISO) control of cooling machines is not capable of controlling the freezing power and super-heating independently (I/O cross coupling).

To deal with the control problem of time varying processes, time delays and I/O cross coupling, several control strategies have been proposed by the control community. Among them, robust control, adaptive control and intelligent control are the most important. A drawback of these sophisticated alternatives is that they are usually expensive and required advanced computational resources.

To face time-varying thermal loads, control loop time delays and I/O cross coupling, new-low cost multi-input multi-output (MIMO) control strategies must be explored. This paper introduces a MIMO control scheme that permits the independent control of the output variables of cooling machines based on the vapor compression cycle. Figure 1 shows the schematic diagram of a cooling machine of this type.

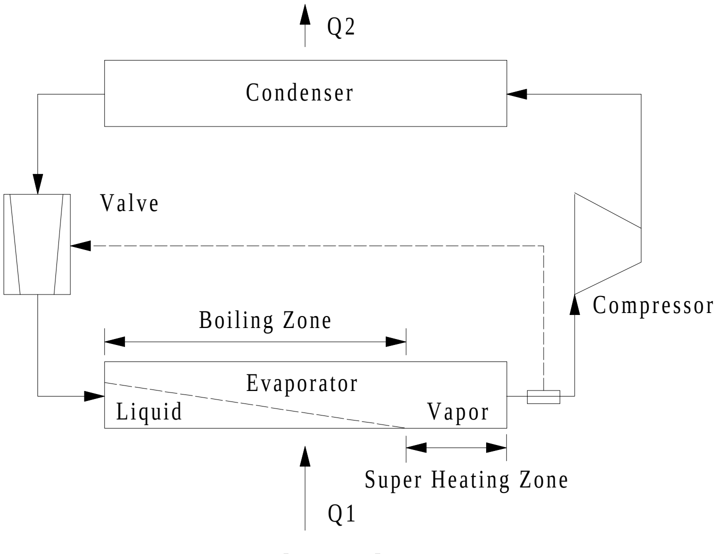

Figure 1. The Cooling System.

2. THE COOLING SYSTEM

This paper focus in the control of the system constituted by the expansion valve, evaporator and compressor (Figure 1). In this case, the system dynamics is defined by a matrix transfer function of the form:

$$\begin{bmatrix} \Delta T(s) \\ Q_1(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} MFR(s) \\ VFR(s) \end{bmatrix} \tag{1}$$

The system inputs are the expansion valve opening position, which defines the mass flow rate (MFR) and the compressor speed, which controls the volume flow rate (VFR). The system outputs are the super heating, ΔT, and the freezing power, Q_1, (Figure 2).

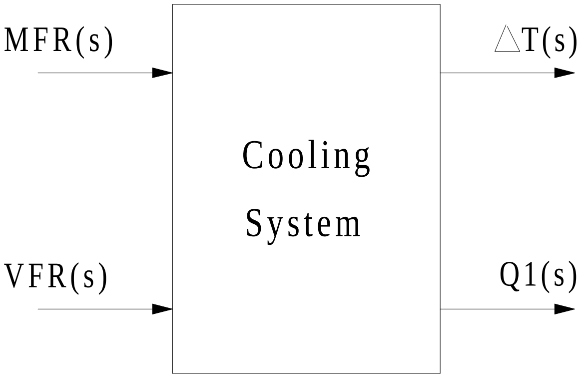

Figure 2. The Open Loop System.

Equation 1 can be written as:

$$[Y(s)] = [G(s)][U(s)] \tag{2}$$

with

$$[G(s)] = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix}$$

and

$$[Y(s)] = \begin{bmatrix} Y_1(s) \\ Y_2(s) \end{bmatrix} = \begin{bmatrix} \Delta T(s) \\ Q_1(s) \end{bmatrix}$$

$$[U(s)] = \begin{bmatrix} U_1(s) \\ U_2(s) \end{bmatrix} = \begin{bmatrix} MFR(s) \\ VFR(s) \end{bmatrix}$$

Ideally, the opening of the expansion valve would be used to regulate the super heating and the velocity of the variable-speed compressor would be used to control the generation of freezing power (Figure 3 with $G_{12}(s) = G_{21}(s) = 0$), unfortunately, this is not the case.

A strong cross coupling interaction among inputs and outputs is a characteristic of these systems, which means that $G_{12}(s)$ and $G_{21}(s)$ can not be neglected in practice. This can be easily understood since each output is a function of both inputs (the valve opening position and the compressor velocity), as shown in Figure 3.

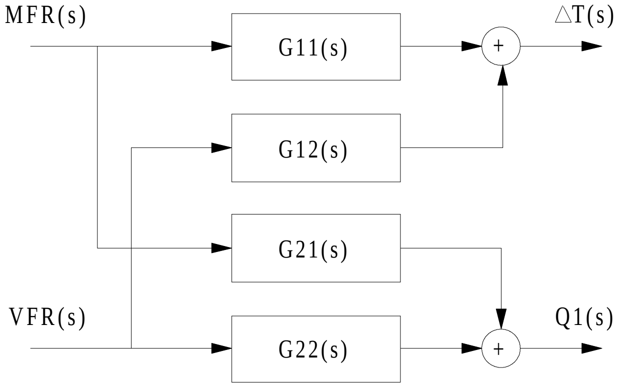

Figure 3. The Cooling System Cross Coupling.

3. MODEL STRUCTURE AND VALIDATION

Several linear and non-linear computational models can be found in the technical literature (Koury, 1998, Machado, 1996, Rocha, 1995 & Outtagarts, 1994). Considering the work by Machado (1986) a 2x2 MIMO model structure was chosen for the cooling machine:

$$[Y(s)] = [G(s)]\,[U(s)] = \begin{bmatrix} \Delta T(s) \\ Q_1(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \begin{bmatrix} MFR(s) \\ VFR(s) \end{bmatrix} \tag{3}$$

where

$$G_{11}(s) = K_{11}\,\frac{1}{T1_{11}\,s+1} \qquad G_{12}(s) = K_{12}\,\frac{(T2_{12}\,s+1)}{(T1_{12}\,s+1)}$$

$$G_{21}(s) = K_{21}\,\frac{(T3_{21}\,s+1)}{(T1_{21}\,s+1)(T2_{21}\,s+1)} \qquad G_{22}(s) = K_{22}\,\frac{(T3_{22}\,s+1)}{(T1_{22}\,s+1)(T2_{22}\,s+1)}$$

The model identification procedure (Machado, 1996) led to:

$$[\boldsymbol{G}(\boldsymbol{s})] = \begin{bmatrix} \boldsymbol{G}_{11}(\boldsymbol{s}) & \boldsymbol{G}_{12}(\boldsymbol{s}) \\ \boldsymbol{G}_{21}(\boldsymbol{s}) & \boldsymbol{G}_{22}(\boldsymbol{s}) \end{bmatrix} = \begin{bmatrix} \dfrac{-5.62}{(45\ \boldsymbol{s}+1)} & \dfrac{-2.49\ (-70\ \boldsymbol{s}+1)}{(59.52\ \boldsymbol{s}+1)} \\ \dfrac{33.89\ (-36.37\ \boldsymbol{s}+1)}{(25.65\ \boldsymbol{s}+1)(67.79\ \boldsymbol{s}+1)} & \dfrac{22.20\ (630\ \boldsymbol{s}+1)}{(80\ \boldsymbol{s}+1)(90\ \boldsymbol{s}+1)} \end{bmatrix}$$

4. THE MIMO CONTROLLER

The structure of a MIMO output feedback control law was defined as:

$$[U(s)] = [K(s)]\,[E(s)] = [K(s)]\,[R(s) - Y(s)] \qquad (4)$$

where

$$[K(s)] = \begin{bmatrix} K_{11}(s) & K_{12}(s) \\ K_{21}(s) & K_{22}(s) \end{bmatrix}$$

and

$$[R(s)] = \begin{bmatrix} \Delta T(s) Setpoint \\ Q_1(s)\ Setpoint \end{bmatrix}$$

Figure 4 shows the MIMO controller structure:

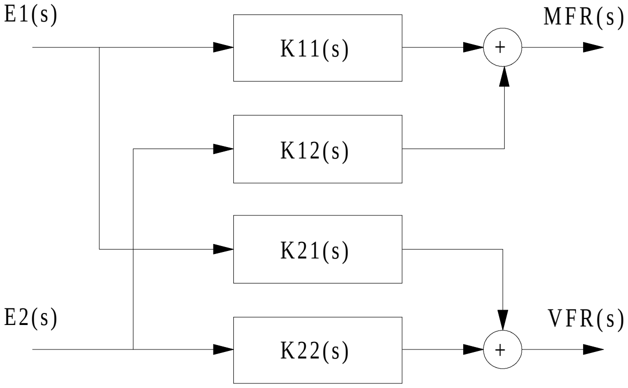

Figure 4. The MIMO Controller Implementation.

The controller tuning procedure led to the following control law:

$$[K(s)] = \begin{bmatrix} K_{11}(s) & K_{12}(s) \\ K_{21}(s) & K_{22}(s) \end{bmatrix} = \begin{bmatrix} \dfrac{-1.0952\ s - 0.0219}{s} & \dfrac{-0.6133\ s - 0.0123}{s} \\ \dfrac{1.6719\ s + 0.0334}{s} & \dfrac{1.3867\ s + 0.0277}{s} \end{bmatrix}$$

Finally, the closed loop transfer function can be determine by (Francis, 1987):

$$T(s) = [I + G(s)K(s)]^{-1} G(s)K(s) \tag{5}$$

It should be noticed that, the entry $K_{ij}(s)$ has the general form of the of a SISO classical PI controller. The designed controller leads to a closed loop transfer function that can be approximated (at low frequencies) by the diagonal matrix transfer function of the form:

$$[\boldsymbol{Y}(\boldsymbol{s})] \cong \begin{bmatrix} \boldsymbol{T}_{11}(\boldsymbol{s}) & 0 \\ 0 & \boldsymbol{T}_{22}(\boldsymbol{s}) \end{bmatrix} [\boldsymbol{R}(\boldsymbol{s})] \Leftrightarrow \begin{bmatrix} \Delta\boldsymbol{T}(\boldsymbol{s}) \\ \boldsymbol{Q}_1(\boldsymbol{s}) \end{bmatrix} \cong \begin{bmatrix} \boldsymbol{T}_{11}(\boldsymbol{s}) & 0 \\ 0 & \boldsymbol{T}_{22}(\boldsymbol{s}) \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{T}(\boldsymbol{s})\, \boldsymbol{Setpoint} \\ \boldsymbol{Q}_1(\boldsymbol{s})\ \boldsymbol{Setpoint} \end{bmatrix} \tag{6}$$

Equation 6 shows the main feature of the proposed controller (due to the space limitation the full form of Equation 6 was omitted), the close loop system is diagonal dominant at low frequency. This fact allows the control of the superheating and freezing power to be independent. Figure 5 shows the block diagram for the closed loop system.

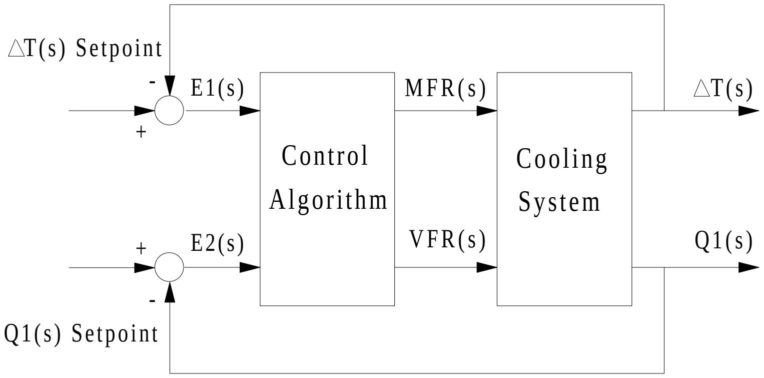

Figure 5. The Closed Loop System.

5. SIMULATION RESULTS

Simulation results are presented here to illustrated the controller performance. Figure 6 presents the system open loop responses. It shows the super-heating (quadrant II) and freezing power (quadrant IV) time responses. It can be observed (in quadrants I and III) the strong effect of the I/O cross coupling. In the ideal case, the time responses shown in quadrants I and III should remain in zero for all time or at least return to zero at steady state. Figure 7 shows the system closed loop responses. It shows the super-heating (quadrant II) and freezing power (quadrant IV) closed loop time responses to a unit step. In Figure 7 also shows (in quadrants I and III) that the effects of the I/O cross coupling were eliminated by the proposed control law.

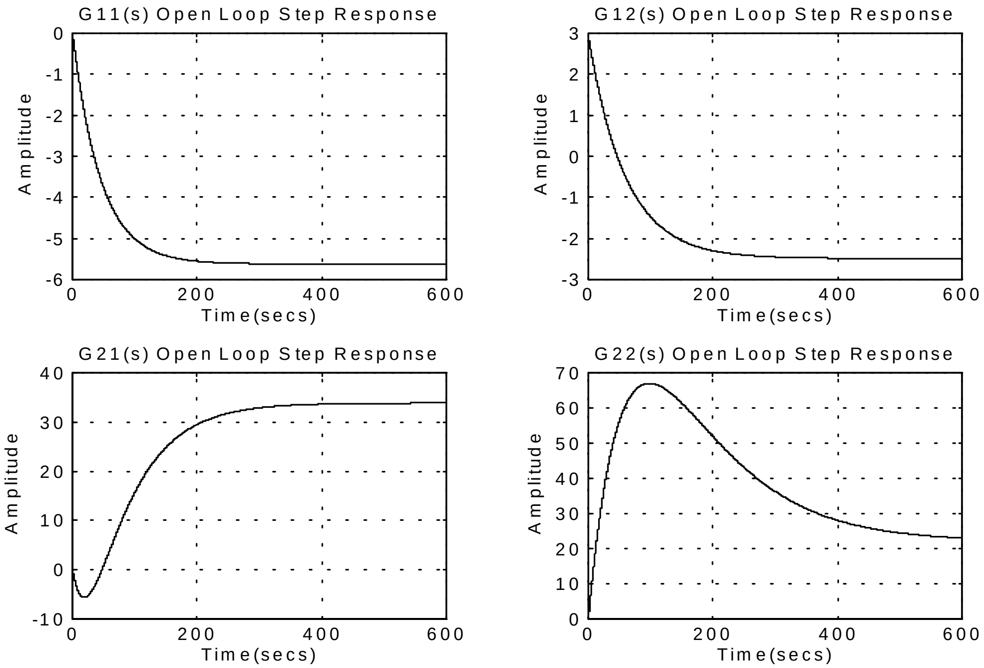

Figure 6. Open Loop Step Responses.

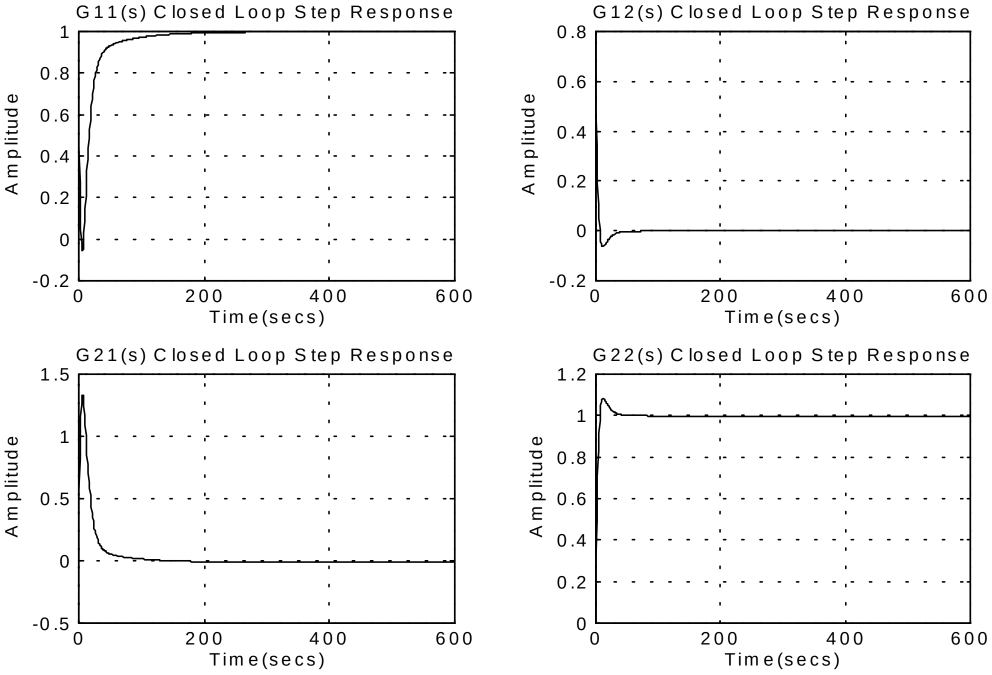

Figure 7. Closed Loop Step Responses.

6. FINAL COMMENTS

Traditionally, classical on-off controllers for cooling machines have shown to be inefficient for energy saving purposes (Rocha, 1995; Machado, 1996). Variable compressor speed operation has recently emerged as the solution for the energy consumption minimization problem. The searching for an inexpensive compressor speed controller is currently on the focus of the attention of the control community and although some fine results can be found in the technical literature the final solution is still under investigation.

This paper shown that independent control of superheating and freezing power in a cooling system based on vapor compression is a feasible task. A MIMO controller for a cooling machine was designed and implemented in computer simulation. The potential of the proposed MIMO controller for saving energy and keeping comfort was verified through simulation.

Further research has to be done including the plant non linearity to assess the full capability of the proposed scheme.

7. REFERENCES

- Arguello-Serrano, B. & Vélez-Reyes, A., “Nonlinear Control of a Heating, Ventilating, and Air Conditioning System with Thermal Load Estimation”, IEEE Transactions on Control Systems Technology, vol. 7, pp. 56-63, January 1999.
- Grosdidier, P. and Morari, M., “Interactions Measurements for Systems under Decentralized Control”, Automatica, vol. 22, pp. 309-319, 1986.
- Imbabi, M.S., “Computer Validation of Scale Model Test for Building Energy Simulation”, Int. J. Energy Res., vol. 14, pp. 727-736, 1990.
- Machado, L., Modele de Simulation et Etude Experimentale d’un Evaporateur de Machine Frigorifique en Regime Transitoire, L’Institut National des Sciences Appliquees de Lyon, France, 1996.
- McAvoy, T. J., “Interaction Analysis - Principles and Applications”, Instrument Society of America, 1983.
- Mees, A.I., “Achieving Diagonal Dominance”, Systems and Control Letters, vol. 1, pp. 155-158, 1981.
- Outtagarts, A., Comportement Dynamique d’un Evaporateur de Machine Frigorifique Alimente par un Detendeur Electronique, L’Institut National des Sciences Appliquees de Lyon, France, 1994.
- Rocha, R., Contribuição ao Estudo de um Sistema de Refrigeração com Compressor Operando a Velocidade Variável, Dissertação de Mestrado, PPGEE-UFMG, Brasil, 1995.
- Stoecker, W.F. & Jones, J.W., Refrigeration and Air Conditioning, McGraw-Hill Book Company, 1982.