Journal of the Korean Society of Marine Engineering, Vol.30, No.7, pp.808~815, 2006(ISSN 1226-9549)

Decoupling Control Design for Variable Speed Refrigeration System of a Ship

Li Hua* · Seok-Kwon Jeong† · Jung-In Yoon**
(Manuscript : Received NOV 3, 2006 ; Revised DEC 4, 2006)

Abstract : In this paper, we suggest decoupling control method based on general PI control law to control variable speed refrigeration system of the ship effectively. In the variable speed refrigeration system, the capacity and the superheat are controlled by inverters and electronic expansion valves respectively for saving energy and improving cost performance. Thus, we propose decoupling model to eliminate the interfering loop between capacity and superheat at first. Next, we design PI controller to control capacity and superheat independently and simultaneously. Finally the control performance was investigated through some experiments. The experimental results show that the PI control design can obtain good control performance under the adjustable control reference and thermal load variation.

Key words : Decoupling model, Superheat, Capacity control, PI control, Variable speed refrigeration system

1. Introduction

As the surrounding environment will be varied when ships move to different region, it is very difficult to design for controlling refrigeration system of a ship effectively. It is inevitable to design practical controller in order to control the refrigeration system of ship for the purpose of saving energy and establishing high efficiency. A basic refrigeration cycle is composed of a compressor, heat exchangers and an expansion valve. Components of the cycle are deeply connected with pipes each other and have nonlinearity inherent. Hence, it is not easy to design a suitable controller.

The conventional control schemes of the refrigeration system are mainly focused on representative two control methods, superheat and capacity control. The superheat has been controlled by expansion device which plays an important role to reduce evaporating pressure and to

† Corresponding Author(Division of Mechanical Engineering, Pukyong National University) E-mail : skjeong@pknu.ac.kr, 051)620-1507
* Department of Refrigeration and Air-Conditioning Engineering, Graduate School, Pukyong National University
** Division of Mechanical Engineering, Pukyong National University

regulate the refrigerant mass flow rate. The superheat is controlled as a certain constant value by adjusting opening angle of the electronic expansion valve(EEV) to improve coefficient of performance(COP) of the refrigeration system. The capacity control is basically conducted to respond partial loading conditions on the purpose of energy saving. Usually, refrigeration machines operate under the partial loading conditions, conventional on/off control of a compressor for responding partial load influences to the compressor durability because of frequent switching actions. Therefore, the on/off control system is now gradually replaced by a variable speed compressor control system with inverters.

In the variable speed refrigeration system, the capacity and superheat can not be controlled independently because of interfering loop when the compressor speed and electronic expansion valve opening angle are varied.

Fig. 1 shows a block diagram of refrigeration system which has interfering loops inside the dash two dot line and dash dot line. Because of the coupling characteristics of refrigeration system, the capacity and superheat were not controlled independently.

Choi suggested a superheat control method to control a variable speed heat pump system[1]. The compressor frequency, the reference of inverters, was calculated by the empirical equation with the varied thermal load. Also, the transfer function between superheat and EEV opening angle was expressed as first-order system with dead time. In the paper, the capacity control was considered only the steady state, the superheat control had very big overshoot and undershoot when it only used a PID controller.

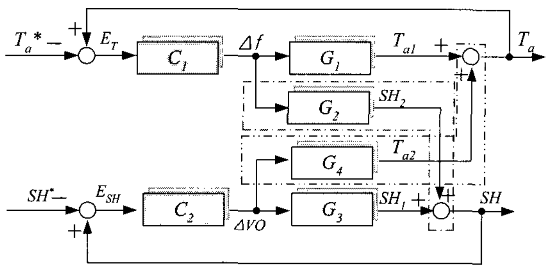


Fig. 1 Block diagram of refrigeration control system

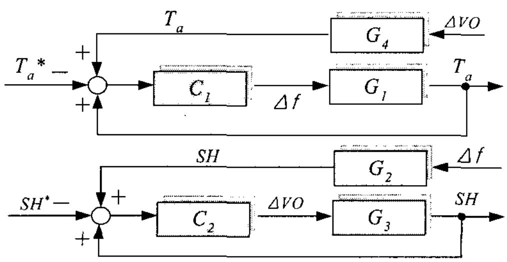


Fig. 2 Block diagram of decoupling control of refrigeration system

In this paper, we suggest the decoupling control method based on general PI control law to control the refrigeration system effectively. Conventional coupling model makes the systematical design of PI controller difficult.[2]-[4] Furthermore, it is a drawback to get good transient characteristics when control reference is changed. Thus, we propose decoupling model to eliminate the interfering loop and each transfer function is obtained from number of experiments at first.

Fig. 2 shows the decoupling control model, which does not have any interfering loop and each influence of operating

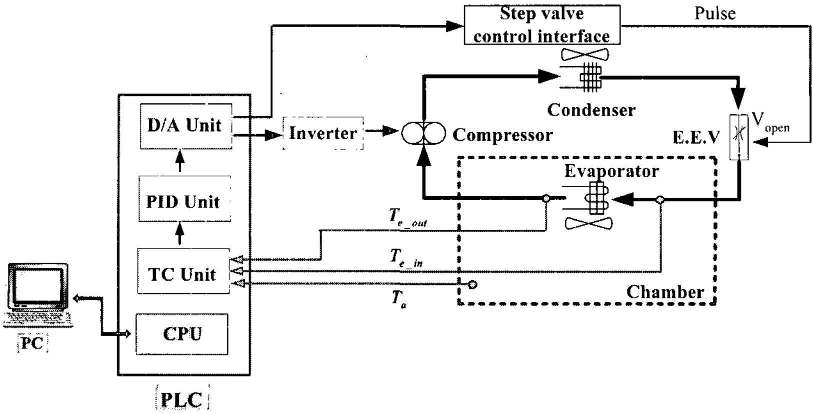


Fig. 3 Schematic diagram of the experimental system

variation such as *VO* and T_a is reflected feedforward to their reference input side. Next, we design PI controller with de-coupling manner and prove that the PI controller can establish not only precise control but also high COP of the variable speed refrigeration system through the experiments.

2. Experiment Equipments

Fig. 3 shows a schematic diagram of experimental system, and Table 1 represents the specification of a test unit of the experimental system. The experimental system was composed of basic refrigeration system and control system.

The elements of control system were inverter, step valve control interface and PLC(Programmable Logic Controller).

The compressor is driven by the induction motor with a general V/f constant type inverter. The stepper motor to drive EEV is operated by a step valve control

Table 1 Specification of a test unit

Compressor	Type	Vertical, Reciprocating	Inverter	Type	PWM
	Power	220V, 60Hz, 1.5kW		HP	2
Condenser	Type	Fan fin type	Step valve control interface	Input voltage	DC 12V
	Capacity	3450 kcal/h		Input signal	1-5VDC or 4-20mA
Evaporator	Type	Fin-tube type		Output	0-400 step
	Capacity	680 kcal/h	PLC	DC unit	32 CH
Expansion Valve Device	Type	EEV		Relay unit	32 CH
	Model	JHEV 14A		D/A unit	16 CH
	Port size	Φ14		PID unit	16 Loop
	Operating range	0 - 506 pulse		TC unit	16 CH
	Rated voltage	DC 12V		CPU	GM2
Refrigerant	Type	R22	Chamber	Size	1200 x 700 x 1650mm

interface. The input control signal of inverter and step valve control interface is gotten from D/A unit of PLC. The PI control is performed by PID unit of PLC. All temperatures are measured by thermo-uples(T-type). The temperature information is transmitted to TC (Thermocouple) unit of PLC with real time.

3. Experimental Result

Fig. 4(a) indicates the relationship between COP and superheat. In the experiment, the chamber temperature was set at 1℃, and the compressor was operated at 40Hz, 50Hz, and 60Hz respectively. It is shown that there is a little difference in COP according to operating frequency even if superheat is same. However, the COP had approximately same value during 0~8℃ of superheat. Also it is found that the COP is decreased according to increase of superheat beyond 8℃ at every compressor speed. Fig. 4(b) shows the relationship between COP and superheat according to change of chamber temperature. From this figure, it can be seen that the COP has also different value according to change of chamber temperature, even though the superheat is same. However, there is very similar pattern in COP within superheat range 0~8℃, and it is decreased gradually beyond 8℃ at the same compressor speed, too.

To establish high COP, the superheat must be kept as a certain constant temperature regardless of the operating conditions such as compressor speed, chamber temperature, etc.

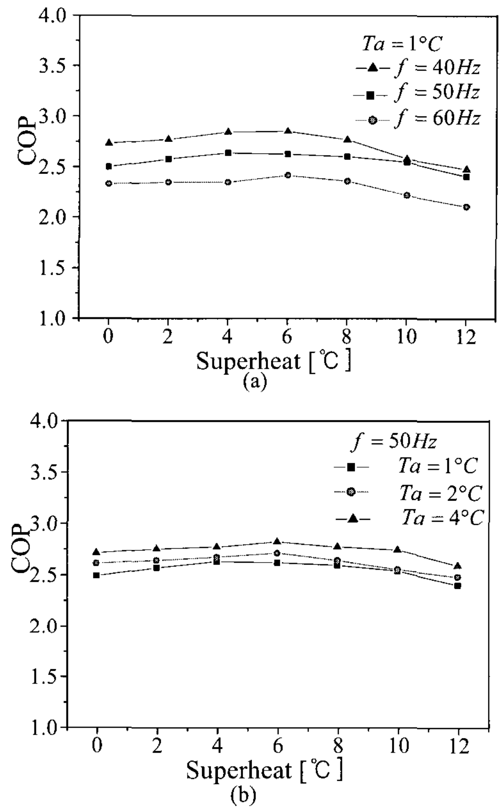


Fig. 4 Relationship between COP and SH

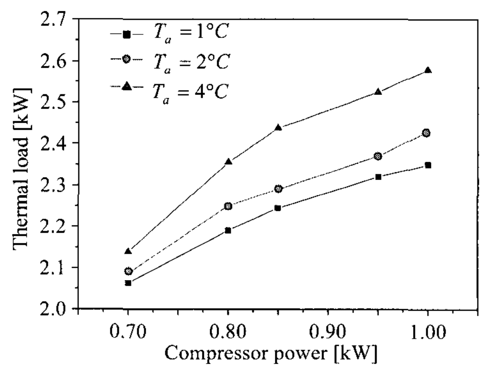
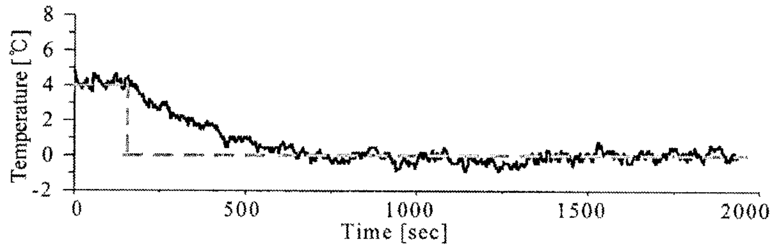
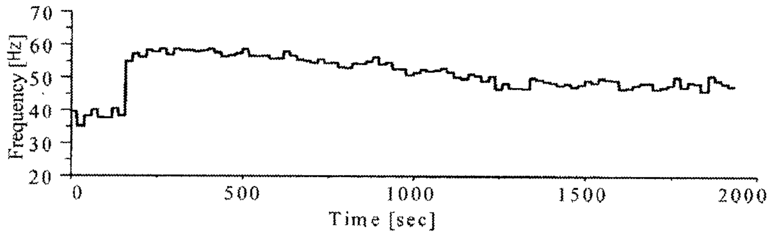


Fig. 5 Relationship between compressor power and thermal load

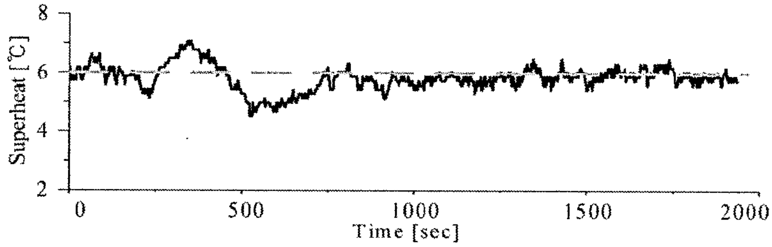
Fig. 5 indicates the relationship between compressor power and thermal load when the superheat is kept at 4~8℃. From



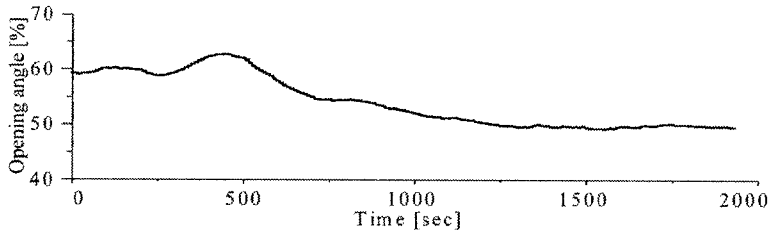
(a) The response of chamber temperature to follow T_a reference



(b) The compressor frequency to follow T_a reference



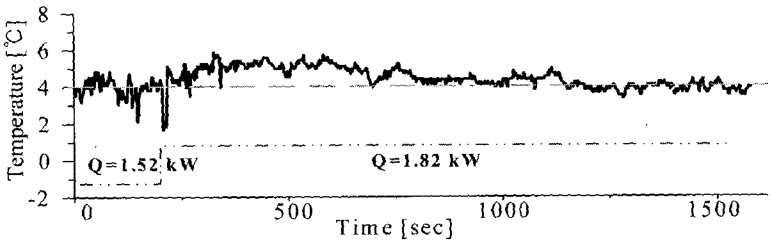
(c) The response of superheat to follow T_a reference



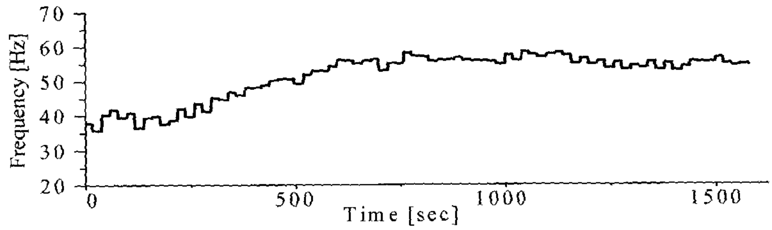
(d) The opening angle of EEV to follow T_a reference

Fig. 6 The decoupling control response of chamber temperature and superheat when the chamber reference temperature was varied

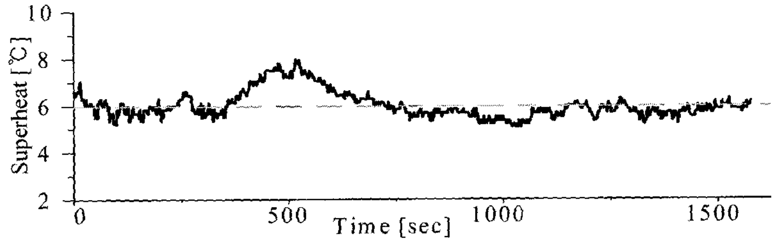
this figure, it can be seen that approximately 1kW power is needed at the conditions of compressor frequency 60Hz, thermal load 2.3kW and the chamber temperature 1℃. Supposing that the ambient thermal load is only varied to 2.06kW from initial condition 2.3kW, the compressor frequency will be decreased to 40Hz. Power of 0.7kW is enough for this condition. Consequently, comparing to constant speed compressor, the variable speed compressor can save energy about 30% corresponding to the thermal loa change actively.



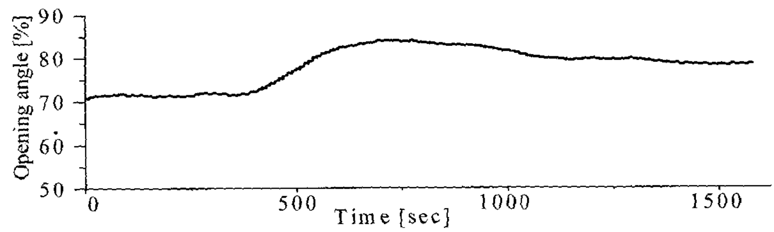
(a) The response of chamber temperature according to the thermal load



(b) The compressor frequency according to the thermal load



(c) The response of superheat according to the thermal load



(d) The opening angle of EEV according to the thermal load

Fig. 7 The decoupling control response of chamber temperature and superheat when thermal load was varied

Fig. 6 describes the decoupling control response of chamber temperature and superheat when the chamber reference temperature was abruptly varied from 4℃ to 0℃. The thermal load is 1.33㎾ and the superheat control reference is 6℃. Fig. 6(a) shows the decoupling control response of chamber temperature when the reference varied. It takes about 400sec from change reference to get close set point value. Fig. 6(b) shows the response of compressor frequency to follow the reference of chamber temperature. It can be seen that the compressor set point frequency for controlling the capacity was very stable.

Fig. 6(c) presents the decoupling control response of superheat according to the chamber temperature reference. The superheat must be controlled when the compressor speed and chamber temperature was varied. The percent overshoot is observed about 17%, but the maximum overshoot of superheat is below 8℃. From Fig. 4, we can see that it is permitted superheat degree in this system. Fig. 6(d) indicates the opening angle of EEV when the PI controller was operated. The set point value of EEV opening angle was adjusted with stable to maintain the superheat 6℃.

These experimental results provide fairly good control performance of PI to control capacity and superheat when the chamber temperature reference was varied.

Fig. 7 describes the PI control response of chamber temperature and superheat when thermal load was varied from 1.52kW to 1.82kW. The chamber temperature reference is 4℃ and the superheat control reference is 6℃. Fig. 7(a) and Fig. 7(b) show the decoupling control responses of chamber temperature and compressor frequency when thermal load was varied respectively. Fig. 7(a) indicates the chamber temperature increased when the thermal load was increased. It takes about 500sec from change thermal load to get close to the reference chamber temperature 4℃. From the Fig. 7(b), we can see that the compressor frequency decreased to maintain the chamber temperature at 4℃. Also, the compressor frequency was varied from 38Hz to 58Hz very stable. Fig. 7(c) presents the decoupling control response of superheat according to the thermal load. The superheat has been controlled as constant value of 6℃ to obtain high COP. Fig. 7(d) shows the opening angle of EEV about the thermal load. The opening angle of EEV has been adjusted as some value depending on the superheat.

The decoupling control responses indicate good control performance of PI to control the capacity and superheat under various thermal load conditions.

4. Conclusion

In this paper, we presented the decoupling control design with PI controller to control the capacity and superheat independently and simultaneously without interfering loops on the purpose of saving energy and progress of COP. The suggested decoupling model was obtained from several experiments under various operating conditions. Also, we designed PI controller based on the decoupling model. Some experimental results show that the designed PI controller is effective to control the variable speed refrigeration system. It is expected that the suggested decoupling control method can establish not only precise control but also high COP of the variable speed refrigeration system of ship.

References

[1] Jongmin Choi, Yongchan Kim and Jinho Ha, "Experimental study on superheat control of a variable speed

heat pump", SAREK, Vol. 13, No. 4, pp. 233-241, 2001(in Korean).

[2] A. Outtagarts, P. Haberschill, M. Lallemand, "The Transient Response of an Evaporator Fed Through an Electronic Expansion Valve", International Journal of Energy Research, Vol. 21, pp. 793-807, 1997.

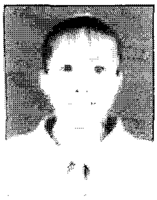
[3] Yoon, S. H. and Chang, H. W., "Empirical modeling and control performance simulation of an inverter heat pump system", Proceedings of the SAREK, pp. 725-730, 2001(in Korean).

[4] LI HUA and S. K. Jeong, "An experimental model for decoupling control of a variable speed refrigeration system", KSPSE, Vol. 10, No. 3, pp. 81~87, 2006(in Korean).

Acknowledgement

This research was supported financially by NURI.

Author Profile

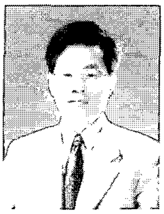


Li Hua

Birth: 1973. 1996: B.Eng., Nanjing Univ. of Science & Technology, China. 2005: M.Eng., Pukyong National Univ., Korea. Current: Ph.D. Student, Pukyong National Univ., Dept. of Refrigeration & Air-conditioning Engg.

Seok-Kwon Jeong

Birth: 1961. 1983: B.Eng., Pukyong National Univ., Korea. 1995: Eng.Dr., Yokohama National Univ., Dept. of Electrical & Computer Engg., Japan. Current: Associate Prof., Pukyong National Univ., School of Mechanical Engg.



Jung-In Yoon

Birth: 1961. 1988: B.Eng., Pukyong National Univ., Korea. 1995: Ph.D.Eng., Tokyo Univ., of A&T, Japan. Current: Professor, Pukyong National Univ., School of Mechanical Engg.