Robust Controller Design for the Automotive Climate System

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Abstract

This paper deals with automotive climate control using optimal control theoryAutomobile Compartment temperaturescontrolled by varying compressor capacity and the positionof the air mixing damper. The goal of this paperis design reduced order robust controller based on balancedrealization techniqu.The simulation show thatwith applied H_2 / H^{∞} the reduced order controller design has good results in frequency and time domain.

Keywords

Automotive Climate; Robust control; Model reduction

I. Introduction

In most air conditioning controllers, temperature is used as feedback and a fix temperature goal. Thefirst vehicle automatic Climate Control (ACC) system was introduced in the 1964 Cadillac after several years of joint development activities among General Motors divisions including Delco Radio Division (now Delphi Electronics and Satiety), Cadillac Motor Car division and Harrison Radiator (now Delphi Thermal).Since an automobile is operated in various weather conditions, such as scorching heat and downpours, compartment temperature is constantly affected by environment changes. An air-conditioning system must maintain a comfortable inside temperature despite these changes. However. an air-conditioning system inevitably used energy,which increases car fuel consumption. Because fuel consumption is a concern, this energy must be minimized. Therefore, an entirely new control procedure is needed to resolve the contradictions of low energy consumption and a pleasant driving climate.[3]

The automatic climate system was designed to meet the following three performance requirements [14] :

1. A comfortable passenger comportment climate should be maintained under all weather and engine operation conditions.
2. The driver should be relived of adjusting controls. He should be able to select his comfort level once and have it automatically repeated during every usage without any attention to controls. It is, of course, realized that changes in body metabolism and dress will at times make a different in-car temperature desirable. In this case only a slight adjustment should be required.
3. The desired in-car temperature should be attained rapidly.

Even though the 1964 Cadillac ACC systems used analog controllers with vacuum actuators, the technology paradigms espoused by the revolutionary ACC system design are still followed today. These include the sensor set selection (ambient temperature thermistor, in-car air temperature thermistor, discharge air temperature thermistor), the principle of air-mixing through the used of a temperature door in the Heating, Ventilation and Air-Conditioning (HVAC) module to achieve any desired discharge temperature, the concept of solar compensation, the linear combination of the sensor inputs (ambient temperature, in-car temperature , and driver set temperature through a potentiometer, hereon referred to as Linear Load Equation) to drive the actuation mechanism, etc. With the maturation of the micro-controller devices, the ACC system made the transition from linear analog amplifiers and vacuum actuators to micro-controllers and electrical motor actuators. This made it possible to implement complex control strategies to achieve comfort and safety objectives. New capabilities such as cold and hot purging into automatic climate control. Significant as it was. Customers overrode the automatic climate control systems and operated in the manual mode for 66% of the driving time. Allison-Fisher advanced automotive features study shows that automatic climate control is the list desired HVAC feature (vs. standard AC, instant heat, left-right individual control, air filtration, etc.) across all vehicle segments [16].

The steady state performance of the ACC systemIs improved by relying on the proper balance of the passenger compartment thermal load and the HVAC air conditioning capacity. This approach recognizes the inherent non-linearity of typical blower and temperature maps and shuns the traditional linear control concept; The transient ACC performance is improved by the introduction of the tenability and transient-steady state separation concepts.

Fig.1 shows an overview of the air-conditioning system under study. The outsideair drawn into the air conditioner is firstcooled by heat exchange within the evaporator.The cooling capability of the evaporatoris controlled by changing the capacityof the variable compressor. Since the compressoris powered by the engine, the lowerthe compressor capacity. the lower the loadon the engine, and the lower the energy consumption.The outside air cooled inside the evaporatorflows in two directions because of theseparation effected by the air mixingdamper. One part flows as cool air. Whilethe other is reheated within the heater coreby heat exchange. Thus. the air mixingdamper adjusts the amount ofoutside air tobe reheated. The cool and warm airare remixedand blown into the car compartmentthrough outlets. Hence, the temperature insidethe automobile is determined by theamount of cooling by the compressor [5]. Theamount of reheating from the air mixingdamper, and the heat balance inside and outsidethe compartment.

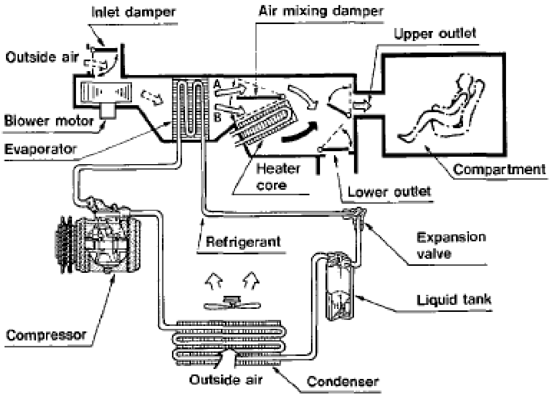

Fig. 1 : Overview of Air-conditioning system

II. Mathematical Model

The principle of energy and mass conservation from thermodynamics are used to model the system. Overall model of the system is derive to show the air temperature and velocity in the cabin. The effect of control parameters is also included in the model [2].The state space of the air conditioning system is defined as a ninth-order model as follows:

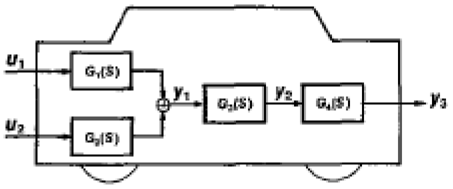

Fig. 2. Block diagram of air-conditioning system

u_1=position of air mixing damper
u_2=capacity of variable compressor
Y_1=temperature inside car compartment

$$\dot{X} = AX+Bu$$
$$Y=CX+Du \quad (1)$$

$$A = \begin{array}{ccccccccc} 0 & -.05 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1.21 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \text{[illegible]} & -1.04 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \text{[illegible]} & 0 & \text{[illegible]} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1.04 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \text{[illegible]} & 0 & 0 & 0 \\ 0 & 0 & \text{[illegible]} & \text{[illegible]} & \text{[illegible]} & \text{[illegible]} & \text{[illegible]} & 0 & 0 \\ 0 & 0 & \text{[illegible]} & \text{[illegible]} & \text{[illegible]} & \text{[illegible]} & 0 & \text{[illegible]} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \text{[illegible]} & \text{[illegible]} & \text{[illegible]} \end{array} \quad (2)$$

$$B^T=\begin{bmatrix} -0.22 & -1.46 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 14.4 & 0.140 & & 0 & 0 \end{bmatrix} \quad (3)$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \quad (4)$$

III. Balanced Realization

Balancedrealization is a model reduction technique for systems leads to reduced order models. During the eighties a robust order reduction technique for time invariant linear system, based on the balancing transformation was developed [9,10].This technique is briefly reviewed considering standard linear time invariant (LTI) dynamical system

$$\dot{X} = AX + Bu$$
$$Y = CX + Du \quad (5)$$

The transfer function of the system is:

$$G(S)=D + C(SI - A)^{-1} B \quad (6)$$

Assumption:The system is asymptotically stable, the pair (A,B) is controllable, and the pair (A,C) is observable. The system controllability and observability Grammian satisfy the algebraic Lyapunov equations [10]

$$AP+PA^T + BB^T = 0 \quad (7)$$

$$A^T Q + QA + C^T C=0 \quad (8)$$

For controllable and observable system both controllability and observability Grammians are positive definite, p>0 , Q>0 . The balancing transformation that makes the controllability and observability Grammians identical and diagonal, that is

$$\tilde{P} = \tilde{Q} = \Sigma = \text{diag}\,(\sigma_1, \ldots, \sigma_r) \quad (9)$$

where $\sigma_i \geq \sigma_{i+1}$; i= 1,2,…,n-1 are Hankel singular values Now partition the balanced system (A,B,C,D) and the Grammian Σ conformably as

$$A = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}, \quad B = \begin{pmatrix} B_1 \\ B_2 \end{pmatrix}, \quad C = \begin{pmatrix} C_1 & C_2 \end{pmatrix}, \quad \Sigma \triangleq \begin{pmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \end{pmatrix} \quad (10)$$

where A_{11} and Σ_1 are r*r (r<n) matrices

$$\Sigma_1 = \text{diag}\,(\sigma_1, .\,.\,, \sigma_r) \ , \ \Sigma_2 = \text{diag}\,(\sigma_{r+1}, .., \sigma_n) \quad (11)$$

Assuming that $\sigma_i \geq \sigma_{i+1}$ then the corresponding reduced-order system transfer function is

$$Gr(S)=D + C_1 \left(SI - A_{11}\right)^{-1} B_1 \quad (12)$$

This reduced-order system is controllable and observable since the corresponding Hankle singular values are all positive. In addition, The reduced-order system is balanced and asymptotically stable. It was shown that H_∞ norm of the reduced-order system, obtained through the above defined truncation, satisfies [16].

$$\|G(S) - Gr(S)\|_\infty \leq 2(\sigma_{r+1}, .\,.\,.\,, \sigma_n) \quad (13)$$

Now we can apply this technique to get reduced-order model as follows:

-0.03409 0.03985 0.08575-0.01201 0.002434 -0.002527 0
0.03976 -0.08874 -0.4012 0.04814 -0.009193 0.0095140
-0.08572 0.4011 -1.173 0.2682 -0.06836 0.072190A=0.01049
-0.04158 0.1906 0.06615 0.02678 -0.02824 0 (14)
-0.001758 0.006995 -0.04988 0.006097 -0.0456 0.09272 0
-6.454e-005 -0.0002823 4.096e-005 0.01464 0.06072-1.4720

0.008603 -0.4464
0.01105 0.3085
-0.004099 -0.5377

B= -0.03968 0.06669 (15)
-0.0108 -0.01171
0.01655 -0.0001043

C=-0.4465 0.3087 0.5378 -0.0776 0.01593 -0.01655 (16)
D =[1.111e-0161.882e-017] (17)

iV. Proposed Controller

Let consider the control structure shown in fig.3. The plant p(s) is an linear time invariant model given. At first, we may also assume that the state vector X is measurable. Here, w denotes the exogenous input vectors. The closed-loop transfer functions from w to z_∞ and z_2 can be expressed $T_{z\infty w}$ and T_{z2w} respectively. The multi objective H_2 / H_∞ control may be described as follows. Find a static state feedback law u = kx such that minimizes $|T_{z2w}|$ 2 subject to $|T_{z\infty w}| < \gamma$. The state feedback formulation of the system described by

$$\dot{X} = AX + B_1 w + B_2 u$$
$$Z_\infty = C_1 X + D_{11} w + D_{12} u$$
$$Z_2 = C_2 X + D_{12} w + D_{12} u \quad (18)$$

where $x \in R^n$ is state vector, Z_∞ , $Z2 \in R^{n_z}$ are out put vectors, $u \in R^{n_u}$ is the control input and $w \in R^{n_w} \in R^{n_w}$ is the exogenous input.H_2 / H_∞ control problem is to minimize the H_2 norm of the T_{z2w} over all state feedback gains k such that also satisfies the H^{∞} norm constraint. with using matlab simulation gain is obtained as

u = kx (19)

$$k = \begin{matrix} -0.0020 & 0.0011 & -0.0005 & 0.0002 & -0.0000 & -0.0000 & 0.0001 \\ 2.1004 & -1.7919 & -0.2899 & -0.0741 & 0.0303 & -0.0111 & 2.2212 \end{matrix} \quad (20)$$

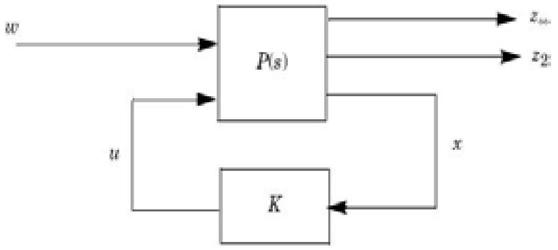

Fig.3 : Block diagram OF $H_2/H\infty$ system

V. Conclusion

Automotive climate control was performed using modern control theory in an air conditioning system with a variable-capacity compressor. We used Balancing approximation method to reduce this model. Then robust controller for automotive climate system has been designed.

The step response and frequency response of the reduced-order system and original system is shown in fig.4,5. It will be seen that there is a very good match between the responses of the original system, and reduce-order system as expected. Therefore it is proper to use six-order model instead of original system for designing controller.

The tracking response of the reduced-order system is shown in fig.6. The compared response between reduced-order system and original system is shown in fig.7 and The error of tracking response is shown in fig.8 and The response signal control is shown in fig.9. The results show that the reduced order has good performance.

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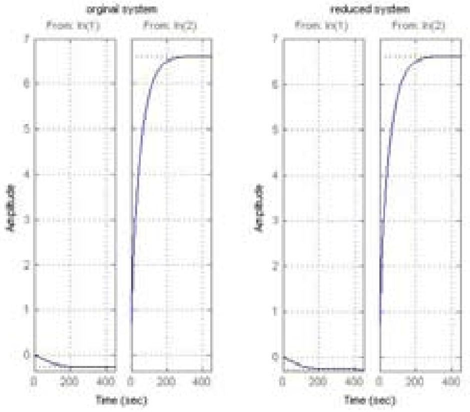

Fig.4 : step response of the reduced-order system and original system

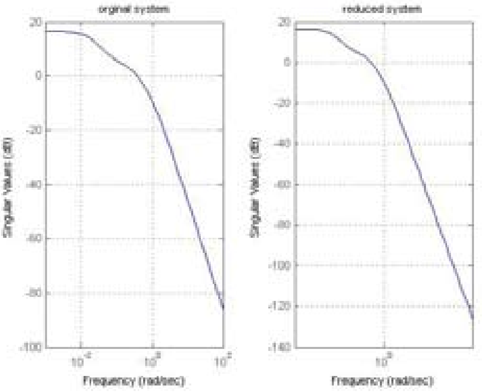

Fig.5 : Frequency response of the reduced-order system and original system

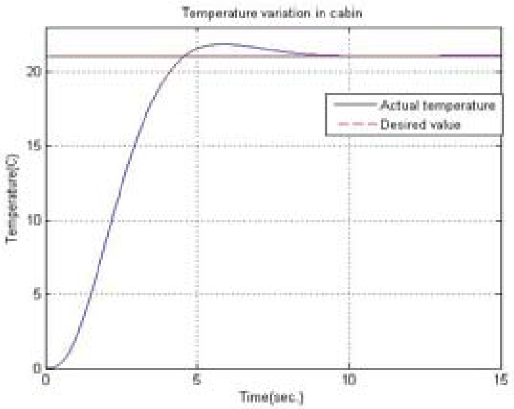

Fig.6 : The tracking response of the reduced-order system (Tracking → 21◦C)

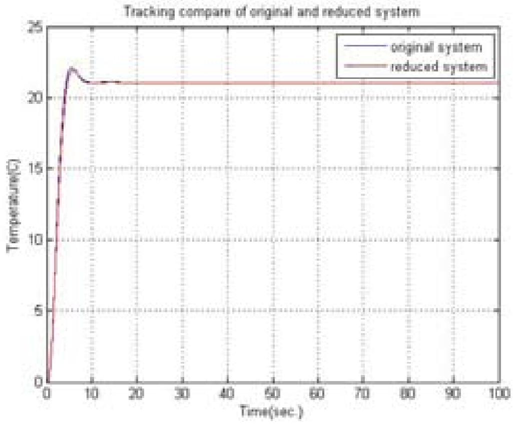

Fig.7 : the compared response between reduced-order system and original system

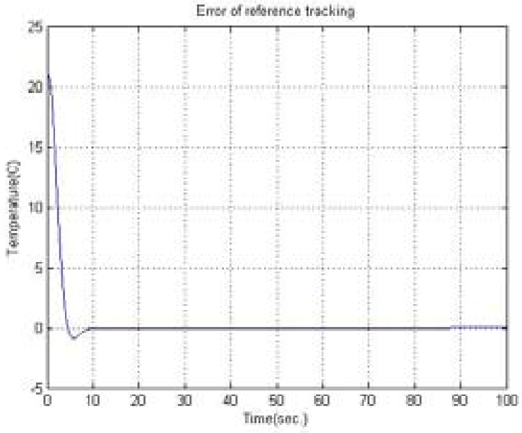

Fig.8 : The error of temperature tracking response of the reduced-order system

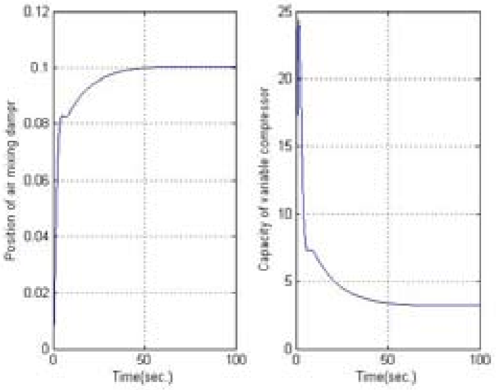

Fig.9 : The response signals control