Robust Controller Design for the Automotive Climate System

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Abstract
This paper deals with automotive climate control using optimal control theory. The goal of this paper is to design the reduced order robust controller based on balanced realization technique. The simulation results show that with applied $H_2/H_\infty$ 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 fixed temperature goal. The first vehicle automotive 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 environmental changes. An air-conditioning system must maintain a comfortable inside temperature despite these changes. However, an air-conditioning system inevitably uses 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 compartment climate should be maintained under all weather and engine operation conditions.
2. The driver should be relieved 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 use 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 systems 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 outside air drawn into the air conditioner is first cooled by heat exchange within the evaporator. The cooling capability of the evaporator is controlled by changing the capacity of the variable compressor. Since the compressoris powered by the engine, the lower the compressor capacity, the lower the load on the engine, and the lower the energy consumption. The outside air cooled inside the evaporator flows in two directions because of the separation of heat by the air mixing damper. One part flows as cool air. While the other is reheated within the heater core by heat exchange. Thus, the air mixing damper adjusts the amount of outside air to be reheated. The cool and warm air are mixed and blown into the car compartment through outlets. Hence, the temperature inside the automobile is determined by the heat of cooling by the compressor [5]. The amount of reheating from the air mixing damper and the heat balance inside and outside the compartment.

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:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

where:
- $x$ is the state vector
- $u$ is the control input
- $y$ is the output vector
- $A$, $B$, $C$, and $D$ are matrices

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

III. Balanced Realization

Balanced realization 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

$$\dot{x} = Ax + Bu$$

The transfer function of the system is:

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

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]

$$A^TP + PA = -Q$$

$$C^TQ + QC = 0$$

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

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

where $\sigma_i \geq \sigma_{i+1}, i = 1, 2, \ldots, n$ are Hankel singular values

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

$$\hat{A} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \quad \hat{B} = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}, \quad \hat{C} = \begin{bmatrix} C_1 & C_2 \end{bmatrix}, \quad \Sigma = \begin{bmatrix} \Sigma_1 \\ 0 \end{bmatrix}$$

where $A_{11}$ and $\Sigma_1$ are $r \times r$ matrices

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

Assuming that $\sigma_1 \geq \sigma_2, \ldots, \sigma_r$ then the corresponding reduced-order
system transfer function is

$$\text{Gr}(S) = D + C_1(SI - A_{11})^{-1}B_1$$

This reduced-order system is controllable and observable since
the corresponding Hankel singular values are all positive. In
addition, the reduced-order system is balanced and asymptotically
stable. It was shown that $\|H\| = \text{norm of the reduced-order system,}

satisfies [16].

$\|G(S) - \text{Gr}(S)\|_2 \leq 2(\sigma_{r+1}, \ldots, \sigma_n)$

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

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \quad \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}, \quad \begin{bmatrix} C_1 & C_2 \end{bmatrix}, \quad \begin{bmatrix} \Sigma_1 \\ 0 \end{bmatrix}$$

$\text{Gr}(S) = D + C_1(SI - A_{11})^{-1}B_1$

for the H∞ control problem is to minimize

$H_2$ norm of the $\text{Gr}(S)$ over all state feedback gains $k$ such that

References

[9,10]
also satisfies the $H_\infty$ norm constraint. With using matlab simulation gain is obtained as 
\[ u = kx \text{ (19)} \]

\[ k = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ (20)} \]

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.

References

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