

The Influence of Vacuum Booster Design Parameters on Brake Pedal Feel

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ABSTRACT

Brake pedal feel characteristic is determined by the structural and kinetic parameters of the components of the brake system. As the servo power component of the brake system, vacuum booster has a significant influence on the brake pedal feel. In this paper, a brake system model for brake pedal feel which has a detail vacuum booster mathematical description is established in the software MATLAB/Simulink. The structure gaps, spring preload, friction force and reaction disc characteristics of vacuum booster are considered in this model. A brake pedal feel bench test under different input velocity and vacuum pressure is completed in order to validate the prediction of the model. Finally, based on the assessment index in pedal travel, pedal force and master cylinder pressure three-quadrant diagram, the influence of vacuum booster design parameters such as structure gaps, spring preloads, press plate and press ring areas, diaphragm effective area and reaction disc stiffness on the brake pedal feel characteristics is analyzed and discussed. This study can serve as important reference for vacuum booster design and adjustment.

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INTRODUCTION

Brake pedal feel refers to the comprehensive feel consist of driver's sense of brake pedal force and pedal travel by feet, and deceleration by the body and visual [1]. As an important quality of the passenger car, brake pedal feel directly affects the customer's evaluation of the vehicle. With the increase demand of the brake reliability and comfort from customer, the study of brake pedal feel draws the attention of vehicle manufacture. As the servo power component of the brake system, vacuum booster design parameters have a direct influence on the brake pedal feel characteristics.

The experiment study of brake pedal feel mainly includes subjective assessment [1, 2, 5] and objective assessment [1, 2, 3, 4, 5]. Assessment index of brake pedal feel mainly contains BFI [1, 3], pedal force - pedal travel curve [1, 2, 4], deceleration - pedal force curve [4], deceleration - pedal travel curve [2, 4] and brake distance - pedal travel curve [5]. Under the background of experiment study, the adjustment of brake pedal feel mainly depends on trial and error method. However, brake pedal feel characteristic is the overall response of each component of the brake system. The lacking of forward design theories makes the adjustment of brake pedal feel requiring large amount of time and cost.

In order to solve the lacking of experiment study, researcher tried to establish the theoretical model of brake pedal feel, which can be used to analyze brake pedal feel characteristics

and guide brake system design. Fortina, A et al.[6] used AMESim to build the model of vacuum booster and validated it by bench test. The influence of reaction disc diameter and vacuum pressure on booster characteristics is analyzed by this model. Johnston M. et al. [7] established a brake system model by GM inner program Brakesyn from the perspective of brake system component. This model can be used to analyze the influence of brake system components on brake pedal feel. Sornioti, A et al. [8] used AMESim software to establish a model for a dual rate vacuum booster and analyzed the effects of booster component stiffness and pre-load on brake pedal feel. Day A.J et al. [9] established a brake system model including brake pedal, booster, master cylinder, brake lines and caliper by AMESim to achieve good pedal feel. Guan et al. [10] established a vacuum booster dynamic model for brake pedal feel by considering the working process of the booster. These studies have important reference value, but there is not a detail mathematical description and a comprehensive consideration of the influence of brake components parameters such as gaps, friction force, preload and reaction disc characteristics.

In this paper, a brake system dynamic model for brake pedal feel is established through MATLAB/Simulink. The spring preloads, friction force, reaction disc characteristic, structure gap and gas characteristic are considered in the vacuum booster model. Then, the effectiveness of the model prediction is validated by the experiments under different input velocity and vacuum pressure on a brake pedal feel test bench. Finally, based on the

assessment index of pedal travel, pedal force and master cylinder pressure three-quadrant diagram, the influence of vacuum booster design parameters such as structure gaps, spring preloads, press plate and press ring areas, diaphragm effective area and reaction disc stiffness on the brake pedal feel characteristics is analyzed and discussed. This study can serve as important reference for vacuum booster forward design and the solution of brake pedal feel problems.

BRAKE SYSTEM MODELING

In order to study the influence of design parameters on brake pedal feel, a model contains the complete brake system needs to be established. According to the physical structure, a brake system can be divided into 4 parts, vacuum booster, master cylinder, pipeline and brake. The ABS/ESP of the brake system is neglected in this study because ABS/ESP only work under limited working condition in which the brake performance and safety are more important than the pedal feel. All the model is established in the software MATLAB/Simulink.

Vacuum Booster Model

Mechanical System Dynamic Model

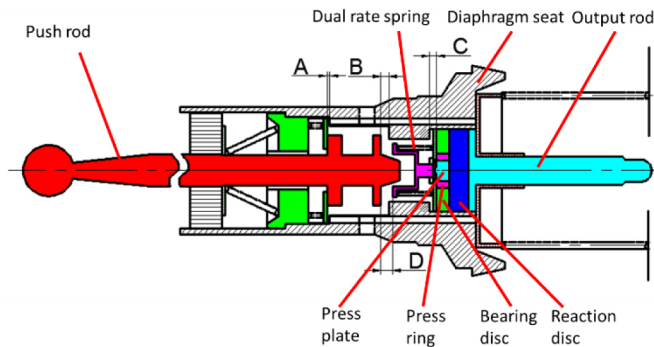


Figure 1. Structure of vacuum booster

Figure 1 show the structure of a vacuum booster. Based on the typical structures and working process of booster [6, 8, 10], the mechanical system physical model of booster is established, considering structure gaps, spring preloads, friction forces and reaction disc features, as shown in figure 2. This model contains 4 lumped mass, m_1 the mass of push rod and valve seat, m_2 the mass of diaphragm and diaphragm seat, m_3 the mass of reaction disc, m_4 the mass of output rod, whose displacement degrees are x_1 , x_2 , x_3 and x_4 respectively. The structure gaps are A the gap between vacuum valve seat and rubber valve, B the gap between push rod and diaphragm seat, C the gap between diaphragm seat and reaction disc, D the gap between push rod and reaction disc, respectively. The spring preloads considered are F_a the push rod return spring preload, F_c the diaphragm seat return spring preload, F_d the dual rate spring preload. F_f is the friction force between diaphragm seat and other components.

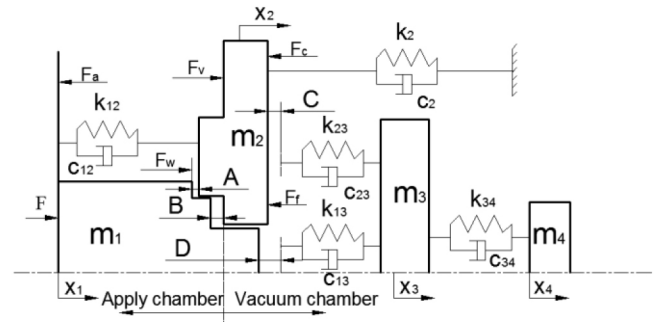


Figure 2. Vacuum booster mechanical model

Under the action of input force and vacuum assist force, the booster rod and diaphragm seat overcome the preload F_a and F_c , and move forward. The diaphragm seat contacts with the reaction disc after moving a distance of C. The movement diaphragm seat compresses the reaction disc, making its center bulge. So that the push rod contact with the reaction disc through the dual spring seat. The force of push rod is passed to the reaction disc through the compress plate and compress ring. At this time, the booster is working at the first boost ratio (smaller one). The push rod continues moving, after overcome the preload of dual rate spring, the push rod force is passed to the reaction disc through compress plate. The booster is working at the second boost ratio (larger one). The dynamic equations of vacuum booster components in this process are as following.

For the push rod:

$$m_1 \ddot{x}_1 = F + F_w - F_{12} - F_{13} - F_a \quad (1)$$

$$F_{12} = k_{12}(x_1 - x_2) + c_{12}(\dot{x}_1 - \dot{x}_2) \quad (2)$$

$$F_{13} = k_{13}(x_1 - x_3 - D) + c_{13}(\dot{x}_1 - \dot{x}_3) \quad (3)$$

$$F_w = (p_0 - p_w) \cdot S_{qf} \quad (4)$$

where F_{12} , k_{12} and c_{12} are respectively the force, stiffness and damping between push rod and diaphragm seat, F_{13} , k_{13} and c_{13} are respectively the force, stiffness and damping between push rod and reaction disc, F_w is vacuum assist force to the plunger, p_0 is the atmospheric pressure, p_w is the apply chamber pressure, S_{qf} is the effective area of valve.

For diaphragm seat:

$$m_2 \ddot{x}_2 + c_2 \dot{x}_2 + k_2 x_2 = F_{12} + F_v - F_{23} - F_c \quad (5)$$

$$F_{23} = k_{23}(x_2 - x_3 - C) + c_{23}(\dot{x}_2 - \dot{x}_3) \quad (6)$$

$$F_v = (p_w - p_v) \cdot S_{dia} \quad (7)$$

where F_{23} , k_{23} and c_{23} are respectively the force, stiffness and damping between diaphragm seat and reaction disc, F_v is the vacuum assist force to the diaphragm, p_v is the vacuum chamber pressure, S_{dia} is the effective area of the diaphragm.

For reaction disc:

$$m_3 \ddot{x}_3 = F_{13} + F_{23} - F_{34} \quad (8)$$

$$F_{34} = k_{34}(x_3 - x_4) + c_{34}(\dot{x}_3 - \dot{x}_4) \quad (9)$$

where F_{34} is force between reaction disc and output rod. It is also the input force of the master cylinder. The rubber material of reaction has the characteristic similar to fluid system which has same pressure everywhere. Therefore the contact stiffness between reaction disc and its adjacent components is determined by the contact area. The reaction disc contact stiffness per unit area is defined as k_r , the preload and effective travel of dual rate spring are respectively F_d and E . The contact stiffness of reaction disc are shown as

$$k_{23} = S_3 \cdot k_r \quad (10)$$

$$k_{34} = S_4 \cdot k_r \quad (11)$$

$$k_{13} = \begin{cases} (S_1 + S_2) \cdot k & S_2 \cdot k_r (x_1 - x_3 - D) \leq F_d \\ S_1 \cdot k_r & S_2 \cdot k_r (x_1 - x_3 - D) > F_d \\ S_4 \cdot k_r & x_1 - x_3 - D > E \text{ or no vacuum} \end{cases} \quad (12)$$

Where S_1 , S_2 , S_3 , S_4 are respectively the area of press plate, press ring, bearing disc and output rod. The contact relationship of reaction disc and its adjacent parts are shown in [Figure 3](#).

The input force of booster push rod is provided by the brake pedal. I is defined as the lever ratio of the brake pedal. Thus the relationship of brake pedal and push rod is shown as [equation \(13\)](#). For the brake system in this study, $I = 3.11$.

$$\begin{cases} F_p = F / I \\ x_p = x_1 \cdot I \end{cases} \quad (13)$$

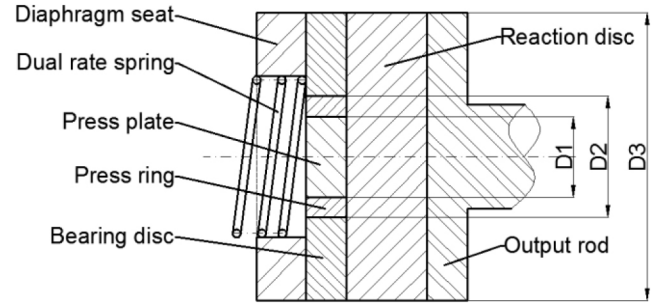


Figure 3. Contact relationship diagram between reaction disc and its adjacent parts

Air Flow Dynamic Model

The gas in apply chamber and vacuum chamber of booster is considered to be ideal gas and has no temperature variation and quality leaking in flowing. Then [equation \(14\)](#) is obtained from the ideal gas state equation. When the push rod moves forward, the air valve opens, the air enters the apply chamber through the air valve, pushing diaphragm moving forward to the vacuum chamber. The mass of air entering the apply chamber is $m_w = Q_w \cdot t$, where Q_w is the air mass flow. The volume of gas in apply chamber is $V_w = V_1 + x_2 \cdot S_{dia}$, where V_1 is the initial volume of gas in apply chamber and S_{dia} is the area of diaphragm. Take m_w and V_w into [equation \(14\)](#), the air flow dynamic model in apply chamber can be express as [equation \(15\)](#). By the same method, the model in vacuum chamber is obtained as [equation \(16\)](#).

$$RTdm = d(pV) \quad (14)$$

$$(V_1 + S_{dia} \cdot x_2) \dot{p}_w + S_{dia} \cdot \dot{x}_2 \cdot p_w = RTQ_w \quad (15)$$

$$(V_2 - S_{dia} \cdot x_2) \dot{p}_v - S_{dia} \cdot \dot{x}_2 \cdot p_v = RTQ_v \quad (16)$$

Gas mass flow is the function of inlet pressure P_i and outlet pressure P_o [11, 12]. When $P_o/P_i \leq 0.528$, the air flow is sonic flow, the mass flow of the air is defined as [equation \(17\)](#). While $0.528 < P_o/P_i \leq 1$, the air flow is subsonic flow, the mass flow is defined as [equation \(18\)](#), where Q_m is mass flow of the gas, C_d is the discharge coefficient, S is the flow area of the orifice, k is the ratio of constant-pressure specific heat and constant-volume specific heat.

$$Q_{m-critical} = C_d \cdot S \cdot P_i \cdot \sqrt{\frac{k}{RT} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} \quad (17)$$