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Finite Element Model of Multi-Body Brake Quarter Car for Braking Analysis

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Abstract. A finite element multi-body model was developed for evaluating the dynamic characteristics of the brake quarter car. All parts of the brake quarter car were modeled as a finite element considering the elastic deformation. Each part was connected by a joint and has a degree of freedom by kinematic constraint. After stabilization by preload, friction braking analysis was performed. The vertical acceleration of the lower control arm was confirmed. Vibration effects due to deformation of the flexible body motion not occurring in the rigid body motion were confirmed at the acceleration level. The coupled thermo-mechanical analysis considering the frictional heat generation was performed using the result of dynamic displacement assuming small deformation in the elastic region. The temperature results of the brake disc were confirmed.

1. Introduction

The quarter car model is the basis for analyzing the dynamic behavior of the full car system. Conventional quarter car model, modelled as a rigid body, was used primarily to analyze the static and ride vibration of mass, spring, and damper systems [1, 2]. However, the rigid body cannot consider the local deformation, so only the low frequency mode analysis is possible for the whole system. This is a simple assumption except for the effect of high frequency vibration mode due to the local deformation of each node point. As computer performance is improved and efficient numerical methods are developed, rigid body models can be replaced with flexible body models [3]. However, static stress analysis and natural frequency analysis are mostly performed for single parts, and there is almost no multi-physics analysis composed of flexible multi-body system.

Braking is basically a phenomenon of energy conversion. A kinetic energy of vehicle speed is converted into thermal energy by friction contact between the brake disc and the pad during braking. The frictional heat generation causes sudden temperature increase on the brake disc and the pad surface. Thermal expansion due to temperature increases thermal stress. Therefore, a thermo-mechanical coupling which can consider structural deformation and thermal deformation is essential in frictional braking analysis.

In this study, the finite element multi-body brake quarter car system was developed to evaluate the local vibration effects and the thermoelastic behavior. The thermo-mechanical coupling conditions are modeled for the heat generation by frictional contact of different parts. Stabilization analysis by gravity and preload of chassis suspension was performed before braking analysis. After the stabilization of the dynamics model, friction braking analysis is performed around the equilibrium



position. The vertical acceleration of the lower control arm due to the suspension vibration was confirmed. Also, the temperature results of the brake disc were confirmed through the thermal model.

2. Modeling of brake quarter car

2.1. Multi-body joint modeling

The brake quarter car analysis model has a McPherson suspension and consists of a brake disc, a caliper, a lower control arm and a hub. Each part is connected by bushings, revolute joints and fixed joints that enable kinematic motion. A schematic diagram of the brake quarter car model is shown in Figure 1. The suspension was modeled by spring-dashpot connector element. The inertial effect by gravity was given to the whole model. The angular velocity was applied to the revolute joint of the brake disc. Table 1 shows the degree of freedom and mechanical property of joints.

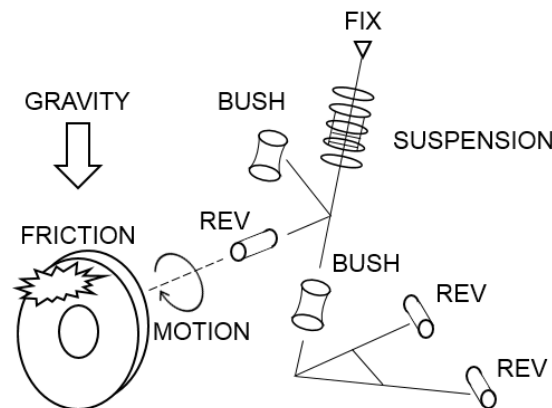


Figure 1. Schematic diagram of brake quarter car model.

Table 1. Degree of freedom and mechanical property of joint.

Joint	Type	D.O.F	Stiffness (N/m)	Damping (Ns/m)
SUSPENSION	Trans.	1	1000	100
BUSH	Trans., Rot.	6	2000	200
REV	Rot.	1	-	-
FIX	-	0	-	-

2.2. Finite element model

In this study, the commercial software ABAQUS Ver. 6.13 was used. All parts are modeled as flexible bodies that allow for deformation. The elements of the caliper, the brake disc and the pad have additional temperature degrees of freedom for calculating the thermal deformation. The suspension is a rigid body model consisting of an equivalent spring and damper system. The finite element model of the brake quarter car is a linear hexahedral mesh with a total of 35,285 nodes and 20,491 elements. Table 2 shows the information of the finite element model.

2.3. Thermo-mechanical coupling condition

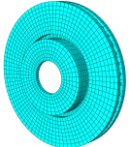
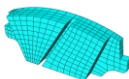
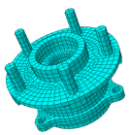
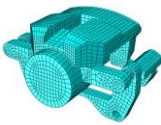
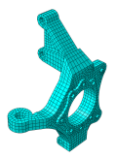
Heat generation by frictional contact causes thermoelastic deformation [4]. To calculate the thermal energy and simplify the thermal model, the following assumptions are made: (i) The materials are all homogeneous isotropic and their thermal properties are independent on temperature. (ii) The friction coefficient is constant. (iii) Convective heat transfer is applied by film coefficient. (iv) Radiation heat transfer is not considered.

The transient heat transfer equation described in the Cartesian coordinate system is given as follow:

$$\rho c \left(\frac{\partial T}{\partial t} \right) = k \left\{ \frac{\partial}{\partial x} \left(\frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{\partial T}{\partial z} \right) \right\}$$

Where ρ , c and k are the density, specific heat and thermal conductivity, respectively.

Table 2. Information on finite element models

Part	Type	No. of nodes	No. of elements	Elastic modulus (GPa)	Density (kg/m ³)
Disc		9,937	4,902	120	7,200
Pad		1,067	667	3	2,252
Piston		436	206	190	7,400
Hub		5,669	3,261	210	7,215
Caliper		9,208	6,197	180	6,850
Knuckle		5,220	3,215	90	4,570
Lower control arm		3,748	2,043	90	4,570

The heat flux coupling conditions are calculated by the energy conversion ratio, the heat distribution ratio, the friction coefficient, the contact pressure, the effective radius and the angular speed between two different friction-contacting parts. All kinetic energy is assumed to be converted to thermal energy and there is no energy loss during the energy conversion process. The heat flux input to the friction surface of the brake disc and the pad is as follows.

$$q_{disc} = (1 - \gamma)\mu\sigma(x, y, t)r\omega(t)$$

$$q_{pad} = \gamma\mu\sigma(x, y, t)r\omega(t)$$

where q is the heat flux, γ is the heat partition ratio, μ is the friction coefficient, σ is the contact pressure, r is the friction radius, and ω is the angular velocity of the brake disc. The heat partition ratio can be obtained as follows [5]:

$$\gamma = \frac{1}{1 + \sqrt{\rho_p k_p c_p / \rho_d k_d c_d}}$$

2.4. Boundary condition

The boundary conditions of the finite element model are shown in Figure 2. In the initial analysis step, the stabilization analysis of the brake quarter car by gravity ($g = 9.81 \text{ m/s}^2$) is performed. Stabilization analysis is the process of converging the static position due to suspension stiffness and damping. The angular velocity ($\omega = 30 \text{ rad/s}$) of the brake disc, which has reached the maximum speed after stabilization, is reduced by the braking pressure ($p = 5 \text{ MPa}$). The braking pressure during braking is constantly applied to the brake pads.

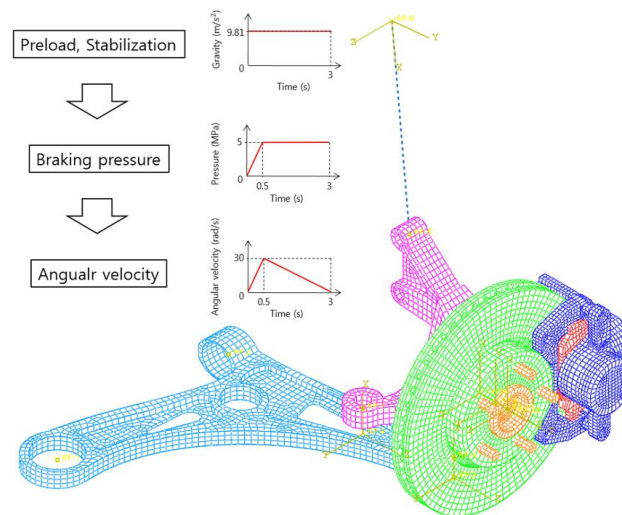


Figure 2. Boundary conditions of the finite element model.

3. Results of braking analysis

3.1. Acceleration.

The vertical vibration acceleration of the lower control arm is shown in Figure 3. The vertical acceleration is gradually reduced by spring stiffness and damping of the suspension. In addition, the local vibration can be confirmed in the acceleration result. This is because the local deformation mode of the flexible body is considered. This local vibration can be easily confirmed by Fast Fourier Transform (FFT) results. Figure 4 shows the FFT for vertical acceleration. The peak of the natural mode of the suspension can be seen at about 6.2 Hz. It can be seen that the peak frequencies of the elastic modes of the flexible body appear in different frequency bands.

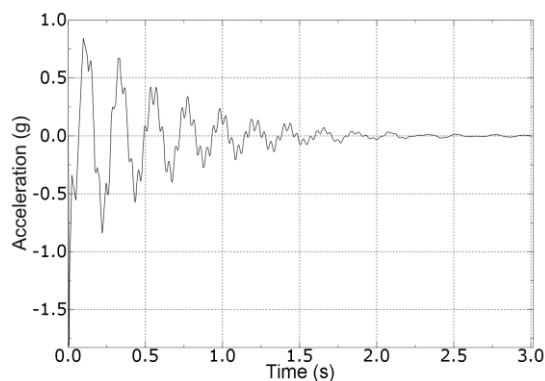


Figure 3. Vertical acceleration of the lower control arm.

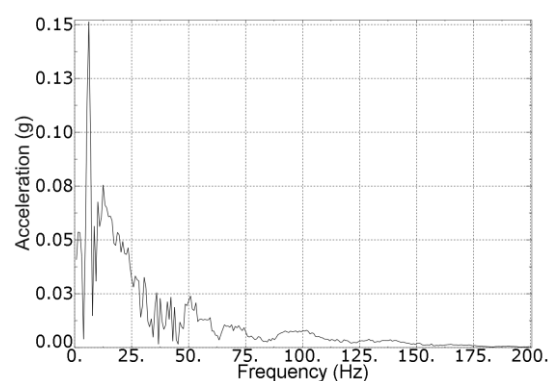


Figure 4. FFT of the vertical acceleration of the lower control arm.

3.2. Temperature.

The temperature distribution of the brake quarter car is shown in Figure 5. A temperature gradient occurs around the brake disc. Figure 6 shows seven temperature peaks on the disc surface. It can be confirmed that the temperature is reduced by convective heat transfer. The maximum temperature and the end temperature are about 53 degrees and 40 degrees, respectively. Therefore, heat generation by the heat flux coupling condition and convective heat transfer to the ambient temperature are well modeled reflecting the physical heat transfer effect.

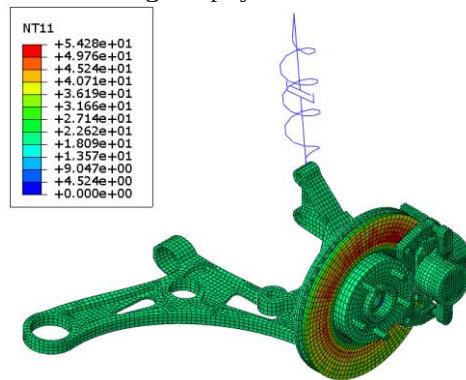


Figure 5. Temperature distribution of the brake quarter car.

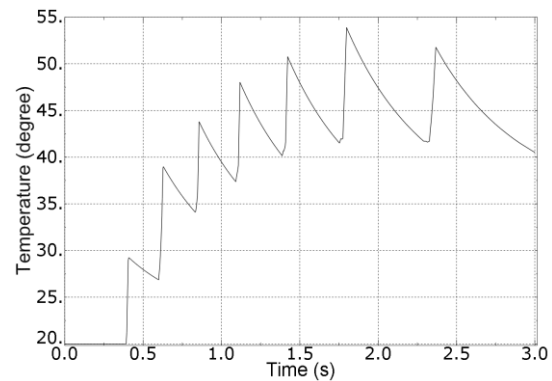


Figure 6. Temperature result of the brake disc surface.

4. Conclusion

The finite element model of the multi-body brake quarter car was developed. The local vibration by the flexible body mode was confirmed from the vertical acceleration acting on the lower control arm. Also, the temperature gradient by frictional heat and convective heat transfer was confirmed. Based on the brake quarter car model, full quarter car model assembled with wheel-tire will be developed. The full quarter car model will be able to analyze not only braking but also ride and handling. In the next study, the validation of the analytical model will be carried out by the brake quarter car dynamo experiment.

Acknowledgments

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