Brake Judder Analysis for Small Size Bus

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ABSTRACT

In this paper, a method to improve judder by changing the front and rear wheel brake force distribution ratio was proposed. ADAMS, a commercial dynamic analysis software was used to model a small size bus and its modeling procedure was explained. By using the ADAMS vehicle model, the judder phenomena of the small bus were analyzed, and based on analysis results, the validity of the improvement method was proposed. Also, in order to lessen the problem of the judder phenomena, by setting force elements, mass (inertia), and geometry of each part of the vehicle as variables, judder sensitivity analysis and test results were proposed.

Keywords : Brake judder, ADAMS, Bus, Sensitivity, Brake force

1. Introduction

There are various types of vibrations when the vehicle is moving at high speed – shake, shimmy, and brake judder to name just a few. Shake is the vertical vibration of the steering wheel when the vehicle is moving at 40~70 km/h. Shimmy is the vibration of the steering wheel in the circumferential direction when the vehicle is moving over 80 km/h. Judder is the vertical vibration of the steering wheel when the vehicle slows down at medium or high speed. The occurring condition for judder and shake is different, but the vibration mode is similar.

Judder can be classified into two different types[(1)]: cold judder and hot judder. Hot judder is caused by the heat expansion, which occurs in the brake when the frictional force on the contact surface is irregular[(2)]. It occurs in the higher frequency region than the cold judder. Especially, when the hot judder occurs, the shake of the pedal is very small or insignificant. Cold judder is caused by the machining error of drum, wheel, and brake disc thickness variation. It usually occurs in the low frequency region. Therefore, the vibration generated when braking will cause steering wheel vibration, brake pedal shake, and floor vibration, which then, is passed onto the driver.

Previous studies related to the judder improvement have tried to minimize the judder by changing the suspension geometry, compliance characteristics, and the damping force of the shock absorber[(3)]. Additional study was done to improve the judder sensitivity by minimizing the brake disc thickness variation[(4)].

In this paper, a method to improve judder by changing the front and rear wheel brake force distribution ratio was proposed. It's limited to the cold judder, and the method to create the small bus simulation model using the commercial software ADAMS (Automatic Dynamic Analysis of Mechanical Systems) was briefly explained. By using the ADAMS vehicle model, the judder phenomena of the small bus were analyzed, and based on analysis results, the validity of the improvement method was proposed in this paper. Also, in order to lessen the judder and the problem of the judder phenomena, by setting force elements, mass (inertia), and geometry of each part of the vehicle as variables, judder sensitivity analysis and test results were proposed.

2. Judder Vibration Analysis

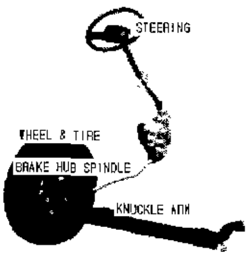

Fig. 1 Mechanism of steering system

Judder is a phenomenon that occurs when the vehicle driving at high speed brakes with magnitude of 0.3 g. When the braking is taking place, brake pedal shakes, steering wheel vibrates in the circumferential, front, and backward direction, and the body vibrates (Fig. 1). First, consider the vibration exciting source.

2.1 Exciting source of judder vibration

The main reason for a judder vibration is periodic change due to non-uniformity and imbalance of the rotating mass[4][5]. Specific reason includes the non-uniformity of the brake contact surface, disc thickness variation, concentricity offset of the brake drum, disc runout, non-uniformity of the tire, slope error of the disc surface, and the rim runout. Vibration due to the non-uniformity and the imbalance of the rotating mass will cause resonance phenomena, which started from vibration combined from tire, steering system, suspension system, and the body.

2.2 Judder phenomena

Vibrating frequency test results, which were obtained by placing the acceleration sensors on the knuckle, steering wheel, and brake pedals, which acts as a path for vibration transfer. Results are shown on Fig. 2~5. From this vibration frequency analysis, following facts were observed.

1) At the knuckle arm and brake back plate, which is close to the vibration source, the vibration frequency was shown as the constituent of 2nd order harmonic vibration.
2) Second order vibration frequency was also observed

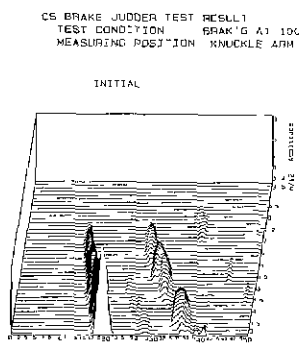

Fig. 2 Vibration characteristics of knuckle arm

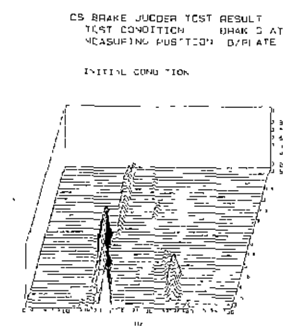

Fig. 3 Vibration characteristics of brake back plate

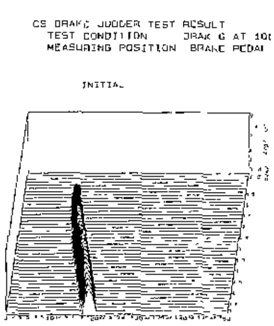

Fig. 4 Vibration characteristics of break pedal

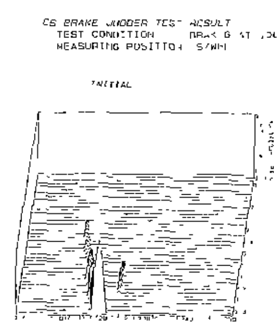

Fig. 5 Vibration characteristics of steering wheel in circumference direction

from the brake pedal and steering wheel, which can be felt by the driver.

3) Therefore, 2nd order vibration frequency is the vibration, which occurs when the imbalance factor of the rotating mass, which vibrates twice while wheel spins once, amplifies due to the resonance of the unsprung region.

From results above, it could be concluded that the brake pedal pulsation is actually a cold judder.

3. Simulation analysis for judder

3.1 Dynamic ADAMS modeling analysis

Using the commercial dynamic simulation software ADAMS, model was constructed in the following order.

1) Decide simulation objective and collect necessary geometry data
2) For each steering and suspension model, finite element beam (Timoshenko beam) was used. and for the bending and twisting moment, force-delta curve was consulted. To prove the validity of the multi-leaf spring stiffness of the simulation model, one eye was connected to rotating joint, and the other eye was allowed to slide, just as it was done in real spring testing.
3) After modeling the spring between the tire mounting position and the ground. find the stable position by static simulation (Fig. 6). In this position. delete the spring model and install the tire model.
4) When modeling the tire, it was created by transforming test results, provided by tire manufacturer, into the ADAMS tire forces. Characteristics considered were normal stiffness, longitudinal slip ratio, lateral slip ratio, camber stiffness, rolling resistant moment coefficient, radial damping ration, maximum dynamic frictional force, and maximum brake frictional force.
5) After completing the vehicle by combining each component, dynamic rolling radius of the tire must be obtained. The method used in this modeling was that after creating the complete vehicle, run the dynamic simulation with the vehicle for twenty seconds. From the simulation. calculate the contact point between tire and the ground. and obtain the dynamic rolling radius.

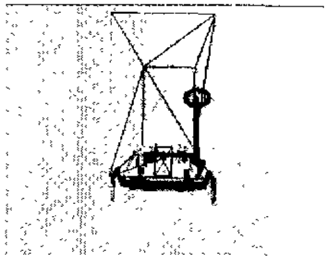

Fig. 6 Static model

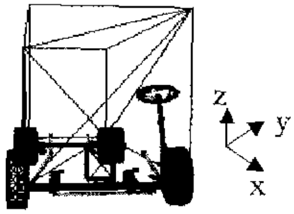

Fig. 7 Full model

6) Modify the model by comparing the simulation results and the test results.

4. System Sensitivity Analysis

In this simulation of ADAMS, judder caused by moving the front wheel center 1 mm from front axle center. Factors which can influence the judder sensitivity are ① force element of the unsprung region (upper part, reference to the spring), and ② geometric and inertial variation of the sprung and unsprung region.

Changing forces in the unsprung region, such as leaf spring stiffness, stabilizer bar stiffness, spring eye bush stiffness and shock absorber damping force will affect the vehicle's ride and handling more than factors stated in second factor. Therefore, in this paper, simulation was primarily done with method described in second factor.

In this paper, geometric variation of the unsprung region and the stiffness variation of the sprung region considered are as follows:

- Position variation for the shock absorber joint and the drag link - knuckle arm joint
- Mass variation for the drag link, the front axle and the rear axle
- Position variation for the tie rod – knuckle joint

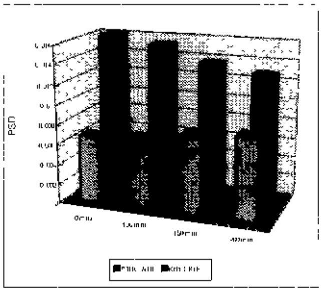

Fig. 8 Position variation of shock absorber hard

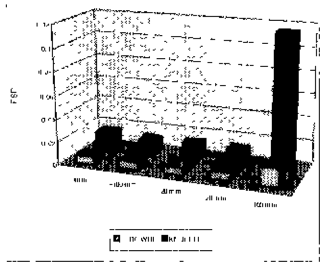

Fig 9 Position variation of Drag Link and knuckle arm joint.

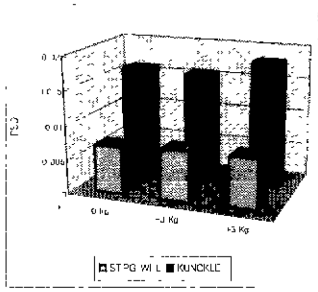

Fig. 10 Drag Link weight variation

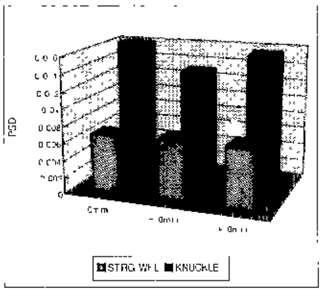

Fig. 11 Position variation of Tie rod, knuckle arm joint.

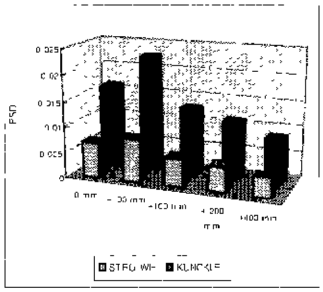

Fig. 12 Position variation of drag Link, knuckle arm joint.

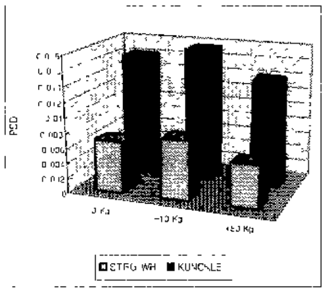

Fig. 13 Front axle weight variation

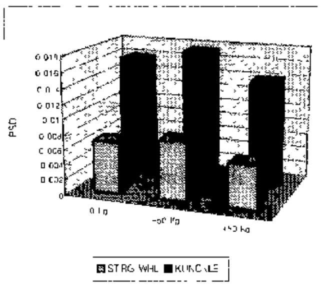

Fig. 14 Rear axle weight variation

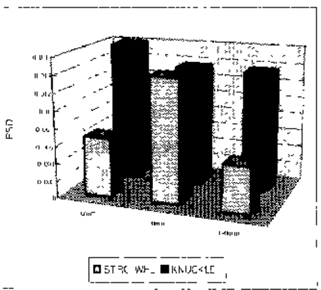

Fig. 15 Center of gravity (CG) position variation.

- X-direction transfer of the vehicle mass center

Results of the simulation were shown in Fig. 8~Fig. 15. It shows PSD results of the second order vibration. From these results, following observations were made;

1) Fig. 8 : Results obtained by fixing the upper point of the shock absorber, and moving the low point in the y direction by 100 mm, 150 mm, and 200 mm.
2) Fig. 9 : Results obtained by moving the drag link – knuckle arm joint in the x-direction.
3) Fig. 10: Results obtained by changing the mass of the drag link
4) Fig. 11: Results obtained by moving the knuckle arm – tie rod joint position

It was found that the factors shown Fig. 8~11 has insignificant affect on judder sensitivity improvement

5) Fig. 12: Results obtained by moving drag link – knuckle arm joint in the y-direction. When the point was moved 20 mm in +y direction, PSD (Power Spectrum Density) of the steering wheel has improved by 21% compared to the original position, and PSD of the knuckle arm was improved by 15%. There was no improvement when the point was moved in –y direction.
6) Fig. 13: Results obtained by changing the front axle load. In case of load decrease, no PSD and frequency decrease was observed at the knuckle arm and

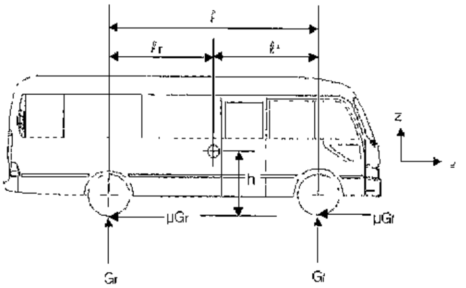

Fig. 16 Overview of middle size

steering wheel. When the load increased, PSD of the steering wheel was improved by 1.1% compared to the original load, but the PSD of the knuckle arm was worsened by 28%.

7) Fig. 14: Results obtained by changing the rear axle load. When the load was lightened by 50 kg, PSD of the steering wheel and the knuckle arm was worsened by 15% and 9%, respectively. When the load was increased by 50 kg, PSD of the steering wheel and the knuckle arm was improved by 15% and 12%, and the frequency region also transferred slightly compared to the original load.

8) Fig. 15: Results obtained by moving vehicle's center of gravity (CG), and the effect due to the change was converted to the percentage respect to the center 0 mm. The results are in parenthesis in Table 1, and as the center moved in +x direction, PSD and frequency of the steering wheel and the knuckle arm improved. When it moved in x direction, it had negative effect on the sensitivity. In Table 1, judder sensitivity improvement effect as the CG moves in the +x direction was shown.

Table 1 CG Variation

CG transfer [mm]	STEERING		KNUCKLE	
	PSD	Freq[Hz]	PSD	Freq[Hz]
0	0.00673	17.578	0 01599	17.578
-100	0 00833 (24% ↑)	17.773 (1.1% ↑)	0.02241 (40% ↑)	17 733 (1.1%↑)
+100	0.00554 (18% ↓)	17 383 (1.1% ↓)	0.01298 (19% ↓)	17.383 (1.1%↓)
+ 200	0.00494 (27% ↓)	17.090 (2.8% ↓)	0.01094 (32% ↓)	17 188 (2.2%↓)
+400	0.00395 (41% ↓)	16 797 (4 4% ↓)	0.00855 (47% ↓)	16.797 (4.4%↓)

From these results, it was observed that the CG transfer and the rear axle load increase will improve the judder phenomenon. Also, from results obtained, CG transfer in particular, has significant effect when it was moved toward back. It represents the inertial variation of the vehicle, and as it moves toward back, judder sensitivity was improved. But, improving the overall inertia of the vehicle is practically impossible. In the next chapter, a practical judder improvement method was discussed.

5. Judder sensitivity improvement method

Results observed in Fig. 15 shows that by decreasing the dynamic rolling radius of the front wheel, brake friction force between the ground and tire decreases, and it means that these factors lessen the vehicle vibration. In this paper, from this point of view, a method to improve the judder sensitivity by instantaneous decrease of the force applied to the front axle when braking was proposed. In other words, when braking, this method weakens the forward movement of the vehicle's instant motion center.

But this method has a weakness also. When the brake distribution between front axle and rear axle is not correct, it can cause vehicle handling problems, so one must distribute the brake forces with care.

5.1 Force transfer while braking

First, observe the relation between forces, which generates in the front and rear axle while vehicle is braking. Fig. 16 represents the free-body diagram of the braking vehicle, and the force and moment equation of equilibrium while braking are, respectively, given by

$$-\quad \sum F_X = 0: \quad m\ddot{x} = -(\mu_f G_f + \mu_r G_r) \qquad (1)$$

$$-\quad \sum F_z = 0: \quad G = G_f + G_r \qquad (2)$$

$$-\quad \sum Mr = 0: \quad hm\ddot{x} = -(l_r G + l G_f) \qquad (3)$$

Where, m is the total vehicle mass, G_f and G_r are the reaction forces of front wheel and rear wheel, h is the heights of CG from ground, l_f and l_r are the distances of front wheel and rear wheel from CG. μ_f and μ_r are the coefficients of dynamics friction. We can

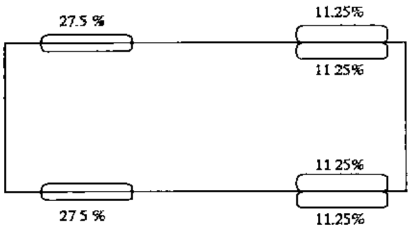

Fig. 17 Brake torque distribution

obtain the force of front wheel in the following form

$$G_f = \frac{h}{l}(\mu_f G_f + \mu_r G_r) + \frac{l_r}{l} G \qquad (4)$$

Where

- $\frac{h}{l}(\mu_f G_f + \mu_r G_r)$: generated force of front wheel while braking
- $\frac{l_r}{l} G$: static force of front wheel

From the equations above, it was observed that when the brake is applied, forces concentrate to the front wheel due to the deceleration of the vehicle. Due to the concentration of the forces, it was shown that the instant motion center moves in the forward direction. Therefore, small imbalance of front wheel can cause large vibration, effecting judder in a bad way. In the next section, judder vibration relief through the simulation was discussed.

5.2 Brake force variation simulation.

Simulation was done using ADAMS vehicle model to analyze the brake force variation applied to the front and rear wheels. ADAMS vehicle model, moving at 98 km/h, was slowed down for 5 second, decreasing speed down to 50km/h. Furthermore, judder caused by moving the front wheel center 1 mm from front axle center. Brake force distribution is as follows; and Fig. 17 shows the brake distribution of case 1

- Case 1 : original distribution (Front:55%, Rear:45%)
- Case 2 . Front 60%, Rear 40%
- Case 3 : Front 52%, Rear 48%
- Case 4 : Front 0%, Rear 50%
- Case 5 : Front 45%, Rear 55%

Table 2 Brake torque variation

Brake Torque	STEERING		KNUCKLE	
	PSD	Freq[Hz]	PSD	Freq[Hz]
Case 1	0.00673	17.578	0.01599	17.578
Case 2	0.009 (33% ↑)	18.066 (2.7% ↑)	0.0229 (43% ↑)	18.066 (2.7% ↑)
Case 3	0.0051 (24% ↓)	16.992 (3.3% ↓)	0.011 (31% ↓)	17.188 (2.2% ↓)
Case 4	0.0045 (33% ↓)	16.602 (5.8% ↓)	0.011 (31% ↓)	17.188 (2.2% ↓)
Case 5	0.003 (55% ↓)	15.82 (5.8% ↓)	0.0052 (67% ↓)	15.869 (9.7% ↓)

Simulation results for each of those five cases were shown in Table 2, and from these results, it was observed that if brake distribution in the rear increases, PSD decreases, and the frequency region moves. This shows that judder sensitivity is improving.

When results of Table 1 and Table 2 were compared, one could see that the variation pattern is similar. Moving CG to the rear and increasing the rear braking force is the same as decreasing the friction force between front tire and the ground. By using this method, it was proved that the judder sensitivity has been improved. Through the simulation, this paper proved the validity of the judder sensitivity improvement.

6. Conclusions

From results obtained, following facts were observed:

1) In this paper, by changing front and rear braking force distribution, it suggested a method to improve judder sensitivity. Through the simulation results, it proved the validity of the method for improving the judder.
2) Also, from Table 1, it was observed that by moving the CG to the rear, judder sensitivity could be improved. But this method, by altering the body stiffness, it can affect the ride and handling in a bad way, thus hard to apply in real situation. In this paper, it was judged to be more practical to improve judder by brake force distribution. Also, as it was mentioned in chapter 5, distribution of brake forces in front and rear wheels has limits.
3) Rigid suspension, compared to the independent suspension, has less parameters (suspension geometry and compliance) available to change in order to improve the judder sensitivity. It is harder to improve the judder sensitivity of rigid suspension.

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