

Handling Analysis of Height control and ECS

Wanil Kim, Jeong-Woo Lee

Mando R&D Center

Hyo-Seok Kim, Won-Joo Do, Young-II Yoo

Hyundai Motor Co.

Jeong-Soo Shim, Jong-Wha Lee

SeoMoon Technology Inc.

ABSTRACT

In this paper we propose an Active Height Control system which consists of an automatic air leveling and semi-active suspension system for an SUV (sport utility vehicle). Prior to a real car installation, to estimate the vehicle performance and tune the control logic, we model the vehicle with flexible body frame and AHC system using ADAMS. We analyzed the vehicle ride and handling performances for various driving conditions by simulation.

1. INTRODUCTION

The reduction of vehicle weight by using advanced material technology leads to a large payload difference between the kerb and gross vehicle weight conditions. This phenomenon is especially severe for SUV and MPV (multi purpose vehicle) which often accept many luggage inside the cabin. But, with conventional a spring and a damper which have fixed characteristics, it is not to easy to meet the customer's request on the vehicle performance

In this study, for our newly released SUV, we propose the AHC system which adjusts the vehicle height automatically with air leveling control and damping forces continuously according to driving

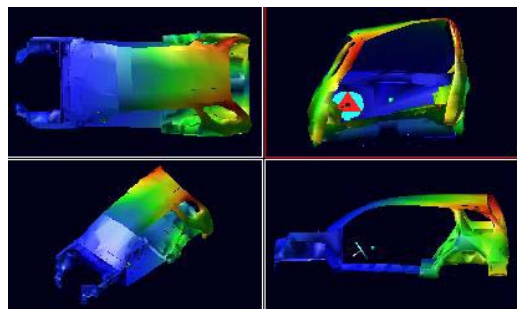
conditions. The system is equipped with four-wheel independently controlled semi-active dampers, two air springs for two rear wheels, one ECU and related sensors. The vehicle body frame is modeled as a flexible body using ADAMS/Flex. We select eight dominant deformation modes. Next, we analyze the vehicle performance such as leveling, ride quality and handing, using multi-body dynamic analysis tool ADAMS in CAR environment. The control logic is coded in Fortran and linked to the ADAMS model by user subroutine. By doing this, before we install the AHC system in a real car, we can estimate the vehicle performance under various driving conditions, develop and tune the control logic in advance.

2. VEHICLE MODELING

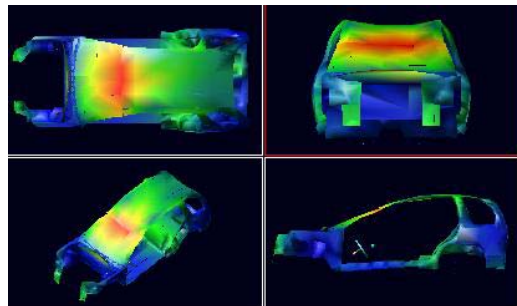
2.1 BIW(Body in white) model

In this study, the vehicle body frame is modeled in two ways: rigid and flexible body. The fundamental frequency of passenger car is normally below 50Hz. To consider the flexible effect of the body frame, we perform BIW (body in white) modal analysis using MSC/Nastran. Next, we convert the analysis result to modal neutral file in order to integrate a flexible body in ADAMS/Car model.

The number of mode shapes is eight. The first mode shape in Fig.1 is torsional around the vehicle longitudinal axis. The second one is bending about the lateral axis. The rest shapes are summarized in table 1.



1st mode (26.9 Hz)



2nd mode (43.8 Hz)
Fig. 1. 1st, 2nd Mode shape

| Modes | Frequency (Hz) |
|-------|----------------|
| 3 | 45.5 |
| 4 | 46.2 |
| 5 | 47.3 |
| 6 | 49.7 |
| 7 | 50.3 |
| 8 | 54.4 |

Table 1. Modal frequencies

2.1 Suspension ,steering system and tire

The front suspension is the McPherson type and the rear one is the double-wishbone type with a semi-trailing arm. The steering system is the rack and pinion

type.

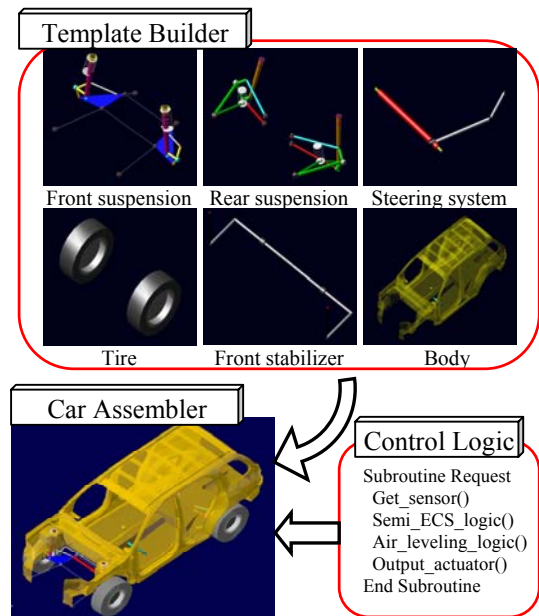


Fig. 2 Adams/Car modeling process

We use the ADAMS/CAR to model the vehicle [1]. First, we build templates for each suspension and body component. Next we make subsystems appropriate for our SUV using the templates. The full vehicle is assembled with the subsystems, and the AHC control logic coded in the Fortran subroutines is linked to the model. The overall modeling process is depicted in Fig. 2. As for the tire, we use the theoretical fiala model, and the front stabilizer is modeled as a torsion bar. We also consider the compliance effects for the front and rear suspension by including the bushings in the model. The rigid vehicle model is basically nonlinear and has 78 DOF by itself. With the additional 8 DOF of BIW, the whole vehicle model has 86 DOF.

3. AHC System Configuration

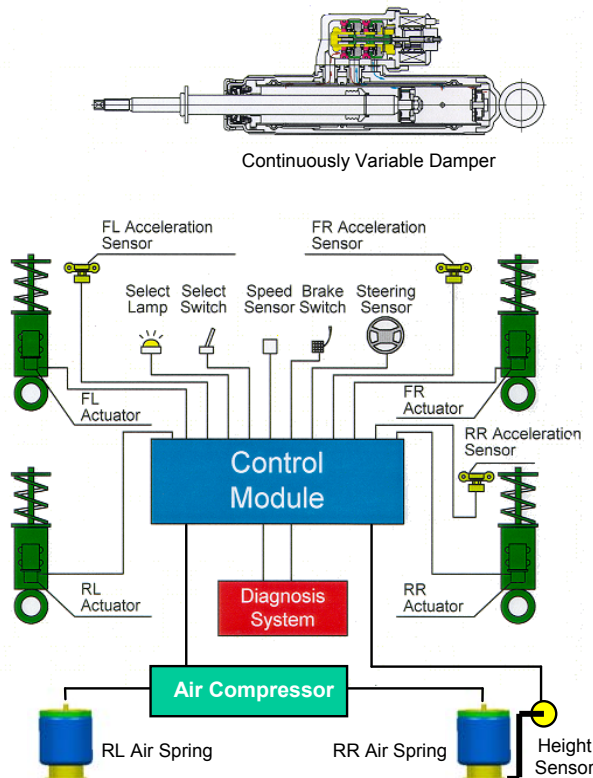


Fig. 3 Configuration of AHC system

The AHC system is composed of an automatic air leveling system and a four-wheel independently controlled semi-active suspension system (Fig. 3). The air leveling system is equipped with two stand-alone type air springs on rear two rear wheel, an air compressor, a potentiometer height sensor which measures the relative distance between the body and wheel, and on/off solenoid valves. It aims at the maintenance of the design height against the payload variation on vehicle rear side.

3.1 Semi-Active ECS

The semi-active suspension consists of four continuously variable dampers, a control module, three vertical acceleration sensors, a steering wheel sensor, a speed sensor, a throttle position sensor, and brake switch.

The damping force is controlled

through the proportional solenoid valve attached to the damper outer shell. We use a so-called reverse-type damper, which has 3 different settings: (1) soft damping for both rebound and compression strokes, (2) hard damping for rebound stroke and soft for compression (H/S), (3) soft for rebound stroke and hard for compression (S/H). (Fig. 4)

One of above three setting is continuously selected according to the solenoid input current, and it allows the sky-hook damper control to be realized easily [2].

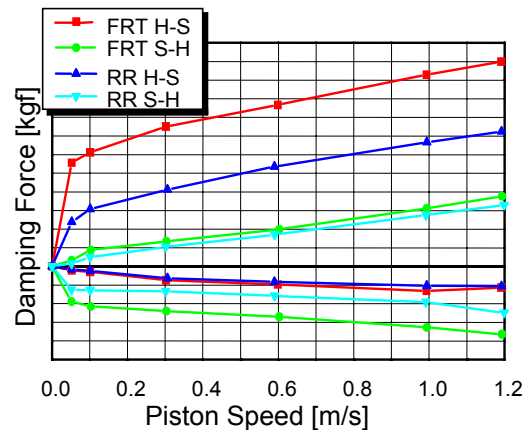
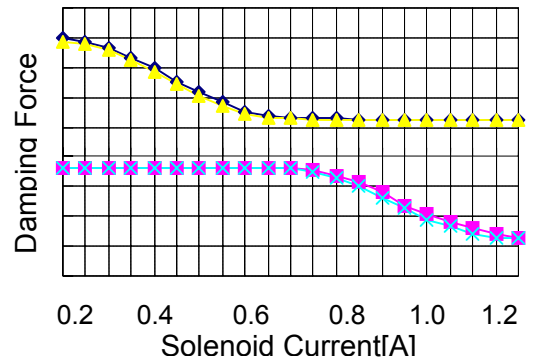


Fig. 4 Reverse Damper Characteristic

3.2 Air Spring

Air springs have nice properties compared to the conventional coil or leaf springs. First of all, we can adjust or maintain the spring height with an auxiliary air supply system. The equivalent spring constant, as depicted

in Eq. 1, increases as the spring load is added so that the ride frequency remains almost the same irrespective of the vehicle weight [3].

$$K_{dyn} = P_e \frac{dA_e}{dx} + n(P_a + P_e) \frac{A_e^2}{V} \text{ [N/m]} \quad (1)$$

,where P_e is the internal pressure, P_a is the atmospheric pressure, A_e is the effective area, x is the stroke, V is the air volume, and $n=1.38$ is the polytropic constant. As for the static conditions, we should set $n=1.0$, which implies a less soft spring constant. The dynamic model for the air spring is derived from the equation of gas as follows:

$$\dot{P}_e = \frac{nRT}{V} \dot{m} - \frac{n(P_a + P_e)}{V} \dot{V} \quad (2)$$

where R is the gas constant, T is the air temperature, and \dot{m} is the air mass flow rate into the air spring.

The dynamic model of the air spring is linked to the ADAMS vehicle model. The dynamic stiffness is shown in Fig. 5 with respect to wheel stroke. When the spring is compressed, i.e. positive wheel stroke, the stiffness is increased parabolically. This implies that the vehicle may have over-steer tendency when the rear wheel stroke is large at the design weight condition.

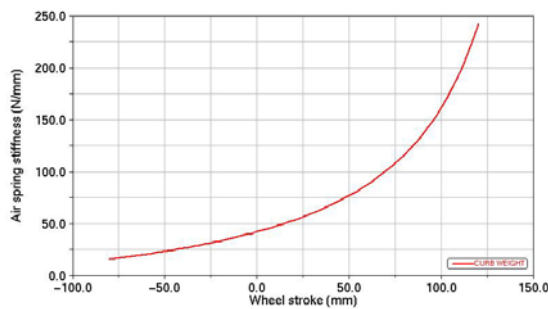
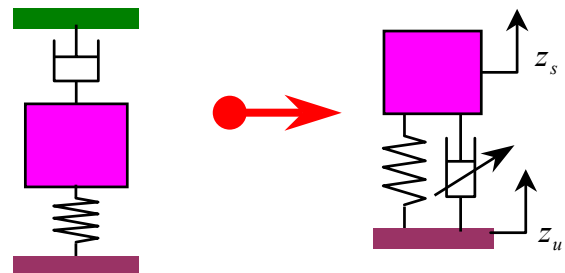


Fig. 5 Air spring characteristics

3.3 AHC Logic

The control logic for the AHC system has two separate parts: semi-active damper control logic and height control logic.

The ECS control logic consists of ride control, anti-roll control, anti-dive and anti-squat control. The ride control is based on the well-known sky-hook damper model, which is realized with the continuously variable damper as



(a) Ideal sky-hook damper (b) Practical realization

Fig. 6 Realization of sky-hook damper follows [4]:

$$\begin{aligned} \dot{z}_s \cdot (\dot{z}_s - \dot{z}_u) &\geq 0 \Rightarrow \text{Hard Damping} \\ \dot{z}_s \cdot (\dot{z}_s - \dot{z}_u) &< 0 \Rightarrow \text{Soft Damping} \end{aligned} \quad (3)$$

The anti-roll control logic detects the vehicle's cornering motion from the

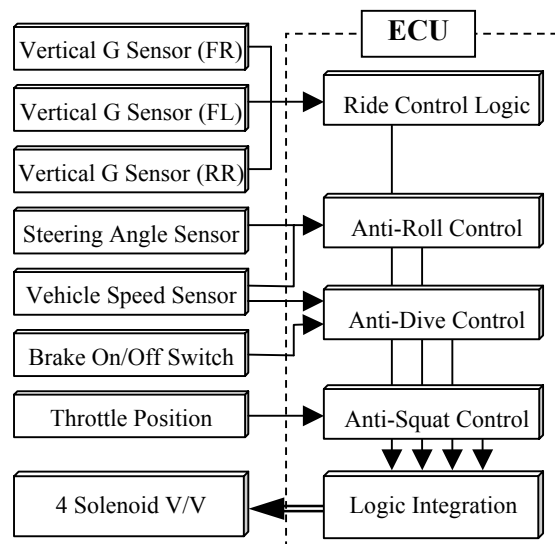


Fig. 7 Semi-active ECS control steering wheel angle sensor, and sets the inner rebounding dampers hard to reduce the body roll motion and to lower the vehicle's center of gravity position. The anti-squat and dive control logic sustains the body pitch

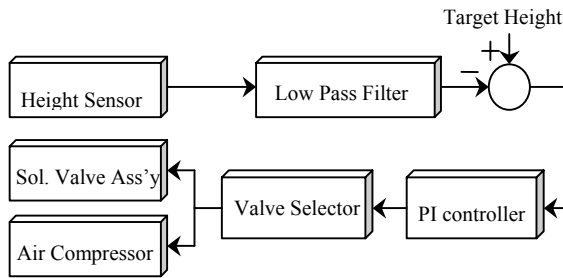


Fig. 8 Height control loop

motion when the vehicle is accelerated or decelerated rapidly. The overall control logic is summarized in Fig. 7.

The height control logic receives relative distance between the vehicle body and wheel from the height sensor. The high frequency component is filtered out so that it captures the spring deflection resulting only from the static vehicle weight variation. Then the PI (proportional-integral) controller and valve selector decide whether the compressed air should be supplied into the spring from the air compressor, or exhaust the air inside the spring to the atmosphere.

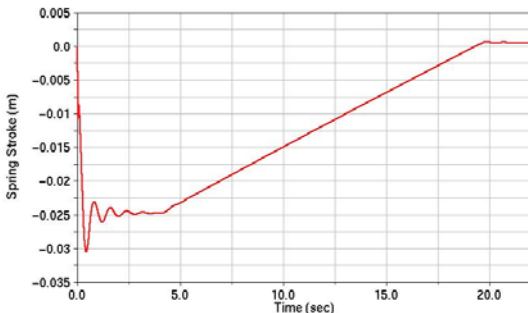


Fig. 9 Height control

Finally, the air compressor and the on/off type solenoid valve assembly are driven correspondingly.

4. SIMULATION RESULTS

Simulation study for the AHC system is done for both the rigid and flexible body models. After we confirm the effect of the flexible body model for the conventional vehicle, we compare the performance of the AHC system only for the flexible

model.

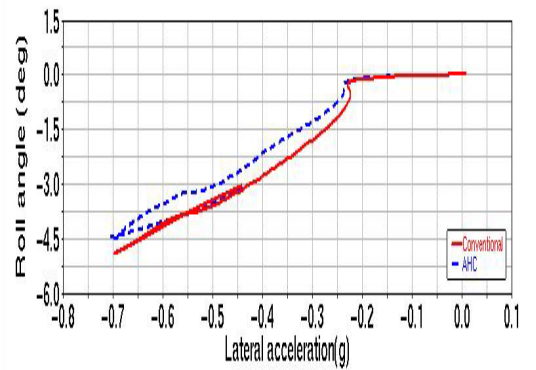
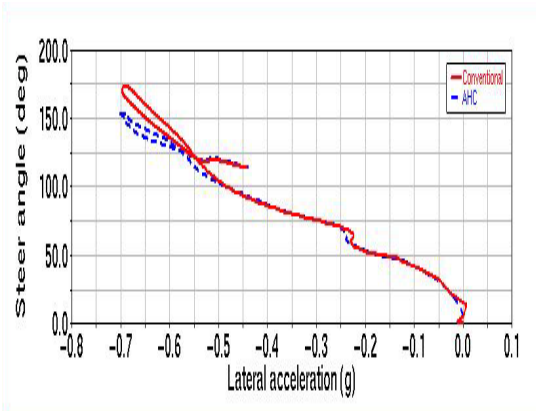


Fig. 10 Steady state cornering

4.1 Height Control

The basic function of the AHC system, the automatic leveling of the design height, is simulated by adding an extra 200 kg on rear side. The corresponding reduction of the spring height about 25 mm is recovered at $t = 19.62$ sec after compressed air is supplied from $t = 4.03$ sec. The leveling speed is about 1.6 mm/sec, which seems reasonable not to cause passenger discomfort.

4.2 Steady State Cornering (ISO 4138)

In a steady state circular test mode, both vehicles show similar understeer tendency as shown in Fig. 10. Since the roll control algorithm of the ECS has not much effect on the steady state, a little lower roll angle of AHC seems to

result from the stroke-dependent stiffness characteristic of the air spring (Fig. 5).

4.3 Step Steer (ISO/DIS 7401)

To identify the transient state of handling and stability of vehicle, step steer has been conducted with reliable correlation with jury evaluation. The velocity of vehicle is 80km/hr, and to reach lateral acceleration to 0.5g. Step steer of steering wheel was applied (steer angle = 58degree).

First, we investigate the effect of flexible body frame for the conventional system during step steering (Fig. 11). The decrease of body frame stiffness with respect to rigid body requires the increase of the roll moment that is sustained at the suspension for the same load condition. This leads to larger load transfer both front and rear sides than the rigid model case. Front tire lateral slip angle variation is shown to be larger than rear one, which means the more understeer effect with respect to rigid body. The outputs we interest of are the response time and amount of both side slip angle and yaw rate.

There is not much difference in the response time between AHC and conventional vehicle (Fig. 12): the roll rate of AHC is also decreased by anti-roll control. But, body side slip angle is larger than the conventional system due to the instantaneous increase of air spring stiffness in the transient state.

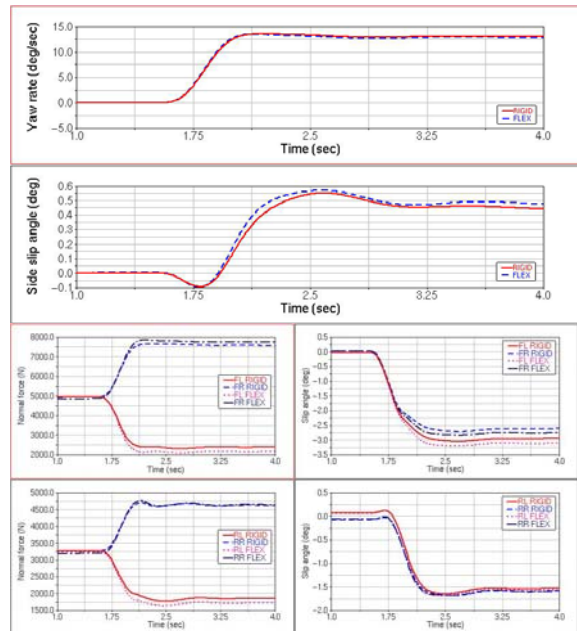


Fig. 11 Step steer: rigid vs. flexible body for conventional vehicle

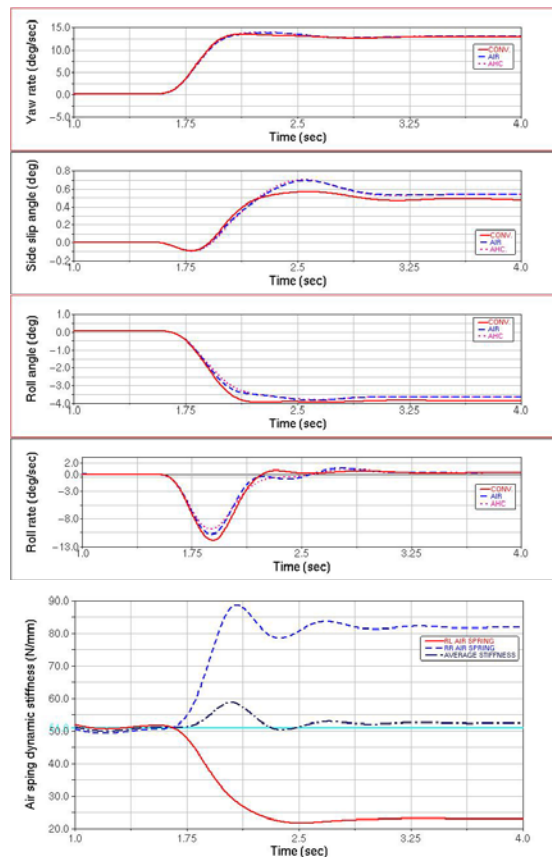
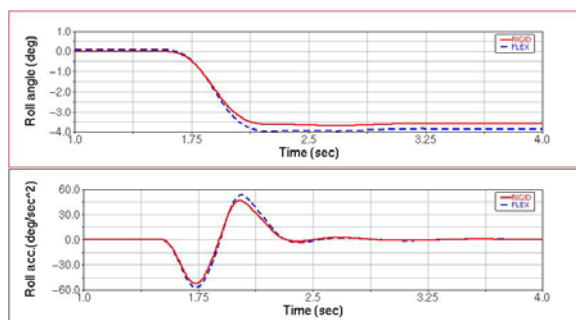


Fig. 12 Step steer: with and without AHC for flexible body



4.4 Pulse steer

The purpose of this test is to analyze the transient response of a vehicle in the frequency domain. Vehicle speed is set to 80km/hr and steering input is chosen to have sufficient PSD(power spectral density) in 1~3 Hz region.

In Fig. 13 where the conventional system is tested, we can see that the yaw response for flexible body is a little faster than rigid one. The damping ratio for flexible body is smaller than that of rigid one (flexible body: 0.53, rigid body: 0.61). Fig. 14 shows that the anti-roll control logic recovers the phase of the yaw rate response in comparison with air-spring-only system.

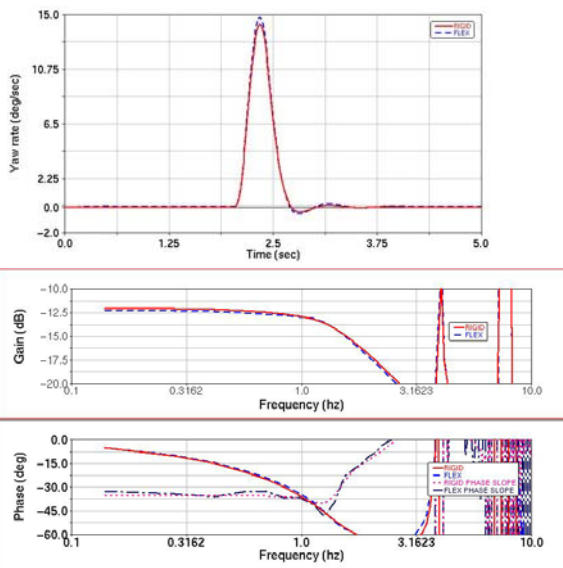


Fig. 13 Pulse steer: rigid vs. flexible body for conventional vehicle

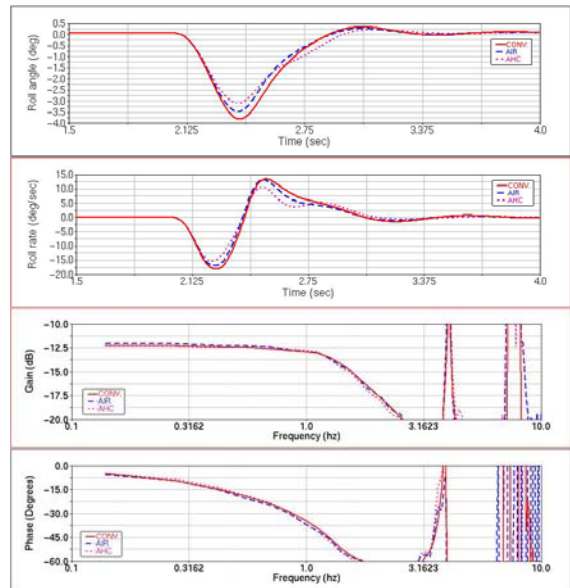
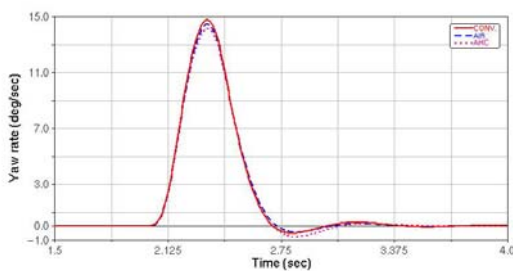


Fig. 14. Pulse steer: with and without AHC for flexible body

4.5 Double Lane Change (ISO/TR 3888)

Recently to provide reliable safety margin to the customer, so-called ELK test mode(Double lane change) is the most focused one that every maker have to survive through the test before launching their new vehicle. In order to add some margin, unlike the former ISO test modes I mentioned, double lane change mode needs driver for passing the course without collision to the pylon.

As stated in other maneuvers, the flexible nature of body contributes to the increase of the amount of load transfer for both front and rear suspnsions. Therefore to manouver the vehicle in right path, more steering effort is required than rigid body case. It is clearly shown that the roll motion is affected most by the flexible deformation modes (Fig.15).

As for the AHC system in Fig. 16, both roll angle and rate are much smaller than those of the conventional vehicle. But at the second lane change,

the vehicle seems a little unstable in terms of yaw motion. Since the relative velocity of dampers does not develop much for the double lane change maneuver, the compensation effect of the semi-active ECS for the oversteer tendency is not clear.

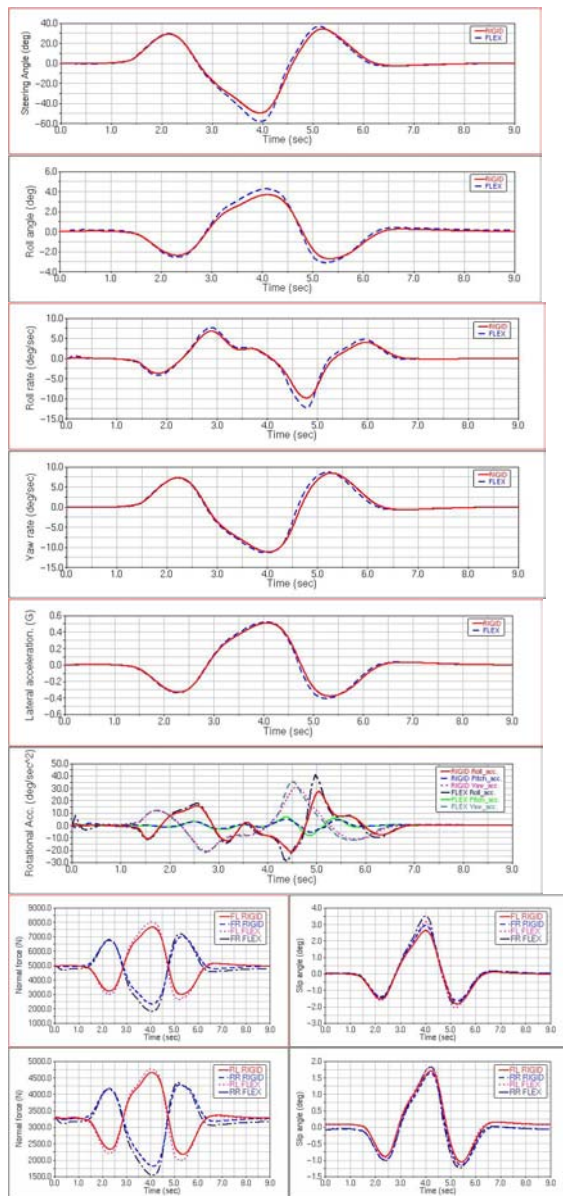


Fig. 15 Double lane change: rigid vs. flexible body for conventional vehicle

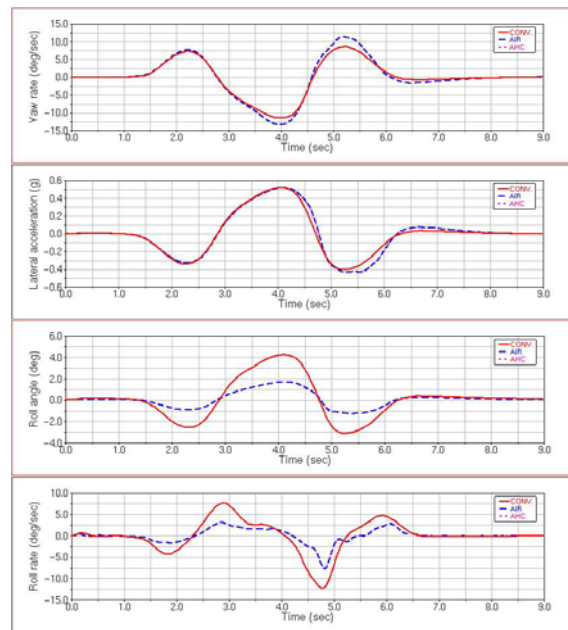


Fig. 16 Double lane change: with and without AHC for flexible body

5. CONCLUSION

In this paper, we proposed an AHC system for an SUV, which can maintain the vehicle design height against vehicle load variation through the air leveling, and improve the ride and handling performance through the semi-active ECS system. We model the vehicle in ADAMS/CAR environment and linked the control logic coded in Fortran to the model. We consider both the rigid and flexible (BIW) body model. We can see that the flexibility of body frame contributes to the amount of load transfer of suspension during cornering. Hence, we regard the body frame as a flexible body to arrive at more realistic analysis result.

By simulation study, it is shown that the AHC system can adjust the rear spring stroke and maintain its design height against the static load variations. Air spring characteristics contributes to over-steer tendency due to the increased spring stiffness of rear suspension in the case of a large out-of-

phase wheel stroke. But the AHC logic compensates this tendency and improves the vehicle body motion with respect to that of a conventional vehicle. It is also clear that the AHC system can contribute to the vehicle handling performance by changing the damping force characteristic when it detects vehicle's cornering motion. Further research directs to the enhancement of the air spring characterizes to reduce the oversteer tendency.

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