Technology Introduction

Development of Active Suspension by KYB

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1 Introduction

The active suspension, which is sometimes called the "ultimate" suspension, is a suspension system that can deliver both high-level riding comfort and high-level handling stability simultaneously. KYB developed a hydropneumatics[Note 1)] -based hydraulic active suspension jointly with Nissan Motor Co., Ltd., which was fitted onto the INFINITI Q45[Note 2)] which was released to the market in 1989 (Photo 1). In Japan, however, the automobile industry shifted from the age of pursuing higher performance to the age of focusing on environmental performance, cost effectiveness and usability. The product was no longer used in Nissan's vehicles in the early 2000s.

Photo 1 INFINITI Q45 (left)
KYB hydraulic active suspension (right)

In Europe, Daimler AG launched its flagship vehicle model equipped with active suspensions in 1999 and has continued using them through performance improvement since then. Other active-suspension-related technologies have also been commercialized, including the active stabilizer that is specifically designed to suppress vehicle roll during cornering.

Another variant of active suspensions is the so-called semi-active suspension. This suspension system delivers limited functionality of active suspensions to enable both performance and cost to go hand in hand and are popularly used in the D-segment (Upper Medium cars) as well as in the C-segment (Lower Medium cars)[Note 3)] mainly in Europe.

Today, some other similar systems have also been devised. One is a system based on semi-active-suspension equipped with an energy source to deliver an active suspension function. Another is an active suspension system that can recover the damped energy of the suspension to save on power consumption. In addition, an electric active suspension system that uses a motor as its power source without using hydraulic power has already been commercialized. This implies that the industry is almost back to the age of active suspensions.

Since the development of the initial hydraulic active suspension, it has been a long-time challenge over more than 30 years for the Engineering Division of KYB to implement an ultimate active suspension. This paper introduces an active suspension system that KYB has designed and prototyped as a Proof of Concept (POC).

Note 1) The term "hydropneumatics" refers to a suspension system that uses the hydraulic power to transfer forces and also uses the gas compression as a spring mechanism. (The use of gas as a spring helps prevent the transfer of small vibration to the sprung mass (practically, the vehicle body), which is generally considered to offer superior ride comfort.)

Note 2) "INIFINITY Q45" is a trademark owned by Nissan Motor Co., Ltd.

Note 3) The term "segment" here refers to the European classification of passenger cars based on car size criteria.

2 What is Active Suspension?

Let us briefly explain suspensions before diving into the subject. A suspension mainly consists of an arm, a suspension spring and a shock absorber. These elements move according to relative movement of the sprung components and the unsprung components (practically, the wheel). The input from the road surface is absorbed by the suspension spring, and the vibration energy of the spring is damped by the shock absorber. A suspension system equipped with the most common shock absorber is called a passive suspension.

For passive suspension, the damping characteristics of the shock absorber is uniquely defined by the input speed. Tuners usually have to find a good level of ride comfort by striking a balance among related factors in the vehicle development stage.

A semi-active suspension has a shock absorber with an integral damping force adjusting mechanism, thereby enabling the vehicle to adjust the damping characteristics according to the road condition.

Unlike the system above that passively outputs force in response to input from the road surface, the active suspension has a mechanism that actively outputs force with its own energy source. How these different suspensions can behave in response to the vehicle movement is simply illustrated in Fig 1.

		Sect.1	Sect.2	Sect.3	Sect.4	Sect.5	Sect.6	Sect.7	Sect.8	
Sprung displacement		None	Up	Up	Down	Down	Up	Down	None	
Direction of movement of SA		–	Comp.	Reb.	Reb.	Comp.	Reb.	Comp.	–	
Passive	Amount and direction of force	–	↑	↓	↓	↑	↓	↑	–	Uniquely defined damping force
Semi-active		–	↑	↓	↓	↑	↓	↑	–	Adjustable damping force
Active		–	↓	↓	↑	↑	↓	↑	–	Vibration damping with active force

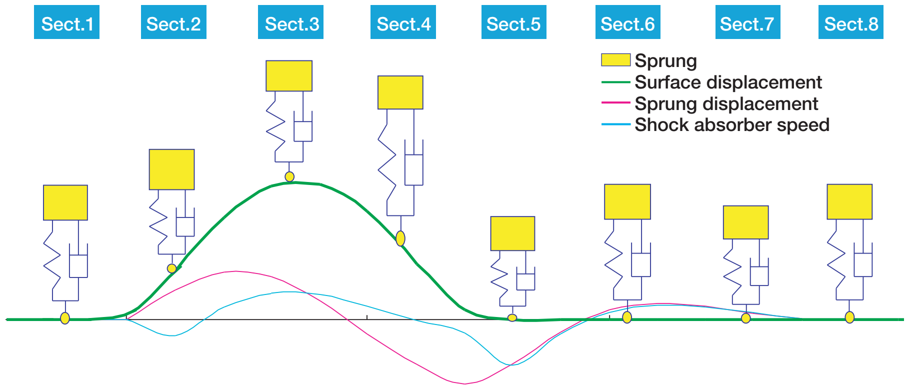

Fig. 1 Characteristics of each suspension during driving

In the sections 2 and 4, in contrast to the passive suspension, the semi-active suspension changes the amount of the damping force to prevent the sprung components from moving. On the other hand, the active suspension only focuses on the movement of the sprung mass to be controlled regardless of whether the shock absorber extends or contracts. It can drastically reduce the ratio of sprung displacement (transfer characteristics) by changing the amount and direction of the force. Unlike the "vibration damping" achieved by the semi-active suspension, the active suspension can offer a state that is as close as possible to "immobilization".

These characteristics are illustrated in Fig. 2 as performance of a single shock absorber. The diagram expresses forces (resistance and exciting forces) according to the relative speed of the sprung and the unsprung in response to input from the road surface. Particularly, the zones colored in orange represent the characteristics specific to the active suspension.

The force characteristics of these types of suspensions are summarized in Table 1. According to the table, only the active suspension can deliver a given amount of force in either direction.

Fig. 3 shows the vibration transfer ratio of these suspensions, i.e., how much they can suppress vibration by using their forces. While the semi-active suspension cannot limit vibration to the road surface displacement or lower at around the resonance frequency of the sprung components (not more than 1 in Fig. 3) the active suspension can do so.

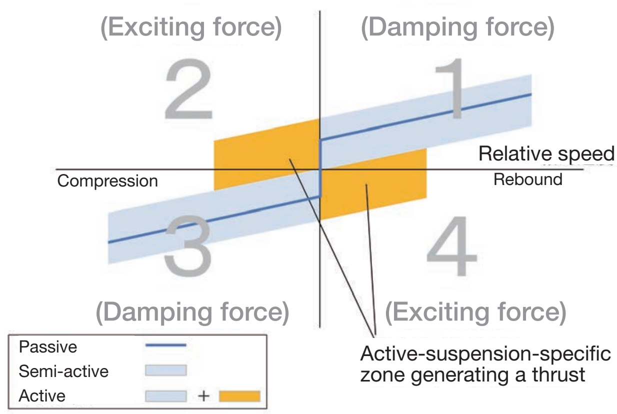

Fig. 2 Forces generated by various shock absorbers

Table 1 Force characteristics of various suspensions

Type	Amount of force	Direction of force
Passive	Uniquely defined	Fixed (resistance)
Semi-active	Variable	Fixed (resistance)
Active	Variable	Switchable (resistance/exciting)

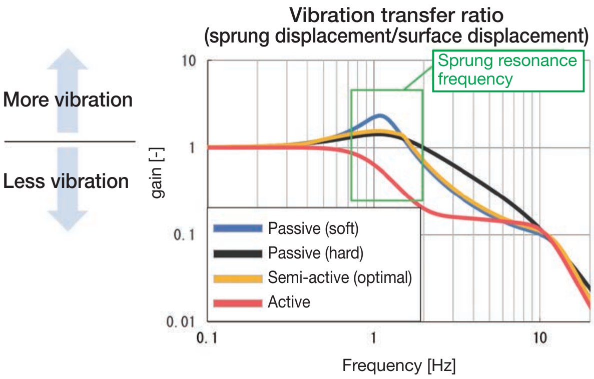

Fig. 3 Example of transfer ratio of vibration from road surface for various suspensions

3 Aim of Development

As described above, the active suspension can freely control the sprung mass. Now, it is necessary to consider of how the sprung components should be moved for good vehicle control. Is it right to immobilize the sprung at all? Conversely, could it make passengers feel uncomfortable? From the viewpoint of vehicles, we had difficulty determining which was the right answer based only on the results of simulation. This necessitated us to establish a vehicle testing scheme that allows people to actually feel the ride comfort of the vehicle controlled in different ways. We therefore decided to build an experimental vehicle.

4 Overview of Experimental Vehicle

4.1 Description of Experimental Vehicle

The requirements for a base experimental vehicle include:

① that the vehicle must be equipped with a high-voltage battery to drive the motor, and;

② that the vehicle must have semi-active suspensions.

A hybrid car of the E-segment (executive cars) meeting the requirements above was selected (Photo 2). The car equipped with highly-responsive, high-performance semi-active suspensions was determined to be appropriate for performance comparison.

4.2 Configuration of Suspension System

Fig. 4 shows the configuration of the suspension system for the experimental car. The system is considerably different from the conventional hydraulic active suspension system in:

Photo 2 Experimental vehicle with active suspensions

① the motorized power source rather than the engine;

② higher responsiveness achieved by excluding the use of hydropneumatics, and;

③ a simple structure for lower cost.

To efficiency build an active suspension system for the experimental vehicle, the control valves were fabricated based on existing internally-developed products, and the motor and other components that can be implemented with general-purpose products were purchased externally, resulting in reduced man-hours.

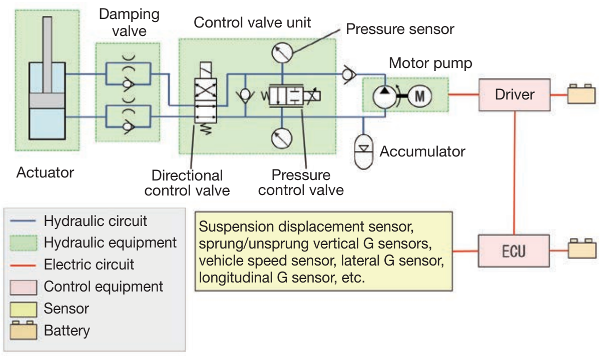

Fig. 4 System configuration

4.3 Concept of Vibration Control

As a general vibration control logic, the Skyhook control [1)] is conventionally well known. In this development effort, we aimed at further improving the existing vibration control. To this end, we discussed measures to reduce vibration using a quarter vehicle model with input from the road surface and an external force applied to the sprung (corresponding to the inertial force of the actual vehicle) in order to determine the mechanism by which the sprung components are vibrated (Fig. 5).

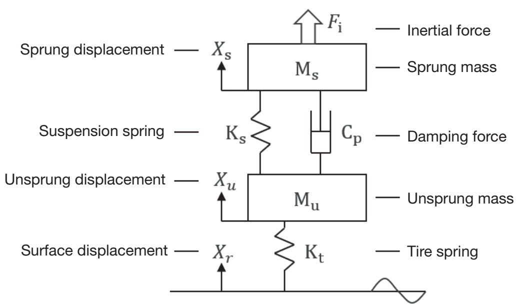

Fig. 5 Monocycle model

The equation of motion of the sprung vibration shown in Fig. 5 can be expressed by:

$$M_s\ddot{X}_s = -C_p(\dot{X}_s - \dot{X}_u) - K_s(X_s - X_u) + F_i \qquad (1)$$

In equation (1), the 1st term of the right-hand side represents the damping force of the shock absorber, and the 2nd term the spring force of the suspension spring. Since the input from the road surface is transferred to the sprung via the unsprung, equation (1) can be converted into a block diagram, shown in Fig. 6, with the unsprung displacement X_u and the inertial force F_i taken as input and the sprung displacement X_s taken as output, where "s" indicates the Laplace operator.

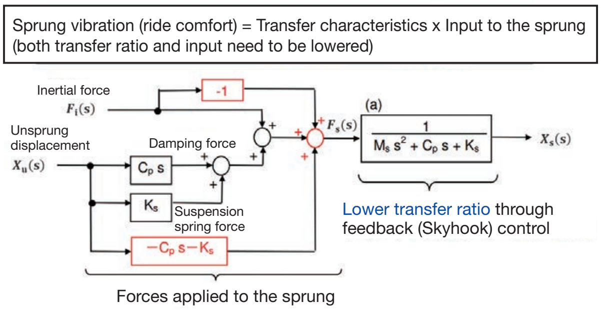

Fig. 6 Block diagram of equation of motion of the sprung

To decrease the sprung vibration, it is necessary to increase the damping force in the block (a) (= sprung vibration control) and decrease the input including C_pX_u, K_sX_u and F_i (= lower input to the sprung).

According to this vibration mechanism, it is effective to take measures to decrease the sprung vibration as compiled in the control policy shown in Table 2. We established a set of control logics to satisfy the policy.

Table 2 Control policy

№	Method
1	Add a force that depends on the sprung speed
2	Reduce the force applied to the sprung via a shock absorber with the unsprung vibration as input
3	Reduce the force applied to the sprung via a suspension spring with the unsprung vibration as input
4	Reduce the force applied to the sprung with the inertial force

5 Performance Verification

5.1 Description of Simulation

First of all, the effect of vibration control was simplified as in a quarter vehicle model shown in Fig. 7 before verification with a full vehicle. Fig. 8 shows the results of simulation using the monocycle model. For simulation of different control patterns related to ride comfort, the methods No.1, 2 and 3 in Table 2 were combined and the resulting data was checked for each control method. The simulation revealed that the model offered substantial effects of vibration control at around the sprung resonance frequency (around 1 Hz). It also showed that the ride comfort was not apparently worsened even at around the frequency (10 Hz) characterized by the so-called "brubru" vibration, proving good control effect. However, it should be remembered that the simulation is only a simplified approach accompanied by calculation based on an assumption that the model just uses an ideal actuator (no delay).

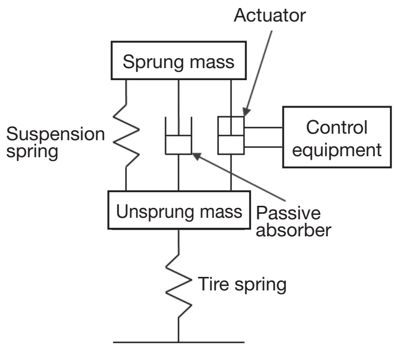

Fig. 7 Quarter vehicle model of active suspension

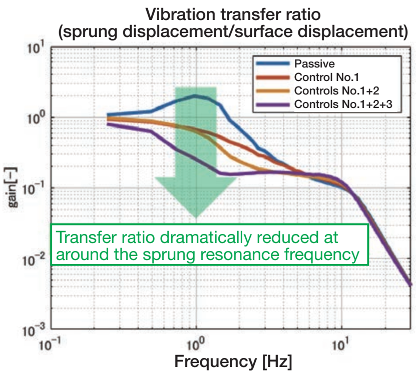

Fig. 8 Simulated sprung vibration control characteristics

5.2 Bench Test

Next, a quarter vehicle suspension system was fabricated to take measurements using a tester (Photo 3). The results of the test showed a trend similar to that obtained through the simulation (Fig. 9). From these test results, the suspension system for the experimental vehicle to be fabricated at this time was verified to have a substantial vibration control effect as initially assumed.

5.3 Testing on Actual Vehicle

5.3.1 Construction and Safety of Actual Vehicle

After verification of the suspension system for its vibration control effect, the system was mounted on the actual experimental vehicle. Before testing, the vehicle, which was unmanned for safety, was subjected to simulated vibration from the road surface by means of a 4-poster vehicle tester to make sure that the system will not be unstable. Furthermore, to ensure that the vehicle can stop the suspension system safely if an unexpected problem

Photo 3 Quarter vehicle tester

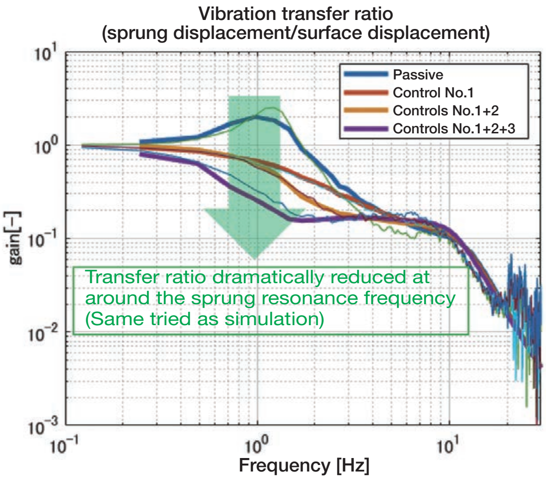

Fig. 9 Measurements using quarter vehicle tester

occurs, an emergency switch was installed so that the power supply to the motor can be interrupted in case of emergency.

5.3.2 Results of Measurement with Actual Vehicle

This experimental vehicle was run on KYB's test driving courses (Figs. 10 to 13, Photo 4). For evaluation of ride comfort, a test driver drove the vehicle on a sine wave road (focusing on the sprung resonance frequency), on a random input road, and on an EU country road (a road surface simulating a typical country side road in Europe). To verify the handling stability (for any sprung variation caused by turning the steering wheel), the driver changed lanes. For the purpose of obtaining reference conditions for comparison purpose, the same measurement was made on the original vehicle (equipped with semi-active suspensions).

The test on the actual vehicle showed the following results:

① Vibration at around the sprung resonance frequency was substantially lower than that for the vehicle with semi-active suspensions.

② On the EU country road with a combination of undulations and slight vibrations, the motion associated with large undulation were eliminated while the harsh caused by slight vibrations remained, proving the vibration control effect at around the sprung resonance frequency.

③ The substantially reduced roll angle made the tires contact effectively with the ground, leading to stable driving.

However, some challenges were found with the experimental vehicle. The ride comfort was worse on a bumpy road (because the control failed to compensate for vibration from the road surface due to insufficient responsiveness of the control valve). Another challenge was the noisy motor that had been scaled up in performance for

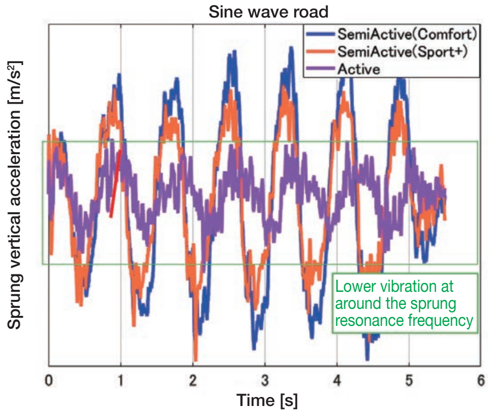

Fig. 10 Sine wave road

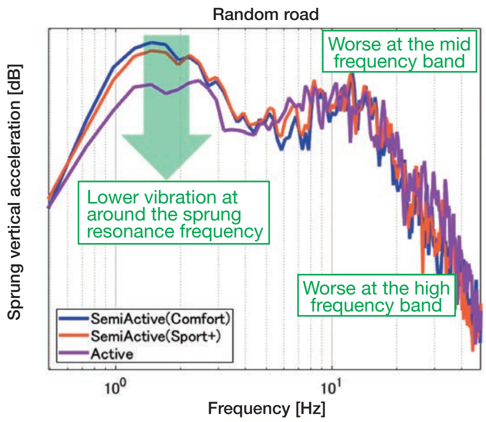

Fig. 11 Random road

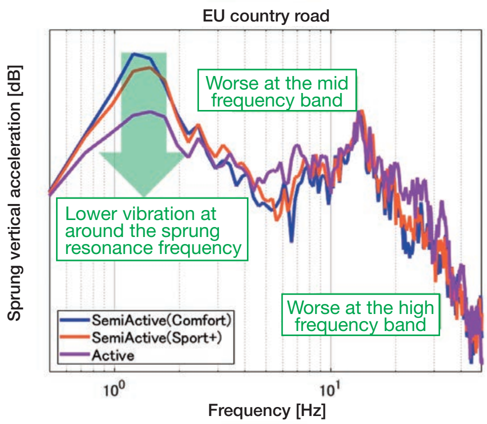

Fig. 12 EU country road

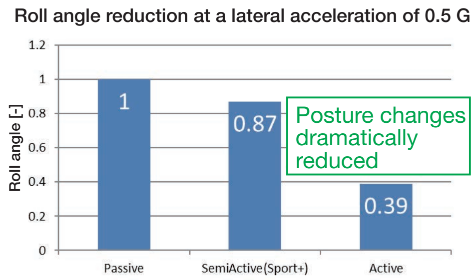

Fig. 13 Lane change

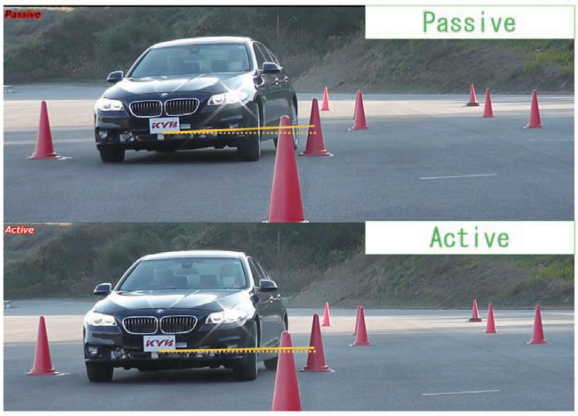

Photo 4 How the vehicle changes lanes

the purpose of verification. Still, the originally assumed performance level was attained.

5.3.3 Results of Test Drive of Actual Vehicle

In a test ride by those concerned, test drivers gave various feedback, for example, "the sprung motion was definitely limited, and I felt very flat, which could not compare with semi-active suspensions," "I felt easy as my head was not swung," and "very comfortable with no swing back."

6 Conclusions

In this activity, we:

① discussed the requirements for implementing the active suspension system and established the system;
② established and verified a set of control logics for improving the vibration control;
③ built a simulation environment for verifying the control effects;
④ fabricated and evaluated an experimental vehicle to allow drivers to feel the effect of the active suspension system; and,
⑤ broadly collected opinions of drivers in a test ride.

Particularly, we not only simulated the control technology but also actually mounted it on the experimental vehicle to provide an environment in which we could collect opinions and evaluation from a broad range of people. This forms the base for us to be able to discuss how the active suspension should be.

When pursuing an active suspension product capable of freely controlling the sprung components, the existence of the experimental vehicle is invaluable in considering the feeling and sensitivity of drivers. This is a meaningful activity toward the future.

With an aim of developing indices for the sensory evaluation of actual vehicles, Experiment Dept., KYB, has launched an activity for quantifying the sensitivity of drivers. As a team KYB, we will try to improve the development capability.

7 In Closing

People say that the automobile industry has entered a period of so big change that occurs once every 100 years. With notable keywords including "Connected," "Autonomous," "Shared & Service" and "Electric" taken into account, motor vehicles are expected to evolve into mobility equipment with various added values, not just a means of transportation. As one of the ideas for contributing to such a society, we have proposed the potential of active suspensions. In order to send an ultimate suspension out into the world again, we want to develop an active suspension system meeting the needs of the times while deepening our understanding of the system, control and sensitivity. Finally, we would like to take this opportunity to sincerely thank all those concerned who gave us guidance and cooperation for this development effort.

References

1) Alonso TORRES: Semi-Active Suspension, Extending the Limits, KYB Technical Review No.56 (April 2018).

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