

Study of Hydro Bush for Reduction of Harshness and Road Noise

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ABSTRACT

Isolation rubber bushes with hydro structures have low dynamic stiffness and high damping, and also allow high degrees of freedom in setting the required characteristics. The project discussed in this paper studied the methods of utilizing these advantages in suspension bushes in order to improve ride comfort and reduce road noise.

With regard to the harshness experienced when driving on a stepped road, the inputs are in phase for the left and right tires in the majority of cases, and this phenomenon formed the focus of this study. Hydro bushes with different characteristics for the right and left sides were used to generate phase differences in the force transmission to the chassis, enabling the development of a method of countering the force transmission on the left and right sides. This method has enabled the force transmission in the chassis on a stepped road to be reduced.

Tire vibration when driving on a rough paved road is transmitted to the cabin through the suspension. It was discovered that considerations of the rubber bush in the suspension system as a spring element and a damping element, and of the arm as a rigid body element and an elastic element, were important factors in the reduction of road noise. Optimization of the hydro bushes on this basis enabled the level of road noise experienced in the cabin to be reduced.

1. Introduction

Harshness when passing over stepped road joints and road noise on rough paved roads are sources of discomfort for passengers, and have a large influence on product appeal. Reducing this vibration and noise is an important issue for vehicle development, and research has been conducted on many areas including the body system and suspension system^{(1), (2)}.

However, the countermeasures for road noise in the body system often lead to worse fuel economy or handling performance due to an increase in the body mass, and the countermeasures for harshness and road noise in the

suspension system are often a trade-off with handling and stability due to lower tire and bush stiffness. For these reasons, such countermeasures could not be implemented.

On the other hand, isolation rubber parts with hydro structures realize both the required dynamic stiffness and damping, and also allow a higher degree of freedom in setting the required characteristics. As such these parts are widely used mainly in the engine mount system, and have dramatically improved ride comfort, noise and vibration performance. Thus, it was thought that applying this technology to the suspension might hold the same potential for dramatically improving product appeal as for the engine mount system.

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We analyzed the behavior of the suspension and the body over road surfaces that produced harshness and road noise using a sedan body style vehicle with double wishbone type suspension (Fig. 1) in both the front and rear. These results were then used to study how the characteristics of hydro bushes should be set to effectively reduce harshness and road noise in a vehicle.

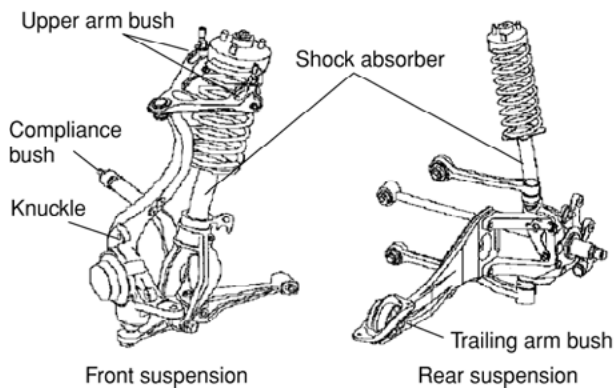


Fig. 1 Double wishbone type suspension

2. Investigation of Methods for the Reduction of Harshness

2.1. Selection of Road Surface and Vehicle Speed

Road surfaces that produce a feeling of harshness have various profiles, and these can be broadly classified as follows.

- (1) Road surface with random shape (such as unpaved roads, etc.)
- (2) Road surfaces with a regular period (such as choppy pavement on U.S. freeways⁽³⁾, etc.)
- (3) Road surfaces with a single stepped joint or multiple stepped joints with a sufficiently long period (such as bridge and overpass joints or repaired sections in paved roads, etc.)

Road surfaces with a random shape or a regular period are suitable for power spectrum analysis, but the next input will excite the suspension before the suspension vibrations stemming from the first input have subsided, so time series analysis is difficult. Road surfaces that are suitable for time

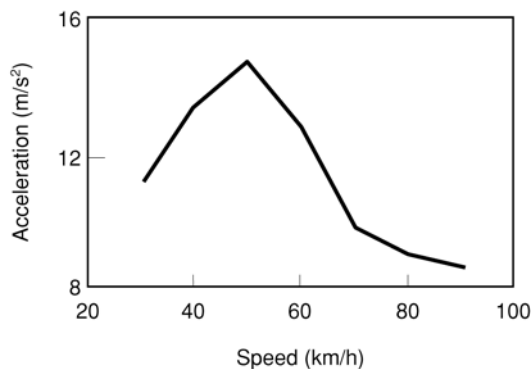


Fig. 2 Relation of speed and longitudinal body acceleration

series analysis are those with a single stepped joint or multiple stepped joints with a sufficiently long period. Therefore, we analyzed the suspension and body behavior over a road surface with only a single stepped joint established on a test ground.

Figure 2 shows the relationship between the speed and the peak value of the longitudinal body acceleration over this stepped road joint. The maximum acceleration occurred at 50 km/h, so this speed was used for analysis.

2.2. Analysis Results

Figure 3 shows the time series wave form of acceleration for the body when passing over the stepped road joint at 50 km/h. This waveform is comprised of an acceleration component due to the tire enveloping and a periodic acceleration component.

The interval up to 0.2 sec is the effect of transmission from the front suspension, and the effect of transmission from the rear suspension is included from 0.2 sec onward. Therefore, Fig. 3 shows only the effects of the front suspension.

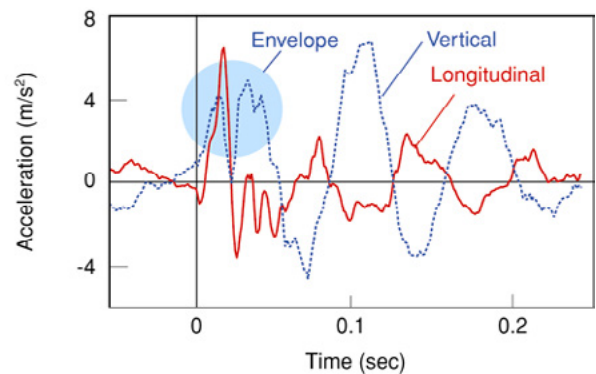


Fig. 3 Acceleration on body on stepped road (time series)

Figure 4 shows the results of analyzing the power spectrum density of this wave form from 0 sec to 0.2 sec.

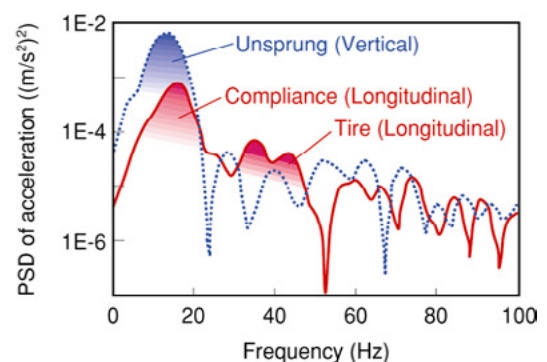


Fig. 4 Acceleration of body between 0sec and 0.2 sec

Looking at the power spectrum density of this acceleration, there are several peaks in the longitudinal direction at 16 Hz, 35 Hz and 43 Hz, and in the vertical direction at 13 Hz. Based on a comparison of the results of vehicle bench tests and tire unit tests, the longitudinal 16 Hz

component is thought to be the unsprung mass compliance resonance, the longitudinal 43 Hz component is thought to be the tire longitudinal resonance, and the vertical 13 Hz component is thought to be the unsprung mass vertical resonance.

The first cycle after contact impulse has a period of 0.028 sec, which corresponds to 35 Hz. The time from contact impulse to the acceleration peak is 0.013 sec, which is longer than 1/4 the cycle period (0.006 sec) of the tire longitudinal resonance. This period is thought to be the stage when the compliance bushes displace in the compliance direction, and is thought to be affected by both the tire and bush characteristics. The length of this period is thought to produce a lower frequency component (35 Hz) than the tire longitudinal resonance (43 Hz).

These vibrations are generated irrespective of the suspension type, so they are universally important. Methods for reducing vibration transmission in the vertical body direction include reducing the radial dynamic stiffness and increasing the damping of the tires, reducing the damping force of the shock absorbers, reducing the dynamic stiffness of the shock absorber mounts, and so on. However, these methods affect product appeal over a wide range from handling and stability to fuel economy. Therefore, the target was set for reducing vibration transmission in the longitudinal body direction.

2.3. Investigation of Hydro Compliance Bush Characteristics

Methods for reducing the longitudinal input to the body include reducing the tire stiffness and reducing the static stiffness of the bush. However, these methods also reduce the handling and stability. A realistic method that does not involve a trade-off with product appeal items other than harshness is to adjust the dynamic characteristics of the compliance bush without changing the static stiffness by using a hydro structure. The subject frequencies are the components of 16 Hz (compliance resonance), 35 Hz and 43 Hz (tire longitudinal resonance). Thus, damping these vibrational components with the compliance bush and reducing the vibration transmitted via the compliance bush were thought to be important.

First, an investigation was conducted to determine which of the frequency components deserved the most attention. The compliance bushes of the front suspension were changed

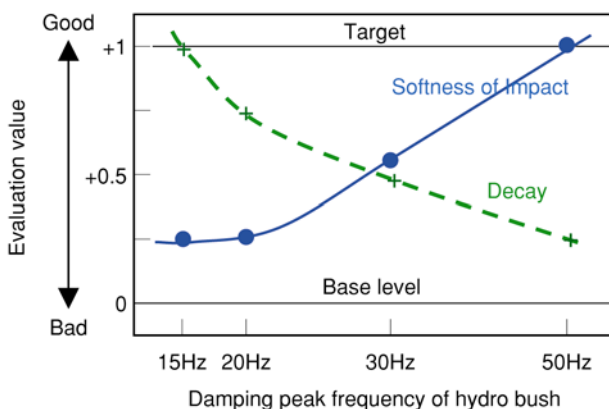


Fig. 5 Subjective analysis of harshness

to hydro bushes (loss tangent peak value of approximately 0.6), four different damping peak frequencies were set, and the relationship between the damping peak frequency of the bushes and the results of subjective evaluation on vehicle test at 50 km/h over a stepped road joint was investigated. (Fig. 5)

The results showed that softness of impact was better when the damping peak frequency of the bush was set near the tire longitudinal resonance frequency, and decay was better when the damping peak frequency of the bushes were set near the compliance resonance frequency. This indicated that the relationship between softness of impact and decay is a trade-off, and a good balance between the two was confirmed when the damping peak was set near 30 Hz.

Figure 6 shows the longitudinal body acceleration for a conventional bush that does not have a hydro structure, and Fig. 7 shows the longitudinal body acceleration for a hydro bush with the damping peak set at 30 Hz.

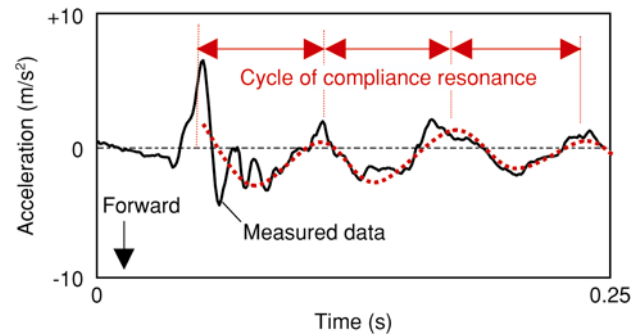


Fig. 6 Longitudinal body acceleration at conventional bush

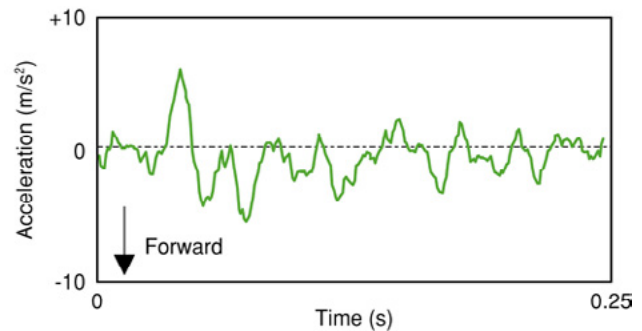


Fig. 7 Longitudinal body acceleration at hydro compliance bush (same phase)

The conventional bush shows poor decay of the compliance resonance, and this overlaps with the high frequency component to form a pointed time series waveform of longitudinal body acceleration. In contrast to this, when using the hydro bush with the damping peak frequency set at 30 Hz, the peak value of longitudinal body acceleration was reduced, and decay of the compliance resonance also improved.

However, in terms of the absolute softness and decay levels, the effects were insufficient and new methods had to be investigated.

2.4. Investigation of Phase Control

Most stepped road joints in the world are joints that stretch perpendicular to the direction of travel (for example, bridge joints, choppy pavement on U.S. freeways, etc.). When passing over these stepped road joints, the right and left tires contact the stepped joint at the same time, and the forces generated on the right and left tires are also transmitted at the same time to the body via the suspension. The phenomenon is thought to increase the body acceleration.

Therefore, a method was devised for canceling the vibrations transmitted from the right and left compliance bushes to the body by giving these vibrations a phase difference so that they interfered with each other. This mechanism is shown in Fig. 8. In order to realize this mechanism, the initial peak (35 Hz component) of the acceleration transmitted from the suspension to the body had to be given a different phase for the right and left bushes. The hydro bush characteristics for performing this phase control were set as follows.

- (1) One bush was given high damping in the 35 Hz range, and the transmission phase angle advance was increased.
- (2) The other bush was given low damping in the 35 Hz range, and the transmission phase angle advance was reduced.

We realized this asymmetry of the right and left bushes by changing the orifice design parameters (section area and length). In addition, we also considered the characteristics of the right and left bushes in the compliance resonance range and tire longitudinal resonance range for reducing the suspension longitudinal vibration. For this reason, the loss tangent peak frequency and peak value were set to ensure damping of 0.15 or more at the loss tangent. Figures 9 and 10 show the characteristics of the hydro bush using this phase control.

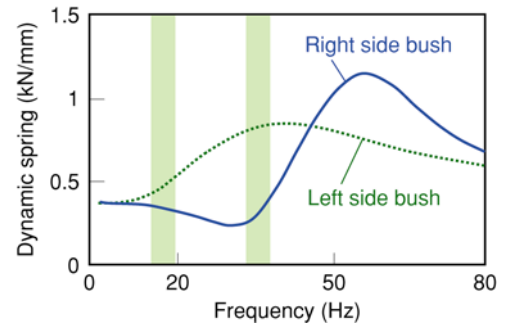


Fig. 9 Dynamic spring of hydro compliance bush

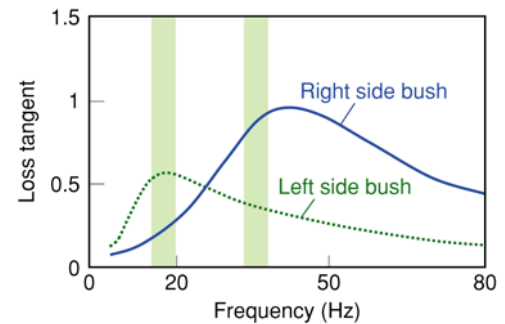


Fig. 10 Damping characteristic of hydro compliance bush

2.5. Effect on Vehicle Test

The effect was confirmed at 50 km/h over a stepped road joint. When the damping peaks were set at 30 Hz for both the right and left compliance bushes, the forces were transmitted

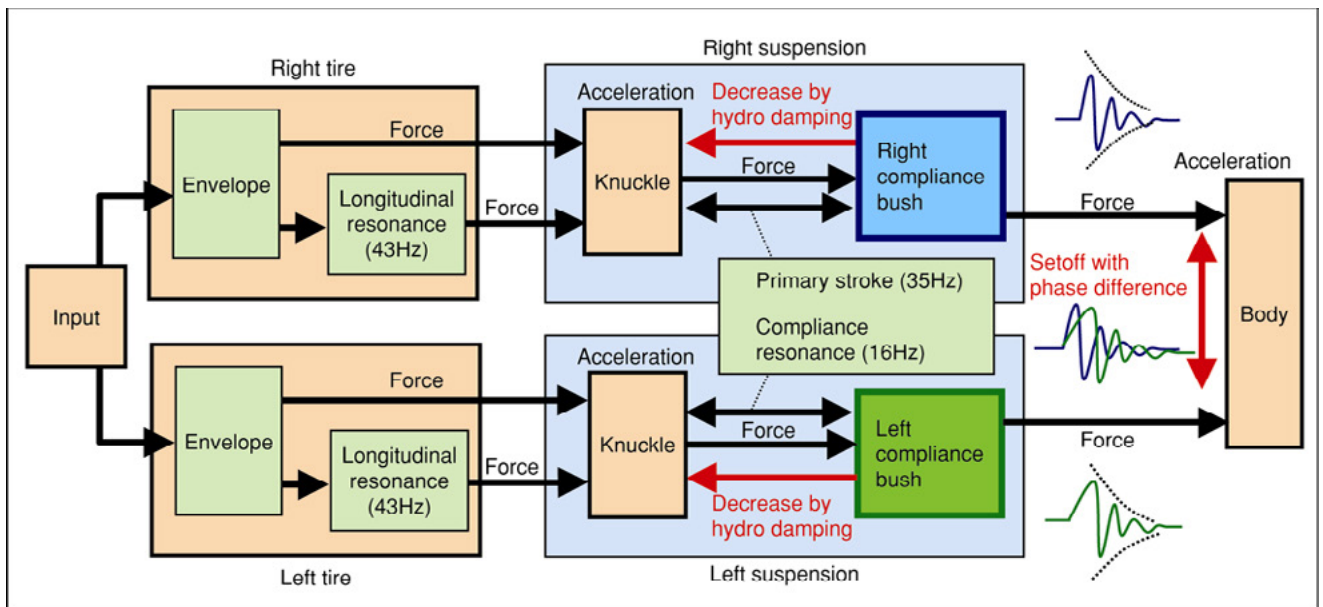


Fig. 8 Mechanism of phase control

in phase from the right and left bushes to the body, so the first peak on the positive side had a pointed shape. In addition, the decay was also poor (Fig. 7). In contrast, Fig. 11 shows the longitudinal body acceleration when phase control is performed using bushes with the characteristics shown in Fig. 9 and Fig. 10. Here, the longitudinal body acceleration peak on the positive side is divided into two peaks, and the peak height has dropped by 30%. In addition, from the second peak onward the force transmitted from the right and left bushes counter each other, and the decay has also improved. Handling and stability were also unaffected which had been a concern with the asymmetrical bush dynamic characteristics. This is thought to be because the bush static characteristics contribute greatly to handling and stability, and this symmetry was maintained.

This mechanism was confirmed to be effective not just for stepped road joints, but also for other harsh road surfaces. Figure 12 shows the body acceleration on choppy pavement on a U.S. freeway.

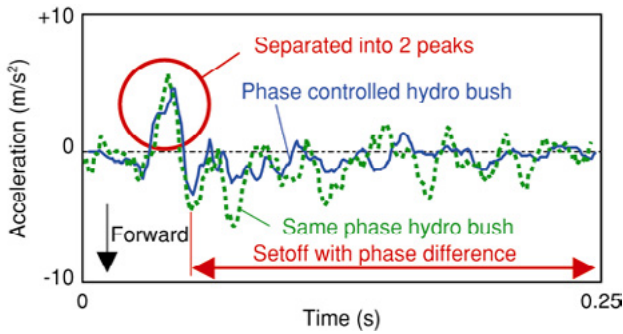


Fig. 11 Longitudinal body acceleration at hydro compliance bush (phase control)

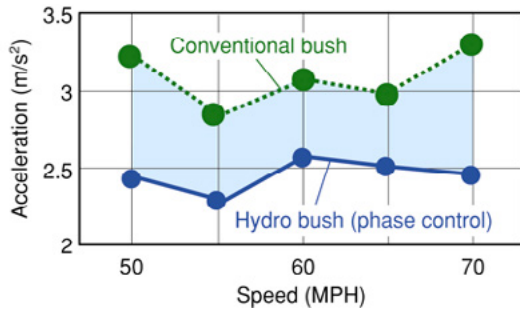


Fig. 12 Maximum longitudinal acceleration of body on choppy road

3. Investigation of Methods for Reduction of Road Noise

3.1. Analysis of Cabin Sound Pressure

Figure 13 shows the power spectrum density (1/3 octave band) for the cabin sound pressure over the road noise evaluation road. The sound pressure is high in the 250 Hz and 500 Hz ranges, so lowering the sound pressure in these ranges is thought to be important.

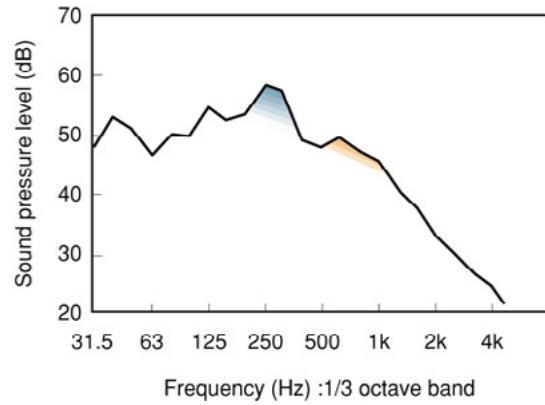


Fig. 13 Sound pressure in a cabin

3.2. Analysis of 250 Hz Range

The 250 Hz range in the 1/3 octave band is known to be caused by transmission of the tire cavity resonance. Narrow band analysis revealed the tire cavity resonance peaks at 230 Hz and 240 Hz. The transfer path of the suspension was analyzed, and the results showed that vertical vibration of the trailing arm bush had a high contribution rate in the tire cavity resonance range, accounting for 22% of the overall suspension. Therefore, it was thought that reducing the vertical dynamic stiffness of the trailing arm bush at 230 Hz and 240 Hz would improve road noise in the 250 Hz range.

3.3. Analysis of 500 Hz Range

A hypothesis was formed that the 500 Hz range in the 1/3 octave band is caused by a rigid-body mode of the suspension arm. Theoretical calculations based on the inertia mass of the arm and the stiffness of the bush led to the presumption that the rigid-body mode of the front upper arm contributes to this range. Therefore, the ball joint side of upper arm was excited using a tester for measuring the dynamic stiffness, the force at the body side of the bush mounting point was measured, and the transmission characteristics were measured. The results confirmed a transmission peak at 480 Hz. (Fig. 14)

Next, the front suspension spindle was excited randomly in three directions, and an acoustic sensitivity peak was

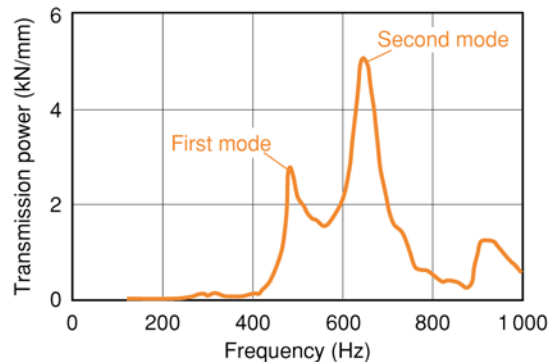


Fig. 14 Frequency response characteristics of arm assembly

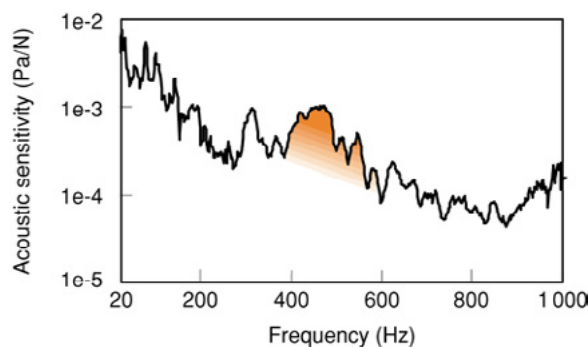


Fig. 15 Acoustic sensitivity of front wheel (random vertical excitation)

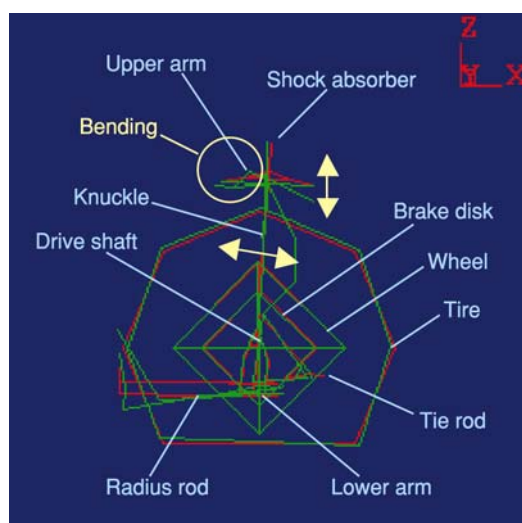


Fig. 16 Modal animation of front suspension at 464 Hz (side view)

confirmed at 464 Hz as shown in Fig. 15. Modal analysis of the suspension at this frequency confirmed the vibration mode shown in Fig. 16. This mode is comprised of a mode in which the knuckle undergoes longitudinal elastic deformation, a rigid-body mode in which the upper arm uses the ball joint as a fulcrum and the bush as a spring element, and the elastic mode of the arm itself.

Based on the above analysis, it is thought that road noise in the 500 Hz range can be improved by giving the bush high damping to suppress the rigid-body mode and elastic mode of the upper arm, and giving the bush a low dynamic stiffness to suppress transmission of these vibrations to the body.

3.4. Reduction by the Trailing Arm Bush

The vertical dynamic characteristics of the trailing arm bush contribute greatly to tire cavity resonance (230 Hz, 240 Hz), so the target was set at reducing the vertical dynamic stiffness at these frequencies.

The dynamic characteristics of the hydro bush are such that as the phase angle approaches 90° , the pumping action of the fluid in the orifice becomes stronger, allowing the dynamic stiffness to be reduced. Conventional hydro bushes use the gap between the inner tube and the stopper as the orifice, and a resonance system is formed by the mass of the

fluid in that orifice and the expansion elasticity of the main rubber. In this case advancing the phase angle reduces the dynamic stiffness in the tire cavity resonance range.

The improved method uses a double orifice type in which a new orifice is added to the stopper portion of the conventional structure. Figure 17 shows this structure model. Resonance of the fluid in one orifice is created at 190 Hz by the resonance system comprised of the mass $M1$ and spring elements $K2$ and $K4$ in Fig. 17, and resonance of the fluid in the other orifice is created at 240 Hz by the resonance system comprised of the mass $M2$ and spring elements $K3$ and $K4$. The presence of these two resonance systems expands the frequency range over which a phase angle near 90° can be obtained, thus expanding the frequency range over which the dynamic stiffness can be reduced by the pumping action of the fluid in the orifices.

This made it possible to further reduce the dynamic stiffness in the tire cavity resonance range, and at the same time to suppress the aggravation of the dynamic stiffness peak value near 300 Hz. The improved hydro bush structure is shown in Fig. 18, and the characteristics are shown in Fig. 19 and Fig. 20.

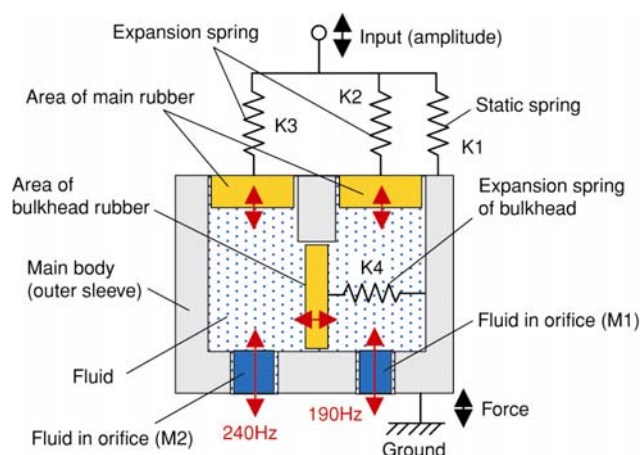


Fig. 17 Structure model of hydro trailing arm bush (double orifice type)

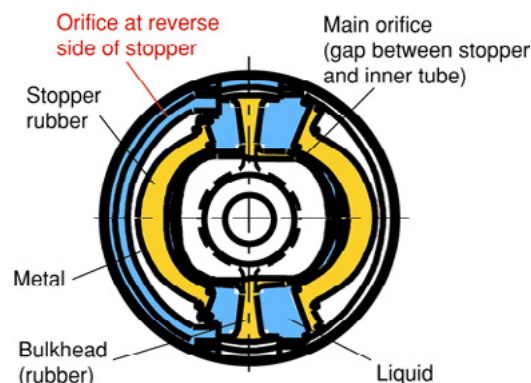


Fig. 18 Structure of hydro bush (trailing arm)

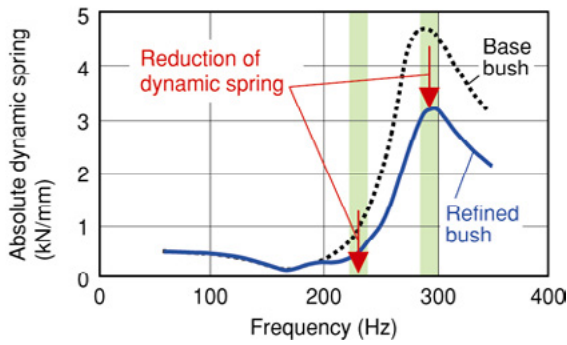


Fig. 19 Dynamic spring of hydro bush (trailing arm)

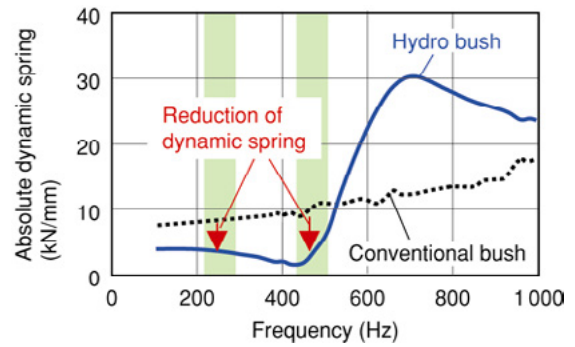


Fig. 22 Dynamic spring of front upper arm bush

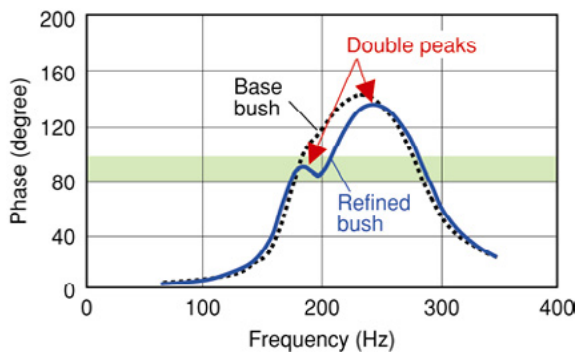


Fig. 20 Damping of hydro bush (trailing arm)

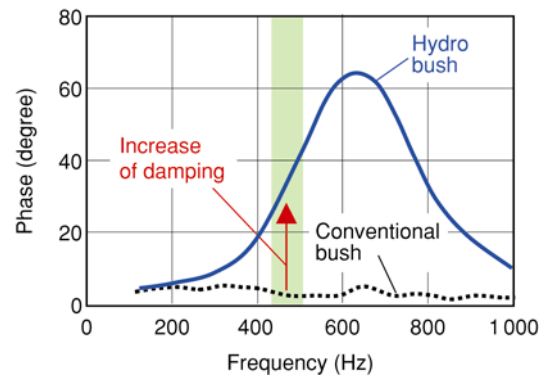


Fig. 23 Damping of front upper arm bush

3.5. Reduction by the Front Upper Arm Bush

Giving the bush high damping to suppress arm resonance in the 500 Hz range and low dynamic stiffness to suppress transmission were thought to be effective measures.

A good method for achieving these characteristics was thought to be to set the resonance of the fluid in the orifices at 600 Hz, and to utilize the pumping action of the fluid in the orifices at lower frequencies. However, the resonance of the fluid in the orifices could not be raised to 600 Hz using a structure with a fluid chamber and orifices like a normal hydro bush.

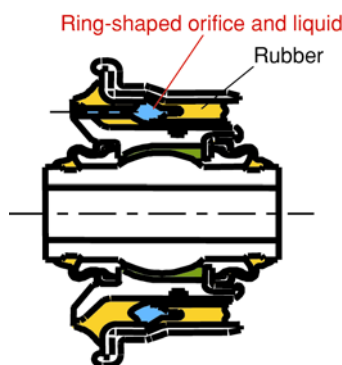


Fig. 21 Structure of hydro bush (front upper arm)

Therefore, a ring-shaped orifice was used as shown in Fig. 21, and this was given both piston functions for pressurizing the fluid and orifice functions. This made it possible to set the resonance of the fluid in the orifice at 600 Hz, and to achieve the ideal characteristics of low dynamic stiffness and high damping in the 500 Hz range. In addition, the dynamic stiffness could also be reduced in the tire cavity resonance range. (Fig. 22, Fig. 23)

3.6. Effects on Vehicle Test

The newly developed hydro bushes were assembled into a vehicle, and the effects were confirmed. As shown in Fig. 24, a reduction of the sound pressure in the 250 Hz and 500 Hz ranges was confirmed.

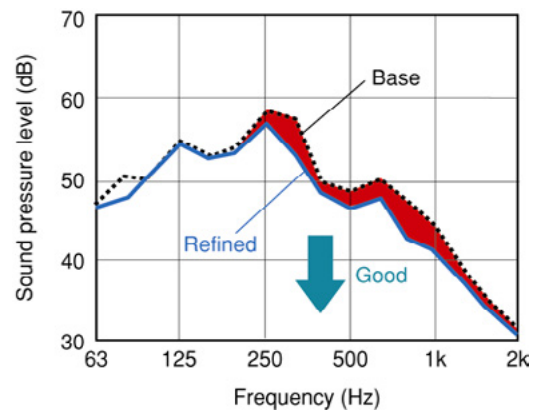


Fig. 24 Effect of road noise refine

4. Conclusion

The suspension behavior was analyzed in detail regarding harshness and road noise, and hydro bushes with new structures were developed based on these results. Through this development, the following knowledge was obtained.

- (1) Body vibration when passing over stepped road joints is affected in the vertical direction by the unsprung vertical resonance and the tire enveloping characteristics, and in the longitudinal direction by the compliance resonance and the tire longitudinal resonance. Reducing the transmission of these resonance phenomena is an effective countermeasure for reducing harshness.
- (2) Factors contributing to road noise include suspension vibration caused by tire cavity resonance, and the rigid-body and elastic modes of the arms. Reducing the dynamic stiffness of the bush is an effective countermeasure for the former, and increasing the damping and reducing the dynamic stiffness of the bush in the rigid-body and elastic modes of the arms is an effective countermeasure for the latter.
- (3) Longitudinal body vibration over stepped road joints can be reduced and harshness can be improved (reduction of maximum longitudinal body acceleration and improvement of decay) by giving the right and left hydro compliance bushes different dynamic characteristics and controlling the phase of the transmission.
- (4) The force transmission and the arm resonance phenomenon could be reduced and road noise could be improved by introducing new hydro structures (double orifice, ring-shaped orifice) for the trailing arm and front upper arm bushes.

This project was able to provide a glimpse of the potential for improving NVH product appeal by applying hydro bush technology to the suspension system.

On the other hand, the suspension system has many limitations such as endurance reliability, production technology and space layout, and there are currently few cases of hydro bushes being applied to mass production vehicles.

In addition to research on methods for utilizing the features of hydro bushes, research to resolve these hardware issues is also considered necessary as a future theme. Hydro bushes have great potential for improving NVH product appeal, and research in this area is expected to expand in the future in order to create even more attractive products (vehicles).

Acknowledgments

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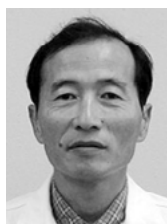
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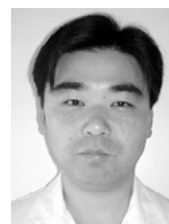
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