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A Study on the Prediction Method of Bush Dynamic Characteristics in Used and High Frequency Domain

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ABSTRACT

As electric vehicles become more prevalent, NVH (Noise, Vibration, and Harshness) performance requirements extend into higher frequency bands (1 kHz and above) due to motor excitation characteristics. Performance verification is often conducted at the concept stage using virtual models. In the medium and high frequency ranges, where mode density is high, NVH problems are typically addressed by reducing the response magnitude rather than designing for mode avoidance. This highlights the critical role of the bush system. However, obtaining bush characteristics that accurately capture the high frequency response remains challenging. This study performs a dynamic stiffness analysis of bushes using a three-dimensional finite element (3D FE) model to validate the approach and explores a method for extending the analysis to the medium and high frequency domains for direct application in vehicle development.

Keywords: NVH Performance, Bush and Mount System, Dynamic Stiffness, Rubber, System Analysis, Prediction Methodology

1. INTRODUCTION

Recently, in the automotive industry, performance evaluations extending to high frequency bands of 1 kHz or more have become necessary for NVH performance, due to motor excitation characteristics and the shift to electric vehicles. Unlike low frequency bands—which check mode frequencies to avoid resonance—medium and high frequency bands have high mode density. Therefore, NVH issues are generally addressed by reducing the magnitude of the response rather than by designing to avoid specific modes. This necessitates the efficient design of vibration-proof and sound-absorbing materials within a bush system or a final response system that reduces vibration transmission through insulation during electric vehicle development.

Performance verification is carried out at the conceptual stage using virtual models to secure target vehicle performance early. In particular, bush characteristics represent a critical factor that often conflicts with both NVH and ride & handling (R&H) performance. Thus, it is important to promptly evaluate NVH performance in a design review that meets both criteria.

In a typical bush virtual model for predicting NVH performance, the dynamic characteristics for six degrees of freedom are represented as constants using a spring element. These dynamic properties are usually derived by applying a lump sum multiplier—typically 1.5 or 2 times—to the static characteristic design targets. Additionally, when the developed bush is applied to a new vehicle, dynamic properties measured at a specific frequency (usually 100 Hz) from test reports are used. Although this method offers a simple approach for constructing a performance prediction model during the design stage, it is somewhat insufficient for addressing vibration noise problems that require precise frequency response characterization. Moreover, while test reports typically provide dynamic characteristics in the translational direction (owing to test equipment limitations), evaluating dynamic characteristics in the rotational direction remains challenging.

Furthermore, although recent dynamic characteristic test equipment can evaluate up to approximately 1 kHz, obtaining bush dynamic data at this frequency is not

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straightforward. More importantly, to address NVH issues arising from electric vehicle motor excitation forces, bush characteristics at even higher frequency ranges (e.g., 1.5 to 2 kHz) are required.

To overcome this limitation, a bush dynamic analysis method using an FE model was investigated to achieve a high correlation between test and analysis results. However, securing accurate rubber material properties—which critically influence the analysis—proved difficult, rendering the method unsuitable for immediate application in vehicle development.

In this study, a bush dynamic analysis using a 3D FE model was conducted to verify its accuracy, and a method applicable to actual vehicle development—with extension to the medium and high frequency domains—was explored.

2. MAIN TEXT

2.1 Rubber properties for analysis

In order to determine the characteristics of the bush through analysis, the following analytical properties, obtained from rubber specimen tests, are required:

1. Static Properties: Strain-energy function and material constants for expressing hyper-elastic behavior.
2. Dynamic Properties: Storage modulus and loss factor for viscoelastic characterization.
3. Poisson’s Ratio.

Conventional elastic materials, such as metals, exhibit linear elastic behavior, meaning that they maintain a proportional relationship between load and deformation and return to their original state once the load is removed. In contrast, rubber materials exhibit elastic behavior even under large deformations where the relationship between load and deformation becomes nonlinear; this behavior is known as hyper-elasticity. When the strain-energy function is modeled as a polynomial that accurately represents this behavior, and the corresponding material constants are determined through tensile and compression tests on the rubber specimen, these properties can be used for analysis. In this study, the hyper-elastic behavior is modeled using the Yeoh function, as illustrated in Figure 1.

$$U=\sum_{i=1}^{N} C_{i0}\left(\bar{I}_1-3\right)+\sum_{i=1}^{N}\frac{1}{D}\left(J^{el}-1\right)^{2i}$$

Yeoh (N=3)	Ci0	D
i=1		
i=2	security	
i=3		

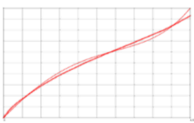

Figure 1 Hyper-elastic Material Constants of Rubber

Viscoelasticity refers to the coexistence of viscosity and elasticity in a material. Unlike metals, rubber materials dissipate energy through internal friction. This behavior is characterized by a complex modulus comprising two components: the storage modulus and the loss factor. These parameters are obtained by subjecting rubber specimens to dynamic strain testing. In this study, the storage modulus and loss factor measured up to 300 Hz, as shown in Figure 2, were used.

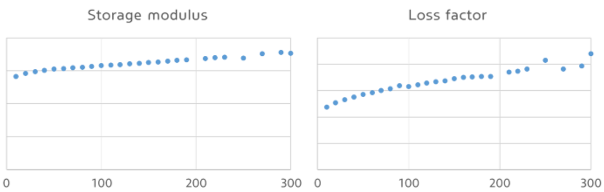

Figure 2 Complex Elastic Modulus of Rubber

Since rubber materials are generally considered to be nearly incompressible, a Poisson's ratio appropriate for this is used.

2.2 3D Bush Dynamic Characteristics Analysis Accuracy Verification

The accuracy of the 3D FE analysis was verified using a G BUSH component from a midsize sedan, which allowed for accurate rubber material characterization. Based on the physical property evaluation of the rubber specimen, the rubber properties used in this analysis included the viscoelastic (hyperelastic, Yeoh model) modulus and the viscoelastic modulus and loss factor measured up to 300 Hz. The static properties of the G BUSH were determined by averaging the stiffness between displacements of 0.5 mm and 2 mm, and the error defined as the difference between the test report and the analysis results is at the level of 7%.

For the dynamic characteristic analysis, although the viscoelastic properties of the rubber specimen were evaluated up to 300 Hz, the analysis was performed at 100 Hz for accuracy verification. The corresponding analysis results were compared with the test report values. As illustrated in Figure 4, the static characteristics in the translational direction were predicted with a maximum error of 7%. Regarding the dynamic characteristics, although the Q direction could not be compared due to the absence of test data, the errors in the P1 and P2 directions were 2% and 14%, respectively, indicating that the dynamic characteristics were predicted with an error within 15%. In the rotational direction, the error in the static characteristics was relatively larger—up to 24% compared to the translational direction—

but this is considered acceptable given that dynamic evaluation in the rotational direction is not feasible, and the analysis method provides values under conditions similar to those used in the static evaluation with high accuracy.

DIR	단위	Static			Dynamic		
		TEST	CAE	Error	TEST	CAE	Error
P1	N/mm	security		7%	security		2%
P2				0%			14%
Q				3%			-
S1	N*mm/rad			24%			-
S2				-			
R				22%			

Figure 4 Comparison of Test/CAE results and errors in all directions

2.3 2.3 Problems and Hypothesis Establishment and Verification

For conventional elastic materials such as metals and glass, “standard physical properties” are typically used to predict performance under uniform conditions, regardless of variations in vehicle type or the personnel responsible for the virtual model. In contrast, due to significant variations in rubber material properties—dependent on material type, mixing ratio, and manufacturing process—it is challenging to adopt a single set of standard physical properties for rubber. When accurate rubber properties corresponding to the manufactured parts (such as those of the G BUSH in a medium-sized sedan) are available, bush characteristics can be predicted within the test error range. In particular, using viscoelastic properties that incorporate frequency characteristics enables the development of bush models that accurately reflect NVH performance.

However, it is impractical to secure all the appropriate rubber material properties for every bush, given the wide range of bush types, manufacturers, hardness levels, and other factors present in actual vehicles. To address this limitation, the hypothesis was proposed that if the ratios of the characteristics in all six degrees of freedom are proportional to the shape of the rubber part, the primary characteristics could be determined using the available properties. Consequently, it was hypothesized that the static and dynamic characteristics in all directions could be obtained through post-processing of the test results available in some directions. The conceptual diagram illustrating this approach is shown in Figure 5.

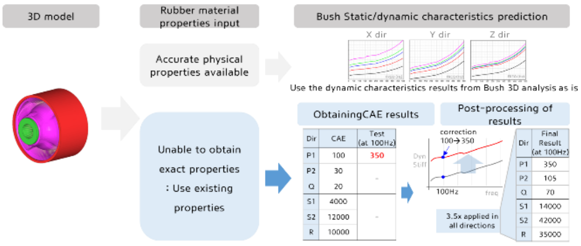

Figure 5 Conceptual diagram for predicting characteristics of Busch 3D analysis

For verification, the previously validated G BUSH model of a medium-sized sedan was employed. The analysis was performed using rubber material properties obtained from other manufacturers that did not match the properties used for the G BUSH model. As shown in the left table of Figure 6, the positive characteristics in the translational and rotational directions exhibited errors of 38% and up to 58%, respectively, compared to the test report.

To adjust for these discrepancies and align the analysis results more closely with the test report, a correlation coefficient of 0.79 was derived by dividing the test report value (237) in the P2 direction by the analysis result (300). This coefficient was then applied uniformly to the basic analysis results in all six directions, as illustrated in Figure 7. The adjusted results yielded a final error of up to 9% in the translational direction and up to 28% in the rotational direction, which is comparable to the results obtained using the accurate rubber properties for the actual G BUSH (with errors of up to 7% and 24% in the translational and rotational directions, respectively).

DIR	Unit	Static of G bush		
		Test	CAE	Error
P1	N/mm	Security		7%
P2				-
Q				3%
S1	N*mm/rad			24%
S2				-
R				22%

Fig. 6 G BUSH Static Characteristics Results

Figure 7 Prediction Results of Using and Aftertreatment of Physical Properties

To extend the validated hypothesis to various types of bushes, the static characteristics of all bushes in a small SUV were evaluated using the same methodology previously applied to the G BUSH of a medium-sized sedan. First, the primary direction—typically the VOID direction (P2) or the axial direction for a shock absorber bush—was identified. The ratio of the test report value to the analysis result in this primary direction was then used as a correlation coefficient, which was uniformly applied across all directions.

Figure 8 presents the static and dynamic characteristics calculated using the proposed method. For static characteristics, the final adjusted results closely matched those from the test report. For dynamic characteristics, values for the remaining five directions—where test data were unavailable—were successfully obtained. Notably, both the static correlation coefficient (c = a/b) and the dynamic correlation coefficient (C = A/B) were determined to be 1.3, an observation that merits further attention.

		Static				Dynamic			
	dir	Test (a)	CAE (b)	Correlation Coefficient1 (c=a/b)	Static (d=b*c)	Test (A)	CAE (B)	Correlation Coefficient2 (C=A/B)	Dynamic (D=B*C)
G BUSH	P1								
	P2	390	300		390	1040	800		1040
	Q			1.3		-		1.3	
	S1			※ P2				※ P2	
	S2					-			
	R								

Figure 8. Prediction Results of G BUSH Static and Dynamic Characteristics of Small SUV

Since the dynamic characteristic correlation coefficient cannot be determined without results from the dynamic test report (as illustrated by the strut insulator in Figure 9), the final static characteristic value (d) was first calculated using the static characteristic correlation coefficient (c = a/b), as described above. The final dynamic characteristic value (F) was then obtained by multiplying this static value (d) by the dynamic ratio (E = B/b) between the static and dynamic characteristics.

		Static				Dynamic		
	Dir	Test (a)	CAE (b)	Correlation Coefficient1 (c=a/b)	Static (d=b*c)	CAE (B)	Ratio (Dynamic/Static) (E=B/b)	Dynamic (F=d*E)
FR STRUT INSULATOR	X							
	Y							
	Z	1200	1500	0.8	1200	3450	2.3	2760
	RX			※ Q방향				
	RY							
	RZ							

Fig. 9 Prediction method of FR STRUT INSULATOR static and dynamic characteristics of a small SUV (1)

However, given that the static and dynamic characteristic correlation coefficients derived from the G BUSH results for the small SUV (as shown in Figure 8) are identical, the final dynamic characteristic can be calculated as illustrated in Figure 10. This result is consistent with the final dynamic characteristic obtained in Figure 9.

		Static				Dynamic			
	dir	Test (a)	CAE (b)	Correlation Coefficient1 (c=a/b)	Static (d=b*c)	Test (A)	CAE (B)	Correlation Coefficient2 (C=A/B)	Dynamic (D=B*C)
FR STRUT INSULATOR	P1								
	P2								
	Q	1200	1500	0.8	1200	-	3450	0.8	2760
	S1			※ Q				※ Q	
	S2								
	R								

Figure 10. FR STRUT INSULATOR Static and Dynamic Characteristics Prediction Method (2)

Based on two prediction methods—one utilizing the dynamic test report and one without—it was possible to predict both static and dynamic characteristics for a total of 10 bushes in small SUV vehicles, and compare them with the test report. Although verifying the accuracy of dynamic characteristics is challenging—since most bushes provide test data for only one major direction—the excellent prediction accuracy for static characteristics, using the same model and analysis method, suggests that the derived dynamic characteristic values are reliable for use in the NVH performance review model.

2.4 Dynamic Properties Prediction Frequency Extension and Application Method

Finally, an approach was reviewed to expand the frequency range over which dynamic characteristics can be predicted. Since the viscoelastic properties of the rubber specimen are measured only up to 300 Hz, the bushing characteristics for a single component are likewise limited to this range. Due to equipment limitations, evaluating material properties at higher frequencies is challenging. Therefore, a linear extrapolation method was employed to extend the available physical property data into the higher frequency domain.

As illustrated in Figure 12, the linear trend of the storage modulus as a function of frequency is first extracted from the measured data (up to 300 Hz). This trend is then extended into the desired higher frequency range, with the measured data used directly up to 300 Hz and the extrapolated data applied beyond that, as shown in Figure 13. The loss factor was similarly extended to 1000 Hz using the same method.

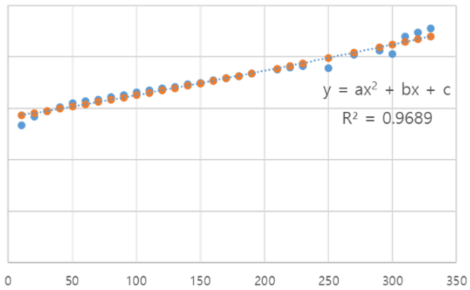

Figure 12 Extracting the Storage Modulus linear trend line of viscoelastic elasticity

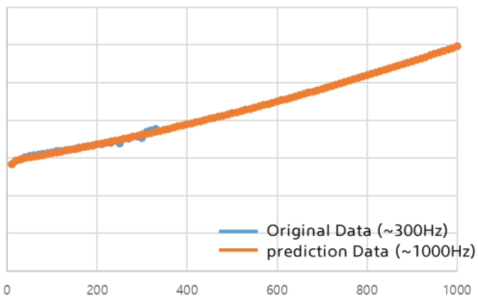

Fig. 13 0~1000 Hz Storage Modulus Prediction Data

The predicted dynamic characteristics of the G BUSH for a small SUV—obtained by extending the rubber properties to a frequency domain of 1000 Hz—are presented in Figures 14.

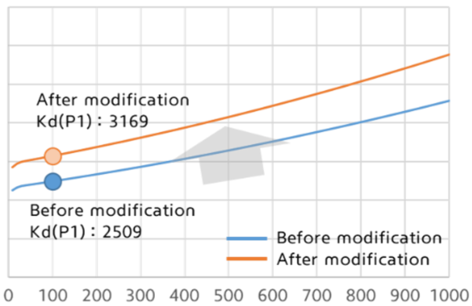

Figure 14 Prediction Results of G BUSH P1 Dynamic Characteristics of Small SUV (~1000 Hz)

3. CONCLUSION

3.1 Conclusion

In this study, we addressed the challenge of obtaining bush dynamic characteristics—required for predicting NVH performance in the middle and high frequency domains—that are difficult to measure in all six degrees of freedom due to limitations of test equipment. To overcome this issue, a 3D shape-based bush dynamic characteristics prediction method was developed, and the following conclusions were reached:

1. Comprehensive Data Acquisition: To improve the accuracy of NVH performance predictions, it is essential to obtain dynamic characteristic values in all six degrees of freedom over the frequency region of interest and incorporate these values into the analysis model. By inputting accurate material properties specific to the bush and utilizing its 3D shape, it is possible to predict properties that fall within the test error range across all directions.
2. Use of Correlation Coefficients: When accurate material properties are unavailable for all directions, a correlation coefficient can be derived using dynamic test results from a specific primary direction (obtained via the initial 3D shape-based analysis and previously secured physical properties). This coefficient can then be applied uniformly to estimate accurate dynamic characteristics in all directions.
3. Frequency Range Extension via Extrapolation: Even when viscoelastic material properties of the rubber specimen are evaluated, securing data up to the desired high frequency range remains challenging. In such cases, extending the measured material property data to the required frequency range via linear extrapolation enables the calculation of bush dynamic characteristics over the higher frequency domain.

Overall, the study demonstrates that predicting bush dynamic characteristics in the middle and high frequency domains using a 3D shape-based approach is a promising method. This approach effectively overcomes equipment limitations and reduces time and cost constraints, ensuring that sufficient dynamic characteristics can be secured for accurate NVH performance evaluation.

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