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Vibration Characteristics of a Passenger Car Steering Column

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ABSTRACT

The vibration characteristics of a passenger car steering column are studied by using a modal test and a finite element (FE) analysis. To verify the FE model and the results, an experiment using the impact exciting method is performed. Two types of the steering column in this study are considered as follows; (i) the non-tilt type steering column and (ii) the upper-tilt type steering column. The experimental results are compared with those of the FE analysis, and it is shown that the results agree with each other. The effects of various design parameters such as the bracket thickness, the column thickness and the column diameter on the natural frequencies are also investigated by FE analysis.

Key Words : Steering column system, Vibration characteristics, Non-tilt type steering column, Upper-tilt type steering column, Modal test, Finite element analysis

1. Introduction

These days, passenger car technology has progressed rapidly with the development of various advanced equipment. While this type of equipment has improved driving comfort, the vibration coming from the vehicle is still harsh to the driver's senses and decreases driving comfort. The vibration of the passenger car takes place for two main reasons; (i) the vibration is transferred from a car body through the tires and (ii) the vibration is generated by the engine. These cause the car body and its components to vibrate. In particular, the steering system is one of the main components from which drivers directly feel the vehicle's vibration.

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$$\frac{750RPM}{60\frac{SEC}{MIN}} \times \frac{4CYLINDER\ ENGINE}{2\frac{FIRING\ CYLINDERS}{CRANK\ REVOLUTION}} = 25Hz \quad (1)$$

If this idling frequency is within or close to the frequency range of the steering system, the system causes resonance. Therefore, in order to reduce the vibration, car manufacturers have made efforts to isolate the resonant frequency of the steering system or to increase the fundamental natural frequency of the steering system. The steering column is one of the main components which has an effect on the natural frequency of the steering system. It is a complex structure which consists of columns, brackets, shafts, the universal joint, bearings, and several other parts. Hence, it is very difficult to theoretically analyze the natural frequency of the steering column, and it would consume a great deal of time and effort.

The finite element analysis (FEA) using commercial programs can be used as an efficient analysis tool these days. Although the preparation of input for the solution takes much time, the FE analysis of complex structures, such as the steering column, is a useful method to predict the natural frequency of the steering column, and thereby investigate the influence on each component in the stage of protocar design.

In this study, the vibration characteristics of the car steering column are studied using the finite element analysis and the modal test. The analysis results are compared with the results from a vibration test using a signal analyzer to validate the FE analysis results, and show that the FE results agree with those of the experiment. The effects of the column thickness, the bracket thickness and the column diameter on the natural frequencies are also investigated by the finite element analysis.

2. Experiments

2.1 Test specimens and apparatuses

Figures 1 and 2 show the steering column of two types considered in this study; (i)the non-tilt type (Fig. 1) and (ii)the upper-tilt type (Fig. 2). These steering columns are fabricated by the M company. One end point of the steering column is connected with the steering wheel, the other end point is connected with the steering gear, and the column is fixed to the vehicle by a bolted bracket.

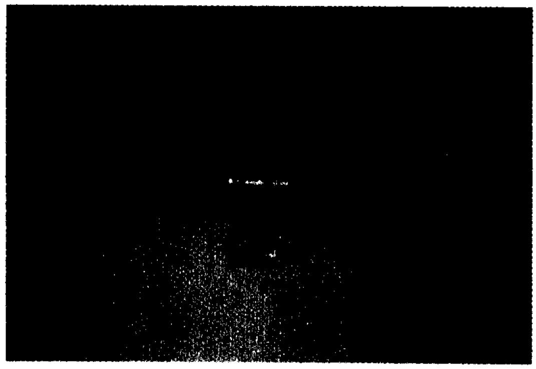


Fig. 1 Shape of non-tilt steering column

Fig. 2 Shape of upper-tilt steering column

It is difficult that the experiment in the actual car is performed to obtain the vibration characteristics of the steering column. Thus, as shown in Figs. 1 and 2, steering columns without the steering gear are considered, and the modal test is conducted on the test bed in the laboratory. For the vibration test of the steering column, the excitation method[2)] by the hammer is used with the Fast Fourier Transform (FFT) analyzer, an impact hammer and an accelerometer.

The dimensions of the test bed are 1,000mm× 800mm× 100mm (L× W× H) and its mass is 850 kg. The external vibration may not influence the fundamental frequency of the specimen. To measure the natural frequency, the following instruments are used : impact hammer (PCB A352B18), accelerometer (PCB 086B03), charge amplifier (PCB 400D06, EA 2), FFT (ONO SOKKI CF-720) and plotter.

2.2 Test methods

To obtain the effects of the steering wheel on the natural frequencies, an experiment of two cases is performed. Case 1 is the model of non-tilt and upper-tilt columns without the steering wheel. Case 2 is the model of non-tilt and upper-tilt columns with the steering wheel. In Case 1, the accelerometer is installed at the bottom of the upper shaft and impacted downwards. In Case 2, the frequencies are obtained under the following conditions: the steering wheel is connected to the steering column, and the accelerometer is installed at the bottom of the wheel.

The experimental data are averaged with the eight root mean square average schemes to minimize experimental error. For the upper-tilt column without the wheel, the mode shapes are determined with measured displacements on the 10 grid points of the column. Figures 3 and 4 show block diagrams of modal tests for the steering column model without (Case 1) and with (Case 2) the steering wheel.

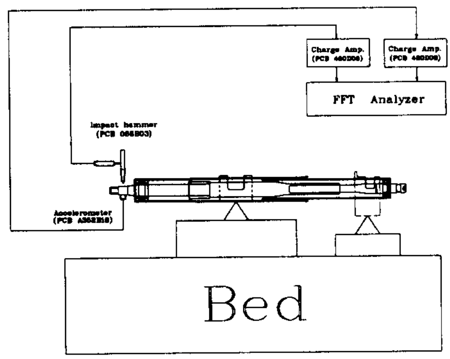


Fig. 3 Block diagram for experimental mo analysis of steering column wit wheel (Case 1)

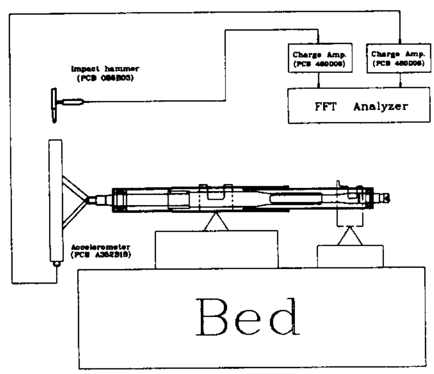


Fig. 4 Block diagram for experimental modal analysis of steering column with wheel (Case 2)

2.3 Test results

The first three natural frequencies of non-tilt and upper-tilt steering columns in the experiment are presented in Table 1. Figures

5~8 show the frequency response function (FRF) and phase angle of test results in each case. In the case of the column without the steering wheel (Case 1), the fundamental frequencies of upper-tilt and non-tilt columns are 195.0 and 237.5 Hz, respectively. The frequency of the non-tilt column has about an 18% higher value than that of the upper-tilt column. In the case of the column with the steering wheel (Case 2), the fundamental frequency of the column for two types is the same value, 39.5 Hz, because that frequency shows the first twisting mode of the wheel only. The second and third frequencies show mixed bending modes between the wheel and the column.

Table 1 The natural frequencies of the steering column by the experiment

Case	Type	Frequency (Hz)		
		1st	2nd	3rd
Case 1	Upper-tilt	195.0	440.0	592.5
	Non-tilt	237.5	310.0	832.5
Case 2	Upper-tilt	39.5	93.0	150.5
	Non-tilt	39.5	67.0	176.0

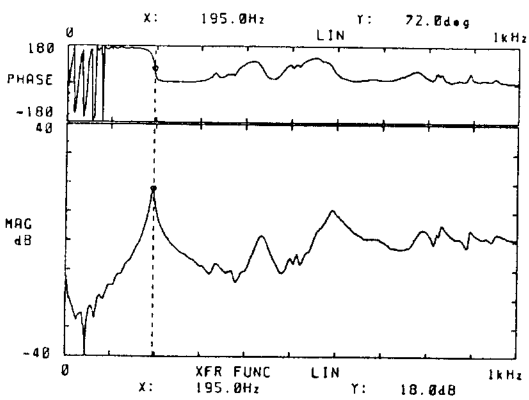


Fig. 5 Frequency response function of upper-tilt steering column without wheel (Case 1)

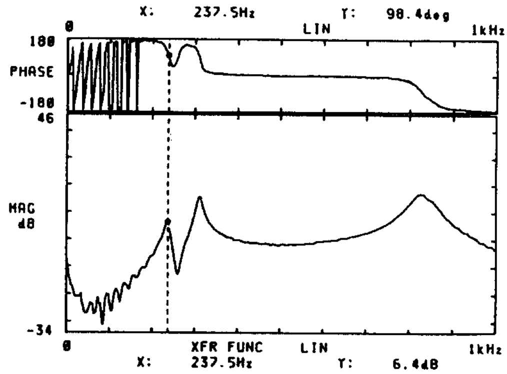


Fig. 6 Frequency response function of non-tilt steering column without wheel (Case 1)

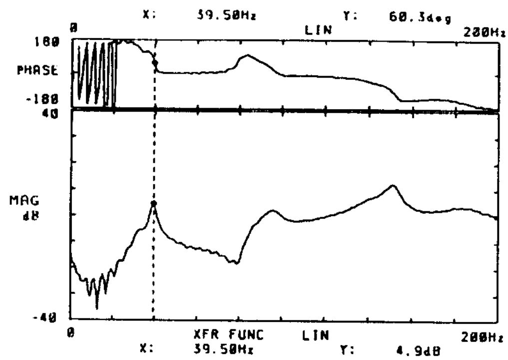


Fig. 7 Frequency response function of upper-tilt steering column with wheel (Case 2)

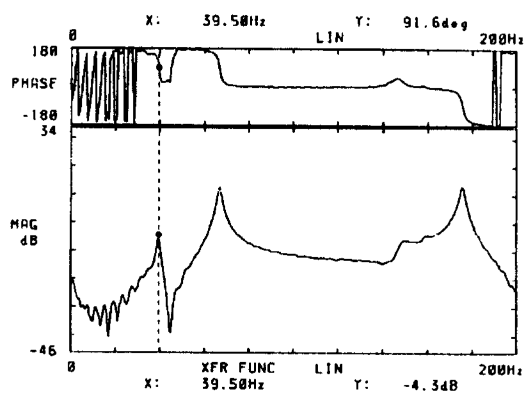


Fig. 8 Frequency response function of non-tilt steering column with wheel (Case 2)

The non-tilt column in Case 1 has a higher frequency than that of the upper-tilt column because the upper-tilt column has tilting parts, which cause stiffness reduction effects.

3. FE analysis

To validate the experimental results, an FE analysis using the ANSYS program[3] is performed. Beam, shell, spring-damper, mass and solid element are used in modeling the two types of steering columns.

The shaft is modeled with the beam element. The area and area inertia moment of the section are inputed. The same method is also used for the hollow part of the shaft. The column is modeled with the shell element, which requires the thickness.

The bearing is modeled using the spring-damper and the mass element[4]. In order to maintain an equal level of bearing stiffness, the spring element has the same stiffness value of the bearing[5]. In modeling the bearing, the nodal degree of freedom of the bearing model is coupled with the node of the column model to prevent axial rigid body motion. For the bracket modeling, the same element is used as that of the column, but its thickness is variable.

In modeling the upper-tilt type steering column, complex structures of the upper column part and universal joint are simplified by beam elements which have equivalent stiffness. By using the mass element, the mass difference between the actual model and the FE model is compensated. Figures 9 and 10 show the FEM model of the two types of steering columns[6].

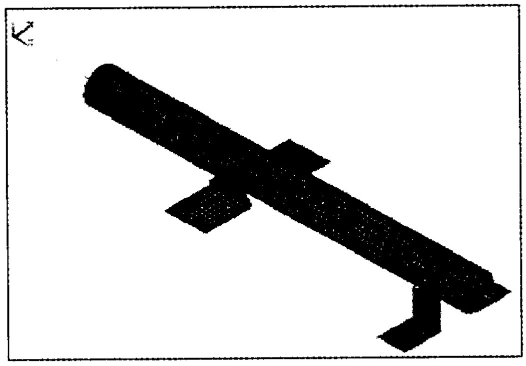


Fig. 9 FEM model of non-tilt steering column

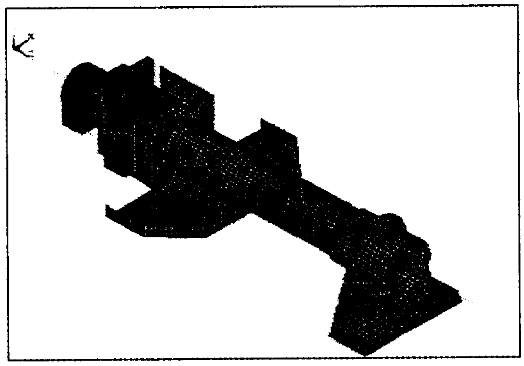


Fig. 10 FEM model of upper-tilt steering col

4. Results and discussion

4.1 Comparison of the FE analysis and experimental results

4.1.1 Non-tilt steering column

Table 2 presents the results of the FE analysis and modal test for the non-tilt steering column. The non-tilt column has a more simple structure than the upper-tilt column. Thus, the FE modeling and experiment are easy, and the two methods give results that agree well within 7%, except the third mode of Case 2 shows the difference of 13.6%. Figures 11 and 12 show the mode shape of the fundamental frequency by FE analysis for Case 1 and Case 2, respectively. In Case 1 without the wheel, the mode shape is the first bending mode of the shaft. In the case of the column with the steering wheel (Case 2), the frequency shows the twisting mode of the wheel only. Due to the stiffness of the wheel, the natural frequency is much lower than that of the steering column.

Table 2 The results of FEM analysis and modal test for the non-tilt steering column

(Unit : Hz)

Case \ Mode		Frequency (Hz)		
		1st	2nd	3rd
1	Exp.	237.5	310.0	832.5
	FEM	222.5	317.1	838.7
2	Exp.	39.5	67.0	176.0
	FEM	39.4	72.2	152.0

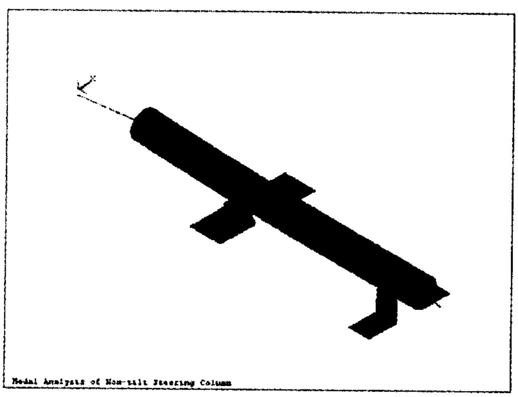


Fig. 11 The first mode shape of non-tilt st column without wheel by FE analysis

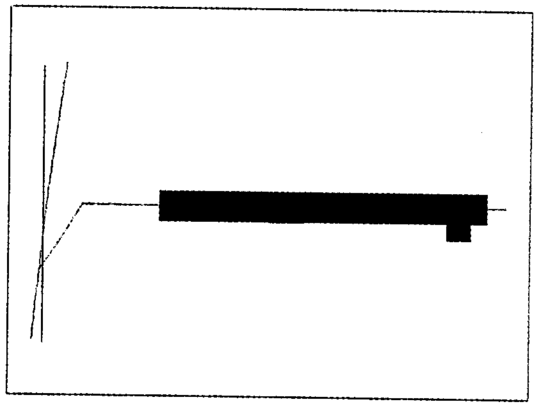


Fig. 12 The first mode shape of non-tilt st column with wheel by FE analysis

4.1.2 Upper-tilt steering column

The upper-tilt steering column has complex structures due to tilting parts, which consist of the universal joint and various components related to the tilting ·mechanism. Therefore the modeling of the upper-tilt column with tilting parts in the FE analysis is more difficult than that of the non-tilt column. The natural frequencies of the upper-tilt steering column by FE analysis and modal test are shown in Table 3.

Table 3 The results of the upper-tilt steering column by the experiment and FE analysis

(Unit : Hz)

Case \ Mode		Frequency (Hz)		
		1st	2nd	3rd
1	Exp.	195.0	440.0	592.5
	FEM	227.3	428.3	678.6
2	Exp.	39.5	93.0	150.5
	FEM	41.1	105.3	149.1

In the case of the column with wheel (Case 2) the differences of the frequency between the FE analysis and the experiment are very small because of the modes of the wheel only. But the second natural frequency has the difference of 11%. Since the air bag part of the wheel in the FE analysis is modeled as the plate, considering the equivalent mass, the difference of the second frequency between two methods occurs.

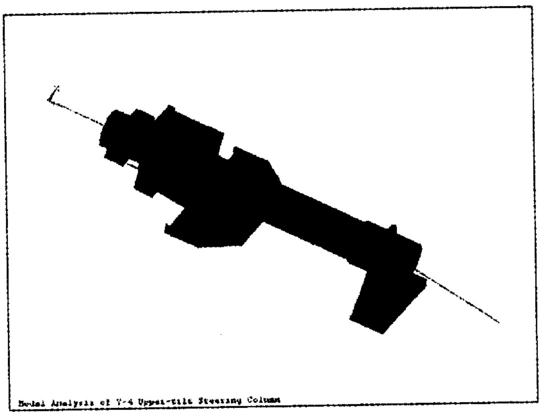


Fig. 13 The first mode shape of upper-tilt s column without wheel by FE analysis

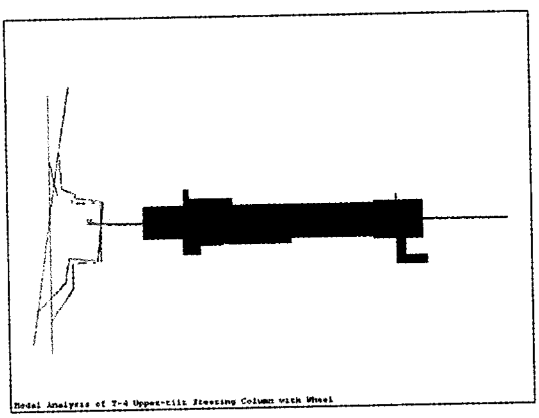
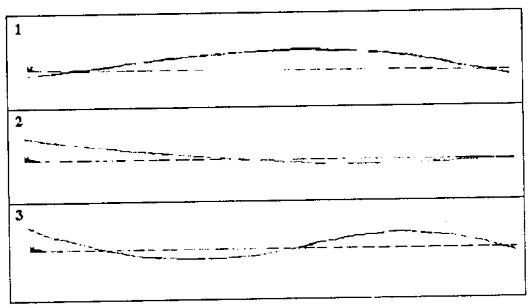
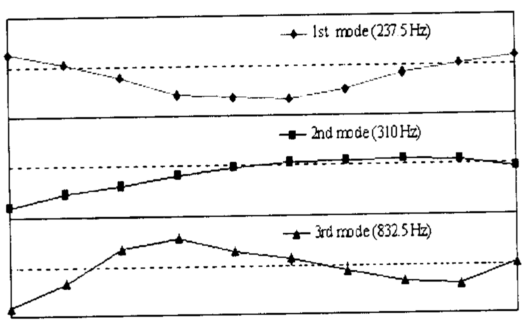


Fig. 14 The first mode shape of upper-tilt s column with wheel by FE analysis

For the steering column without the wheel, the fundamental frequencies by experiment and FE analysis are 195.0 and 227.3 Hz, respectively. Figures 13 and 14 show the first mode shape of each case. As shown in Fig. 13, the mode of the column is the first bending mode of the interior shaft with the universal joint. In Case 2, the wheel is shaped twisting backward, similar to the non-tilt column. In the case of the steering column without the wheel (Case 1), the largest discrepancies between the experiment and FE analysis results are 6.3% for the non-tilt column and 14% for the upper-tilt column.



(a) FE analysis



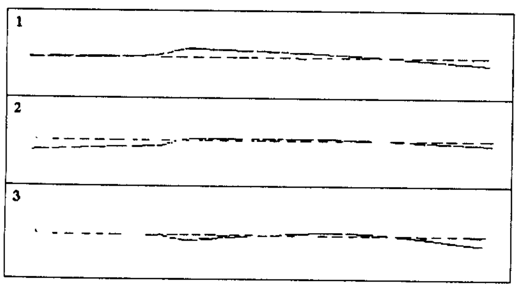
(b) Experiment

Fig. 15 The first three mode shapes of non-tilt steering column without whe

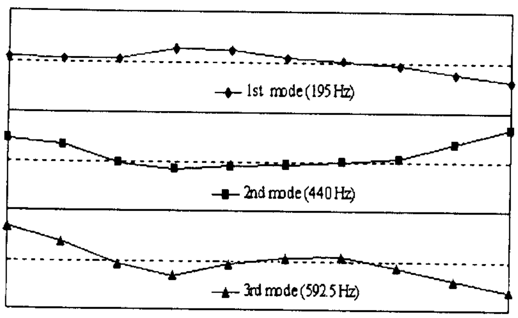
4.1.3 Mode shapes

Figures 15 and 16 show the comparison of the first three mode shapes of the non-tilt and upper-tilt steering columns without wheel by two methods, respectively. From the mode shapes one can see that the lowest frequency corresponds to a bending mode which is basically governed by an interior shaft. Those behaviors show the same mode shapes as those of the two point supported beam[7].

To compare the mode shapes between an experiment and FE analysis, the MAC(Modal Assurance Criterion) values are calulated using an experimental mode shape(ϕ_i) and an FEA one (ϕ_j).



(a) FE analysis



(b) Experiment

Fig. 16 The first three mode shapes of upper-tilt steering column without w

This is also defined by[2]:

$$MAC_{ij} = \frac{(\phi_i^T \cdot \phi_j)^2}{(\phi_i^T \cdot \phi_i)(\phi_j^T \cdot \phi_j)} \qquad (2)$$

The MAC is a method for quantitatively determining how similar or correlated two mode shapes are to one another. If the MAC value is one, then the two mode shapes are alike. If their MAC value is less than one, the two mode shapes are dissimilar. If the value is zero, the two mode shapes are orthogonal to one another.

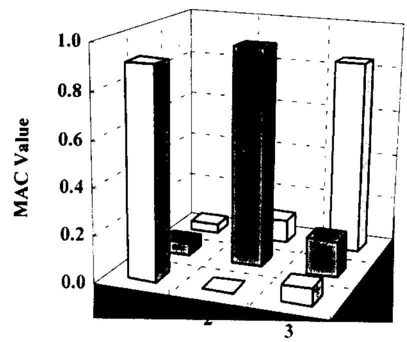


Fig. 17 MAC values of experimental and FE modes of non-tilt column

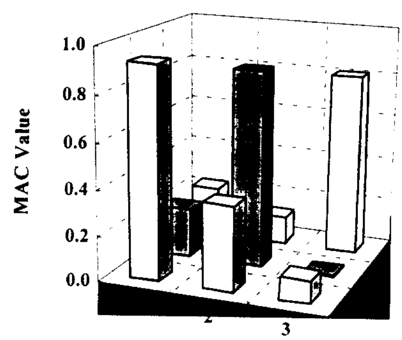


Fig. 18 MAC values of experimental and FE modes of upper-tilt column

Figures 17 and 18 show the MAC values between an experiment and an FE analysis of non-tilt and upper-tilt steering columns, respectively. When comparing the MAC values between these two methods, it can be concluded that they are similar because of the high diagonal MAC values (0.8～1.0) for the first three modes. As a result, the natural frequencies and mode shapes by FE analysis agree well with experimental results, showing the validity of the FE modeling.

4.2 Effects of various parameters of steering column

As shown in Figs. 1 and 2, the steering column is an assembly of various components such as columns, shafts, bearings, brackets and a universal joint connecting the shafts.

When those components are assembled, the vibrational behavior of the steering column is complex. Thus, to estimate the effects of various parameters of the steering column without the wheel on the natural frequencies, the bracket thickness, the column thickness and the column diameter are considered, and analyzed by the finite element method.

4.2.1 Bracket thicknesses

The bracket is used in the steering column to fix the car body. The effects of various thicknesses of the bracket on the frequencies are studied. Tables 4 and 5 show the FE analysis results of the non-tilt and upper-tilt column, respectively. The actual model thickness in Table 4 is that of the specimen considered in the experiment. For the non-tilt column, the thickness of the bracket is changed from 2.2mm to 5.2mm. The fundamental frequency is slightly increased with the thickness of the bracket. But the frequency of the second mode is more sensitive than the first frequency because it is related to the column mode the bracket connected.

Table 5 shows the effects of the bracket thickness for the upper-tilt column on the natural frequencies. For this case, the thickness of the lower bracket is fixed as 4.0mm which is the same as the experimental model, and that of the upper bracket is considered in the range from 1.6mm to 5.2mm. In the case of the upper-tilt column, the frequency variations increasing the thickness are larger than that of the non-tilt column, except the frequency of the third mode. When the thickness is thin, the effects of the thickness on the frequencies are larger than in case of the thick bracket.

As a result, the thickness of the bracket is not effected by the third mode of the column. But the first two frequencies are increased because the column stiffness with the bracket thickness increases.

Table 4 The natural frequencies of the non-tilt column for various bracket thicknesses

(Unit : Hz)

Mode \ Thickness (mm)	2.2	3.2*	4.2	5.2
1	218.6	222.5	223.7	224.4
2	289.7	317.1	329.9	343.2
3	820.3	838.7	843.2	845.9

※ : Actual model thickness

Table 5 The natural frequencies of the upper-tilt column for various bracket thicknesses

(Unit : Hz)

Mode \ Thickness (mm)	U:1.6 L:4.0	U:3.2* L:4.0**	U:5.0 L:4.0
1	196.6	227.3	230.8
2	387.5	428.3	583.7
3	678.1	678.6	679.9

* : L is the thickness of actual lower bracket

** : U is the thickness of actual upper bracket

4.2.2 Column thicknesses

In the case of the non-tilt steering column, the column is composed of two hollow pipes as shown in Fig. 19. Regions "a" and "c" on the figure present the thickness of the upper and lower column parts, respectively. Region "b" is the overlapping part of the two pipes. When the thickness of the part "c" is fixed as 1.6mm, the effects of several thicknesses of the part "a" are studied, and listed in Table 6. In this case the effects with the thickness of the part "a" are the largest for the frequency of the second mode.

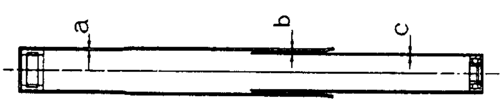


Fig. 19 The schematic view of the non-tilt column with various thicknesses

Table 7 presents the natural frequencies of the upper-tilt column with various column thicknesses. When the thickness is increased, the first and third frequencies are slightly varied. But similar to the case of the bracket thickness, since the frequency of the second mode related to the thickness of the column, the increment of the second frequency is large compared to the other frequencies as the thickness increases.

Table 6 The natural frequencies of the non-tilt column for various column thicknesses

(Unit : Hz)

Mode \ Thickness (mm)	a=1.5 c=1.6	a=2.0* c=1.6*	a=3.0 c=1.6
1	215.9	222.5	233.0
2	295.5	317.1	349.2
3	837.8	838.7	844.4

* : Actual model thickness

Table 7 The natural frequencies of the upper-tilt column for various column thicknesses

(Unit : Hz)

Mode \ Thickness (mm)	1.6*	2.6	3.6
1	227.3	227.6	227.9
2	428.3	435.6	440.9
3	678.6	679.0	679.0

* : Actual model thickness

From the result of this study, when the column thickness is thickened partially or entirely, it is found that the effects of the thickness on the natural frequencies are larger in the case of the non-tilt column than in case of the upper-tilt column. That is to say, the vibrational behavior of the non-tilt column is influenced by changing the column stiffness due to the simple structure.

4.2.3 Column diameters

When the diameter of the column is considered in the range from 37mm to 57mm, the effects of the column diameter are investigated, and the results are presented in Table 8. In this case, other geometrical shapes are the same dimensions as the model tested. The first and third natural frequencies with the diameter are increased, although the increment of the value is very small. But the second frequency is linearly increased about 4% with the column diameter. Those results are the same trend as the results of the FE analysis to estimate the effects of bracket and column thicknesses. In other words, among the first three frequencies, the second frequency showing the bending mode of the column is largely effected by the variation of the diameter due to the stiffness increment as the diameter increases.

Table 8 The natural frequencies of the upper-tilt column for various column diameters

(Unit : Hz)

Diameter (mm) / Mode	37.0	47.0*	57.0
1	226.7	227.3	227.8
2	410.3	428.3	443.7
3	677.1	678.6	678.6

* : Actual model diameter

5. Conclusions

The major conclusions from this study are as follows:

1) For non-tilt and upper-tilt columns, the natural frequencies from the FE analysis agree quite well with those from the experiment, showing the validity of the current FE modeling.

2) In the case of the column with the steering wheel, the fundamental frequency of non-tilt and upper-tilt columns in the experiment is the same, 39.5 Hz, and the mode is the first twisting mode of the wheel only. In the case of the column without the wheel, the fundamental frequencies of non-tilt and upper-tilt columns are 237.5 Hz and 195.0 Hz, respectively. It is shown that the first bending mode of the interior shaft is dominant.

3) When the bracket thickness, the column thickness and the column diameter are increased, the natural frequencies are slightly increased due to the higher stiffness. Especially, the natural frequency of the second mode is largely influenced by changing the various parameters because is is related to the bending mode of the column.

4) It is expected that the FE model and analysis results in this paper can be used for the estimation of vibration characteristics to avoid the resonance between the steering wheel and the column in the development stage of the new passenger car steering column.

Acknowledgement

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