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Development of Test-based Assessment for Perceived Vehicle Comfort in Two Types of Vibration: Body Control and Ride Comfort Evaluation

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ABSTRACT

This paper proposes a method of developing quantitative indices for ride quality evaluation based on actual road driving tests. The assessment of vehicle comfort is divided into two parts, i.e., body control, which evaluates wavy motion in a frequency range of 0.5 to 5 hertz, and ride comfort, which focuses on secondary vibration in a range of 5 to 80 hertz. The indices for the assessment of each part are developed separately and have different evaluation formulae. All vehicles are tested in the proving ground of Korea Automobile Testing & Research Institute (KATRI). The measured signal of motion and vibration is calculated in terms various physical quantities considered as independent variables. Subjective evaluation is conducted using a jury test. The results of signal calculation and the scores obtained from the jury test are examined using exploratory factor analysis and linear regression analysis. The quantitative evaluation indices of ride quality are expressed in the form of a linear equation for the two parts, and the contribution rate of each variable is computed as an indicator of the dominant calculated quantities.

Keywords: Vehicle vibration, Ride quality, Vehicle comfort, Quantitative evaluation
I-INCE Classification of Subject Number: 49

1. INTRODUCTION

The vehicle industry has experienced rapid technical growth during the century since the first mass production of vehicles. The technical aspects of vehicles were examined first, for example, mechanical performance such as higher fuel efficiency and performance. However, the emotional qualities of driving have become an important

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issue with the advent of highly developed modern technology. The subjective perception of passengers is affected negatively by noise and vibration during an actual vehicle trip. In particular, the vibrations transmitted to the interior of vehicles cause several negative effects such as discomfort and nausea. In the vehicle industry, this sensitivity to vibration is expressed as ride quality, and it is an important index for assessing automotive performance. Vehicle comfort is evaluated through empirical tests conducted at work sites. A few experts drive target vehicles and grade them. This conventional method simply ranks vehicles; however, the score is strongly influenced by the personal mood and physical condition of testers. Owing to this inherent disadvantage, empirical evaluation is considered as an unclear test method. Therefore, an experimental evaluation method is required for the accurate and robust assessment of ride quality.

This paper proposes a test-based method for the assessment of the ride quality of vehicles. Perceived vehicle comfort is divided into two parts. Body control indicates the primary ride condition, which is like a swing motion when a vehicle passes a wavy road. Ride comfort indicates the secondary ride condition, whose vibration frequency is higher than that of the primary condition. The experimental methods for assessing the two different parts are developed separately, and the indices for each part are extracted independently. Quantitative models are developed based on a combination of subjective and objective evaluation. The scores of vehicles are valued subjectively through a jury test with actual driving. Vibrations are measured during an objective experiment and computed in terms of various physical variables. Finally, correlation analysis is conducted to determine the relationship between rated scores and computed variables. The obtained correlation is formulated into a linear model. The developed test-based method for assessing vehicle comfort shows high accuracy and effectiveness. It is verified through appropriate validation. All details about the driving test and data are concealed as confidential documents.

2. EXPERIMENT

2.1 Test Environment

The experiments for subjective and objective evaluation are conducted in identical conditions. The number of vehicles is six, and the same types of vehicles are considered to equilibrate the expected vehicle comfort. The driving tests are performed on 17 pavements. Nine roads are considered for body control evaluation; these roads contain various kinds of wavy road conditions such as bumps and twists. Therefore, the motion of the entire vehicle body is considered. Eight roads are considered for ride comfort evaluation; these roads represent the pavements of diverse regions. The travel speed for a single trial is fixed using a cruise control system. As the transmitted vibration varies with vehicle speed, different speed in same pavement is assumed to other road condition.

2.2 Objective Measurement

The vibrations and motions of test vehicles are measured as acceleration signals. Signal data are acquired using tri-axial piezoelectric accelerometers and the LMS SCADAS Mobile front end, which are shown in Figure 1. Prior to the main objective test, the validity of signal acquisitions is verified by employing a pretest process. Vehicle body motion is in a vibration range of 0.5 to 5 Hz. The vibration at low frequencies is measured at vehicle hard points because the motions of the vehicle are directly transmitted to the human body. Vehicle motions are typically measured using gyro sensors. However, in this study, only tri-axial accelerometers are used because of simple and nondestructive instrumentation. As shown in Figures 2 and 3, the roll and pitch rate are measured by utilising an accelerometer and a gyro sensor. The error rates of roll and pitch motions are close to 8 % and below 1 %, respectively. Hence, the motion measurement using tri-axial accelerometers is reliable. The vibration range of 5 to 80 Hz is expressed as ride comfort vibration. This higher-range signal is acquired at the point of contact with human body. The repeatability of signal acquisition is verified based on the fact that the coherence values of entire tests are over 91 % in repeated trials.

Figure 1. *Equipment for vibration signal acquisition: tri-axial piezoelectric accelerometer (right) and LMS SCADAS Mobile (left)*

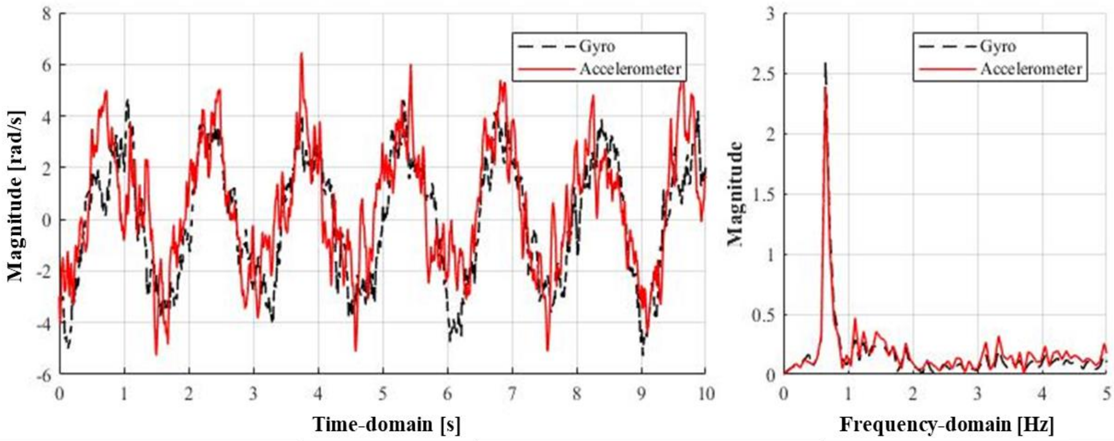

Figure 2. *Roll rate measured by gyro sensor (dashed line) and accelerometer (solid line)*

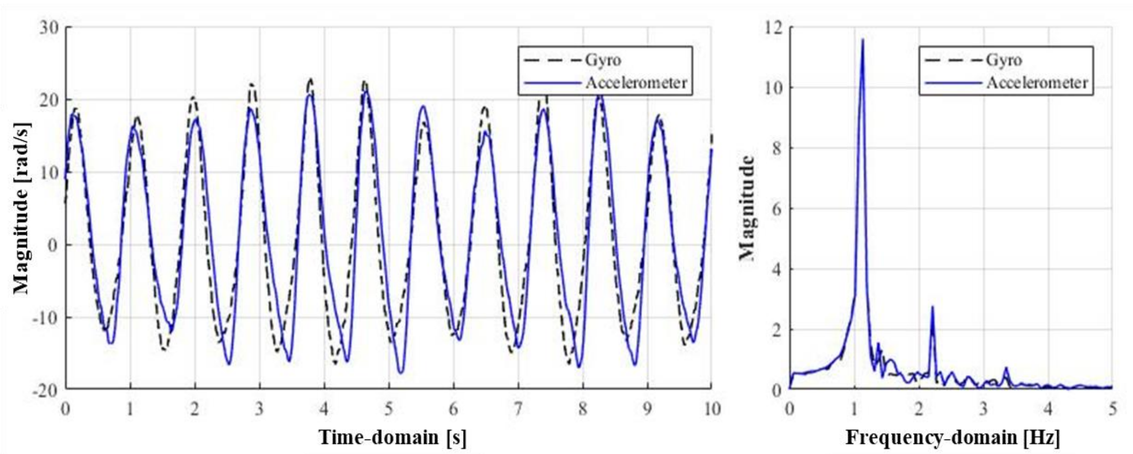

Figure 3. *Pitch rate measured by gyro sensor (dashed line) and accelerometer (solid line)*

2.3 Subjective jury test

The scores of target automobiles are evaluated by eleven well-trained juries. The category scaling method of seven-step scales is used with a ranking procedure. Testers drive test vehicles on given road conditions and assign the scores of body control and ride comfort to the vehicles. The sequences of test vehicles and pavements are individually randomised to eliminate biased evaluation. Figure 4 shows the scores obtained through subjective jury testing.

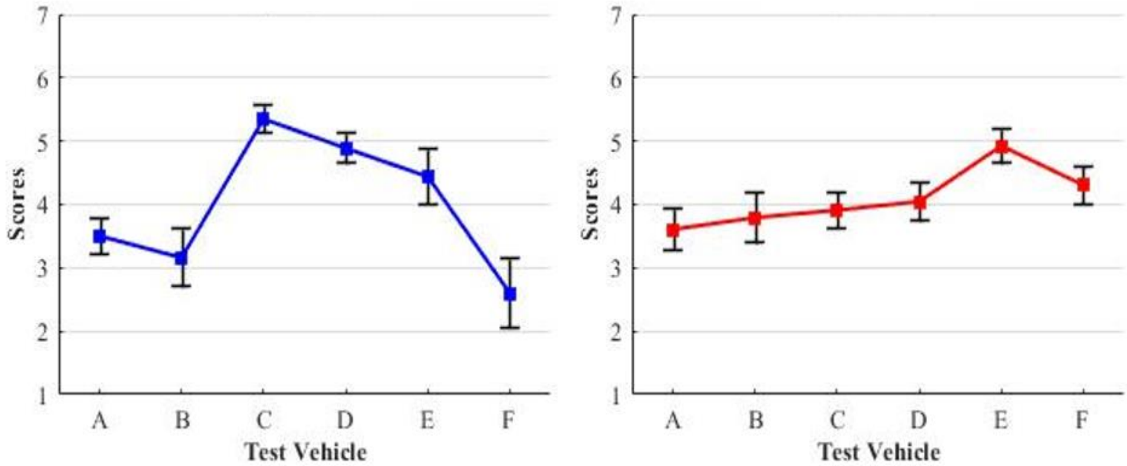

Figure 4. *Jury test scores of body control (left) and ride comfort evaluation (right)*

3. DESIGN OF QUANTITATIVE MODEL

3.1 Pavement Selection

Even though the evaluation performed using 17 pavements provides the most accurate result, the entire process is time consuming and complicated. Therefore, the numbers of road conditions are minimized to develop a simplified and efficient test method. Experimental factor analysis is used for pavement selection. The dimension of the entire data is statistically decreased through experimental factor analysis, and potential factors are obtained. The number of potential factors is less than analysed variables due to the dimensional reduction. The total score distributions for body control and ride comfort are categorised into three factors. The road conditions for body control consist of bump, twist-shape, and wavy pavements. The road conditions for ride comfort evaluation are comprised of asphalt and concrete pavements.

3.2 Computation of Variables

The measured vibration signal is computed in terms of several variables. Transmitted vibrations are compensated with the spectral weighting curves of ISO2631-1. Vehicle body motions are weighted with the curve, W_e, referred to in ISO2631-1 and calculated in terms of variables including peak amplitude, overall power, and skewness of the spectrum curve. Ride comfort vibrations are weighted with the curves of ISO2631-1, W_k, W_d, and W_c, and calculated in terms of root-mean-square values and root-mean-quad values. According to Stevens' power law given by Equation 1, perceived human response ψ is logarithmically related to the intensity of stimulus, I, with proportionality constant κ and exponential constant α. Hence, the variables are computed as logarithmic values.

$$\psi = \kappa I^{\alpha} \tag{1}$$

3.3 Linearized Quantitative Index

Linear regression analysis is generally used to define the relationship between a dependent variable and independent variables. The error minimization between observed variable y_i and estimated variable y_i' is conducted based on the least square method expressed in Equation 2.

$$error(y_i, y_i') = \sum_{i=1}^{n}(y_i - y_i')^2 \quad (2)$$

Based on this optimisation, the linear equation given by Equation 3 is obtained with regression coefficients β_i and the selected independent variables of measured vibrations, x_i. Linear models are typically verified using the coefficient of determination, significance probability, and variance inflation factor. The regression coefficients of designed models and the variables selected for assessing vehicle comfort are not revealed in this paper owing to the confidentiality of detailed information.

$$y' = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots \quad (3)$$

3.4 Model Validation

The probabilistic reliability of the developed quantitative models should be verified before their application. There are three important and effective indicators for the validation of models, i.e., the coefficient of determination (R^2), significance probability (*p*-value), and variance inflation factor (*VIF*). The statistical indicators of the two developed models are computed and provided in Table 1. Mean error ratio *e*, which is the ratio of squared error to the mean distance of dispersed data, is calculated as an additional indicator.

Table 1. *Statistical indicators of the designed models for test-based assessments*

Indicator	Body Control	Ride Comfort
R^2	0.9967	0.9994
Adjusted R^2	0.9917	0.9984
p-value	< 0.0898	< 0.0366
VIF	< 1.8662	< 2.3816
e	0.0651	0.0412

The accuracy of both models is verified by R^2 values, which are more than 0.9. The *adjusted* R^2 value is almost the same as the R^2 value. The *p*-values of both models are below 0.1, and the *VIF* indices are less than 3. Therefore, the statistical validity of each model is verified with adequate values of indicators. Mean error ratio *e* is the ratio of the squared difference between observed and estimated vehicle comfort to the standard derivation of tested data. As *e* is below 7 %, the models are reliable and suitable for evaluation of vehicle comfort. Furthermore, as shown in Figure 5, the contribution of vibratory variables is obtained from the regression coefficients included in the models. The influences of each variable are analysed and standardised as numerical values.

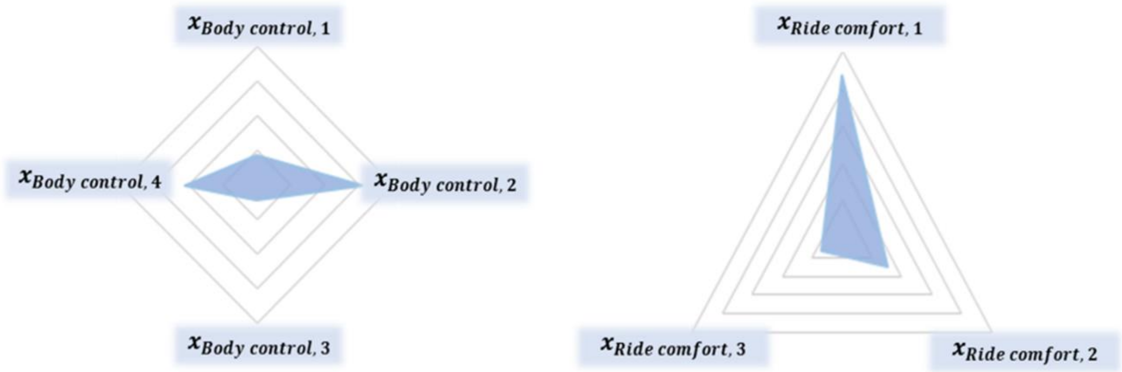

Figure 5. *Contributions of variables included in body control (left) and ride comfort (right) models*

4. CONCLUSION

In this study, two quantitative models are developed for the test-based assessment of vehicle comfort. Linear indices are utilized for evaluating body control and ride comfort. Compared to former studies on the quantification of ride quality, vehicle comfort is assessed and estimated more precisely using the designed models. The absolute mean value of estimated error is 0.36 for the conventional method, which is simply adding the root-mean-squared vibrations of all coordinates. The assessment performed using the developed models shows a lower mean error of 0.02. In addition, as a result of contribution analysis, it is possible to suggest a guideline about which vibration should be mainly reduced for better ride quality. Consequently, the designed models are suitable for assessing vehicle comfort owing to their superior accuracy and reliability.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Eberhard Zwicker and Hugo Fastl, *"Psychoacoustics: Facts and Models"*, Vol. 22. Springer Science & Business Media (2013)
2. *Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration—Part 1: General requirements*, International Standard ISO 2631–1: 1997, International Organization for Standardization, Geneva, Switzerland, (1997).
3. Michael J. Griffin, *"Discomfort from feeling vehicle vibration"*, Vehicle System Dynamics, 45.7-8 (2007): 679-698.
4. Peter Múčka, *"Road roughness limit values based on measured vehicle vibration"*, Journal of Infrastructure Systems 23.2 (2016): 04016029