PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Estimation method of input power from road to tire based on experimental SEA

Hiroki NAKAMURA[1]; Kaito SAWADA[2]; Atsushi KITAHARA[3]; Toru YAMAZAKI[4]

[1, 2, 4] Kanagawa University, Japan

[3] Bridgestone Corporation, Japan

ABSTRACT

A tire is a composite structure and a viscoelastic body, and its mode density is high. Then, detailed methods such as Finite Element Method are unsuitable to apply for broadband vibration problems. Under the circumstances, the authors are conducting research for predicting tire vibration and noise using Statistical Energy Analysis based on the energy propagation. The mechanism of tire vibration and noise goes through three processes of input, propagation and radiation. Initial examination of Experimental SEA model construction method and input power evaluation methods is to be conducted for propagation and input based on SEA theory. In this report, the authors first propose a method to estimate the input power from the road surface. For the problem of the subdivision in estimation input power, we established a method to make the experimental SEA models a total of two subsystems, one for each tread and one for each sidewall. Furthermore, we showed that the input power becomes constant regardless of the subdivision angle.

A test bench which can measure force on tire surface is constructed to examine the validity of estimated input power. As a result, it is suggested that proposed method can estimate input power from road surface to tire with experimental SEA model.

Keywords: Road/tire interaction, Input power, Statistical Energy Analysis

1. INTRODUCTION

Recently, noise caused by road and tire interaction (road-tire noise) has been a strong focus in consideration of automotive traffic noise. This is mainly because noise from the power train has been reduced, thereby the relative contribution of road-tire noise has increased. Interest in road-tire noise is likely to grown even more with the spread of electric vehicles. The road-tire noise contribution is dominant at speeds above 30 km/h in light vehicles and above 80 km/h in heavy vehicles, as calculated using sound-source models of motor vehicles[1]. The emission and propagation of road-tire noise depend greatly on the characteristics of the road surface (e.g., its texture, flow resistivity, and acoustic absorbance) and the structure and tread pattern of the tires. These phenomena are tightly interlinked, making road-tire noise a complicated issue.

The European Union is engaged in establishing a more comfortable environment for its citizens. As part of this, it has proposed and adopted several regulations concerning road-tire noise. Regulation UN-R51-03 contains provisions regarding the sound emitted by motor vehicles and applies to vehicles in categories M and N. Also, regulation UN-R117-02 applies to new pneumatic tires in classes C1 to C3 regarding their sound emissions, rotating resistance, and adhesion performance on wet surfaces (wet adhesion). Japan has also adopted these regulations, and UN-R117-02 has been in effect since April 2018. Annex 3 of UN-R51-03, in particular, which regulates road-tire noise, would have a strong effect on automotive and tire manufacturers. For testing road-tire noise, the test road surfaces are specified by the International Organization for Standardization (ISO), and so they are called ISO standard road surfaces. At present, testing for compliance with R117-02 and R51-03 is often expensive.

[1] hiroki-nak@kanagawa-u.ac.jp

[4] toru@kanagawa-u.ac.jp

ISO 11819 standardizes how the influence of road surface characteristics on road-tire noise is measured by specifying the statistical pass-by method and the close-proximity method. These methods are intended for two main uses, namely, to classify surfaces that are in typical and good condition according to their influence on traffic noise (surface classification), and to evaluate how different surfaces influence traffic noise at particular sites irrespective of condition and age. However, these methods have some limitations and require a test field and large equipment.

Furthermore, road-tire interaction is extremely complex because tires are made of multi-layered, highly elastic and viscous materials and have many types of surface (tread patterns). This complexity has prompted various studies of road-tire interaction from a physical perspective. Problems involving tires are multi-scale, from microscopic models of chemical molecules to macroscopic models of vehicle behavior. Also, tire development must consider both cost and performance, the latter being represented mainly by rotating resistance for fuel consumption, wet adhesion for safety, and noise for comfort.

Our research on tires and road-tire interaction is set against the above background. We take a comprehensive view of the problem and intend to help engineers manufacture their products in the near future. We have studied the implementation of vibration energy propagation analysis such as statistical energy analysis (SEA)[2,3] and structural intensity analysis[3,4] to design actual mechanical productions such as automotive vehicles and office machines[5]. We have also shown that an experimental SEA model of a wheel with a tire is useful for developing low-noise tires[6]. There are, however, few reports on the application of SEA to tire.

As described above, the problems for tires are well known as multi-scale problems. Analysis from the micro perspective of tire vibration and noise issue is difficult and computationally intensive. Instead, we adopt a macroscopic perspective, using our method for reducing machinery noise and vibration. In mechanical engineering, the identification of input to the system is highly important to reduce the noise and vibration by addressing the source of the problem. Road-tire noise is classified roughly as either structure-borne or air-borne sound. Structure-borne sound radiates from the tire surface and its properties depend on the tire characteristics. Air-borne sound is generated in the air space between the tire and road surface and is classified as either resonance sound from the inner tube or stick–slip sound. Herein, we focus on structure-borne sound due to tire vibration. The force between the tire and road surface is the most important quantity here, but it is difficult to measure this force directly or to locate a force transducer on the tire surface, meaning that an alternative measurement method is required.

We propose a new method for identifying the power input from the road to a rotating tire. The method involves an experimental SEA model constructed for static conditions and measuring the vibrations of the tread and sidewall of a tire using three-axis accelerometers on each. We begin by introducing our ideas and associated research plan, whereupon we explain our proposed method. We then constructed a test bench which can directly measure interacting force between tire tread and roller (as road). The result of power input estimated with ESEA model and measured at the test bench is compared to demonstrate the validity of proposing method with ESEA.

2. ESTIMATION OF POWER INPUT BASED ON EXPERIMENTAL SEA

2.1 Statistical Energy Analysis

It is difficult to measure the force between the tire and the road, but the velocity is relatively easy to measure on the inner surface of tread. Therefore, we require a model that can estimate the power from only vibration measurements. Herein, we use a model based on experimental statistical energy analysis (ESEA).

SEA allows us to understand how vibration energy propagates in a complex structure. In SEA, the target system is assumed to comprise various subsystems, and the vibration energies of these subsystems are taken as the main variables. The power-balance equation for each subsystem is formulated as

$$\mathbf{P}_{in} = \omega \mathbf{L} \mathbf{E}\,, \tag{1}$$

$\mathbf{P}_{in}$ is the external power input, ω is the band center angular frequency, $\mathbf{L}$ is an SEA model, and $\mathbf{E}$ is the subsystem energy vector. From Eq. (1), we can identify the power inputs $\mathbf{P}_{in}$ by measuring the subsystem energies $\mathbf{E}$ and using the SEA model $\mathbf{L}$ of the tire. Thus, the power from the road to the tire can be estimated.

Furthermore, the SEA tire model can supply the vibration propagation on the tire and the exterior noise radiated from the tire vibration. The SEA tire model can also be used to analyze interior noise such as road noise. As for the structure-borne component of tire–road noise, the power input identified by this scheme can be used by road planners, road administrators, contractors, and manufacturers to assess how the choice of road surface influences traffic noise. However, it can also be used by car manufacturers to assess the road noise generated by automotive bodies and tires.

A rotating tire is deformed considerably where it is in contact with the road. This deformation may change how the tire vibrates compared to when it is rotating freely. However, it is difficult to consider the effects of such deformation, and we begin instead by assuming a tire rotating with constant speed and consider the time-averaged phenomenon by applying a fast Fourier transform (FFT) for data processing. Using a constant speed and an FFT makes any one part of the tire almost the same as all other parts. Under that assumption, we begin by using an ESEA model to measure the power input from the road to the tire.

2.2 Experimental SEA Model

As described in Section 2.1, we use the ESEA equation given by Eq. (1). In SEA modeling, the system is subdivided into various subsystems. We subdivide the tire into two subsystems as shown in Fig. 1: subsystem 1 is part of the sidewall and subsystem 2 is part of the tread. The SEA model based on Eq. (1) is

$$\begin{Bmatrix} P_1 \\ P_2 \end{Bmatrix} = \omega \begin{bmatrix} \eta_1 + \eta_{12} & -\eta_{21} \\ -\eta_{12} & \eta_2 + \eta_{21} \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \end{Bmatrix}, \tag{2}$$

where E_1 and P_1 are the subsystem energy and external input power, respectively, for subsystem 1, ω is the band center angular frequency, and η_1 and η_{12} are the internal loss factor (ILF) of subsystem 1 and the coupling loss factor (CLF) from subsystem 1 to subsystem 2, respectively.
The ILFs and CLFs are determined using Eqs. (3) and (4), respectively:

$$\eta_{ij} = \frac{E_{ji}/P_i}{\omega E_{ii}/P_i \; E_{jj}/P_j}, \quad \eta_i = \frac{1 - \omega \sum_{j \neq i}^{n} \left(\eta_{ij} E_{ii}/P_i - \eta_{ji} E_{ji}/P_i \right)}{\omega E_{ii}/P_i}, \qquad (3),\ (4)$$

where E_{ij} is the vibration energy of subsystem i when input power P_j is supplied to subsystem j by using an impulse hammer and so on. These values are determined using Eqs. (4) and (5), respectively:

$$E_{ji} = \frac{1}{2\omega^2} m_j \left| A_j \right|^2, \quad P_i = -\frac{1}{2\omega} \mathrm{Im}\left[F_{in} A_{in}^{*} \right], \qquad (5),\ (6)$$

where m_j and A_j are the mass and the total three-dimensional acceleration, respectively, of subsystem j, and F_{in} and A_{in} are the excitation force and the acceleration on the excitation point in the same direction as the excitation force, respectively.

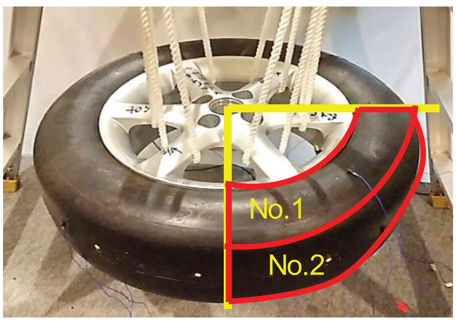


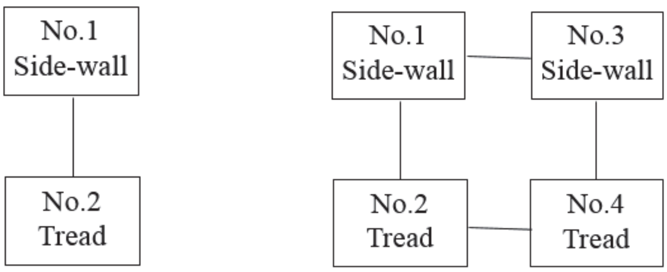
Figure 1 – Subdivision of tire into two subsystems, and test appearance for constructing experimental SEA model (ILF and CLF) under impact-hammer excitation.

2.3 Adequacy of ESEA Tire Model with Two Subsystems

Here, we consider whether using only two subsystems for the ESEA tire model is sufficient for evaluating the power input from the road to the tire.

Considering two subsystems as shown in Fig. 2 (a), the SEA equation (2) can be rewritten as Eq. (7) by using the power P_{di} dissipated from subsystem i and the net power Π_{ij} transmitted from subsystem i to subsystem j; this case is referred to as "one set," with one subsystem on the tread and one on the sidewall:

$$\begin{cases} P_1 = P_{d1} + \Pi_{12} \\ P_2 = P_{d2} + \Pi_{21} \end{cases}. \tag{7}$$



(a) One set with two subsystems (b) Two sets with four subsystems

Figure 2 – Subdivision of tire into (a) one set with two subsystems and (b) two sets with four subsystems to evaluate power input from road to tire.

Considering four subsystems as shown in Fig. 2 (b), the SEA equation of Eq. (2) can be rewritten as Eq. (8); this case is referred to as "two sets:"

$$\begin{cases} P_1 = P_{d1} + \Pi_{12} + \Pi_{13} \\ P_2 = P_{d2} + \Pi_{21} + \Pi_{24} \\ P_3 = P_{d3} + \Pi_{34} + \Pi_{31} \\ P_4 = P_{d4} + \Pi_{43} + \Pi_{42} \end{cases}. \tag{8}$$

Subsystems 1 and 3 on the sidewall can be the same subsystem, and likewise subsystem 2 can be regarded as being the same as subsystem 4. Therefore, the power inputs into subsystems 1 and 3 and subsystems 2 and 4 correspond to $P_1 = P_3$ and $P_2 = P_4$, respectively. The power dissipated in those subsystems is also considered to be equivalent, that is, $P_{d1} = P_{d3}$ and $P_{d2} = P_{d4}$. Moreover, the net transmitted powers are deemed equivalent, that is, $\Pi_{ij} = -\Pi_{ji}$, whereupon the relationships $\Pi_{12} = \Pi_{34}$ and $\Pi_{21} = \Pi_{43}$ are satisfied. Substituting all these equivalences into Eq. (8) leads to the same equations as Eq. (7) for the one-set case, namely,

$$\begin{cases} 2P_1 = 2\left(P_{d1} + \Pi_{12}\right) \\ 2P_2 = 2\left(P_{d2} + \Pi_{21}\right) \end{cases}. \tag{9}$$

Consequently, we can obtain an SEA equation with the two subsystems of one set when we have n sets, as

$$\begin{cases} nP_1 = n\left(P_{d1} + \Pi_{12}\right) \\ nP_2 = n\left(P_{d2} + \Pi_{21}\right) \end{cases}. \tag{10}$$

2.4 Comparison of Power Input Determined by Different Subsystem Sets

Here, we discuss the absolute values of the input power by describing the SEA method of the previous section. In constructing the ESEA tire model, we use the ILFs and CLFs of the two subsystems (one on the tread and one on the sidewall) as estimated using Eqs. (3) to (6) with data from impact-hammer tests. Eqs. (3) and (4) indicate that the loss factors are proportional to the subsystem mass, that is,

$$\eta_{ij} \propto \frac{E_{ji}}{E_{ii}E_{jj}} \propto \frac{1}{m_i}, \quad \eta_i \propto \frac{1}{E_i} \propto \frac{1}{m_i}. \tag{11), (12}$$

Meanwhile, Eq. (5) indicates that the energy of a subsystem is also proportional to its mass. Consequently, the power input is independent of subsystem mass, meaning that the evaluation of the power input from road to tire is independent of the number of tire subdivisions. Thus, we conclude that the power input from road to tire can be evaluated using the ESEA model with two subsystems, one on the tread and one on the sidewall.

3. EXPERIMENT

3.1 General Conditions

To examine validity of input power estimated with proposed method, bench test is carried out. An original test bench which can measure force and acceleration on tire tread is constructed; An impedance head is pressed on rolling tire as contact between road and tire; accelerations of side wall and tread is measured simultaneously. With this test bench, direct measured input power and estimated input power with experimental SEA model is compared. Detail of the test bench is shown in Fig. 3 (a) to (c). Front and side views of apparatus are shown in (a) and (b), and (c) is enlarged view around impedance head. A roller is installed between the tire and impedance head, so only vertical force on tire is measured and circumference force is minimized. Also, as a mark of measurement (or trigger), thin tape is pasted on the tire; when the tape run over the impedance head, impulsive input is measured. It enables that the contact patch is distinguished from others.

(a)Front view (b)Side view

(c)Input

Figure 3 – Apparatus: the test bench to measure input power on tire

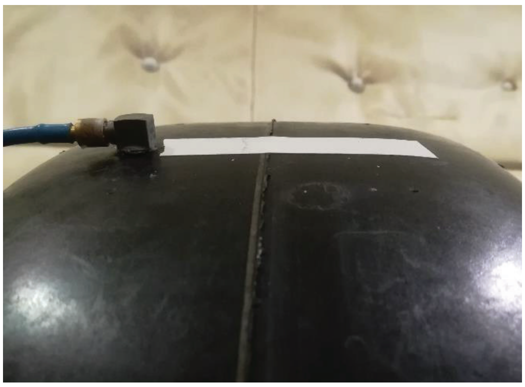


Figure 4 – A bump on the tire with thin tape; a trigger to synchronize input force and accelerations

3.2 Direct measurement of tire input power

First, direct measured accelerations on tread of 6.4 sec. are shown in Fig. 5. Three directions X, Y and Z axis each represents axial, tangential, and radial direction of tire respectively. Impulsive acceleration is observed when the tape on the tire tread run over the impedance head. Input power is calculated with force shown in Fig. 6 and acceleration on tire tread shown in Fig. 5.

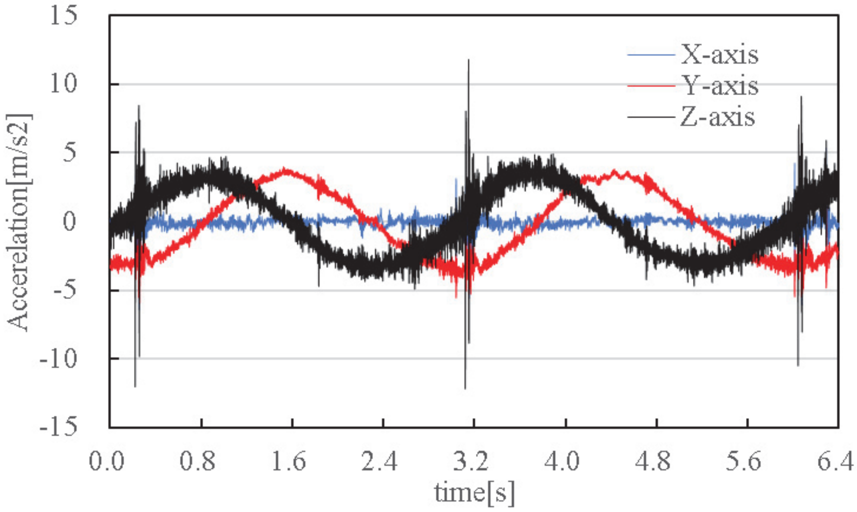


Figure 5 – Measured accelerations on tire tread

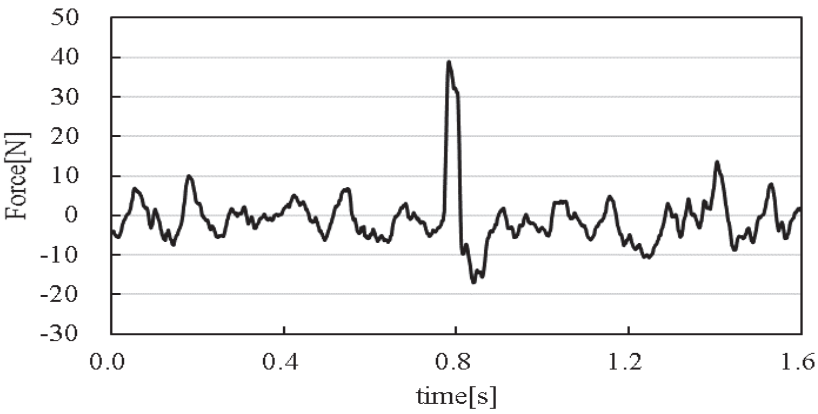


Figure 6 – Measured input force between roller and tire

3.3 Estimation of Input Power with Experimental SEA

3.3.1 Construction of ESEA model

As described in Section 2.2, we use the ESEA model that is referred to **L** in Eq. (1) or η_i and η_{ij} in Eqs. (3) and (4). The tire is subdivided into two subsystems as shown in Fig. 1, whereupon we model it using Eq. (2). The ESEA model comprises two ILFs for each subsystem and two CLFs between the two subsystems. As shown in Fig. 1, the tire was suspended horizontally from strings attached to the wheel spokes. Based on the ESEA model construction in Section 2.2, the loss factors were evaluated by measuring an impact-hammer force and accelerations. Fig. 8 shows the evaluated loss factors. We note that the loss factors depend on frequency in a way that can be classified into three frequency ranges, namely, below around 200 Hz, above 1 kHz, and the range in between. The difficulty of understanding the structure of vibration transmission is increased in the case of super-elastic or anisotropic material and when considering viscosity. These loss factors were confirmed by comparing the subsystem energies between those predicted by the constructed ESEA model and those measured by the hammer test for the case in which the input power is applied to subsystem 2 (i.e., the tread part).

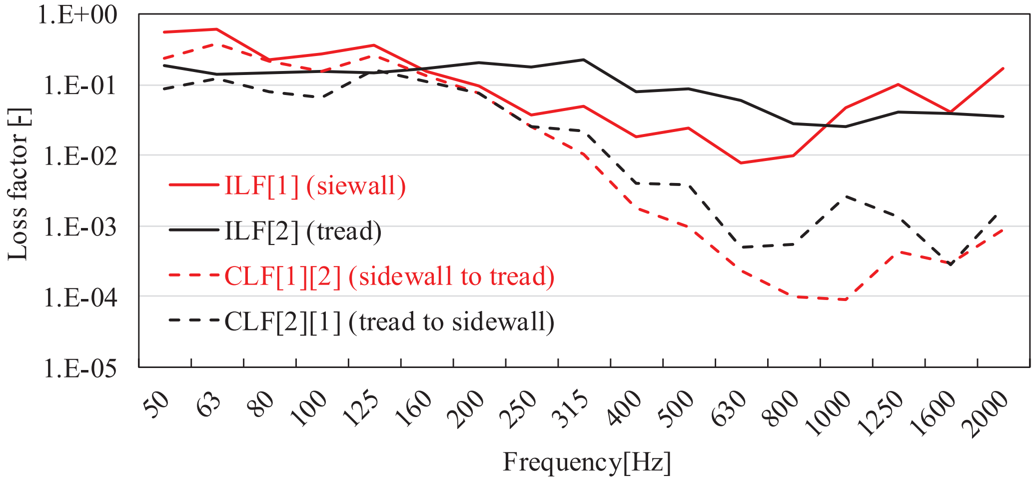


Figure 7 – Internal and coupling loss factors in experimental one-set SEA model: "1" indicates the subsystem on the tire sidewall, "2" indicates the subsystem on the tire tread.

3.3.2 Measurement of tire vibration on test bench

The vibrations on the tread and sidewall were measured by using two three-axial accelerometers on each rotating part. Examples of the measurement results are already shown in Fig. 6. The acceleration response in the radial z direction is the highest, followed by that in the tangential y direction; the axial response is the lowest because only simple rotation is present. The responses around the trailing edge are larger than those around the leading edge.

3.3.3 Measurement of subsystem energy

The subsystem energies **E** in Eq. (1) or E_1 and E_2 in Eq. (2) are calculated from the accelerations by using an FFT. As such, the subsystem energies depend on the signal for the FFT. For example, we can estimate the input power for the leading edge, contact patch, and trailing edge from time-series data. Herein, the data are measured for around 10 s of motion, and those data are analyzed to evaluate the subsystem energies. Examples of the results are shown in Fig. 8. The energy on the tread is larger than that on the sidewall.

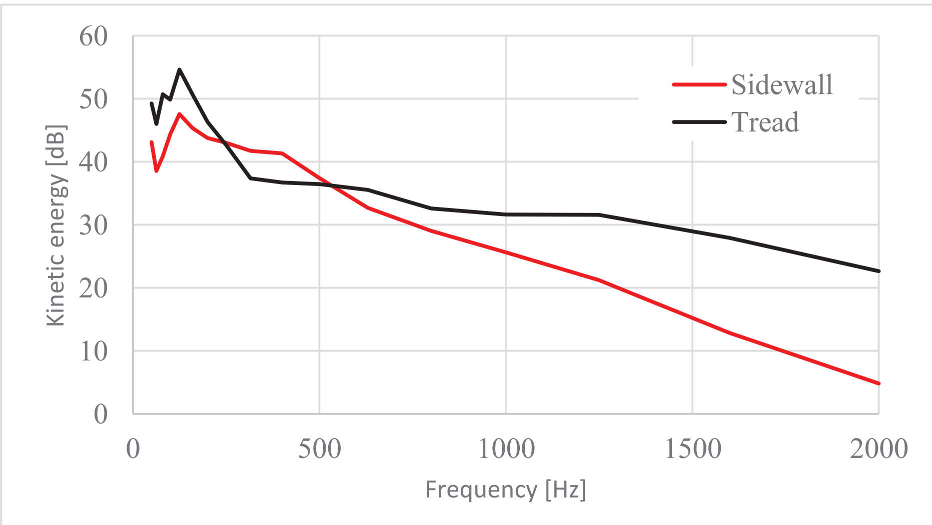


Figure 8 – Kinetic energy of each subsystem

3.3.4 Estimation of input power

The power input from the roller (road) to the tire can be identified from the ESEA model of a smooth tire, **L**, and the subsystem energy **E** under rotation based on Eq. (1) or (2). The identified input power is shown in following section with direct measurement (Fig. 9). The tire is contacted on the tread, and the power transmitted into the tread can be assessed.

3.4 Validity of Estimated Input Power with Experimental SEA

Comparison of input power estimated with ESEA and direct measurement is shown in Fig. 9.

Estimated input power is calculated with ESEA model matrix ***L*** derived from hammering test; and direct measurement is calculated by input force and acceleration on tire tread. Two lines show the same tendency and the difference is small especially in low frequency. It suggests that the estimation method based on ESEA is reasonable.

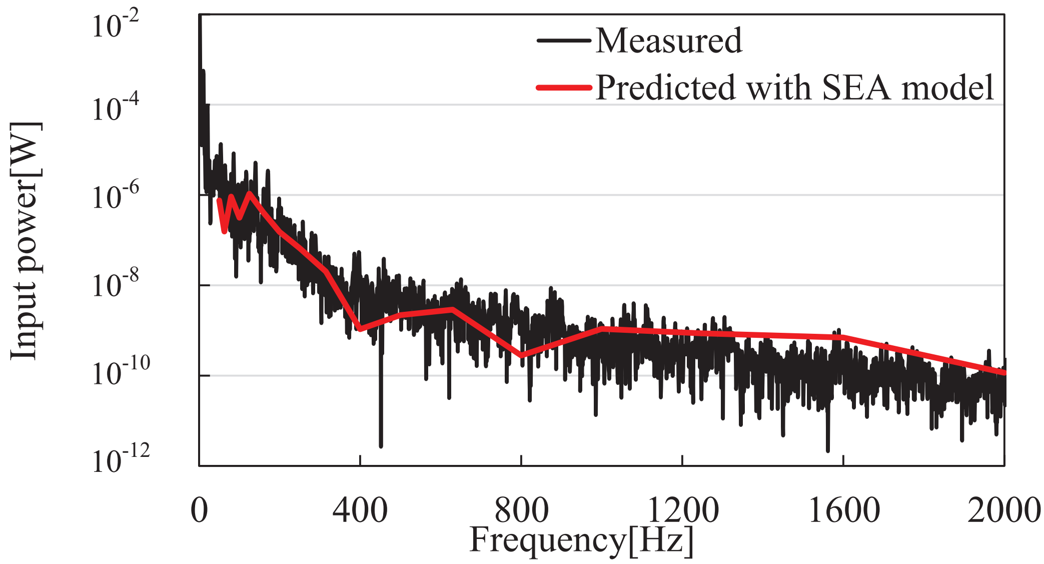


Figure 9 – Comparison of input power estimated with ESEA model and direct measured

4. CONCLUDING REMARKS

This paper discussed a new method for estimating input power from road to tire by using experimental SEA. The concluding remarks are as follows.

We introduced a research plan for using SEA to evaluate and predict the interior and exterior noise emitted from the interaction between tire and road from a global perspective. In this paper, we focused on identifying the power input from road to tire by using experimental SEA. The method for estimating input power may also be used to label tires and road surfaces.

We showed that the input power can be estimated by using the vibration responses of each tread and sidewall obtained by three-axis accelerometers during rotation.

The method was used to estimate the power input and validity was shown with a test bench. As a result, it suggests that the estimation method based on ESEA is reasonable. The results confirmed that the identified input powers are validated in quantitative manner.

REFERENCES

1. COMMISSION DIRECTIVE (EU) 2015/996, establishing common noise assessment methods according to Directive 2002/49/EC of the European Parliament and of the Council, (2015).
2. Lyon, R. H. and DeJong, R. G., Theory and Application of Statistical Energy Analysis, 2nd ed., RH Lyon Corp, (1998).
3. Miyama Takeshi, Hiroki Nakamura, Atsuko Miyazaki and Toru Yamazaki, Low-Vibration Design of Panel Structure by Using Vibration Energy Propagation Analysis, Proceedings of the INTER-NOISE 2016, 2495-2505, (2016).
4. T. Miyama, H. Nakamura and T. Yamazaki, Structural Design Implementation By Structural Intensity Analysis, Proceedings of Noise and vibration emerging methods, (2018).
5. T.Yamazaki, K.Kuroda and S.Ohno, A structural design process for reducing structure-borne sound on machinery using SEA, Proceedings of International Conference on Noise and Vibration Engineering, isma2008_0468.pdf, (2008).
6. Kameyama Yohei, Hiroki Nakamura, Ryuya Nakajima and Toru Yamazaki, Correlation between tire noise level and CLF of experimental SEA, Proceedings of the INTER-NOISE 2016, 2468-2476, (2016).