

Development of Virtual Road Wheel Input Forces for Belgian Ground

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ABSTRACT

Numerical durability analysis is the only approach that can be used to assess the durability of vehicles in early stages of development. In these stages, where there are no physical prototypes available, the road wheel forces (or spindle forces) for durability testing on Belgian PG (Proving Ground) must be predicted by VPG (Virtual Proving Ground) or derived from the measured forces of predecessor vehicles. In addition, the tuning parts and geometry are not fixed at these stages. This results in the variation of spindle forces during the development stages. Therefore, it is not reasonable to choose the forces predicted at a specific tuning condition as standard forces. It is more reasonable to determine the standard forces stochastically using the DB of the measured forces of predecessor vehicles.

The spindle forces measured or predicted on Belgian PG are typically stationary random. To treat the force signals stochastically, it is necessary that the forces are expressed in analytic formulation. Without analytic expression, it may be impossible to reproduce the forces reasonably.

In this paper, we propose a methodology to reproduce the spindle forces measured on Belgian PG as an analytic formulation with sufficient accuracy. In addition, the coefficient of the analytic format can be treated stochastically. Using the coefficients, we can reproduce standard forces to be used for numerical durability testing. The effectiveness of the methodology is verified by comparing the results of the fatigue lives of suspension parts of A-segment vehicles using the standard forces with those using the measured forces.

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INTRODUCTION

Most research on numerical durability analysis is focused on the prediction of spindle forces by VPG or other hybrid methods [1, 2, 3] or parametric studies on the spindle forces with changing geometry or tuning parts. In the early stages of development, it is impossible to predict the final geometry and tuning conditions exactly. Variation of spindle forces is inevitable during vehicle development stages because of the changing geometry and tuning parts to balance the vehicle's performance.

In addition, several subsystems or chassis parts are commonly used in carry-over vehicles or other vehicles on the same platform recently. In the viewpoint of the subsystem or the parts, the spindle forces being subjected are not unique. The prediction of spindle forces at a specific state is not as

important in the viewpoint of developing parts or subsystems of vehicles. The more important point is the variation of the spindle forces during development stages and how to reasonably determine standard spindle forces using statistical approach on the forces.

Two approaches exist to study the variation of spindle forces of vehicles in the same segmentation. One is using the DB of the measured forces of predecessor vehicles and the other is using the forces predicted by VPG for vehicles with various geometry and tuning conditions.

It is not easy to use the DB of predicted forces in the viewpoint of selecting of vehicle geometry and tuning conditions properly, and it also requires many MBD simulations. In addition, it is a complex problem to choose a specific tuning condition as

standard because the severity of pseudo-damage of each force component at a specific condition is independent and different from each other.

Thus, we tried the first approach, using the DB of measured forces of predecessor vehicles. The remaining problem is how to treat the random forces. If the forces can be expressed as an analytic formulation, typically the coefficients of the formulation can be treated stochastically and the standard forces can be easily reproduced by the analytic formulation.

We searched for an analytic approach to reproducing the spindle forces generated on traveling Belgian Blocks but we were unsuccessful. The reasons are as follows:

1. The forces have strong non-linear peaks that are difficult to express analytically.
2. Some forces are asymmetric so they cannot be expressed by simple Fourier series.
3. The most difficulties come from attempting to define the phase of each force component. The spindle forces typically consist of 20 channels except for driving moments. It is very difficult to define the phases of all the components in a general rule.

How to solve those difficulties is following.

ANALYTIC REPRODUCTION OF ROAD WHEEL FORCES GENERATED BY TRAVELLING ON BELGIAN PG

Road wheel forces generated by travelling on Belgian PG as shown in [Figure 1](#) are stationary random in general. For statistical analysis, forces in frequency domain are preferred to those in time domain because of the randomness of them. Using Fourier's series such as [\(1\)](#), we can reproduce the force analytically.

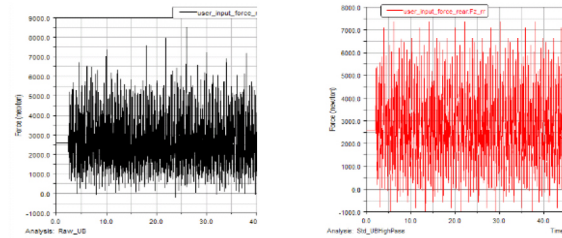
$$F_{eqv}(t) = SF \left(\sum_{i=1}^n A_i \times \sin(\omega_i t + \phi_i) \right) \quad (1)$$

SF is a scaling factor introduced to make the damage of $F_{eqv}(t)$ equal to the measured force we need to reproduce. It is calculated using the finite number of frequencies.



Figure 1. A typical road wheel force generated by traveling on Belgian PG.

However, a specific force such as a vertical wheel in [Figure 2](#) is asymmetric and also has some irregular peaks. General Fourier's series such as [equation \(1\)](#) cannot reproduce the properties exactly, so we introduce a new nonlinear amplification function, $NLA(t)$ in [equation \(2\)](#).



(a) A measured force

(b) A simple equivalent

Figure 2. Comparison of a measured force with simple equivalent force generated by general Fourier's series.

The modified force can be expressed as

$$F_{eqv}^{NL}(t) = SF \left(NLA(t) \sum_{i=1}^n A_i \times \sin(\omega_i t + \phi_i) \right) \quad (2)$$

where $NLA(t)$ is an n^{th} order polynomial function expressed as [equation \(3\)](#).

$$\begin{aligned} NLA(t) &= \left(\frac{1}{a_u} - 1 \right) R_u(t)^n + 1, & F_{eqv}(t) &\geq 0 \\ &= \left(\frac{1}{a_l} - 1 \right) R_l(t)^n + 1, & F_{eqv}(t) < 0 \end{aligned} \quad (3)$$

a_u , a_l , $R_u(t)$ and $R_l(t)$ are determined by Crestor factor, the maximum, the minimum, and RMS(Root Mean Square) of the measured force. The details are omitted.

[Figure 3](#) shows that the reproduced force modified by $NLA(t)$ is more similar with the measured force than the previous force.

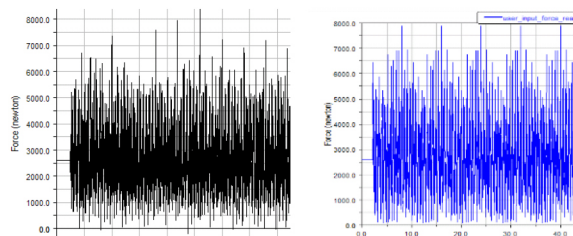


Figure 3. Comparison of the reproduced forces after modification by a non-linear amplification function, $NLA(t)$.

[Figure 4](#) shows typical histories of the vertical direction force component, F_z and the longitudinal direction moment, M_x of an A-segment vehicle. The red line indicates F_z and blue line M_x . The components have a phase difference of 180 degrees from each other. This correlation is also effective in all the vehicles of other segments.

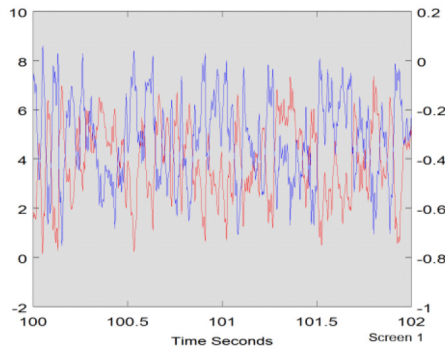


Figure 4. The phase characteristics between Fx and Mz in time domain.

Figure 5 shows the above phase relationship as another plot. The X and Y coordinates of a point in the plot represent the value of Fz and Mz, respectively, at a time. We call it a phase correlation plot. The negative inclination of the plot indicates that a 180 degrees phase difference exists between the components. If the inclination is positive then the phase difference between the components becomes 0. This plot is very useful to study the phase difference between two arbitrary components of road wheel forces.

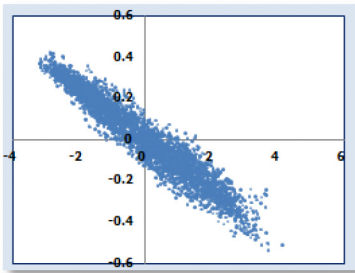


Figure 5. The phase characteristics between Fx and Mz expressed in a phase correlation plot.

Figure 6 shows a typical frequency characteristic of rear wheel forces of an A-segment vehicle. The frequency characteristics of Mz are very similar with those of Fx and the frequency characteristics of Mx are also similar with those of Fz. These phase and frequency response characteristics are commonly shown in all types of vehicles.

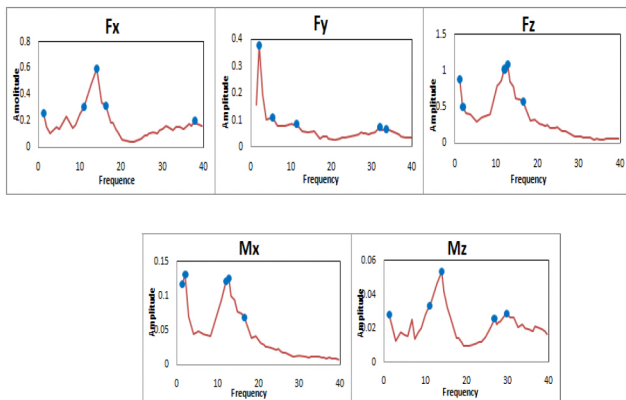


Figure 6. Typical frequency spectrums of rear wheel forces of an A-segment vehicle.

In general, it is not difficult to make an analytically reproduced force with the same pseudo-damage for just one component of a measured force. In this case, the phase information has little effect on pseudo-damage. However, each road wheel has 5 force components (because driving moment is typically negligible) and inherent phase relationships exist among the components. All the components, totally 20 components, are to be reproduced considering the inherent phase relationships in order to represent vehicle behavior correctly.

In this study, we analyzed the phase relationship between two arbitrary components of all the wheel forces of an A-segment vehicle and then found the following common phase relationships. In addition, these relationships are also effective for other vehicles with different types of suspension in the other segments.

We define the phases of front wheel forces as the following equations (3), (4), (5), (6), (7) for left-hand side forces. These definitions are also effective in RH side forces but the direction of $\delta(i)$ in equation (3) and those of $\gamma(i)$ in equation (5) and (7) are opposite.

$$\phi_i^{FR}(Fz) = \theta(Fz_LH) - \delta(i) = \theta_i(Fz_LH) \quad (3)$$

$$\phi_i^{FR}(Fx) = \theta_i(Fz_LH) + \alpha(Fx_LH) \quad (4)$$

$$\phi_i^{FR}(Fy) = \theta(Fy_LH) - \gamma(i) \quad (5)$$

$$\phi_i^{FR}(Mx) = \theta_i(Fz_LH) + \alpha(Mx_LH) \quad (6)$$

$$\phi_i^{FR}(Mz) = \theta_i(Fz_LH) + \alpha(Mz_LH) + \gamma(i) \quad (7)$$

Subscript, i , indicates the i^{th} frequency used to reproduce the real force component. We set the phase of Fz, θ as reference and $\alpha(A)$ indicates the phase difference between Fz and force component A. The phase of Fy is treated as another independent component. The phase values are independent of the suspension type used. $\gamma(i)$ is a factor that represents the correlation of Fy of LH and RH. $\delta(i)$ is a parameter for the relative displacement between RH wheel and LH wheel. They depend on the type of suspension but the absolute values of them are quite small, less than 10 degrees in general.

$$\phi_i^{RR}(Fz) = \theta_i(Fz_LH) + \beta(i) \quad (8)$$

$$\phi_i^{RR}(Fz) = \theta_i(Fz_LH) + \alpha(Fx_LH) + \beta(i) \quad (9)$$

$$\phi_i(Fy) = \theta(Fy_LH) + \gamma(i) \quad (10)$$