

Effect of Terrain Roughness on the Roll and Yaw Directional Stability of an Articulated Frame Steer Vehicle

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ABSTRACT

Compared to the vehicles with conventional steering, the articulated frame steer vehicles (ASV) are known to exhibit lower directional and roll stability limits. Furthermore, the tire interactions with relatively rough terrains could adversely affect the directional and roll stability limits of an ASV due to terrain-induced variations in the vertical and lateral tire forces. It may thus be desirable to assess the dynamic safety of ASVs in terms of their directional control and stability limits while operating on different terrains. The effects of terrain roughness on the directional stability limits of an ASV are investigated through simulations of a comprehensive three-dimensional model of the vehicle with and without a rear axle suspension. The model incorporates a torsio-elastic rear axle suspension, a kineto-dynamic model of the frame steering struts and equivalent random profiles of different undeformable terrains together with coherence between the two tracks profiles. The simulations are performed to determine the stability limits of the ASV models while operating on different terrains, namely: a perfectly smooth surface, plowed field, pasture, gravel road, and the MVEE random course. The directional stability limits are defined in terms of the static and dynamic rollover thresholds, rearward amplification ratio, and critical speed corresponding to snaking instability under steady and transient steering inputs. The results suggest that the tire interactions with the rough terrains affect the stability limits of both the unsuspended and suspended vehicles in a highly adverse manner. The suspended vehicle responses, however, show less sensitivity to variations in the road roughness profile.

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INTRODUCTION

Owing to their enhanced mobility and maneuverability on off-road terrains, articulated frame steer vehicles (ASV) are widely used in the construction, forestry, agricultural and mining sectors. These vehicles exhibit relatively low roll and yaw stability limits, particularly greater snaking tendencies, which is mainly attributed to the high mass center and large variations in the vehicle load coupled with kinematics and dynamics of the steering system [1, 2, 3, 4]. Moreover, ASVs are usually unsuspended and directly suspended on large diameter soft tires to realize improved traction and ride performance during off-road operations. Using large diameter soft tires, however, provide lower effective tire roll stiffness and track width, which result in lower roll stability limit of

the vehicle, particularly when operating on paved roads at relatively higher speeds.

In spite of lower stability limits, the roll and yaw stability of off-road vehicles have been investigated only in very few studies considering very simple models while the extensive studies on heavy road vehicles have evolved into not only comprehensive simulation models but also a series of directional performance measures [6, 7, 8, 9, 10, 11, 12, 13, 14]. This may be partly attributed to lower operating speed of off-road vehicle, which could reduce the possibility of vehicle directional instability. The ASVs, however, also operate on paved roads at relatively higher speeds and there are still increasing demands on the higher speed ASVs (above 60km/h) for both on- and off-road operations when the directional stability limits would be of concern. In addition, roll instability may occur even at low speeds due to greater

lateral load transfers and sprung mass roll displacement moment attributed to uneven sinkage of left and right wheels on deformable terrains. Moreover, the lateral displacement of the ASV cg location, when the vehicle is steered, could yield lower directional stability of the vehicle even at low speed [7].

The few reported studies on directional stability of off-road vehicles are mostly limited to static roll stability analysis while those related to ASVs mostly focus on yaw stability of the vehicle considering linear 3-DOF yaw-plane models. In these studies, the steering system has been characterized by equivalent linear torsional stiffness and damping elements, while the kinematic properties of the steering mechanism are entirely ignored [1, 2, 3, 4, 15]. Pazooki et al. performed comprehensive analysis of the frame steering mechanism considering the kineto-dynamic properties of the steering system [5]. The study showed the considerable effects of the kineto-dynamic properties of the steering system on the effective damping at the articulation joint and thus lateral stability of the vehicle.

The above studies, however, have invariably investigated the directional stability limits of ASVs assuming negligible contributions of the terrain roughness while, unlike the heavy road vehicles, the dynamic interactions of tires with off-road terrains could cause substantially higher terrain-induced variations in the vertical and lateral tire forces, and thereby considerably affect the vehicle directional performance. Moreover, the tires' interactions with rough terrains could yield greater vehicle roll and lateral load transfer responses, and thereby affect the roll as well as yaw stability limits in a highly adverse manner. It is thus desirable to assess the dynamic safety of ASVs in terms of their stability limits while operating on different terrains. Comprehensive analyses of the directional properties of ASVs, however, require complete three-dimensional simulation models incorporating kineto-dynamics of the frame steering system and dynamic tire interactions with random off-road terrains. Such models could provide important design guidelines for the suspension and steering mechanism for realizing improved directional performance of the vehicle.

In this study, the effects of terrain roughness on the directional stability limits of an ASV are investigated through simulations of a comprehensive three-dimensional model of the vehicle with and without a rear axle suspension. The model incorporates a torsio-elastic rear axle suspension, a kineto-dynamic model of the frame steering struts and equivalent random profiles of different undeformable terrains together with coherence between the two tracks profiles. The proposed model is validated on the basis of the field-measured data for a 90° right-turn maneuver. The yaw and roll dynamic responses of the vehicle are evaluated under steady and transient steering inputs and their sensitivity to variations in the terrain roughness are further presented.

DEVELOPMENT OF THE 3-DIMENSIONAL VEHICLE DYNAMICS MODEL

An integrated three-dimensional model of an unsuspended and suspended ASV was developed to assess the influence of terrain roughness on the directional performance of the vehicle. The suspended vehicle model incorporates a rear-axle torsio-elastic suspension that has shown substantial reductions in the terrain-induced ride vibrations, while providing high effective roll stiffness [15]. The torsio-elastic suspension is introduced at the rear axle of the vehicle by eliminating the rigid coupling between the chassis and the rear axle, while providing high effective roll stiffness due to restoring moment capability of the torsional shafts [15, 16, 26]. In other words, high effective roll stiffness and kinematic effect of the torsio-elastic suspension provide higher roll stability of the vehicle compared to linear beam axle suspensions [16]. For the unsuspended ASV, each unit together with the axle is considered as a rigid body with six-degrees-of-freedom (x -longitudinal; y -lateral; z -vertical; Φ -roll; Θ -pitch; and ψ -yaw). Figure 1 illustrates the unsuspended ASV model in the pitch, roll and yaw planes. For the suspended vehicle, the rear axle is modeled as a rigid body with three-DOF: lateral, y_j ; roll, Φ_j ; and vertical z_j (Fig. 2). Each suspension unit comprises two elastic torsion bars, reinforced with a steel rod, coupling the sprung and unsprung units. The coupler link is modeled as a rigid body with three-DOF: lateral, y_j ; roll, Φ_j ; and vertical z_j , where $j=L, R$ denotes the left- and right-suspension units. The coupled equations of motion for the front ($i = f$) and rear ($i = r$) units are derived considering respective body-fixed coordinate systems (i_{si}, j_{si}, k_{si} ; $i = f, r$), as shown in Fig. 1, and expressed as:

Longitudinal:

$$m_{si}\dot{u}_{si} - m_{si}(r_{si}v_{si} - q_{si}w_{si}) = F_{xTi} + F_{xSr} + F_{xHi} + F_{xCi} + F_{xGi}$$

Lateral:

$$m_{si}\dot{v}_{si} - m_{si}(p_{si}w_{si} - r_{si}u_{si}) = F_{yTi} + F_{ySr} + F_{yHi} + F_{yCi} + F_{yGi}$$

Vertical:

$$m_{si}\dot{w}_{si} - m_{si}(q_{si}u_{si} - p_{si}v_{si}) = F_{zTi} + F_{zSr} + F_{zCi} + F_{zGi}$$

Roll:

$$I_{xxsi}\dot{p}_{si} - (I_{yy_{si}} - I_{zz_{si}})q_{si}r_{si} = M_{xTi} + M_{xHi} + M_{xSr} + M_{xCi}$$

Pitch:

$$I_{yy_{si}}\dot{q}_{si} - (I_{zz_{si}} - I_{xx_{si}})p_{si}r_{si} = M_{yTi} + M_{yHi} + M_{ySr} + M_{yCi}$$

Yaw:

$$I_{zz_{si}}\dot{r}_{si} - (I_{xx_{si}} - I_{yy_{si}})q_{si}p_{si} = M_{zTi} + M_{zHi} + M_{zSr}$$

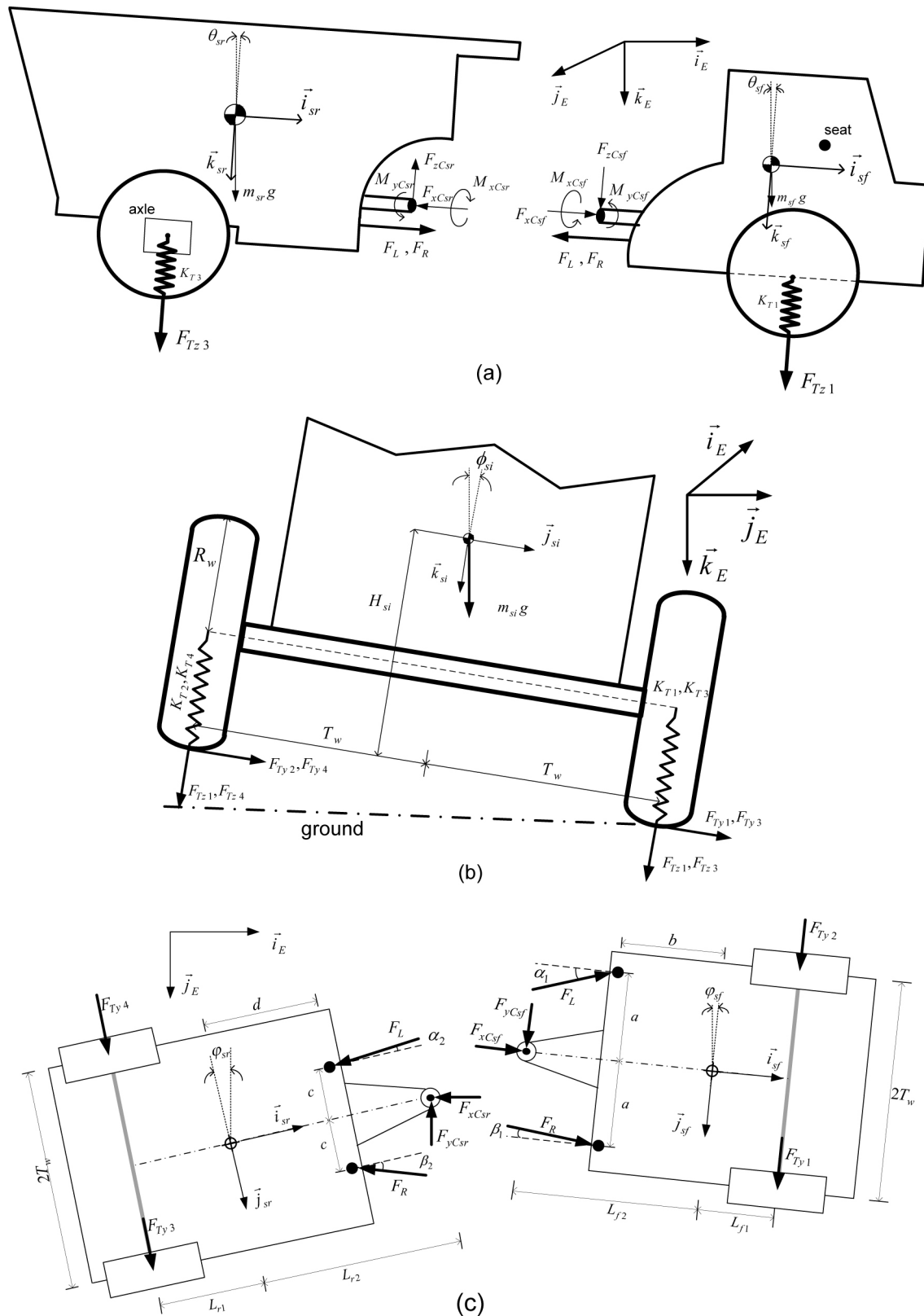


Fig. 1. Schematic representation of the integrated ride and handling model of the vehicle: (a) pitch-plane; (b) roll-plane; and (c) yaw plane.

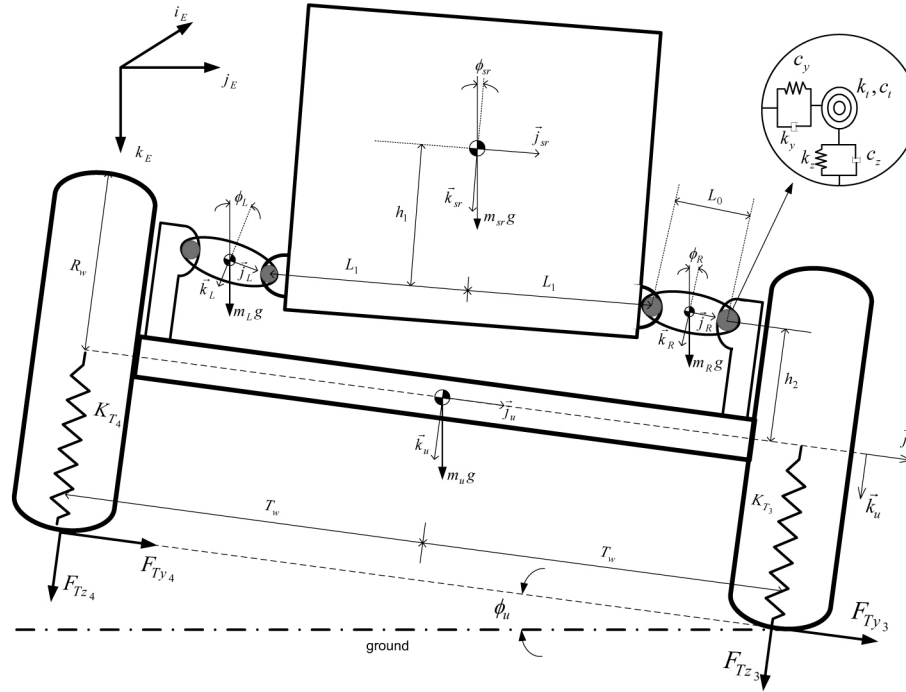


Figure 2. Roll plane model of rear unit with a torsio-elastic suspension (rear view)

where m_{si} is mass, and I_{xxsi} , $I_{yy_{si}}$ and $I_{zz_{si}}$ are the mass moments of inertia about the fixed axis (i_{si} , j_{si} , k_{si}) of unit i ($i = f, r$), respectively. These represent the total values for the rear unit of the unsprung model. (u_{si} , v_{si} , w_{si}) are the translational velocities along the corresponding body-fixed axis k ($k = x, y, z$) of unit i , and (p_{si} , q_{si} , r_{si}) are the corresponding roll, pitch and yaw velocities. $F_{kTf} = F_{kTl} + F_{kT2}$ and $F_{kTr} = F_{kT3} + F_{kT4}$ are the total tire forces acting on the front and rear unit along the body-fixed axis k ($k = x, y, z$), respectively, and M_{kTi} are the corresponding moments, while F_{kTl} is the force developed by tire l ($l = 1, \dots, 4$). (F_{xHi} and F_{yHi}) are the steering strut forces imposed on unit i ($i = f, r$) along the respective body-fixed x - and y -axis, respectively, and M_{kHi} are the corresponding moments about the body-fixed axis k ($k = x, y, z$). F_{kSr} and M_{kSr} are the suspension forces and moments acting on the rear unit, when present, along the axis k , and F_{kGi} are the components due to the gravity force of unit. The articulation constraint forces and moments acting on i ($i = f, r$) unit along axis k are represented by F_{kCi} and M_{kCi} , respectively.

For the suspended ASV, the equations of motion for the unsprung mass are derived using the body-fixed coordinate system (i_u , j_u , k_u) attached to the center of mass (cg) of the rear axle, while those of the linkages are formulated with respect to an axis system fixed to center of each linkage (i_j , j_j , k_j); $j = L, R$.

Unsprung mass:

$$\begin{aligned} m_u \dot{v}_u - m_u (p_u w_u) &= F_{yTu} + F_{ySu} + F_{yGu} \\ m_u \dot{w}_u + m_u (p_u v_u) &= F_{zTu} + F_{zSu} + F_{zGu} \\ I_{xxu} \dot{p}_u &= M_{xTu} + M_{xSu} \end{aligned}$$

(2)

Suspension linkage masses:

$$\begin{aligned} m_j \dot{v}_j - m_j (p_j w_j) &= F_{ySj} + F_{yGj} \\ m_j \dot{w}_j + m_j (p_j v_j) &= F_{zSj} + F_{zGj} \\ I_{xxj} \dot{p}_j &= M_{xSj} \end{aligned} \quad (j = R, L)$$

(3)

In the above, m_u is the unsprung mass and I_{xxu} is its roll mass moment of inertia, and, v_u , w_u and p_u are the lateral, vertical and roll velocities, respectively. F_{yTu} and F_{zTu} are the total forces due to rear tires along the y - and z -axis fixed to center of the unsprung mass, respectively, and M_{xTu} is the corresponding roll moment. F_{ySu} and F_{zSu} are the total suspension forces acting on the unsprung mass along the y - and z -axis due to the left- and right-suspension, respectively, and M_{xSu} is the resulting roll moment. F_{yGu} , F_{zGu} , and F_{yGj} , F_{zGj} are the components of the gravity force along the y - and z -axis due to unsprung mass and the linkages, respectively. m_j and I_{xxj} are the mass and roll mass moment of inertia of the suspension link j , $j = L, R$, respectively. v_j , w_j , and p_j are the lateral, vertical and roll velocities of the link j , respectively, F_{ySj} , F_{zSj} and M_{xSj} are the total suspension

forces and moment due to suspension linkage j ($j=L, R$) acting along y -, z - and x -axis of the coordinate system fixed to the linkage mass. The forces and moments developed due to kineto-dynamics of the articulated steering mechanism, constraint and the lateral tire forces are briefly described in [Appendix I](#) together with the vehicle model parameters. The forces developed by the suspension and vertical compliance of the tire have been presented in [\[16\]](#).

Assuming small side-slip angles of tires, constant forward speed of the front unit and that the traction force developed is balanced by the motion resistances, the equation of motion along the x -axis may be omitted. The vehicle attitude and trajectory are defined with respect to a fixed inertial coordinate system (i_E, j_E, k_E), as shown in [Figs. 1 and 2](#). The relationships between the body-fixed and the inertial axis systems are obtained using the corresponding Euler angles, which define yaw (φ), pitch (θ), and roll (ϕ) rotations of each rigid body with respect to the inertial axis system [\[16, 17\]](#).

METHOD OF ANALYSIS

The equations of motion for the vehicle models are solved to determine directional responses of the unsuspended and suspended articulated dump truck to steady and transient steering inputs in the presence of terrain excitations arising from two tracks of different road profiles. The simulation parameters corresponding to a small-size fully loaded articulated dump truck are presented in [Table 1](#), which were mostly obtained from manufacturer specifications and personal communications [\[18\]](#).

Terrain Profiles

The characterization of off-road terrain roughness is quite complex since it varies with the local conditions of a region, soil properties and the number of vehicle passes [\[19, 20, 21\]](#). The terrain roughness properties of various undeformable off-road terrains have also been characterized and expressed by the following power relation [\[22, 23, 24, 25\]](#):

$$G_Z(\Omega) = \alpha_r \Omega^{-\beta}; \quad (5)$$

where G_Z is spatial power spectral density (PSD) of the terrain roughness, and α_r and β are the roughness coefficients and wavinesses, respectively, which are generally identified from the measured terrain profiles.

The effects of the terrain roughness on the roll and directional stability limits of the articulated dump truck are investigated considering a perfectly smooth road and four different terrain profiles, namely plowed field, pasture, MVEE (Military Vehicle Engineering & Establishment) test course, and a gravel road. The roughness PSD together with the power relation parameters of the selected terrains are compared in [Fig. 3](#) [\[22, 24, 25\]](#). The comparisons suggest higher roughness coefficient of the plowed field compared to the other profiles, while the roughness gravel road is lowest. The roughness of both the pasture and MVEE course are

quite comparable. The waviness of the plowed field is identical to pasture, which is also evident in [Fig. 3](#).

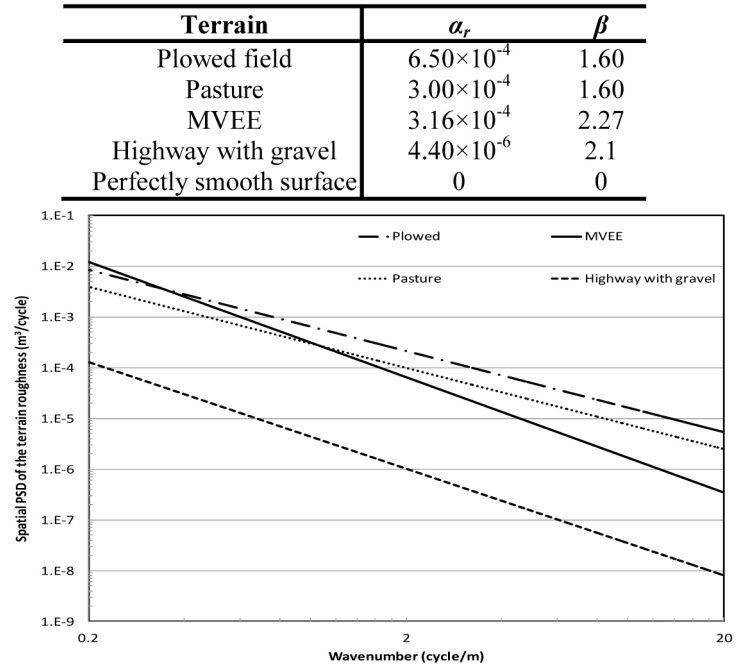


Figure 3. Comparisons of roughness PSD of selected terrain profiles [\[22, 24, 25\]](#)

As, it has been explained in more detail in [\[26\]](#), the time histories of the road profiles was estimated from the regression model in [Eq. \(5\)](#). For this purpose, the power relation in [Eq. \(5\)](#) is described by a frequency response function $Q(\omega)$ and the time history of the roughness profile was synthesized by applying white noise signals $r(t)$ to this frequency response function, as illustrated in [Fig. 4](#). During off-road operations, the two vehicle tracks are invariably subjected to different terrain elevations that contribute to roll motions and thus directional stability performance of the vehicle, which is known to be substantial for off-road terrains. The roughness profiles of the two tracks can be estimated by assuming a coherence function describing the linear dependence of two random profiles. A coherency function, $\gamma_{LR}^2(\omega)$ is thus considered for estimating the roughness of the two parallel terrain tracks, such that:

$$\gamma_{LR}^2(\omega) = \begin{cases} 1 - 0.9 \left(\frac{\omega}{2\pi} \right) & ; \omega \leq \omega_1 \\ 0.1 & ; \omega > \omega_1 \end{cases} \quad (6)$$

where the transition frequency ω_1 is assumed to be near 1 Hz for off-road terrains. The roughness profiles of the two tire-tracks were estimated assuming the above coherency function between the two tracks, as illustrated in [Fig. 4](#) [\[26\]](#). The obtained time-history of the left and right tracks of the road profiles are then applied to obtain the tires forces, as