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The verification and demonstration of a unique course-profile-measurement methodology

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ABSTRACT

This paper presents an experimental methodology for regeneration of course profiles, with tire acceleration and speed, suspension force and pitch data collected from an instrumented trailer wheel running over the course profile to be identified. The collected data is used to derive the course profile as a function of time, while the speed data is used to map the ground elevation data from a time domain into a spatial domain. To verify the course re-generating rationale, the required test data was simulated with the data extracted from a trailer model running over selected course profiles. The regenerated course profiles are then compared against those used as the inputs to the trailer model, demonstrating the feasibility of using the methodology to regenerate course profiles which statistically align with real-world course profiles. The methodology may be used to develop the inputs statistically equivalent to realistic course profiles as needed in dynamic simulation of terrain-vehicle systems.

INTRODUCTION

Given that the excitations arising from ground roughness play a key role in the performance analysis of light armored vehicle systems, the need to use realistic ground inputs in dynamic modeling of terrain-vehicle systems is critically important. With today's advanced data acquisition technology, it is possible in reality to measure various off-road ground profiles at high degrees of precision. An extensive literature review, however, reveals that the majority of the reported course-profile-measurement techniques did not turn out to be as cost-effective and time efficient as expected. While certain techniques were reported to derive ground profiles based upon the data collected by an instrumented vehicle over different terrains, the accuracy and efficiency, as well as limitations of the approach used, have yet to be fully demonstrated and verified under specific ground inputs and operational conditions. A successful ground-profile-measurement technique should be based upon a fully verified rationale from both experimental and analytical perspectives.

LITERATURE REVIEW

Off-road profile measurement remains a challenging task in comparison to paved surface measurement, since the off-road profiles are generally more time-varying than paved-roads, leading to greater vehicle excitations and thus more severe vibration environments that may significantly deteriorate the quality of the test data collected. In addition, it is difficult to maintain a constant speed when traveling over extreme terrains and the dynamics of the suspension will be excited well beyond the points of small angle approximations and linearity assumptions [1]. A number of different methods, in use worldwide, involve either measuring the ground roughness directly with profile-meters [2-3] or deriving the ground profile from measured vehicle response to road roughness e.g., using Dynamic Force Measurement Vehicle (DFMV) developed by the Nevada Automotive Test Center [4-5]. There are also reports addressing specific profiling methods [6-9]. While a variety of profiling methods are available, a simple cost-effective yet efficient methodology remains to be investigated and demonstrated under specific inputs.

This paper presents a unique experimental approach conceptually for regenerating longitudinal course profiles based on inputs from an instrumented trailer wheel running over course profiles to be identified. The efficiency and accuracy of the approach is demonstrated with simulation results from the trailer model under selected course inputs.

METHODOLOGY

An Adams model of a two-wheel trailer pulled by a four-wheel vehicle through a linkage frame, as shown in Figure 1 and Figure 2, was created to simulate the profiling hardware used in test scenarios. The trailer tires were designed with a significantly smaller radius in comparison to those of the tractor tires to ensure the measurement of short wave-length components of the profile. The tractor drives along a straight flat road, pulling the trailer run over the course profile to be regenerated. Compared to the method using DFMV, the geometric and stiffness characteristics of the trailer wheels can be designed solely for the purpose of data acquisition, with the effect from suspension dynamics of the tractor completely isolated from the instrumented trailer wheel (particularly in the simulation process). The sprung mass is supported by the suspension over the trailer wheel, which allows the translational and rotational movements between sprung mass and trailer wheel. The tire acceleration and speed, suspension force and pitch angular displacement of sprung mass of the trailer wheel are extracted from the Adams model (or measured by sensors in real profiling tests) in order to regenerate the course profile.

The sprung mass, suspension characteristics and tire stiffness of the trailer wheel are designed to avoid any potential resonant vibrations arising from ground inputs at the speeds selected for simulations, with tire-ground contact maintained throughout the entire simulation process (corresponding to data collection process in a profiling test).

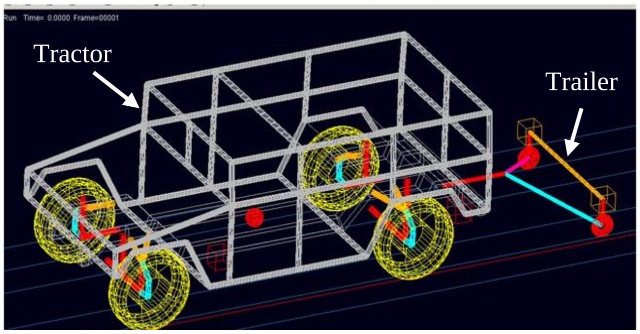

Figure 1: Tractor and trailer model in Adams

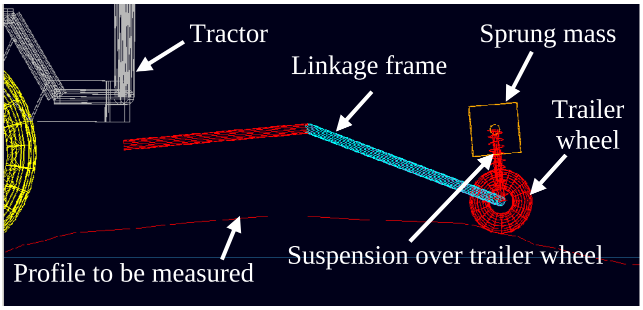

Figure 2: Trailer and its components in Adams

By applying Fast Fourier Transform /Inverse Fast Fourier Transform (FFT/IFFT) techniques, the tire acceleration, suspension force and pitch angular displacement of sprung mass (extracted from the trailer in Adams model) are used to derive the course elevations as a function of time, while the speed data (measured at the center of the trailer wheel) is used to convert the regenerated ground elevations from a time domain into a spatial domain. The regenerated course profile is then compared to the course profile used as the inputs to the trailer model in terms of root-mean-square (RMS) values and illustrated in a time domain, showing the efficiency of the approach in regenerating realistic ground profiles.

MATHEMATICAL MODEL

Figure 3 and Figure 4 show the physical model of the trailer tire and its free-body-diagram.

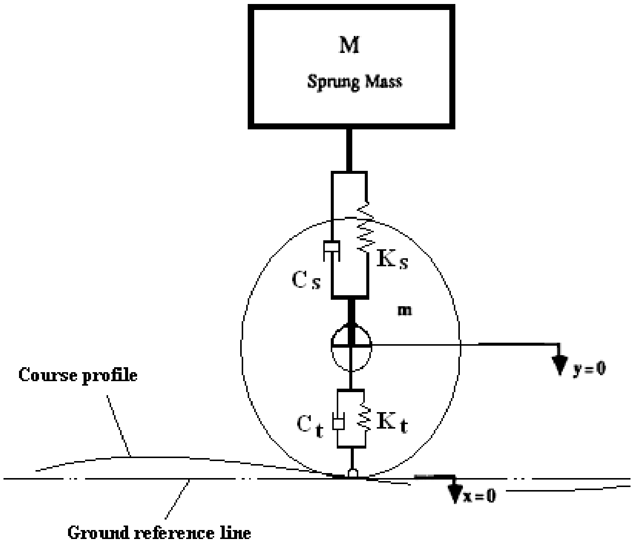

Figure 3: Physical model of trailer tire

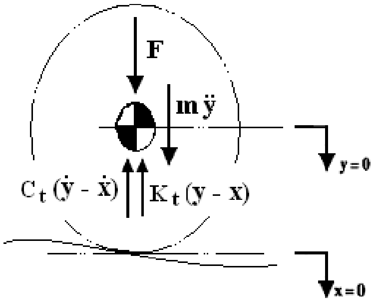

Figure 4: Free-body-diagram of trailer tire

In Figure 3 and Figure 4 where:

x =Displacement at tire-ground interface, unit: m
y =Displacement at tire center, unit: m
F =Resultant of suspension forces, unit: N
m =Mass of trailer tire assembly, unit: kg
M =Sprung mass (over trailer wheel), unit: kg
K_s =Suspension stiffness coefficient, unit: N/m
C_s =Suspension damping coefficient, unit: Ns/m
K_t =Trailer tire stiffness coefficient, unit: N/m
C_t =Trailer tire damping coefficient, unit: Ns/m

Applying Newton's second law on the trailer wheel (in the vertical direction), it can be written:

$$F = m\ddot{y} + c(\dot{y} - \dot{x}) + k(y - x) \qquad (1)$$

Note that in Equation (1), c and k (with subscript t omitted) are the damping and stiffness coefficients of the trailer tire, respectively, which are assumed to be constants. By re-arranging the items in equation (1) and noting F , x and y are functions of time, it can be written:

$$c\frac{d\dot{x}(t)}{dt} + kx(t) = m\frac{d\ddot{y}(t)}{dt} + c\frac{dy(t)}{dt} + ky(t) - F(t) \qquad (2)$$

Note that

$$d = tV \qquad (3)$$

$$n = \frac{f}{V} \qquad (4)$$

$$T = \frac{L}{V} \qquad (5)$$

Where

d =Distance traveled, unit: m
t =Time, unit: s
V =Speed of tire, unit: m/s
n =Wave number per meter, unit: cycles/m
f =Frequency in time domain, unit: Hz
T =Duration of measured data, unit: s
L =Length of course measured, unit: m

Taking the Fourier transform of Equation (2) over duration T leads to:

$$[k + j2\pi fc]X(f,T) = [k - (2\pi f)^2 m + j2\pi fc]Y(f,T) - F(f,T) \qquad (6)$$

In Equation (6):

$$X(f,T) = \int_0^T x(t)e^{-j2\pi ft}dt \qquad (7a)$$

$$Y(f,T) = \int_0^T y(t)e^{-j2\pi ft}dt \qquad (7b)$$

$$F(f,T) = \int_0^T F(t)e^{-j2\pi ft}dt \qquad (7c)$$

Rearranging Equation (6):

$$X(f,T) = \frac{k - (2\pi f)^2 m + j2\pi fc}{k + j2\pi fc}Y(f,T) - \frac{1}{k + j2\pi fc}F(f,T) \qquad (8)$$

Or

$$X(f,T) = \frac{1}{\frac{k + j2\pi fc}{k - (2\pi f)^2 m + j2\pi fc}}\left(Y(f,T) - \left(\frac{1}{k - (2\pi f)^2 m + j2\pi fc}\right)F(f,T)\right) \qquad (9)$$

Assuming:

$$H_1(f) = \frac{1}{k - (2\pi f)^2 m + j2\pi fc} \qquad (10a)$$

$$H_2(f) = \frac{k + j2\pi fc}{k - (2\pi f)^2 m + j2\pi fc} \qquad (10b)$$

Equation (9) can be rewritten:

$$X(f,T) = \frac{1}{H_2(f)}\left(Y(f,T) - H_1(f)F(f,T)\right) \qquad (11)$$

The Fourier transform of vertical acceleration $A(f)$ is given by:

$$A(f,T) = -(2\pi f)^2 Y(f,T) \qquad (12)$$

It follows that:

$$Y(f,T) = -\frac{A(f,T)}{(2\pi f)^2} \qquad (13)$$

Substituting Equation (13) into Equation (11) results in:

$$X(f,T) = \frac{-1}{H_2(f)}\left(\frac{A(f,T)}{(2\pi f)^2} + H_1(f)F(f,T)\right) \qquad (14)$$

Given m, k and c, the frequency response functions, $H_1(f)$ and $H_2(f)$, can be determined by equation (10a) and (10b). After solving equation (14) with appropriate tire parameters, the vertical displacement (elevation) time history of the course may be obtained by performing inverse Fourier transform of Equation (14):

$$x(t) = \int_0^{f_c} X(f,T)e^{j2\pi ft}df \qquad (15)$$

In Equation (15), f_c is the upper cut-off frequency of the computation (Nyquist frequency), which is determined by the sample rate of raw data recorded by the trailer wheel. With use of Equation (3), the vertical displacement (elevation) time history course may be converted into elevation versus distance traveled. Note that the above derivation is consistent with those presented in reference [4].

Apparently, the challenge is solving Equation (14), which is a complex function containing both real and imaginary parts, expressed in terms of $A(f,T)$ and $F(f,T)$, and $H_1(f)$ and $H_2(f)$. Note that each of these four complex functions is in digitized format. The numerical implementation of the mathematical model is described in the next section.

IMPLEMENTATION of IFFT

A MATLAB program was developed based upon the complete set of analytical equations derived in the previous section. The inputs to the program include the measurements at the center of the trailer wheel: (a) the acceleration in vertical and longitudinal directions; (b) the resultant suspension force; (c) the pitch angle of suspension or sprung mass and; (d) the velocity.

Note that the formulations derived to perform IFFT are based upon the assumption that the tire stiffness and tire damping (in vertical direction) are constants, which is correct when the center of tire-ground contact patch is directly beneath the tire center. However, when considerably large pitch angular displacement (of suspension over trailer wheel with respect to the vertical axis) occurs (as shown in Figure 5), the tire stiffness and tire damping in the vertical direction becomes a variable, which is a function of the pitch angle, as explained below.

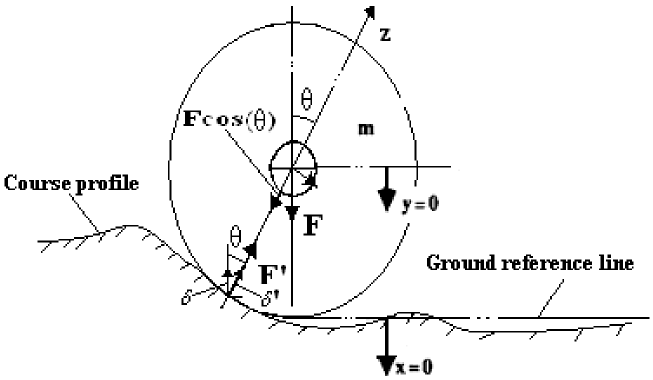

Figure 5: Illustration of pitch angle and normal force

In Figure 5, F' is the ground force normal to the ground surface, while F is the tire load in vertical direction, θ the pitch angle of suspension relative to the vertical axis, δ' and δ are tire deformations in normal and vertical directions, respectively.

In the normal direction (along the z-axis), the tire stiffness and tire damping are assumed to be constants, with tire stiffness determined by:

$$K_t = \frac{F'}{\delta'} \qquad (16)$$

Note the following relationships stand:

$$F' = F\cos\theta \qquad (17a)$$

$$\delta = \delta'\cos\theta \qquad (17b)$$

In the vertical direction, the tire stiffness, which is a function of the pitch angle, can be determined by:

$$K = \frac{F}{\delta} = \frac{F'/\cos\theta}{\delta'\cos\theta} = \frac{F'/\delta'}{\cos^2\theta} = \frac{K_t}{\cos^2\theta} \qquad (18)$$

With the above observation, the acceleration and force data in longitudinal and vertical directions (consistent with tri-axial sensors used in a profiling test) are converted into normal direction to maintain the validity of the mathematical model previously described. The output $x(t)$ in Equation (15), which is in normal direction, should be projected onto the vertical direction as $x(t) \cdot \cos[\theta(t)]$, which is the ground elevation versus time as required.

Similarly, when mapping elevation data in a time domain into a spatial domain by integrating velocity, the center of the tire-ground contact patch, which is the point where the road profile is to be identified at time instant t, should be determined as:

$$\int V(t)dt \pm (R_0 - \frac{F'}{K_t})\sin[\theta(t)] \qquad (19)$$

In Equation (19), F' is equivalent to the product of the unsprung mass of the trailer wheel assembly and the normal acceleration at the time instant t, R_0 the unloaded radius of the trailer tire, $V(t)$ the longitudinal speed at the tire center, with the sign after the integral determined by the relative position of the tire center with respect to the center of tire-ground contact patch (positive when the tire is “climbing up” and negative when the tire is traversing “down a hill”).

Note the regenerated course profile, in terms of ground elevation versus travel distance needs to be filtered with appropriate band-pass filter. The lower cut-off frequency of the filter should be determined by the longest wavelength that needs to be considered; while the upper cut-off frequency is determined by the shortest wave length that can be measured by the sensors installed at the tire center, which is determined by the potential maximum length of the trailer tire-ground contact patch and the sampling rate used in data collection. Signal processing techniques, such as windowing and averaging, are essential to ensure the accuracy of the course profile regeneration process, while scaling factors are needed to “calibrate” the model for different ground roughness levels. Since the core part of the current work is focused on using FFT/IFFT to regenerate course profile, the signal processing-related subjects are beyond the scope of this paper.

The efficiency of the algorithm is shown through the comparison of the course profiles regenerated against those used as the inputs to the trailer model. Sample simulation results are demonstrated in the next section.

SIMULATION RESULTS

To demonstrate the efficiency of the unique approach, the course profile rms3 measured at Yuma Proving Ground (YPG) are used as the inputs to the trailer model in Adams described previously. With the simulation run at a selected vehicle speed, the tire acceleration and the suspension force, in both vertical and longitudinal directions, as shown in Figure 7-10, are extracted from the model. The acceleration and force data are then projected to normal direction (as shown in Figure 11-12), using the extracted pitch angle history shown in Figure 13. The normal acceleration and force data are then used to derive the course profile in a time domain, while the speed data, as shown in Figure 14, is used to map the ground elevations generated in time domain into a spatial domain, as shown in Figure 15. Note that the suspension force is the resultant of the spring force and damping force from the suspension over the trailer wheel, which can be estimated by measuring the relative movement (compression or extension) of the suspension. Ideally, the reproduced course profile derived based on the acceleration and force data is expected to be identical to the ground inputs to the Adams model or the course profile in reality. Figure 15 illustrates fairly good agreement between the regenerated course profile and the input rms3 course. Figure 16 further shows the comparison of the probability density functions (PDF) of the YPG data and the regenerated profile, showing an agreement in a statistical sense.

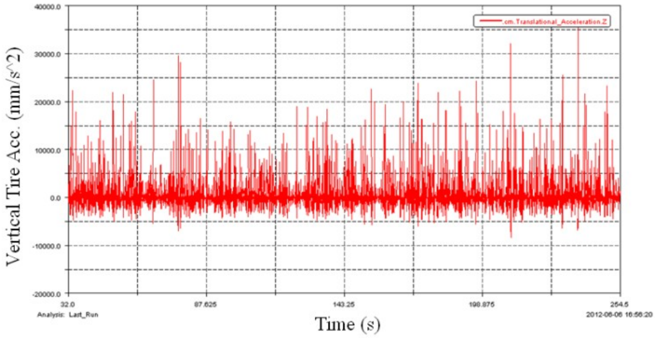

Figure 7: Vertical tire acceleration (rms3 course)

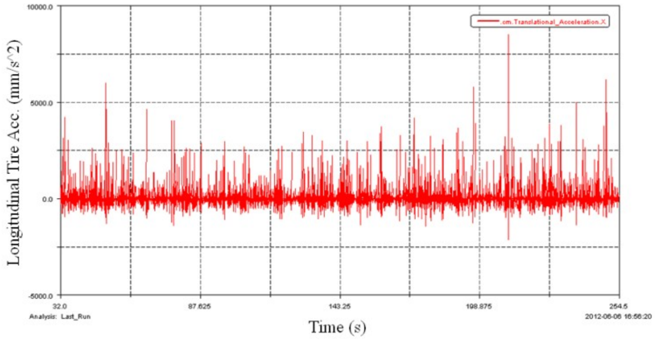

Figure 8: Longitudinal tire acceleration (rms3 course)

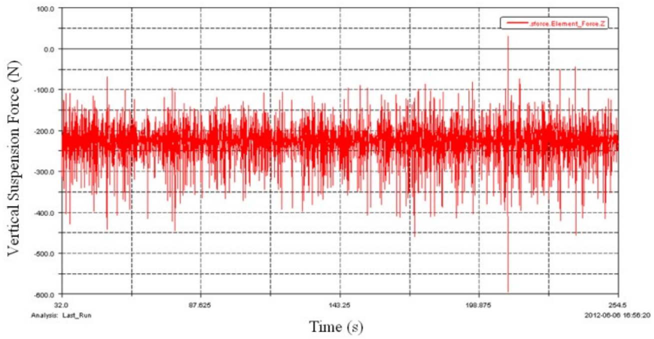

Figure 9: Vertical suspension force (rms3 course)

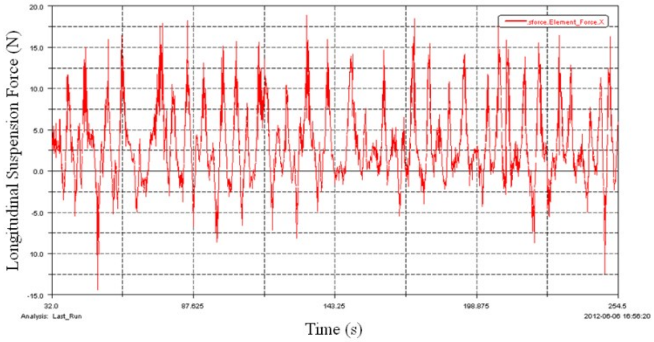

Figure 10: Longitudinal suspension force (rms3 course)

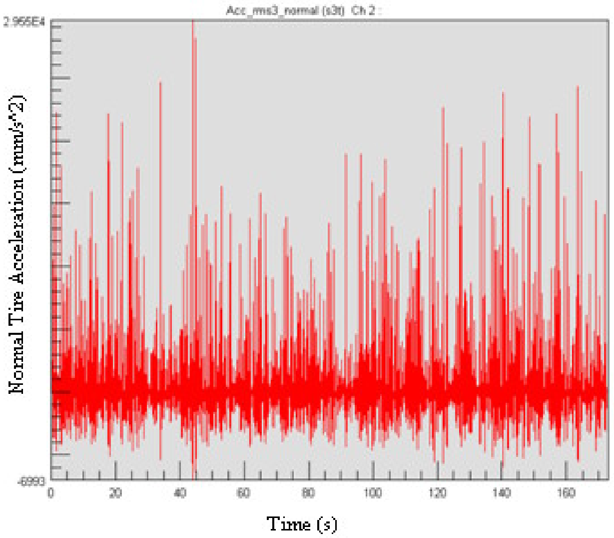

Figure 11: Normal tire acceleration (rms3 course)

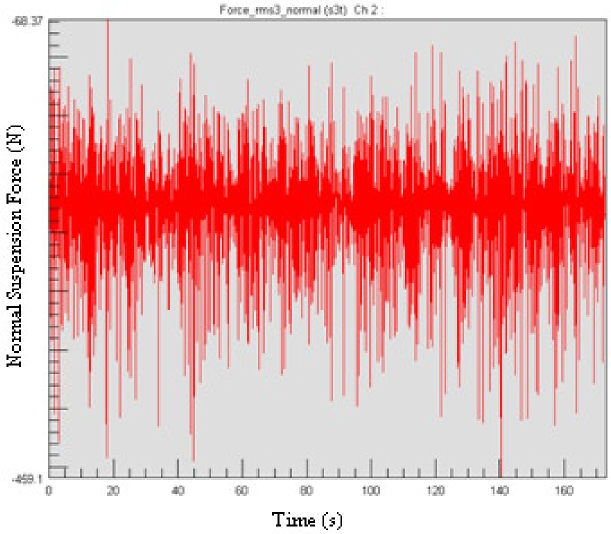

Figure 12: Normal suspension force (rms3 course)

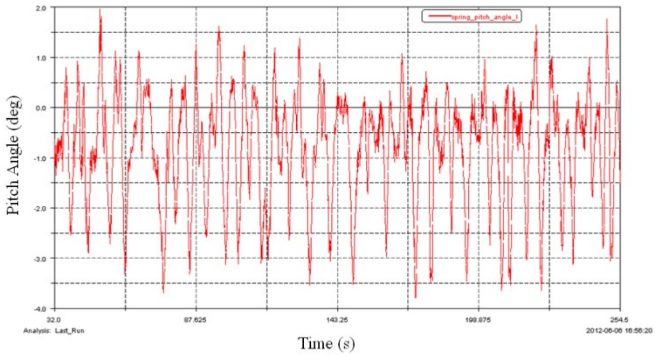

Figure 13: Pitch angle (rms3 course)

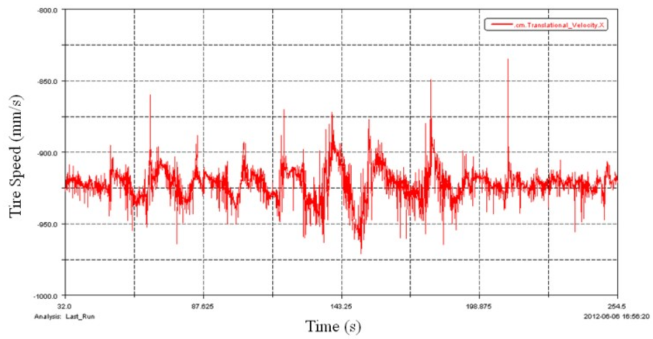

Figure 14: Speed at tire center (rms3 course)

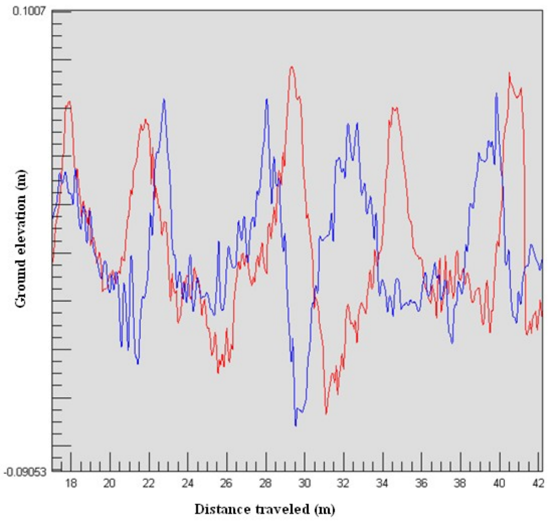

Figure 15: Comparison of the regenerated course profile with the input course profile (rms3)
(Red line – Yuma data; Blue line–regenerated)

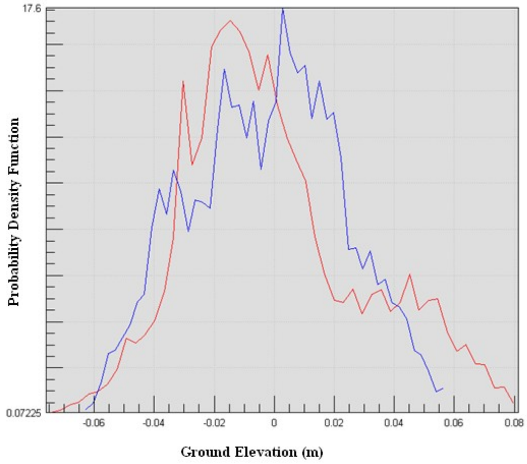

Figure 16: Comparison of the PDF of regenerated course profile with that of the input (rms3)
(Red line – Yuma data; Blue line–regenerated)

Figure 17-18 further show the regenerated rms4 and rms5 course profiles, in comparison to the Yuma data (the inputs to the Adams model), which also illustrates fairly good agreement between the regenerated course profiles and those measured at YPG.

Table 1 shows the comparison between the inputs (Yuma data) and the regenerated course profiles in terms of root-mean-square (rms) values, showing the accuracy of the unique approach proposed.

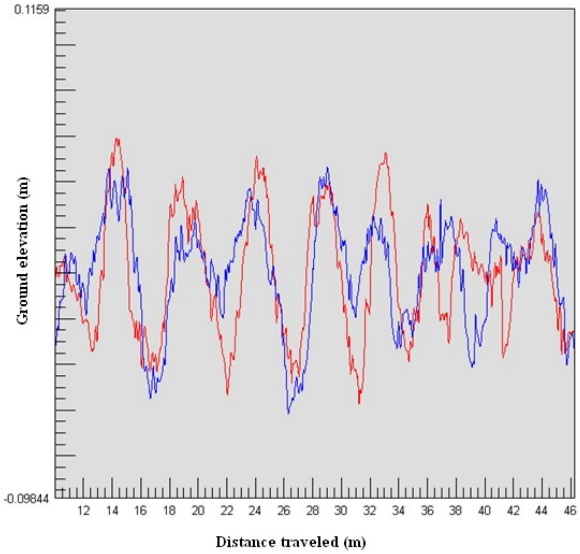

Figure 17: Comparison of the regenerated course profile with the input course profile (rms4)
(Red line – Yuma data; Blue line–regenerated)

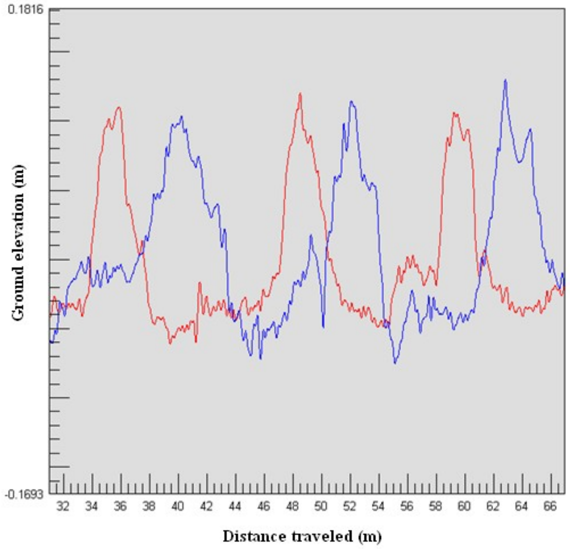

Figure 18: Comparison of the regenerated course profile with the input course profile (rms5)
(Red line – Yuma data; Blue line–regenerated)

Table 1: Root-mean-square values of course profiles

Course	Original (m)	Regenerated (m)	Error (m)	Error (%)
Rms3	0.02956	0.02982	0.00026	0.88
Rms4	0.0438	0.0433	0.0005	1.14
Rms5	0.08	0.082	0.002	2.5

CONCLUDING REMARKS

This paper presents a unique off-road course profiling approach, which appears to be conceptually simple yet efficient, which was verified from a computer simulation perspective. The rationale of the methodology is primarily based on the reported study [4] but the technical implementation of the mathematical model is different in that using the trailer wheel to isolate the instrumented tire from the interference of DFMV's suspension dynamics, and also in that the small-radius trailer tire can be designed particularly for data collection purpose, ensuring wider frequency range for data collection. The technique is considered to be valid for random courses without limitation to Gaussian PDF.

The data presented is not intended for quantitative analysis. The simulation results from the selected off-road courses, however, reveal the efficiency of the proposed course profiling methodology and the feasibility in its potential applications.

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