Powering Innovation To Move Our World

Real data integration in a data-driven approach for track signal definition

Methodology to generate road profiles for predicting vehicle behaviour in a virtual environment: reproduction of real road and off-road conditions.

by Lorenzo Bellorini[1], Pier Luca Todesco[2], Federico Bavaresco[1]
1. Dana Incorporated- 2. Alten Italia

The more progress is made in developing a new product, the more expensive it becomes to make changes. Hence the need to identify possible problems in advance and make changes at an early stage, before the product becomes ready for mass production.

Although designers and engineers evaluate the probability of iterations against the probability of success step by step, a single verification test is often not enough: changes and rethinking may occur in the design process and consequently costs may increase rapidly. Integrating simulation into the design development process is increasingly important to guide design decisions, and accelerate development times, product optimization, and performance prediction.

Analysis in a virtual environment allows the influence of the design parameters on product performance to be understood before a physical prototype is available, enabling successful strategy implementation from the outset. Simulation has therefore become more and more important in recent years and industry is increasingly requiring the exclusive use of virtual validation to replace field testing, especially in the early stages of product development.

The ability to use an accurate, reliable and validated virtual model typically reduces development costs and time considerably, enabling prototype testing to be restricted to the final design stages. Reducing the use of resources, materials and energy consumption during validation by minimising the number of times tests are performed adds enormous value and supports sustainability.

Integrating real data into the virtual model is, however, key to improving the accuracy of simulation results. This is the topic of discussion in this article, which focuses on evaluating track signals from field data for use in a virtual environment.

Objective

To replicate a vehicle field test in a virtual simulation environment, the many physical phenomena that are involved must be accounted for, including vehicle kinematics and dynamics, suspension hydrodynamics, thermal, electrical, and structural aspects.

In an Off-Highway environment, it is especially important to incorporate the increased excitations of the vehicle that are caused when it traverses a bumpy track. Since we do not have a database of bumpy tracks, our aim was to define a generalizable method to reconstruct the profile of the roads on which a vehicle has travelled based on the acceleration signals measured at its hubs. Using this approach, our goal was to compile a repository of classified tracks to use in a virtual environment.

The virtual tracks generated should be similar to the actual ones in terms of energy content, and in terms of the amplitude and frequency of the accelerations that the virtual model of the vehicle experiences as it traverses the track, which should be comparable to those measured in the field. The virtual tracks derived must be independent of the type and speed of the vehicle used to characterize them.

The available regulatory documents could be used as a starting point for the creation of these virtual tracks. For example, the ISO8608 standard proposes a classification of road profiles for determining the average energy content of a track. It specifies an 8-band classification grid and a power spectral density (PSD)-based analysis.

From this categorization, certain artificial and random paths per specific class can be deduced. However, these artificial profiles frequently do not accurately represent the real amplitudes or frequency content. Hence, the need to define a procedure based on actual field data to obtain realistic tracks for use in design and validation.

Step 1a: Primal Drive Signals (DS)

The method proposed in this article focuses on a data-driven approach: our aim was to develop multiple meta-models in the form of response surface functions (RSM) by exploiting the potential of modeFRONTIER. The models were to be trained on a large enough database of dummy tracks to represent all possible scenarios and dynamics.

As previously mentioned, the first thing required were the data sets from an acquisition campaign. To this end, an equipped vehicle sampled the accelerations occurring at the hubs as the vehicle traversed various tracks. These acceleration signals were fed into the model to reconstruct the road tracks.

Secondly, a multibody model of the vehicle used for data acquisition was developed using the Adams View software. This model was validated and found to be representative of the vehicle being studied.

Step 1b: Domain creation

We used modeFRONTIER to define a domain for the RSM training and then constructed a design of experiment (DoE) with many scenarios. A wide range of dummy tracks, resulting from the random superposition of sinusoidal functions with various amplitudes and frequencies, was inserted into the DoE, which generated a set of consequent accelerations occurring at the hubs of the multibody vehicle model as it traversed the tracks.

Step 1c: RSM training

We then developed an RSM training routine. After obtaining the Fast Fourier Transform (FFT) of the dummy tracks previously defined, the frequency components were sorted into decreasing amplitudes for each of them.

Next, we selected the N frequency components recurring most often among all evaluated scenarios. These represent the most significant N frequency components to describe all the tracks.

The routine invokes the Scilab scripts and modeFRONTIER successively in batch-mode to generate $2*N$ meta-models: i.e. for a specific frequency component, there is one RSM for its real part (Re) and one for its imaginary part (Im). Each of these meta-models is trained on the input of all N components, Re or Im, of the acceleration signals obtained previously and on the specific Re or Im of the displacement component related to that RSM.

Therefore, the acceleration input signal provided to the model is broken down into the N fundamental frequency components used in the training phase. Subsequently,

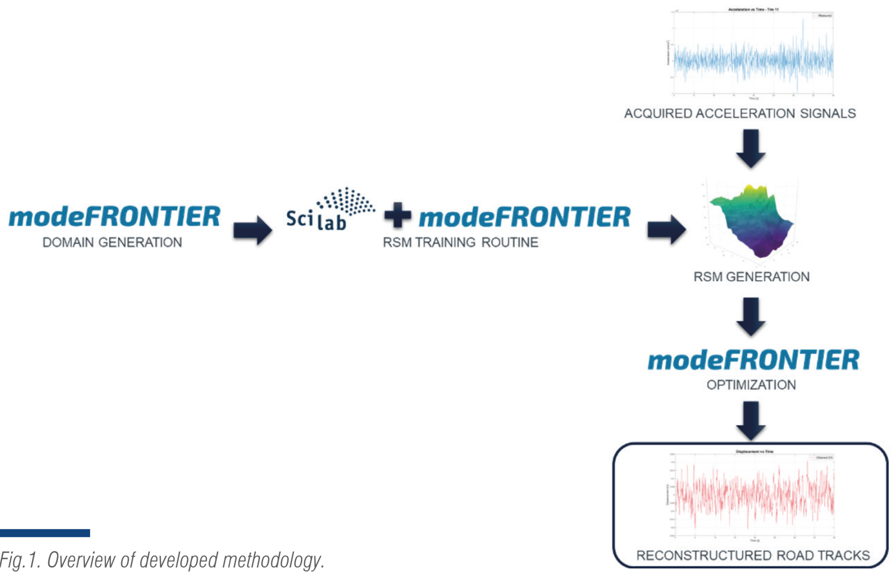

Fig.1. Overview of developed methodology.

for each of the $2*N$ RSMs, the Re and Im parts of all specific frequencies are obtained, the i^{th} amplitude A_i and the phase ψ_i are derived, and the displacement signal is reconstructed using Fourier by superimposing N sinusoidal functions, each characterized by A_i and ψ_i.

Given that there is no two-way correspondence between excitation frequency and output frequency, we accept that all acceleration components can contribute to defining the specific displacement component and vice versa.

If the proposed method were able to use and combine real track signals into the training domain it would be more valuable since the N components selected as fundamental would have a better congruence with real stresses. The backward analysis revealed inaccuracies in the first version of the drive signals, so corrective measures were taken.

Step 2: Optimization

The method was improved by implementing an optimization process with modeFRONTIER. This mitigates potential sources of error including the effect of the reciprocal influence between the vehicle's four wheels. Therefore, the modeFRONTIER optimization workflow (Fig.2) simulates the entire vehicle by exciting all four wheels simultaneously.

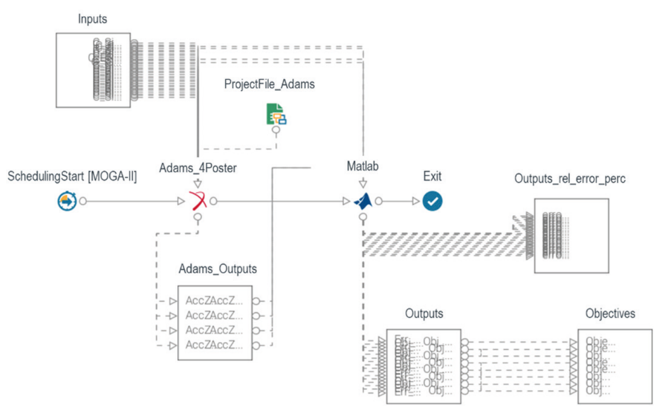

Fig.2. modeFRONTIER optimization workflow.

The optimization process aims to minimize the differences occurring between the measured acceleration PSDs and those obtained from the multibody simulation.

Eight objective functions describing the disparities between PSD acceleration curves in terms of subtended area, therefore energy content, and in terms of shape, were thus defined.

To reduce the objective functions to zero, the initial track signals were tuned by adding sinusoidal functions for each specific frequency range. Twenty-eight input variables, seven for each vehicle tyre, one per frequency range, were then used as modifying coefficients of the linear combinations of the additional sine waves and configured at each optimization step.

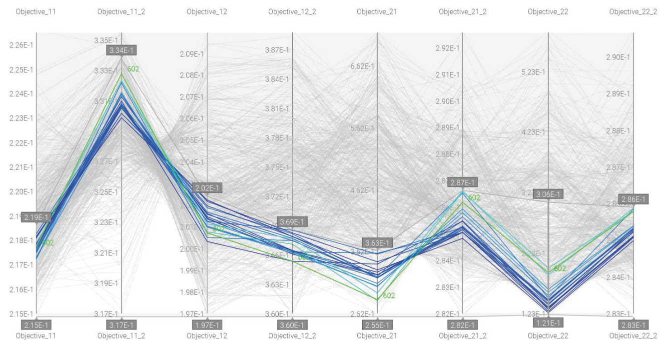

Fig.3. Qualitative post-processing using a parallel coordinates diagram.

The previously defined number of objective functions and input variables is a first attempt: these values can be increased to improve the initial results shown in this article while striving for a trade-off between accuracy and computing cost. This and the large number of variables are the reason a MOGA-II algorithm was used with discretized steps of the input variables.

With the large number of parameters involved, a single optimization step is typically not sufficient to achieve the desired accuracy. Therefore, post-processing (Fig.3) was performed after every iteration using qualitative and quantitative analysis to refine the variation domains of the input variables and to guide the optimization process into the following cycle. The optimization process ends after a few cycles once sufficient qualitative or quantitative accuracy has been achieved.

Results

An initial implementation of the full proposed methodology yielded the results shown in Fig.4. These results refer to a vehicle travelling at an almost constant speed of 8km/h across a field consisting of soft ground and containing boulders.

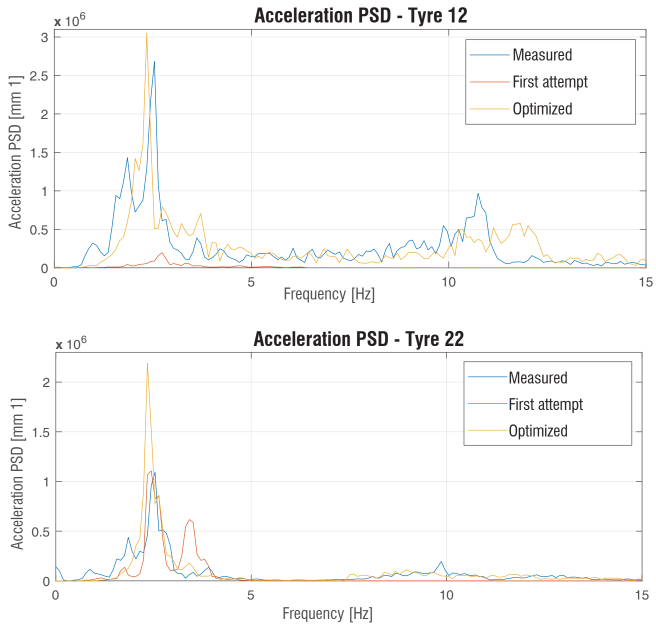

Fig.4. Optimization results: right side tyres.

Development phases	Required calculation time
Primary road tracks	2 days
1st optimization	5 days
2nd optimization	4 days
3rd optimization	2 days

Table 1. Required calculation time.

	Objective function 0-7.5Hz		Objective function 7.5-15Hz	
	First trial	Optimized	First trial	Optimized
11	93.35%	21.83%	99.89%	33.70%
12	90.97%	19.98%	99.78%	37.07%
21	36.09%	27.91%	99.81%	29.14%
22	14.19%	19.67%	99.85%	29.30%

Table 2. Evolution of objective functions.

The procedure with its individual phases required the calculation time shown in Table 1. A major improvement (Table 2) was achieved thanks to the optimization procedure undertaken, with errors of less than 37%.

A compromise was sought between the desired accuracy and acceptable computing times. Improved results could have been achieved by revising the number of parameters in the optimization, as specified above.

Conclusions

The approach developed works towards the goal of reproducing the tests usually conducted in the field during all stages of product development in a virtual environment. The aim is to perform a final validation of the product by running simulations that harness a reliable virtual model of the vehicle and realistic road profiles.

Focusing on the second aspect, the methodology presented demonstrates how to reconstruct a road track's characteristics using measured accelerations and a virtual model of the associated vehicle.

The main purpose of the method is to ensure that accelerations of similar energy content to the actual signals acquired occur for the virtual model of the vehicle in transit over the entire frequency domain of interest.

The development of this methodology has enabled the creation of a repository of classified tracks that can be used in a virtual environment to guide design and validate components.

For more information:
Stefano Carrino – EnginSoft
s.carrino@enginsoft.com

About Dana

Dana is a leader in the design and manufacture of highly efficient propulsion and energy-management solutions that power vehicles and machines in all mobility markets across the globe. The company is shaping sustainable progress through its conventional and clean-energy solutions that support nearly every vehicle manufacturer with drive and motion systems; electrodynamic technologies, including software and controls; and thermal, sealing, and digital solutions.

Based in Maumee, Ohio, USA, the company reported sales of $10.6 billion in 2023 with 42,000 people in 31 countries across six continents. With a history dating back to 1904, Dana was named among the "World's Most Ethical Companies" in 2023 and 2024 by *Ethisphere* and as one of "America's Most Responsible Companies 2023" by *Newsweek*. The company is driven by a high-performance culture that focuses on valuing others, inspiring innovation, growing responsibly, and winning together, earning it global recognition as a top employer.