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A Co-simulation Solution for Vehicle-Track Interaction Dynamics Problems

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Abstract

A co-simulation solution based on direct equilibrium of contact forces is proposed to simulate vehicle-track interaction (VTI) dynamics. It is developed in two platforms, which presents an iterative feedback loop that exchanges contact force files and structure response field in real-time. The load vector acting on the structure is described by a moving Gaussian pulse, which approximates the Dirac-delta function. Through this approach, system matrices are not exported and the additional identification of the correspondence between structure nodes and vehicle positions is avoided, which is contrary to the typical scheme in existing co-simulation methods for VTI problems. The direct information exchange in the current solution simplifies the VTI model development, making it easier for the application in track design and maintenance phase. The solution is demonstrated by a general beam model subject to a quarter car and has been calibrated and verified by benchmark cases coded in MATLAB. The example presented is a baseline model for demonstration purposes. And the proposed scheme allows for flexibility in incorporating more complex structure configurations and vehicle motions for further study.

Keywords: finite element method, iterative method, railway track design, track maintenance, vehicle-track interaction, track geometry irregularities.

1 Introduction

Accurate simulations of dynamic vehicle-track interaction (VTI) are gaining importance in both track design and maintenance phase. For new lines, VTI description contributes to the improved track design. It quantifies the increase in dynamic amplification caused by factors such as stiffness variation and compares the performance of alternative design solutions. By coupling with an optimisation framework, which supports a trade-off between different track design parameters, VTI simulation contributes further to optimal design solution(s) with given constraints and criteria. For existing lines, the conventional 'inspect-repair' maintenance strategy is increasingly complemented by a 'monitor-predict-prevent' regime, where onboard measurements provide an indirect tool for infrastructure condition monitoring and maintenance planning. This process also requires accurate VTI simulation as vehicle responses are analysed to infer track properties and detect potential defects [1].

Studies on the VTI dynamics result in various VTI models that vary from a simplified analytical beam on elastic foundation to complex numerical models mainly developed through the finite element (FE) method [2]. Numerical solutions are often developed by self-programmed codes or FE software. The software is more flexible for complex structure configurations but is often computationally intensive. To reduce the computational time and simplify the structure modelling, some propose a combined solution where system matrices are exported from an FE software to a programming platform, and equations of motion (EOM) are solved through programming. However, as the vehicle position changes with time, the correspondence between the structure and vehicle position needs to be defined before solving the EOM. This means the structure nodes adjacent to the contact points need to be identified, for example, when formulating the overall stiffness matrix [3] and modal matrix [2].

The current study proposes a co-simulation solution in two platforms: the vehicle model is developed in MATLAB and the structure is generated in COMSOL. It presents an iterative feedback loop where a contact force file is exported from MATLAB to COMSOL; then the response field processed from COMSOL is called in MATLAB for updating the force profile. System matrices are not used. The force vector is described by a moving Gaussian pulse. It reproduces internal moving loads on the structure and the additional node identification process is avoided. The solution is demonstrated by a general beam model subject to a quarter car and has been calibrated and verified by benchmark cases coded in MATLAB.

2 Methods

The VTI problems are generally defined by two methodologies: one that unifies the vehicle and structure and formulates coupled system matrices [4]; the other separates the subsystems and EOM are solved by direct equilibrium of contact forces, condensation method [5], and variational formulation based on energy principle [6].

The proposed procedure applies the contact force equilibrium principle as this matches the co-simulation idea. The methodology is presented for a bridge subject to vehicle vertical motions. The bridge is represented by a Euler-Bernoulli beam. The vehicle considers wheel and carbody masses connected by a spring-damper system, as shown in Figure 1. The system EOM is written as:

$$\mathbf{M}_v\ddot{\mathbf{U}}_v+\mathbf{C}_v\dot{\mathbf{U}}_v+\mathbf{K}_v\mathbf{U}_v=\mathbf{F}_v \tag{1}$$

$$\mathbf{M}_b\ddot{\mathbf{U}}_b+\mathbf{C}_b\dot{\mathbf{U}}_b+\mathbf{K}_b\mathbf{U}_b=\mathbf{F}_b \tag{2}$$

where **M**, **C**, and **K** represent the mass, damping and stiffness matrices respectively. Subscript 'v' and 'b' represent vehicle and bridge respectively. **U** denotes the displacement vector. **F** is the load vector. $\mathbf{F}_b$ is the force on the bridge and at time step i it is given by:

$$\mathbf{F}_{bi} = (\mathrm{W} - \mathbf{M}_v\ddot{\mathbf{U}}_{vi}) \times \mathbf{N}_{bi} \tag{3}$$

where W is the vehicle gravity; $\mathbf{N}_{bi}$ is the element shape function distributing the load to the corresponding degrees of freedom of the bridge. The location of $\mathbf{F}_b$ is commonly described by a time-dependent Dirac-delta function $\delta(x - vt)$. Here for numerical solutions the Dirac-delta function is regularised by a Gaussian function as follows [7].

$$\delta(x - vt) \approx \frac{1}{\alpha\sqrt{\pi}} \exp\left[-\frac{(x-vt)^2}{\alpha^2}\right] \quad \text{when } \alpha \to 0 \tag{4}$$

The force that the bridge acts on the vehicle is calculated by:

$$\mathbf{F}_c = -\mathrm{k}_s \cdot [\mathbf{U}_{vc} - (\mathbf{U}_{bc} + \eta)] \tag{5}$$

where $\mathbf{U}_{vc}$ and $\mathbf{U}_{bc}$ respectively represent the displacement of the vehicle and bridge at contact point. η is the irregularity profile, which is location specific.

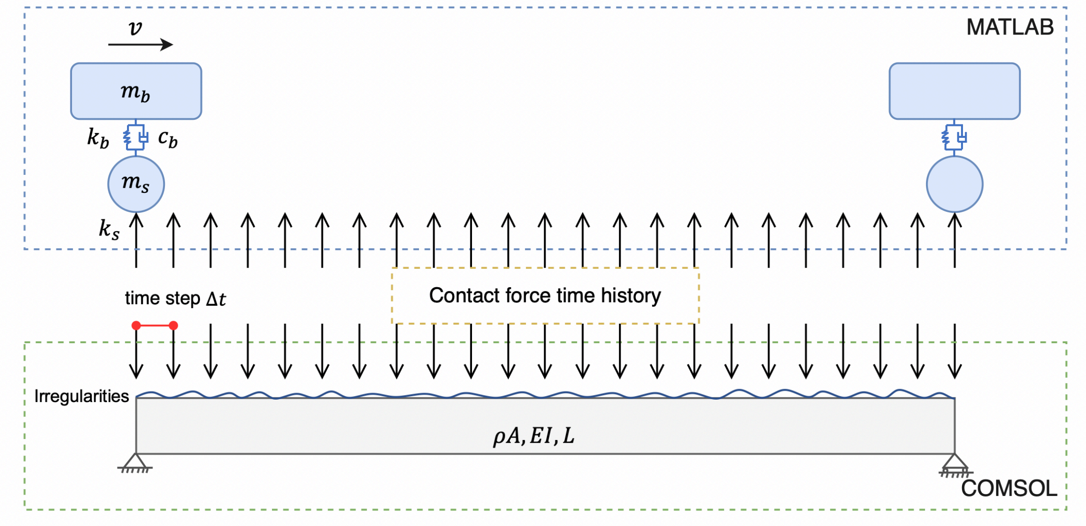

Figure 1: Demonstration of the co-simulation scheme.

As shown in Figure 1, the co-simulation scheme requires an iterative procedure where first assuming zero bridge motion,

1) the vehicle EOM (Equation (1)) is solved in MATLAB by the Newmark-β method. The result is a contact force history for all time steps stored in a text file (Equation (3));
2) MATLAB exports the force file to COMSOL; the load position is realised by a moving Gaussian pulse and bridge EOM is solved in COMSOL (Equation (2&4));
3) COMSOL exports the bridge displacement profile to MATLAB and solves vehicle EOM by combining the profile (Equation (1&5)), resulting in an updated contact force history (Equation (3));

4) convergence is checked between the updated (Step 3) and previous (Step 1) force profiles. Return to Step 2 for a new iteration if the convergence criterion is not satisfied.

3 Results

The performance of the co-simulation scheme is analysed by two demonstration examples. The first is for model calibration. The parameter values correspond to the benchmark case in [1], written in MATLAB. In the second example, for verifying the proposed scheme, the calibrated model is employed considering a crack at midspan, which causes stiffness loss near the crack, modelled by the approach in [8]. The vehicle parameters are also altered and presented in Table 1.

Bridge properties	Vehicle properties-Case 1	Vehicle properties-Case 2
$EI = 1.85 \times 10^7 kN/m^2$ $\rho A = 28{,}035$ kg/m $L = 15$ m Note: case 2 concerns damage level $\theta = 0.2$; EI- and ρA-values are varied according to [1, 8].	$m_b = 17{,}300$ kg $m_s = 700$ kg $k_b = 400$ kN/m $c_b = 10$ kNs/m $k_s = 1700$ kN/m $v = 25$ m/s	$m_b = 17{,}000$ kg $m_s = 725$ kg $k_b = 20$ kN/m $c_b = 10$ kNs/m $k_s = 1500$ kN/m $v = 25$ m/s

Table 1: Parameter values used in demonstration examples.

As the contact force profile is retrieved once for all time steps, the correspondence between the vehicle and structure needs to be defined at every step. The Newmark-β method for solving the vehicle EOM has a time step 0.0005s. The bridge EOM is solved by the Generalized-alpha method and the solver is switched to strict time-step as 0.0005s.

The Dirac-delta function is regularised as a Gaussian pulse. As the α-value influences the accuracy and smoothness of the approximation function, the α-value is calibrated by static analysis, which results in $\alpha = 0.01$ given the current time-step setting. Figure 2 presents calibration results regarding (a) the bridge midpoint displacement history; (b) bridge displacement at contact point; (c) vehicle axle accelerations and (d) carbody accelerations.

The second demonstration model considers a damage level $\theta = 0.2$ at midspan. It indicates a crack at location $x = 7.5$m, which causes stiffness loss corresponding to a 20% loss of depth [1, 8]. The influence area is 2.7m long near the midpoint. The stiffness reduction in corresponding beam elements is realised in the co-simulation and MATLAB programme. Figure 3 compares the results from the two solvers: (a) and (b) have a maximum difference of 10.61% and 4.10%, respectively; (c) and (d) show that the co-simulation results agree well with those generated from MATLAB.

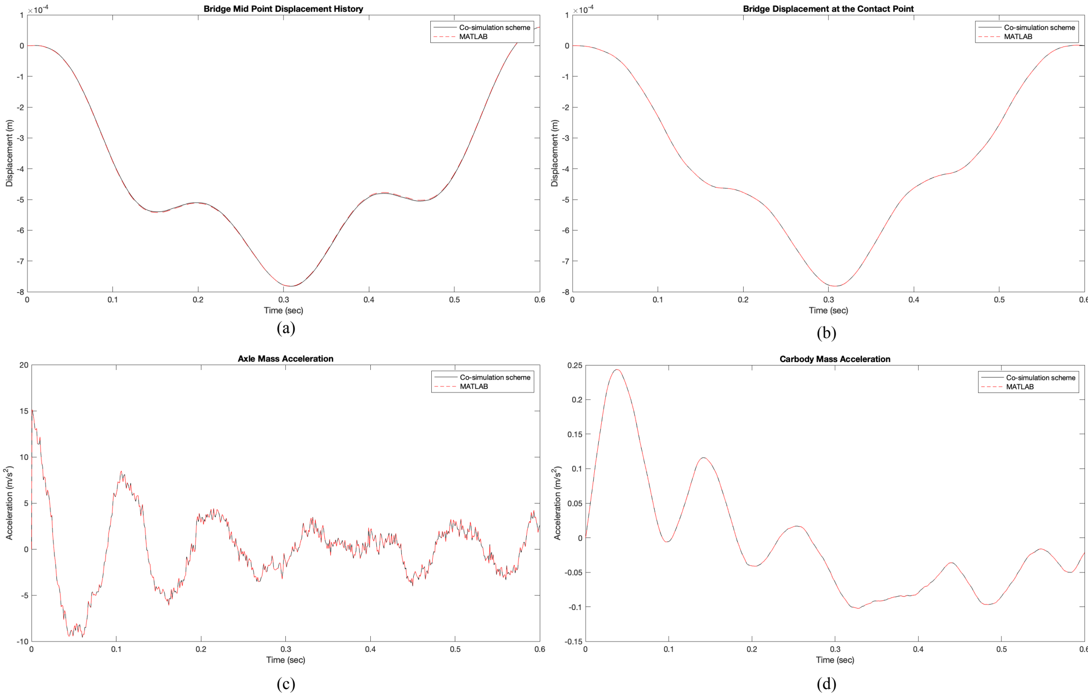

Figure 2: Model calibration: (a) midpoint displacement history; (b) bridge displacement at contact point; (c) axle accelerations; and (d) carbody accelerations.

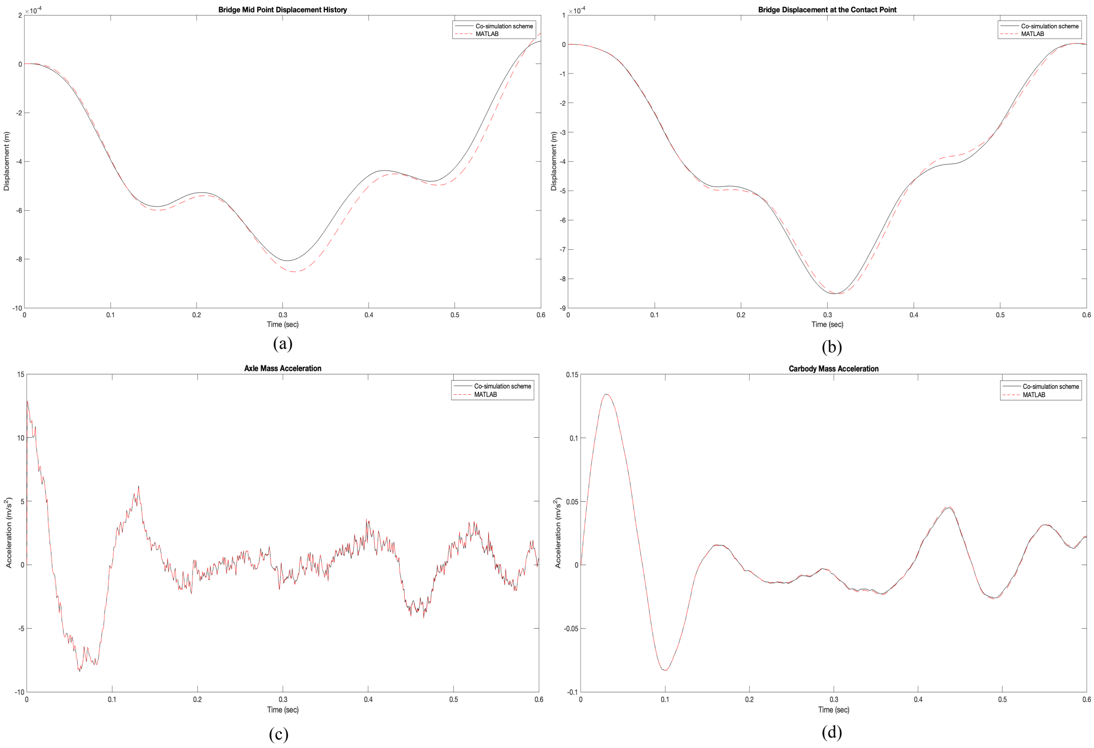

Figure 3: Model validation: (a) midpoint displacement history; (b) bridge displacement at contact point; (c) axle accelerations; and (d) carbody accelerations.

4 Conclusions and Contributions

The co-simulation approach has flexibility in modelling the supporting structure with complex geometry, elements, and material types to solve the VTI problems. It also saves computational time compared with the process that only utilises the FE software packages [2]. The typical way in the co-simulation approach is to export system matrices from the FE software to the programming platform and then perform further analysis and postprocessing through programming. However, the structure nodes adjacent to the moving vehicle positions need to be identified in the connection process. The proposed solution directly exchanges the contact force file and structure response field in real-time, where system matrices are not used and the additional node identification process is avoided.

The procedure has been calibrated by a benchmark case coded in MATLAB, which properly selects the α-value in the Gaussian pulse and other parameters in the solver setting. Then, for model validation the calibrated model is tested for a damaged bridge associated with varied system parameter values. The results from the current solution are compared with those generated from MATLAB, and a good match has been observed.

The direct information exchange in the current solution simplifies the VTI model development, making it easier for the application in the track design and maintenance phase. The example presented is a baseline model for demonstration purposes. The proposed scheme allows for flexibility in modelling more complex structures with advanced structural elements, complex geometry and nonlinear behaviour. Vehicle models with more degree of freedoms and additional effects such as loss of contact with the structure can also be incorporated for further study.

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