

Article

On New Ideas for Design of Road Infrastructure: Hybrid Fatigue Analyses

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Abstract: To increase the pace of the design of safer road infrastructure and raise the active and passive safety features of road structures on the global stage, innovative and smart virtual tools are essential. One of the basic steps for such ground breaking numerical simulation technology would be to develop advanced smart hybrid techniques with dynamic adaptation into mainstream design and simulation tools that are used by engineering offices. In the research work herein, a new numerical framework including dynamic zoning, advanced grid interfacing, new computationally-efficient solvers, and genetic algorithm symbolic-regression has briefly been presented to address long-standing problems of speed, accuracy, and reliability of numerical tools. The fundamental physical and mathematical aspects of the new simulation framework are concisely presented. In addition, some outcomes of real-world case studies utilized using the proposed hybrid analytical and data-driven (i.e., machine learning, ML) scheme have been shown, where the design rule for road gantry structures is interrogated using the developed virtual tool. One of the main contributions of this paper is to show the benefits of using hybrid simulation technologies to model engineering systems along with the ML-based method to optimize their designs.

Keywords: hybrid physical-data driven models; fluid–structure interactions; dynamic zoning; genetic algorithm; symbolic regression; fatigue analyses

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1. Introduction

The use of conventional numerical techniques including discretization and solutions of computational domains have been extensively utilized in the past fifty years to predict and design the responses of engineering systems. However, these design optimizations have come at high costs as extensive computational time, power, and efforts are required to handle difficult technical challenges related to the simulations of complex systems. The challenging task of bringing together the advanced computational models (with reasonable computational time) with the detailed aspects of mainstream design of large engineering systems has promoted the introduction of innovative frameworks [1–4]. The time and effort associated with the accurate virtual simulation of large engineering systems and the sophisticated nature of their designs have historically been challenging for mainstream design applications [5,6]. The process of initial design/analyses under possible design life-time scenarios along with accurate virtual optimization of these dynamic systems has always been computationally stimulating and various representative (discrete and continuous) techniques have been proposed. Hence, the implementations of innovative concepts, including smart finite zoning and continuous/discrete interfacing along with the use of artificial intelligence (AI) and machine learning (ML) notions for data-driven virtual optimizations, have been proposed herein.

The combination of physical, mathematical, and computational approaches has been used herein in response to the fundamental question of optimum virtual design of large systems. For large engineering systems like road/rail infrastructural network (e.g., large

gantries), the use of new simulation technology has been promoted herein. Instead of having a single numerical domain with its associated grid (mesh), the emerging idea includes a new approach to represent various complexities (joint fatigue life, buffeting, and so on) within limited dynamic zones in the computational domain. This works for both implementing advanced mathematical models (e.g., plasticity and fatigue models) as well as lowering computational time. The concept provides the basis for multiple numerical domains, running in parallel with multiple instances of solvers that communicate using advanced interface routines (e.g., mapping and condensation techniques). The interaction/communication of zones within the simulation system can be managed smartly using AI and ML technologies and optimum design can be carried out using the combination of analytical and smart data-driven schemes.

One of the main concerns for these new-generation techniques is how to represent changes of the dynamic system (e.g., fatigue, cracking, and non-linearities) to understand the consequences of solutions on design decisions. The research work herein is the fundamental idea for the procedure to combine a complexity-driven solution technique (e.g., non-linearity within individual dynamic zones) with efficient interfacing. These are accomplished within a designed computationally-efficient parallel simulation environment. The technique relies on separate and parallel efforts devoted to predicting the response of complex road/rail infrastructure (e.g., large gantries) and preventing the failure and damage to the vital infrastructure. The framework would also combine the sophisticated elastic-plastic material modelling on predicting damage and failure through the implementation of cross scale micro-macro mechanical models at selected dynamic zones.

For the real-world case studies, using the new simulation system, dynamic response and fatigue characteristics of large lightweight lattice gantry structures under external loads were investigated. In these case studies, problems of dynamic and pressure wave loading were considered for new design of large highway lattice structures, and special attention was devoted to the dynamic response and fatigue characteristics. Two full-scale field measurements data were used for the verification/calibration of the simulation system. After the full verification, the results of a comprehensive design scenario-table were used to define a “code of practice” using genetic algorithm symbolic regression approach for large road/rail lattice structures. The characteristics of the simulation system were shown graphically herein, using documented numerical examples where the efficiency of the new simulation technique is highlighted. The purpose of this paper is to present a new prospect, which improves the design of safe road/rail infrastructural systems under various external loads. Because of limited space, it has not been intended for the paper herein to publish all the detailed mathematical formulations and results of the new simulation framework; rather, the focus is on describing new physical and hybrid trends for the future of infrastructural simulations and designs.

2. Review of Discretization Concepts

The most essential issue related to the numerical simulations of engineering systems is to generate accurate and reliable response predictions in a reasonable computational time frame. On the other hand, these numerical domains are required to have reasonable details and realistic service life conditions for the verified design processes. The conventional finite element (FE) and computational fluid dynamic (CFD) solvers have generally been employed as basic simulation techniques for solving complex systems. Overall, the concepts of spatial discretization and meshing for coordinational-space to define simpler subspaces (elements) with approximate solutions have been used in the last seventy years. Different types of the so-called meshing/gridding schemes that fragment the single numerical space into small elements/cells/particles have been developed and heavily used. Today’s meshing technology is able to discretize a wide variety of complex geometries, adapt into large deformation of the engineering systems (e.g., adaptive re-meshing), and cope with non-conformal aspects of multibody grids. These novel meshing capabilities raise new challenges to the designing practice of safe engineering systems that can only

be met if the design and simulation integrate so that fast optimization cycles become available.

There have also been various attempts to introduce innovative discretization techniques [7–10] for dynamic systems (with evolution in time, like cracking phenomena) and interfacing technology for moving grids (e.g., moving vehicles). Most of these techniques have been developed for numerical simulation of complex multi-body systems based on the solution technique (e.g., discrete and continuous), accuracy, computational time, and the degrees of complexities. Although fixed Lagrangian grid has extensively been used for domain discretization in solid mechanics [8–10], its application for systems with large deformation and internal evolutions is limited. In the Lagrangian as well as the updated Lagrangian (with adaptive re-meshing) approaches, the process of large deformation of an engineering system is simulated as a material deformation fixed to the grid, where each cell transports its own properties (such as density, among others). For history-based transient simulations, as the deformation of the system advances, its properties may change in time (e.g., softening and physical cracking). Accordingly, the procedure of simulating and tracking of material deformation by predicting the time-transient histories of each numerical cell/grid is conventionally defined as the Lagrangian description. In the Lagrangian/updated Lagrangian algorithms, each individual cell/grid within the preliminary computational domain follows its fixed material zone during the deformation of the body.

On the other hand, for the Eulerian fixed/moving mesh approaches, rather than following each material cell (deformation front), the evolution of the material flow properties at every point in coordinatial space and time can be visualized. This means that the simulation of material deformation properties at a specified grid/cell depends on its spatial location (at coordinational space) and time. The computational mesh is conventionally fixed for this scheme, while the material deforms with respect to the mesh. The large deformation and distortions of the engineering systems can be simulated with more ease, but generally, it might have resolution issues for material deformation at free boundaries. Figure 1 shows a conventional Lagrangian fixed-grid finite element (FE) mesh and its stress results for gantry boom-leg joints.

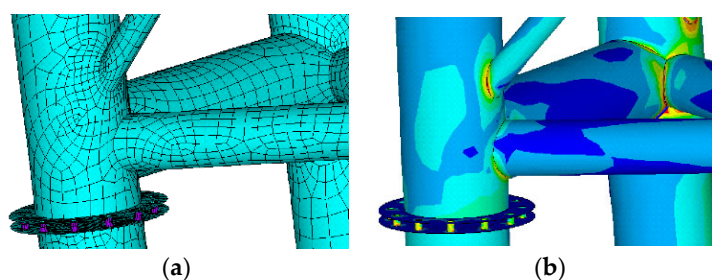


Figure 1. (a) Finite element (FE) numerical mesh for a gantry boom and (b) its typical stress contour results.

As both of Lagrangian and Eulerian methods have some shortcomings for real-world dynamic simulations of large structural systems, alternative hybrid techniques have also been developed [11–15] that combine the best features of both the Lagrangian and Eulerian approaches (arbitrary Lagrangian–Eulerian, ALE; mixed Lagrangian–Eulerian, MILE; multi material ALE, and so on). In these hybrid techniques, the grids of the computational mesh can move with the material deformation (in a Lagrangian fashion), or be fixed (in Eulerian manner), or even move in an arbitrary way to give a continuous rezoning capability. For the problems with moving and interfacing boundaries (e.g., a high sided vehicle, “HSV”, moving under a large gantry), different numerical approaches have been proposed to trace the boundaries during the simulation [16–18]. More detailed

discussions about conventional discretization and solution techniques can be found in the engineering textbooks [10–18].

3. New Zonal Concept and Mesh Interfacing

One of the main concerns for the conventional simulation techniques is how to represent changes of mesh and domain boundaries for the dynamic systems (e.g., moving objects, extension of domain, and cracking) to define the consequences of these changes on the solutions. The concepts of dynamic and evolving domain (internal and external) and its discretization techniques have been developed recently [19–21] to overcome numerical problems related to the continuous evolution of numerical domains. The transient nature of some numerical domains (e.g., moving vehicle under road structure) and its continuous changes/expansion have conventionally been handled using either element birth and death approach or the splitting of element layer at the stationary-moving interface. However, the newly proposed approach would treat the changing/evolved parts of the domain as a dynamic zone that can move/evolve in a predefined or calculated manner (e.g., movement of a truck under a gantry on a slow lane). These generated dynamic zones would be attached to the main domain through smart overlapping boundaries.

As the generated zones (or sub-domains) are interfaced into the main domain, a comprehensive mapping procedure (including nodal condensation, energy transfer or propagation interface, and so on) would be applied to the hybrid domain to handle the new material/energy input. The dynamic single/multiple zones can be stationary or moving depends on requirement of numerical model for the design process (e.g., passing of HSV or trains under a gantry structure). Figure 2 shows a digital model of a truck within a moving zone along with a portal gantry model and its meshing setup, as well as buffeting of HSVs' fatigue-scenario arrangement under a gantry structure.

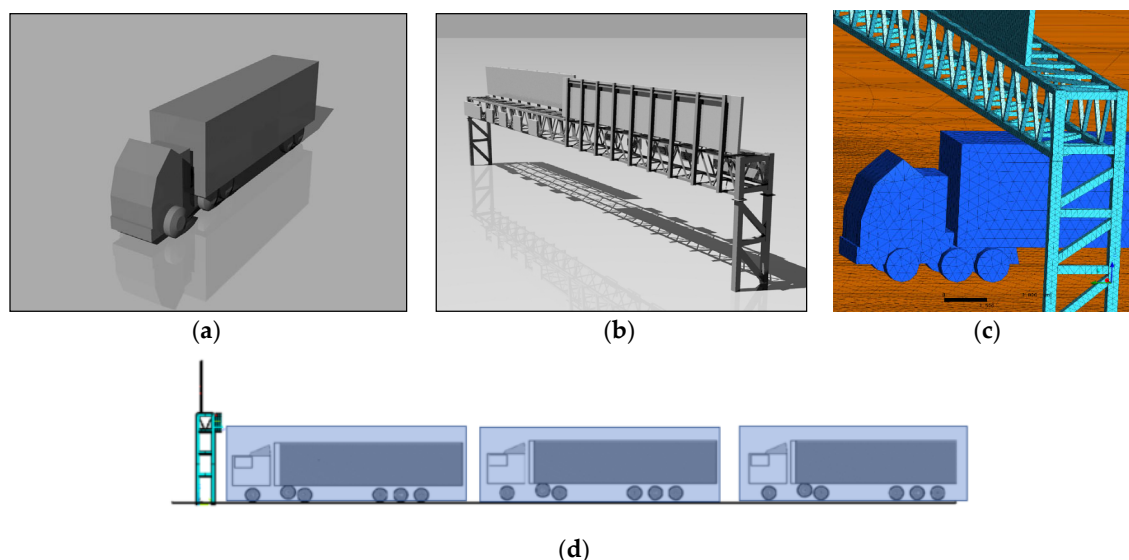


Figure 2. (a) CAD models for a typical high sided vehicle (HSV); (b) gantry structure (stationary zone); (c) overlapped discretized numerical domain; and (d) HSVs' arrangement for fatigue assessment scenarios with three moving zones.

As the numerical solution is performed on a full parallel-processing machine, multiple instances of the same solver (or alternatively different solvers) can be employed for the main domain and multiple zones, independently. The generated zones can gradually join the main domain (and become a part of main domain) or stay independent for further processing as the changes within the zones (i.e., movement, nonlinearities) come to an end. As shown in Figure 2a, the virtual porotype of a typical HSV can be placed with a dynamic moving zone for passage under a gantry model (defined as stationary high-

resolution zone) and the HSVs' fatigue passage scenario can be performed using three vehicle zones and a single stationary zone.

New zones and their associated mesh/grid are generated and moved during the simulation within the main numerical domain to capture the dynamic nature of the engineering system. As the generation of new material/energy within the dynamic domain produces numerical instabilities, it is essential to distribute the physical effects of new entries through balancing schemes [19]. Different types of material/energy evolution within the numerical domain can be perceived for dynamic engineering systems; namely, internal moving (e.g., vehicle movement) and evolving zones with different sources of energy sink/sourcing within the domain (kinetic energy during passage). The new concepts of dynamic zoning and finite local/global zonal systems can promote new generation of simulation techniques for dynamic engineering systems. It can also have an effect on reducing the field study costs as well as CPU (Central Processing Unit) time for the design of complex systems within mobility applications. The effect of propagation from local zone into global domain (e.g., vehicle buffeting pressure-wave propagation) and balancing/optimizing of computing power between stationary and moving zones can be accommodated into the simulation framework, as can be seen in Figure 3.

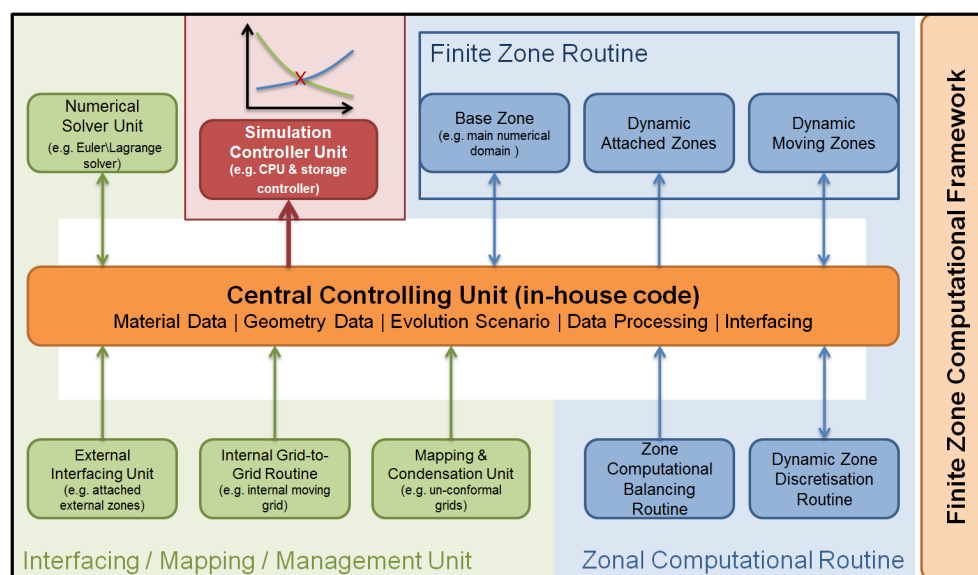


Figure 3. Components of dynamic finite zone computational framework and its central unit.

4. Overlapped Discretization Concepts

Today's simulation technologies are able to virtually examine a wide variety of design scenarios for complex engineering applications. These novel capabilities pose new challenges to the practice of conventional design that can only be met when the design and scenario-driven simulations are integrated. The design modification cycles can be sharply accelerated using these CPU-efficient virtual tools. The aim of this section is to present some new concepts for the next generation of discretization and solution techniques.

4.1. Multiple Grids Concepts

The conventional discretization of complex geometries to consider simpler elements and approximate the underlying physical variations within the element has long been established. Although the direct discretization of numerical domains using two layers of partitioning, which include initial meshing of domains and secondary partitioning for parallel-processing, are typical practices among design engineers, the computational efficiency of the scheme is under scrutiny. To manage the numerical discretization of the

engineering system in a more efficient manner, the concepts of overlapping/isolated zones having “actual” and “potential” grids are introduced [19]. Based on the evolution scenario within the numerical domain (e.g., passage of vehicle under a road structure), a zoning-plan for the numerical domain is defined and each zone is coded with a specific status number. These zones can be defined as main, void, partial overlapping, full overlapping, and high resolution zones, among others, which interact with each other. In the next step, discretization of individual zones is carried out based on their specific requirement (continuous, meshless, particle, and so on) and, depending on the defined scenarios, the actual and potential interface grids are defined. These grids are assembled into a finite zone simulation system using various types of interfaces (active and passive interfaces) to be sent to the parallel computational solvers. Different instances of same and/or different solvers would be employed on different zones and an appropriate number of processors is chosen for each computational zone to achieve the best computational balance (minimum waiting time).

For complex design scenarios, a smart auxiliary virtual unit would also be employed where AI and ML technologies are mobilized to reduce the number of design cycles in high resolution zones (e.g., detailed design zones within the main numerical domain). Figure 4 shows the schematic architecture of the numerical system with its component units.

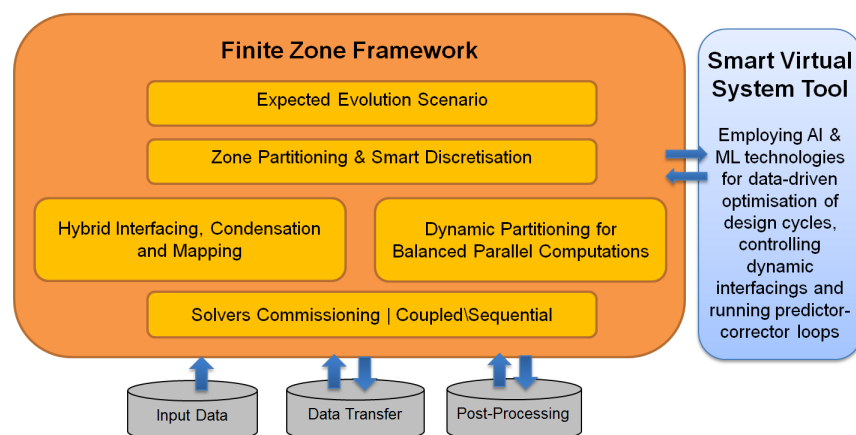


Figure 4. Schematic architecture of finite zone computational system. AI, artificial intelligence; ML, machine learning.

4.2. Numerical Stability

The discretization of the domain and its multi-zones have to be managed in a numerically efficient manner to avoid numerical instabilities and excessive iteration. For the simulation of engineering systems with internal zones (i.e., fatigue prone zone), the high resolution zonal grid interfacing technique can be employed and zonal discretization with a dynamic grid-to-grid interface (GGI) can be implemented. The dynamic mapping of zones into the main domain is performed by considering a void zone (VZ) concept. The new concept of a VZ creates a virtual zone within the domain, which replaces the actual zone to exchange the variables at zone boundaries. Different methodologies are used for the mapping scheme; namely, direct mapping to the zone boundaries or indirect mapping through overlapping of the zone grid with VZ mesh. Figure 5 shows some partial and full overlapping grids for simple 2D numerical domains [22].

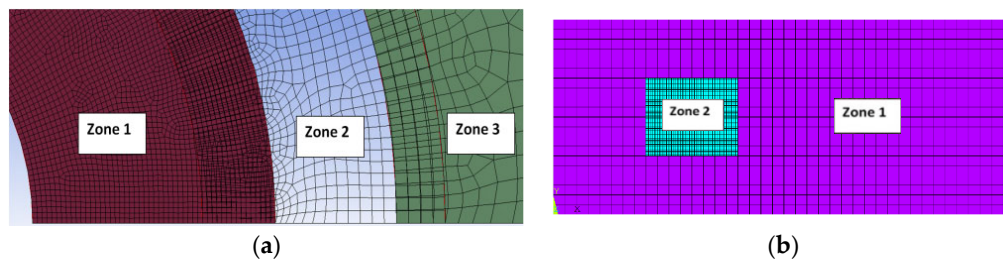


Figure 5. Zonal concepts for (a) partial and (b) full overlapping grids.

The multi-zone simulations are developed within this framework, where physical phenomena at different scale/resolutions (e.g., micro-cracks and fatigue) can also be handled using continuous and discrete high-resolution zones. For the discrete approach, the physical phenomena at high resolution are simulated at discrete points (gauss integration points in FE, among others) using lattice/structured grid and the results correspond to the higher scale grid. While for the continuous technique, full or partial overlapping zones can be employed in several layers to bridge the scale/resolution within the numerical domains. In Figure 5b, simple overlapping 2D meshes are outlined, where the concept of VZ is initially used to define the high-resolution area and its boundaries. The introduction of a second overlapping high-resolution zone is carried out using the balance material/energy initiation scheme, where the distribution of material and energy through boundaries is carried out [22].

5. Fast Solver Technology

The concept of finite zoning and advanced interfacing techniques has already been presented in the previous sections. However, without a fast and efficient numerical solver technology that can dramatically reduce the computational time, the proposed virtual design system would not be able to deliver an optimum mechanical design in a practical time frame. This section highlights a brief description of the development and adaptation of the novel spectral-Eigen technique [23–28] for the introduction of a new solver technology in design of infrastructure systems. The technique has been developed to accelerate the computation of damped dynamic responses of large systems.

5.1. Complex Damped Spectral Solver

The frequency-domain damped spectral Eigen element approach, which has already been developed for vibrational analysis [23–28], benefits from the speed and accuracy of fast Fourier transform (FFT) and the fractional derivative damping models. The technique has a fundamental difference from FE method, where exact wave shape functions are used for element formulation instead of simple approximate shape functions in the FE method. These exact shape functions are used to formulate spectral elements, which can also be used to find the natural frequencies and mode shapes of structures. Although many parts of the technique have been presented extensively in previous publications [23–30], some extended parts are represented here to elaborate on the efficiency of the method for damped vibrating systems. Consider a simple case of a beam with pinned joints, as shown in Figure 6.

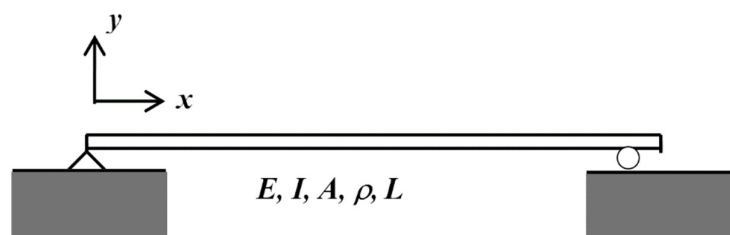


Figure 6. Simply supported beam.

The spectral solution for the flexural vibration of a beam can be assumed as [23–26]

$$\hat{u}_n(x) = A_n e^{-i\kappa_n x} + B_n e^{-\kappa_n x} + C_n e^{-i\kappa_n(L-x)} + D_n e^{-\kappa_n(L-x)} \quad (1)$$

where κ is the wavenumber. The boundary conditions at each frequency steps are

$$x = 0, L \rightarrow \hat{u} = 0 \quad (2)$$

$$x = 0, L \rightarrow EI \frac{d^2 \hat{u}}{dx^2} \hat{u} = 0 \quad (3)$$

which gives the four conditions in sine and cosine format as

$$\begin{cases} A + C = 0 \\ A \cos \kappa L + B \sin \kappa L + C \cosh \kappa L + D \sinh \kappa L = 0 \\ A - C = 0 \\ -A \cos \kappa L - B \sin \kappa L + C \cosh \kappa L + D \sinh \kappa L = 0 \end{cases} \quad (4)$$

It can be seen that $A = C = 0$, and

$$\begin{bmatrix} \sin \kappa L & \sinh \kappa L \\ -\sin \kappa L & \sinh \kappa L \end{bmatrix} \begin{bmatrix} B \\ D \end{bmatrix} = 0 \quad (5)$$

As the hyperbolic term is zero, only when $\kappa L = 0$, then

$$\sin \kappa L = 0 \rightarrow \kappa L = n\pi \rightarrow \sqrt{\omega} \left[\frac{\rho A}{EI} \right]^{\frac{1}{4}} \quad (6)$$

$$L = n\pi \rightarrow \omega = \frac{n^2 \pi^2}{L^2} \left(\frac{EI}{\rho A} \right)^{\frac{1}{2}} \quad (7)$$

which gives the exact solution for the spectral Eigen frequencies of the beam element. An interesting point here is that, as the spectral solution uses an exact stiffness formulation, there is no limit on the frequency resolution. This exact solution of the governing differential equation of motion gives an infinite number of discrete resonant frequencies ($n = 1, 2, 3, \dots$) using a single spectral element. To assess the efficiency of the spectral solution, consider a conventional FE numerical model of a beam based on an approximate interpolation shape function. The displacement, stiffness, and consistent mass matrices can be written as

$$[u] = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}; \quad [K] = \frac{EI}{L^3} \begin{bmatrix} 4L^2 & 2L^2 \\ 2L & 4L^2 \end{bmatrix} \quad (8)$$

$$[M] = \frac{\rho AL}{420} \begin{bmatrix} 4L^2 & -3L^2 \\ -3L^2 & 4L^2 \end{bmatrix} \quad (9)$$

and for free vibration, the conventional FE Eigen equation of the beam can be written as

$$\left\{ \frac{EI}{L^3} \begin{bmatrix} 4 & 2 \\ 2 & 4 \end{bmatrix} - \omega^2 \frac{\rho AL}{420} \begin{bmatrix} 4 & -3 \\ -3 & 4 \end{bmatrix} \right\} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (10)$$

The approximate natural frequencies can then be obtained by letting the determinant equal zero, which gives

$$\omega_1 = \frac{\sqrt{120}}{L^2} \sqrt{\frac{EI}{\rho A}}; \quad \omega_2 = \frac{\sqrt{2520}}{L^2} \sqrt{\frac{EI}{\rho A}} \quad (11)$$

Comparing these two Eigen equations shows that the conventional FE method has about 10% error for the first natural mode, and about 25% error for the second natural mode (with a single element) compared with the exact solution (spectral Eigen solution). It should be noted that, as there are two degrees of freedom for the FE model, only the first two natural frequencies can be extracted in the conventional method, compared with the infinite mode numbers/shapes that can be extracted in the spectral method (with a

single spectral element). This is a basic novel concept for decreasing the number of elements (as well as CPU time, memory, and data storage) for large structural systems within the next generation of simulation tools. The interest herein is in transient analyses of 3D frame structures, which, as a starting point, consider the governing system of equations for dynamic motion describing undamped free vibration of a three-dimensional structure as

$$[K][u] + [M][\ddot{u}] = 0 \quad (12)$$

As the structure is in free vibration mode (harmonic motion),

$$u(t) = Ae^{i\omega t} \rightarrow \{[K] - \omega^2[M]\}[u] = 0 \quad (13)$$

which is a system of algebraic homogeneous equations where the non-trivial solutions exist when the determinant of the coefficient matrix is zero. The determinant equation can be written as [28–30]

$$(\omega^2)^N + c_1(\omega^2)^{N-1} + c_2(\omega^2)^{N-2} + \dots \dots c_N = 0 \quad (14)$$

where N is the dimension of the system matrices and $c_1, c_2 \dots$ are constants. The roots of this polynomial equation are the square of the natural frequencies. There are as many frequencies as the order of the system equations. The natural frequencies and their corresponding mode shapes (eigenvectors) can then be used to form generalised mass and stiffness matrices for the coordinate transformation as

$$[\tilde{K}][v] + [\tilde{M}][\dot{v}] = [\varphi]^T[F] \quad (15)$$

where $[\tilde{K}]$, $[\tilde{M}]$, and $[F]$ are generalised stiffness, mass, and force matrices, respectively. The system would then be uncoupled and each equation would be similar to that for a single degree of freedom system. As all real structures have some type of damping (viscous, hysteretic, coulomb, and so on) and the damping is usually small, then certain simplifying assumptions can be made in the conventional FE method as [8]

$$[K][u] + [C][\dot{u}] + [M][\ddot{u}] = [F] \quad (16)$$

where $[C]$ is a damping matrix. The spectral solution for the equation of motion can be presented as [30]

$$u(x, t) = \sum_n \hat{u}_n(x, \omega_n) e^{i\omega_n t} \quad (17)$$

and the spectral representation for the time derivative as

$$\frac{\partial u}{\partial t} = \frac{\partial \sum \hat{u}_n e^{i\omega_n t}}{\partial t} = \sum i\omega_n \hat{u}_n e^{i\omega_n t} \quad (18)$$

Then, the differential equation in spectral format can be rewritten as

$$\sum_n \left\{ \hat{u}_n + c_1 \frac{d\hat{u}_n}{dx} + c_1 \frac{d\hat{u}_n}{dx} + c_2 i\omega_n \hat{u}_n + c_3 \frac{d^2 \hat{u}_n}{dx^2} + c_4 (i\omega_n)^2 \hat{u}_n + c_5 (i\omega) \frac{d\hat{u}_n}{dx} + \dots \right\} e^{i\omega_n t} = 0 \quad (19)$$

After some mathematical manipulations, the equation can be written as

$$C_1(x, \omega_n) \hat{u}_n + C_2(x, \omega_n) \frac{d\hat{u}_n}{dx} + C_3(x, \omega_n) \frac{d^2 \hat{u}_n}{dx^2} + \dots = 0 \quad (20)$$

where coefficients $C_1, C_2 \dots$ are complex values. The summation of n frequency components reconstructs the time dependency for the dynamic response. For a linear differential equation with constant coefficients, the spectral solution can have the form $Ce^{i\kappa x}$, where κ is called the wavenumber and can be obtained by solving the characteristic equation. The complete spectral solution of any differential equation can be obtained by the summation of the modes for each of the frequency values [30], as follows:

$$u(x, t) = \sum_n (C_{1n} e^{i\kappa_{1n}x} + C_{2n} e^{i\kappa_{2n}x} + \dots + C_{mn} e^{i\kappa_{mn}x}) e^{i\omega_n t} \quad (21)$$

Now, consider the equation of motion for a damped large structural system as [8]

$$ku + c\dot{u} + m\ddot{u} = F(t) \quad (22)$$

The general solution of the homogenous form, $F(t) = 0$, of this equation can be found [9] as

$$u(t) = e^{-\omega_u \zeta t} (c_1 e^{-i\omega_d t} + c_2 e^{+i\omega_d t}) \quad (23)$$

where $\omega_u = \sqrt{\frac{k}{m}}$ is the undamped natural frequency, $\omega_d = \omega_u \sqrt{1 - \zeta^2}$, and $\zeta = c/2m\omega_u$. If the general time history dynamic load is written in the spectral decomposition format as

$$F(t) = \sum_{n=0}^{N-1} \hat{F}_n e^{+i\omega_n t} \quad (24)$$

the response of the system can also be decomposed as

$$u(t) = \sum_{n=0}^{N-1} \hat{u}_n e^{+i\omega_n t} \quad (25)$$

where $\hat{F}_n$ and $\hat{u}_n$ are the unknown force and displacement amplitude spectrum and N is the number of frequency components. The governing equation of motion for a dynamic system can be written in spectral format as

$$\sum_{n=0}^{N-1} \hat{k}_n \hat{u}_n e^{i\omega_n t} = \sum_{n=0}^{N-1} \hat{F}_n e^{i\omega_n t} \quad (26)$$

where $\hat{k}_n$ is the dynamic stiffness term. As this equation should be true at any frequency and time, after removing the summation, the equation can be solved using conventional assembled matrix algebra. A more comprehensive discussion about the fundamentals of the complex spectral technique can be found in [23–30].

5.2. Numerical Damping Models

This part of the paper presents a methodology to incorporate damping into the exact spectral-Eigen method. The fractional derivatives damping models have already been developed [31] to model the material intrinsic damping as well as damping devices in engineering systems. One of the simplest fractional derivatives damping models [26] has been incorporated into the spectral element technique for transient analyses herein. Consider the governing differential equation of motion for a simple element as

$$\frac{d^2 \hat{u}}{dx^2} + \omega^2 \lambda \hat{u} = 0 \quad (27)$$

where $\lambda = \rho/E$. The damped form of the equation can be written as [28]

$$\frac{d^2 \hat{u}}{dx^2} + \omega^2 \lambda(i\omega) \hat{u} = 0 \quad (28)$$

where, in this case, $\lambda(i\omega) = \frac{\rho}{E(i\omega)}$. The only change that occurs in the spectral relation for the damped element is

$$\kappa_c = \pm \omega(\lambda)^{\frac{1}{2}} \xrightarrow{\text{fractional}} \kappa_f = \pm \omega[\lambda(i\omega)]^{\frac{1}{2}} \quad (29)$$

where subscripts c and f represent the conventional and fractional derivative module cases, respectively. The following spectral relation is given when the fractional derivative constitutive relation is employed:

$$\kappa_f = \pm \omega \left[\frac{(1 + a(i\omega)^b)\rho}{e + f(i\omega)^c} \right]^{\frac{1}{2}} \quad (30)$$

and the fractional derivative element shape function can be written as [23,28]

$$\hat{u}(x) = \left(\frac{\sin \kappa_f (L - x)}{\sin \kappa_f L} \right) \hat{u}_1 + \left(\frac{\sin \kappa_f x}{\sin \kappa_f L} \right) \hat{u}_2 \quad (31)$$

Thus, the dynamic stiffness matrix, which includes the fractional derivative damping modulus effects, is

$$[\hat{K}_f] = \begin{bmatrix} \frac{\kappa_f L}{\tan(\kappa_f L)} & \frac{-\kappa_f L}{\sin(\kappa_f L)} \\ -\kappa_f L & \frac{\kappa_f L}{\tan(\kappa_f L)} \\ \sin(\kappa_f L) & \tan(\kappa_f L) \end{bmatrix} \quad (32)$$

An important point here is that the dynamic stiffness matrix includes the damping effects; therefore, there is no need to assemble an individual numerical damping matrix for the structure. For the more general case of viscoelastic material damping modelling, a simplest conventional constitutive equation that adequately describes the infinitesimal deformation of a viscoelastic body can be written as [27]

$$\sum_{n=0}^{\infty} u_n \frac{d^n \sigma(t)}{dt^n} = \sum_{m=0}^{\infty} q_m \frac{d^m \varepsilon(t)}{dt^m} \quad (33)$$

where u_n and q_m are constant coefficients. The stress and strain in this form are related through multiple derivatives in time. One of the advantages of the spectral method is that time-dependent effects can be easily incorporated into the formulation. The spectral form of Equation (23) is [30]

$$\left[\sum_{n=0}^{\infty} u_n (i\omega)^n \right] \hat{\sigma} = \left[\sum_{m=0}^{\infty} q_m (i\omega)^m \right] \hat{\varepsilon} \quad (34)$$

or it can be written in simple form as

$$\hat{\sigma} = \frac{\sum_{m=0}^{\infty} q_m (i\omega)^m}{\sum_{n=0}^{\infty} u_n (i\omega)^n} \hat{\varepsilon} \quad (35)$$

which is the viscoelastic form of the linear-elastic constitutive relation. The more familiar form of the viscoelastic behavior that adequately describes the infinitesimal deformation of a viscoelastic engineering systems has been proposed as [27]

$$\sigma + a \frac{d\sigma}{dt} = b\varepsilon + c \frac{d\varepsilon}{dt} \quad (36)$$

where a , b , and c are constants. This linear differential equation can be expressed in fractional derivative form as

$$\sigma(t) + \sum_{i=1}^M a_i D^{b_i} [\sigma(t)] = e_0 \varepsilon(t) + \sum_{j=1}^N f_j D^{c_j} [\varepsilon(t)] \quad (37)$$

where a_i , b_i , c_j , e_0 , and f_j are model parameters. As previous experimental tests [31,32] indicate that most viscoelastic materials can be accurately modelled using only the first fractional derivative term in each series, the result is a five-parameter model expressed as

$$\sigma(t) + a D^a [\sigma(t)] = e \varepsilon(t) + f D^c [\varepsilon(t)] \quad (38)$$

Taking the Fourier transform leads to

$$\hat{\sigma}(i\omega) + a(i\omega)^b \hat{\sigma}(i\omega) = e \hat{\varepsilon}(i\omega) + f(i\omega)^c \hat{\varepsilon}(i\omega) \quad (39)$$

where the time variational terms are formulated in the frequency domain instead of a direct formulation in the time domain, and $\hat{\sigma}(i\omega)$ and $\hat{\varepsilon}(i\omega)$ are the stress and strain histories in transform coordinates. The more familiar relationship between stress and strain can be obtained by rearranging as

$$\hat{\sigma}(i\omega) = \frac{e + f(i\omega)^c}{1 + a(i\omega)^b} \hat{\varepsilon}(i\omega) \quad (40)$$

which can also be written as

$$\hat{\sigma}(i\omega) = \hat{E}(\omega) \hat{\varepsilon}(i\omega), \quad \hat{E}(\omega) = \frac{e + f(i\omega)^c}{1 + a(i\omega)^b} \quad (41)$$

which is similar to the conventional $\sigma = E\varepsilon$ for elastic materials. However, in the fractional derivative model, the modulus is complex; frequency dependent; and, most importantly, a function of fractional powers of frequency.

6. Mechanical Systems—Case Study Application

The basic concepts of dynamic zone techniques using partitioning, meshing, and interfacing have been briefly presented in the first part of the paper. In this part, the application of the technique for the optimum design of road/rail structures is presented. The real-world case study of a large road gantry design including its vibrational and fatigue behavior was investigated. Large gantry structures experience cyclic pressure waves under wind gust and vehicle buffeting loads, which have to be taken into account for their design. The external air flow over HSVs generates aerodynamic pressures, which would affect the dynamic and fatigue performance of the large highway structures.

6.1. Moving Zones—CFD Application

The CFD technique has been broadly used in the last fifty years for the fluid and fluid–structure interaction problems. Predictions of the fluid motions around structures along with the pressure wave generated by moving objects are crucial for the design of engineering systems (fluid–structure problem) in many branches of engineering. Until recent decades, only the wind tunnel and full-scale field studies could represent the service life conditions for the fluid–structure interactions and fluid dynamics around large structures. However, with the rapid developments of advanced numerical techniques, including the expansion of computational power and parallelization, sophisticated pre- and post-processing capabilities, and more efficient algorithms, CFD becomes a viable tool for making numerical simulations of complex geometric fluid–structure interaction problems.

Large space structures like road/rail gantries may be subject to vibrational resonance owing to aerodynamic effects from environmental wind (gust effects) and/or HSV buffeting. In addition to ultimate strength and static/dynamic forces considered for the design of these vital structures, there are also other dynamic effects like fatigue service life that need to be considered in the design. These dynamic considerations can be characterized into two major effects: firstly, it can induce significant fatigue effects through large cyclic stresses, which have to be considered to avoid premature fatigue failures during expected life; secondly, it can have excessive vibrational effects and resonance (flexural and torsional), which can either cause structural and equipment damages or prevent/reduce their service functionalities.

The simulations of moving objects/zones within numerical domains that include fluid and solid boundaries have always been a challenging task among scientist and practicing engineers. The motion of a virtual vehicle under a solid/flexible gantry model needs to be accurately modeled to generate an appropriate dynamic pressure wave for the design. Some early aspects of the advanced zoning technique have been developed recently to overcome numerical problems related to continuous motion/generation of objects

within a numerical domain [19]. The dynamic nature of the numerical domain in these simulations has conventionally been ignored or modelled through some pseudo-static techniques. However, using the efficient interfacing technology and the advance grid to grid interface, the movement of the vehicle zone against the stationary gantry zone (within the main atmospheric domain) can be simulated for road/rail structure application. The standard formulation for the conservation of the variable (ϕ) for a control volume V with moving boundaries is [33–36]

$$\frac{d}{dt} \int_V \rho \phi dV + \int_{\partial V} \rho \phi (u - u_g) \cdot dA = \int_{\partial V} \Gamma \nabla \phi \cdot dA + \int_V S_\phi dV \quad (42)$$

where ρ and u are the fluid density and velocity, respectively, and u_g is the velocity of moving interface. The time varying conservation term in Equation (42) can be numerically calculated using the backward difference method as

$$\frac{d}{dt} \int_V \rho \phi dV = \frac{(\rho \phi V)^{n+1} - (\rho \phi V)^n}{\Delta t} \quad (43)$$

and the change in the control volume during the simulation can also be written as

$$V^{n+1} = V^n + \frac{dV}{dt} \Delta t = V^n + \left(\int_{\partial V} u_g \cdot dA \right) \Delta t = V^n + \left(\sum_j^f u_{g,j} A_j \right) \Delta t \quad (44)$$

where A_j is the face area vector and f is the number of faces on the control volume. More comprehensive discussions about the conventional moving mesh theory can be found in [36,37]. Among dynamic mesh methods, the moving finite volume method [10,18] and the moving finite difference method have attracted considerable interest for dynamic simulation in recent years.

To start the building of a numerical domain, the digital geometry of the gantry structure (high resolution zone) and part of the road along with the geometry representing the external vehicle boundaries (moving zone) and its surrounding atmospheric environments (main domain) can be generated. Figure 7 shows the initial CAD model of a large portal gantry along with HSV and its track under the gantry.

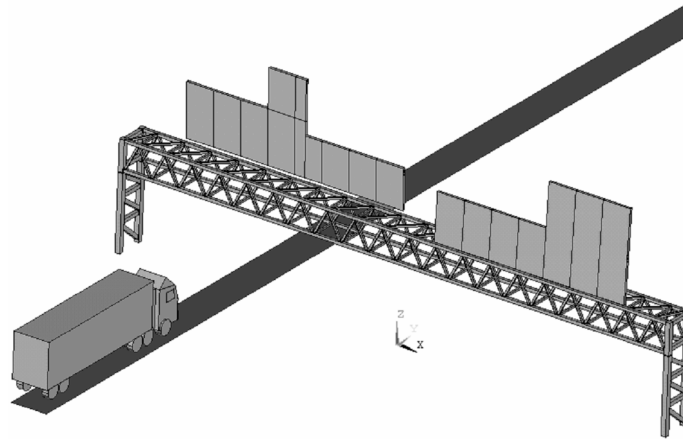


Figure 7. CAD model of HSV (moving zone), portal gantry (high resolution stationary zone), and zonal evolution track (lane in a carriageway).

6.2. Buffeting Simulations and Verifications

The size of pressure waves generated by the passage of HSV depends on the size, speed, and aerodynamic properties of the vehicle, as well as the geometry of the gantry structure and clearance between the structure and vehicle. The dynamic response of a gantry structure to a pressure wave can be evaluated using full-scale field measurement. Alternatively, a carefully-setup downscaled wind tunnel test can also provide data for the size and trend of dynamic pressure exerted on the gantry structure during the passage.

Neither of these methods are a financially feasible technique for design data generation considering a wide variety of vehicle types/sizes (truck, buses, double-decker buses, and so on), their aerodynamic properties (with/without air deflector, among others), and speeds.

In addition, after calculating the pressure waves, dynamic and fatigue analyses of the large gantry structures have to be carried out using solid mechanics techniques. Traditionally, it has been accomplished using the history-based FE method, where time transient linear/nonlinear simulation of the structure is carried out at sequential time steps followed by a fatigue assessment analyses. Although the application of the FE method to structural dynamics and fatigue assessment is popular and successful, long computational times are expected for transient simulation of large structures under pressure-history loading. Hence, in the research work herein, a software code written based on the complex damped spectral Eigen technique (CDSET) scheme, which has been presented in the previous sections, is employed. The technique is concerned with the synthesis of waveforms from the super-position of many frequency components. It is based on the exact wave solution of the governing differential equation for the dynamic motion of structures. However, it differs from the classical FE method because it uses fast Fourier transform for conversion purposes.

To start the vehicle buffeting investigation using the finite zone technique herein, it is essential to carry out a verification study to validate the reliability and accuracy of the results. A 3D verification case study was proposed to verify the results of developed multi-zone CFD simulation compared with the results of full-scale field studies as well as basic physical principals of fluid–structure interactions. In the study herein, the reported measurements for full-scale field study of a HSV under cantilever mast [38] were simulated using the multi-zone CFD technique. A HSV vehicle-zone model along with a model of a signal box as well as atmospheric environment (main domain) were developed and exported to the solver for vehicle buffeting analyses. Figure 8 shows the field-study details including a cantilever mast, signal box, and HSV vehicle.

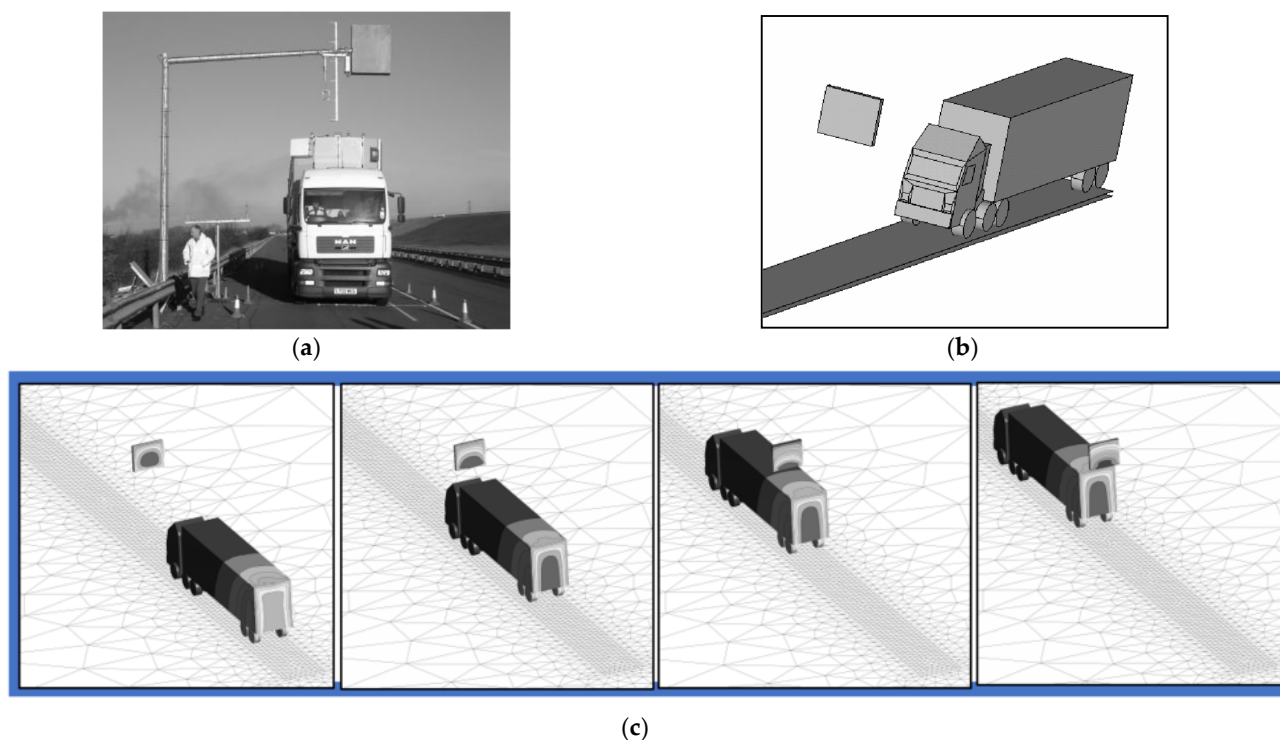


Figure 8. (a) Field study setup (HSV and signal box cantilever gantry, [38]); (b) simplified HSV model with its signal box; and (c) snapshots of HSV passage simulation under the signal box.

The identical speed of the vehicle and the positions of measurement points above the centerline of the vehicle are chosen to simulate the replica of the field study data. A three-dimensional geometry model of the simulated test is also shown in Figure 8, where the geometry of the cantilever is neglected because of its minor effects on the generated pressure wave. The overall dimensions of the HSV are taken into account for the 3D geometry model, although the detailed shape is not identical to the real HSV. The movement of the HSV within the simulation domain (within atmospheric condition with air at 25 °C) and its pressure contours variation on signal box are also shown in Figure 8.

The generation of the dynamic pressure wave on the signal box was calculated in the multi-zone CFD domain using the motion of the HSV zone against the main fluid domain (atmospheric air), while the signal box zone is assumed to be stationary. The variations of peak pressure with height above the centerline of the HSV are shown in Figure 9a for measured field-study and zonal-CFD simulated results. Figure 9b also shows the simulated time-history pressure variations for different points above the centerline of HSV as it travels under the signal box. The positive pressures increased as the front of the HSV approached the signal box, while a pronounced suction was generated as the leading edge of the trailer passed beneath the box. This was followed by a decrease in the suction as the rest of the trailer passed beneath the box.

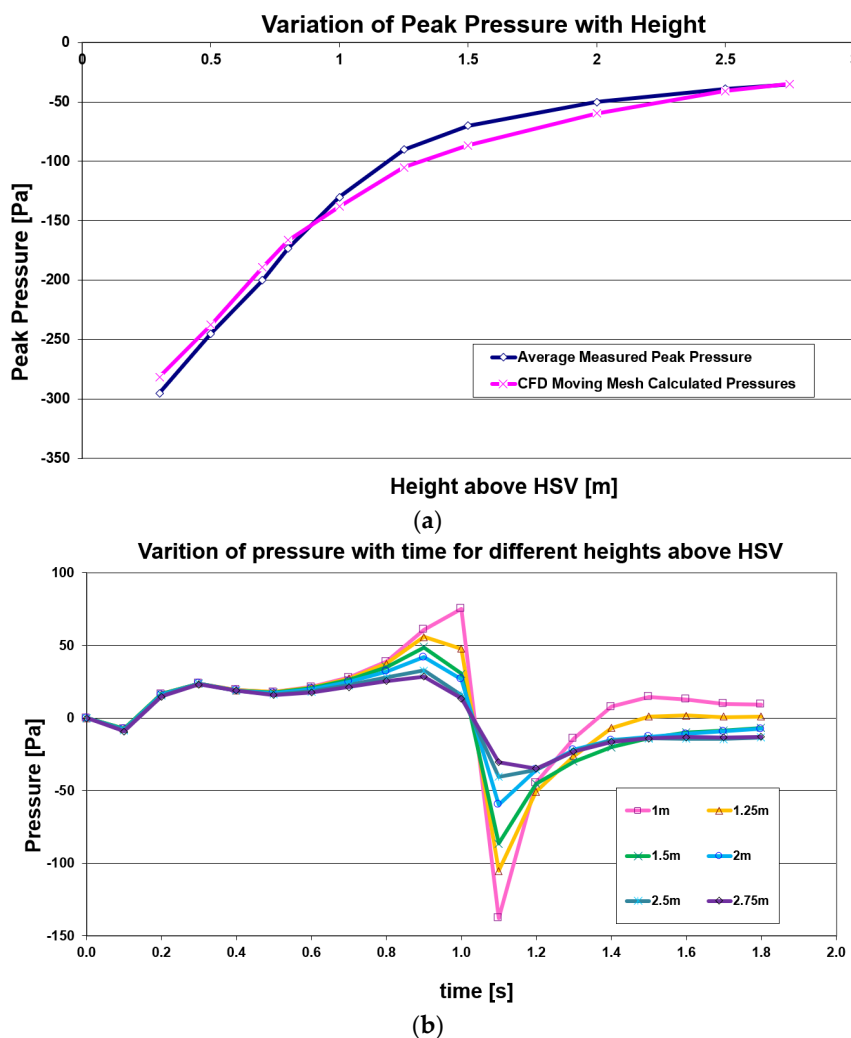


Figure 9. (a) Comparison of average peak pressure results for field study and computational fluid dynamic (CFD) zonal simulation and (b) calculated time-history pressure records at different height above the HSV.

A small negative pressure was then generated by the wake flow bubble behind the trailer. The amount of peak negative pressure generated during the passage scenario depends on the height of the calculation point above the centerline of HSV, with greater suction closer to the vehicle. The comparison of the simulated and real world field-study results shows a very encouraging trend, where the new multi-zone CFD simulation technology prompts a real alternative for the expensive field-study and wind tunnel experiments. In the work herein, a couple more verifications were carried out (not reported herein because of space limitation) and the simulation results were scrutinized using available experimental as well as basic fluid–structure theories. The CPU time for the above-mentioned simulation with three different zones and four available parallel cores was reported as 11,850 s (over three hours of CPU time) by the solver.

7. Design Applications

Some new algorithms as well as novel computational approaches have already been developed by scientist and practicing engineers to improve and optimize the design process across the board. However, owing to complexity, computational time, and interfacing obstacles, many of these modelling techniques have not been mobilized within the mainstream engineering design firms. Hence, with a carefully-designed framework, it is possible to combine these state-of-the-art technologies (i.e., finite zoning, advance meshing, novel solver techniques, and so on) to reduce the required design time/cost and accelerate the use of efficient virtual tools.

7.1. Design Rules Implimentation

To investigate the feasibility of innovative design (and design rules) for new road/rail structures, a series of comprehensive simulation scenarios were carried out to establish the dynamic and fatigue design rules. Hence, the environmental wind gust and buffeting effects of HSV were considered for the design of large portal gantries. Initially, the results of a comprehensive field-study [39] were used to verify the outcomes of the new simulation system for the large portal gantries. Full-scale field study data were collected using a full set of measuring devices (pressure and height sensors, ultrasonic anemometer, and video cameras) to record the physical quantities during the passages of HSVs under a large portal gantry. Figure 10 shows the real-world gantry structure, where the pressure waves were measured at different heights above the HSV in the slow lane as well as the virtual CAD model (vehicle, gantry zones).

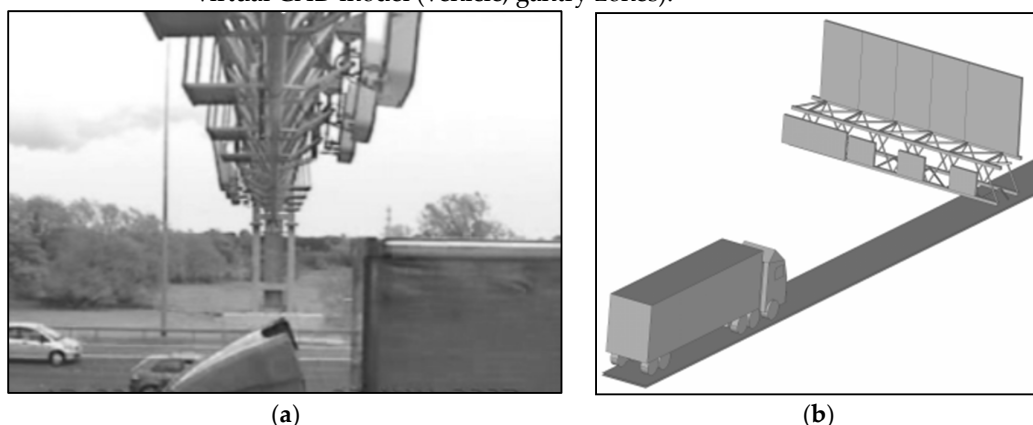


Figure 10. (a) Typical passage of an HSV under portal gantry for field study [39] and (b) CAD model of HSV and partial gantry boom.

For the zonal-CFD technique, the geometry of the HSV was simplified and the gantry legs were neglected owing to minimal effects on the buffeting results. The far-filed gantry boom over the opposite traffic lanes was also modeled because of its negligible pressure

effects (for CFD simulation, not for vibration simulation). The surface geometry of the simulated HSV developed in earlier stages was imprinted in the moving vehicle zone and the height of the vehicle was adjusted to 4.4 m. The partial 3D geometry model of the gantry boom includes the traffic signals and a large traffic sign, which were modelled to resemble the field study conditions. Both HSV and gantry zones are imported into main fluid domain (air at 25 °C) using appropriate coordinate system. The discretization of the main domain as well as moving/stationary zones were carried out using advanced mesh control routines to create finer mesh zones for the areas of interest in the domain (top of the HSV and area around the gantry boom).

The numerical simulations of HSV passage under the virtual portal gantry model are shown in Figure 11a at different time steps. The variations of peak calculated pressure against the height above the centerline of the HSV and its smoothed design graph are also shown in Figure 11b.

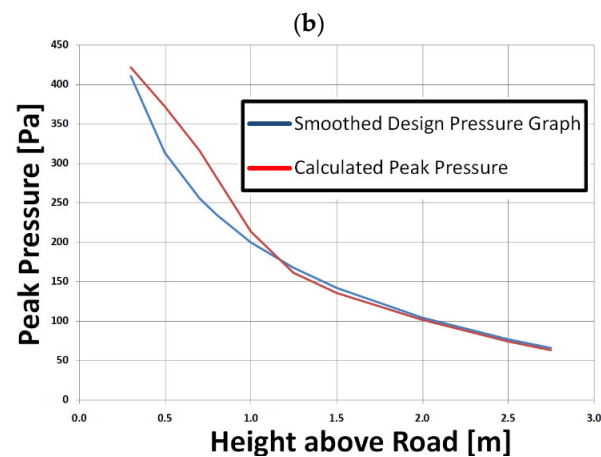
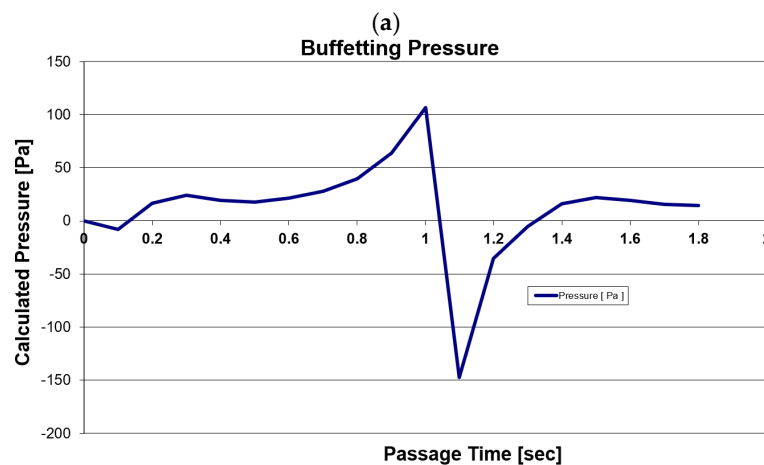
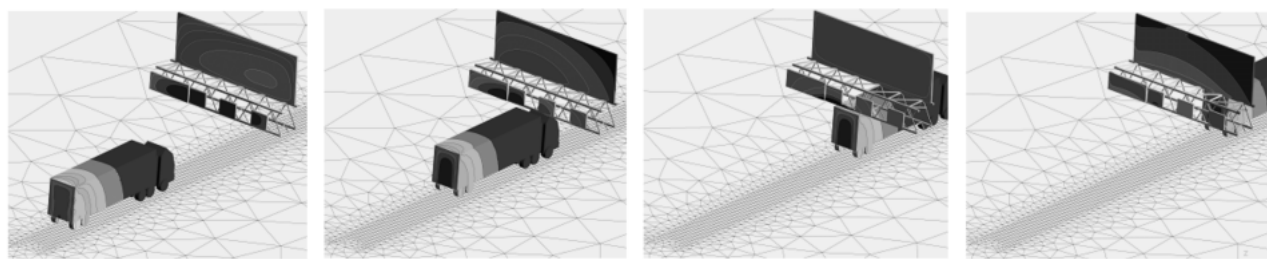


Figure 11. (a) Snapshots of HSV passage under gantry boom, (b) calculated time-history pressure results, and (c) calculated peak pressure and its smoothed design curve.

7.2. Hybrid Modelling—Genetic Algorithm Regression

New hybrid physical-data driven modelling schemes have steadily been developed over the last three decades and the use of machine learning (ML) and artificial intelligence (AI) technologies has increasingly been promoted in engineering analyses and design routines. The power of hybrid modelling for engineering problem-solving routines is becoming ostensible for many branches of engineering including structural analyses and design procedures. These modelling and design techniques share the same fundamental propositions, namely faster and more accurate modelling and the ability to dynamically change the rules using new data. The source of engineering data for economical and efficient design is growing broader by the introduction of experimental, field study, and simulation data along with smart fitting and extrapolation power of data-driven technologies.

For the design of large infrastructural systems, ML and AI are employed as algorithm-based and data-driven schemes, which can be combined with physical analytical and numerical schemes for better optimization and problem-solving capabilities. For these applications, the hybrid models can be categorically grouped into different groups; namely, auxiliary, augmented, full, and dynamic hybrid models, where different optimization applications can be handled using an appropriate type of a hybrid model. While for auxiliary hybrid models, parameters in the physical/empirical models are function-fitted using ML and AI tools, in the case of augmented hybrid models, physical models are augmented with terms/parts derived by function-fitting features of ML and AI tools. For the full hybrid models, data trends from ML and AI can be used along with physical laws to derive the hybrid model. Finally, in the case of trained (or dynamic) hybrid models, existing hybrid models can be subjected to further ML and AI tools for improvement and updating (based on new data).

As these techniques are improving and attracting more research into their effectiveness, the drive towards greater scrutiny and examination of the scheme for wider applications in engineering design routines has been raised. These emerging applications can have a great potential for the future of the design of complex systems and their sub-systems, where it can save time and efforts during the design process along with more predictive power for the response of the final engineering system. On the other hand, different machine learning schemes have been developed as a part of general data-driven models, which can handle data classification and pattern recognition. As machine learning algorithms require accurate and reliable data (a sufficient volume of data) to train and learn, experimental, simulated, and/or mined data should be provided for design purposes.

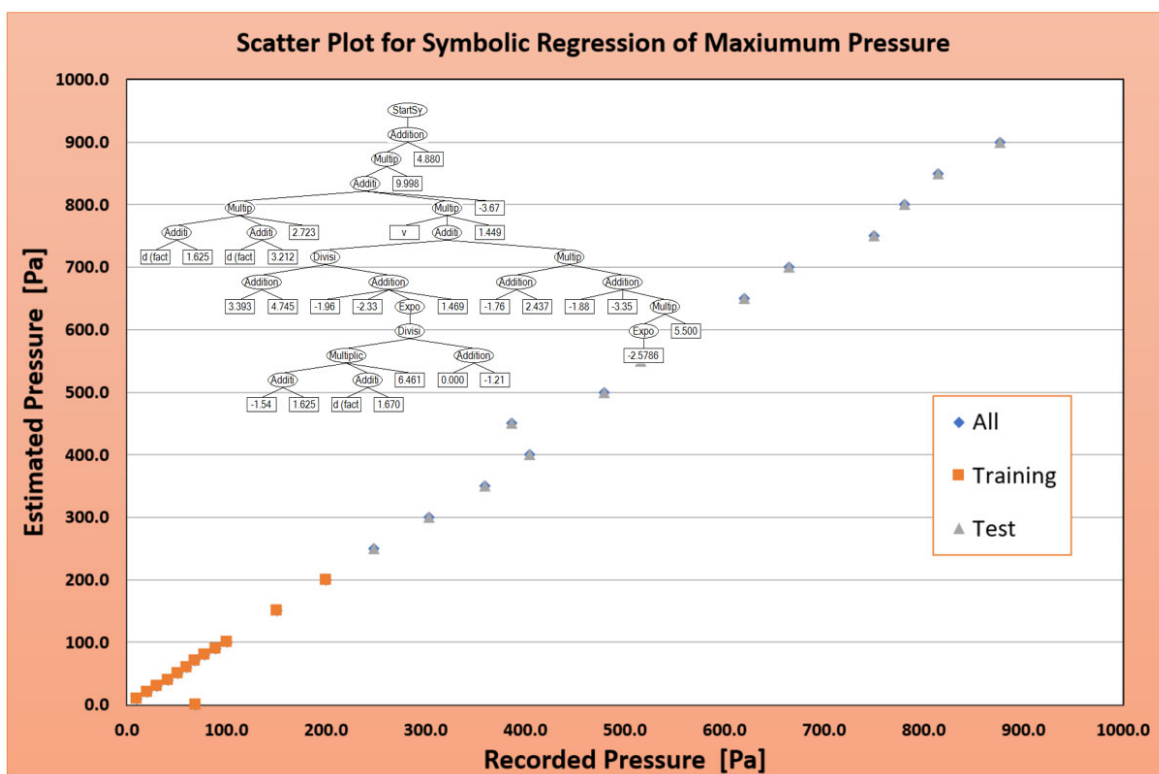
Genetic Algorithm Symbolic Regression (GASR) characterizes a data processing scheme where measured or calculated data can be fitted by a suitable mathematical formula (from different family of functions, operators, and so on) using genetic and/or evolutionary algorithms. The GASR technique has been gradually developed for computer implementation in recent years and some computer tools are already available based on GASR technologies. HeuristicLab [40] is one of the open/source academic software tools that have been developed to deal with a variety of data-driven modelling problems. It is prominently useful for problems where computational simulations are combined with optimization and design features within structural engineering projects. In the work herein, the simulation scenario table was set up to define design graphs based on various vehicle speed and distance between vehicle and gantry for roadside structural design using optimized data. The simulation-based data optimization procedures were performed to find symbolic functions for maximum generated pressure during passage. A multi-dimensional search space based on two defined variables and HeuristicLab software (based on genetic algorithm symbolic regression technique) were used to derive appropriate design functions.

A scenario table was defined for the maximum pressure wave calculations based on varying vehicle speeds and gap distance between the vehicle and gantry structure. Table 1 shows the scenario table for the numerical simulations, where different scenarios based on speeds of vehicle passages under the gantry and the minimum distance between the

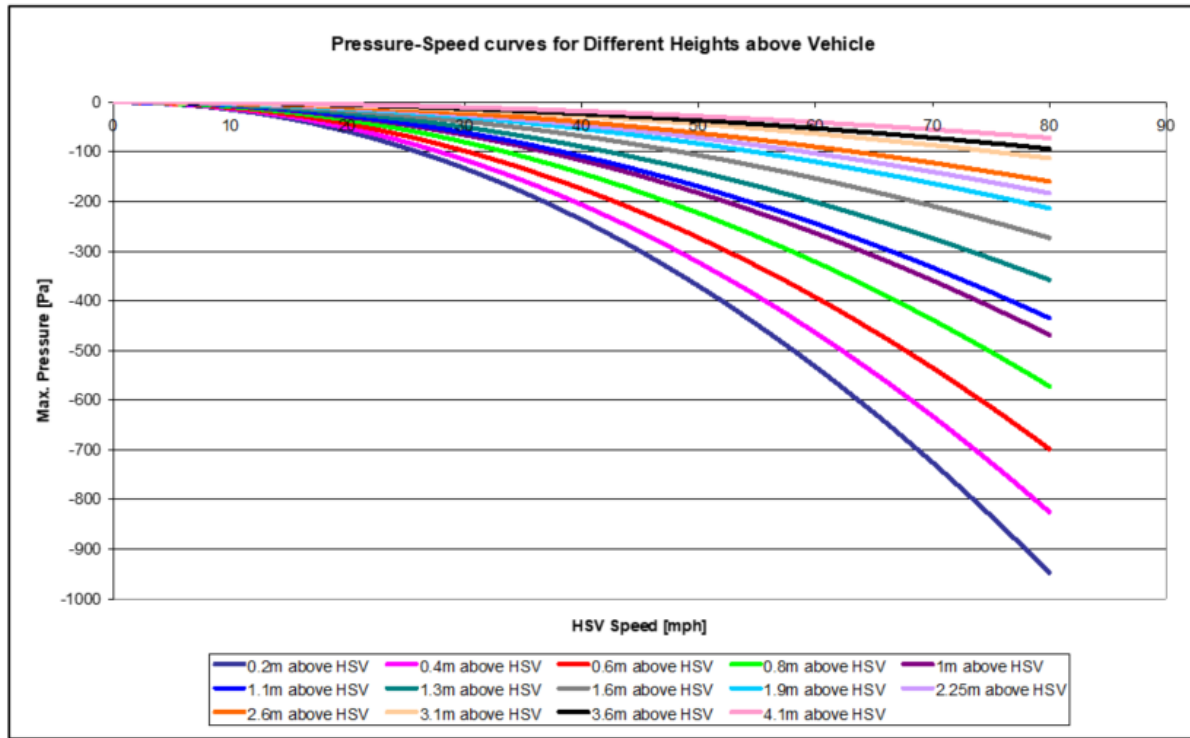
top of the vehicle and road gantry structure are defined. For the data handling and post-processing of the maximum pressure data, the GASR technique was employed. Figure 12 shows the symbolic regression process and its functional results along with design curves for vehicle velocity and gap distance variables. The resulting data-driven function was then employed to define the design curve for the maximum pressure exerted on the gantry boom. The fatigue vehicle setup shown in Figure 2d was finally used to create the possible vibrational resonance for the whole structural system, where fatigue service life can be estimated.

Table 1. Scenarios table for different vehicle speeds and distances.

Vel. [mph]	10	20	30	40	50	60	70	80
Distance [m]								
0.2	x	x	x	x	x	x	x	x
0.4	x	x	x	x	x	x	x	x
0.6	x	x	x	x	x	x	x	x
0.8	x	x	x	x	x	x	x	x
1.0	x	x	x	x	x	x	x	x
1.1	x	x	x	x	x	x	x	x
1.3	x	x	x	x	x	x	x	x
1.6	x	x	x	x	x	x	x	x
1.9	x	x	x	x	x	x	x	x
2.25	x	x	x	x	x	x	x	x
2.6	x	x	x	x	x	x	x	x
3.1	x	x	x	x	x	x	x	x
3.6	x	x	x	x	x	x	x	x
4.1	x	x	x	x	x	x	x	x



(a)



(b)

$$P = \left(\left((c_0 + c_1 \cdot v) \cdot (c_2 + c_3 \cdot v) \cdot c_4 + v \cdot \left(\frac{(c_5 + c_6 \cdot v)}{(c_7 \cdot v + c_8 \cdot (d = 0.22) + \exp\left(\frac{(c_9 + c_{10} \cdot v) \cdot (c_{11} + c_{12} \cdot v) \cdot c_{13}}{(c_{14} + c_{15} \cdot v)}\right) + c_{16}} \right) + (c_{17} \cdot (d = 1.6) + c_{18} \cdot (d = 0.25)) \cdot (c_{19} + c_{20} \cdot v + \exp(c_{21} \cdot v) \cdot c_{22}) \cdot c_{23} + c_{24} \right) \cdot c_{25} + c_{26} \right) \right)$$

(c)

Figure 12. (a) Graphical representation of the calculated scatter plot for genetically-driven function and its derivation tree, (b) design curves for maximum exerted pressure in terms of speed and gap distance, and (c) resulting functional from genetical algorithm symbolic regression for maximum pressure in terms of vehicle speed v and distance gap d .

The use of genetic algorithm symbolic regression has opened up opportunities for generic development of design curves for cyclic loading of gantry structures in main roads. It would also help to design a better configuration for commercial large vehicles like trucks and buses based on their aerodynamic performance, which was a subject of the large European project “Configurable & Adaptable Trucks and Trailer for Optimal Transport Efficiency (TRANSFORMERS)” [41]. A more comprehensive discussion about the regression technique and genetic algorithm can be found in [40].

7.3. Fatigue Life Assessment

In addition to ultimate static/dynamic forces considered for the design of highway structures, there are other dynamic effects like fatigue that need to be considered. To design these vital structural systems for dynamic and fatigue effects, appropriate design rules/graphs have to be defined for practicing engineers [42]. In the study herein, a comprehensive simulation scenario table was defined to take into account the shapes (truck, double-decker bus, and so on), conditions (with/out air deflector, among others), and speeds of HSVs for gantry designs. The results of this comprehensive verified study were used to verify design rules for vehicle buffeting effects (e.g., British BD94/07 [43] code of practice as well as interim advice note IAN 86/07 [44]).

Different variations of HSV dimensions with different speeds were simulated to take into account the size and shapes of real-world HSV traffic under the gantry. The variations

of peak calculated pressure against the height above the centerline of the HSV were calculated and its smoothed design curves are extracted. The dynamic and fatigue simulations (using the spectral Eigen technique) of the gantries are then conducted based on global and local analyses concept using the prescribed multi-resolution zonal technique. Figure 13 shows the global spectral Eigen model of two gantry systems with and without traffic signs/boxes along with their mode shapes.

The global dynamic analyses can initially be performed using the damped spectral Eigen technique for buffeting and gust pressure wave loading conditions. The calculated stresses on the gantry members and joints are post-processed to flag out the areas prone to fatigue failures. The local fatigue analyses were also performed using the high-resolution zonal technique to calculate the stress cycles and fatigue life, where 3D-detailed shell models of the members/joints were created using high-resolution mesh. Figure 14 shows the global CAD geometry model along with the 3D-detailed computational model (high-resolution zones) of the high-stress zones for the fatigue life assessment.

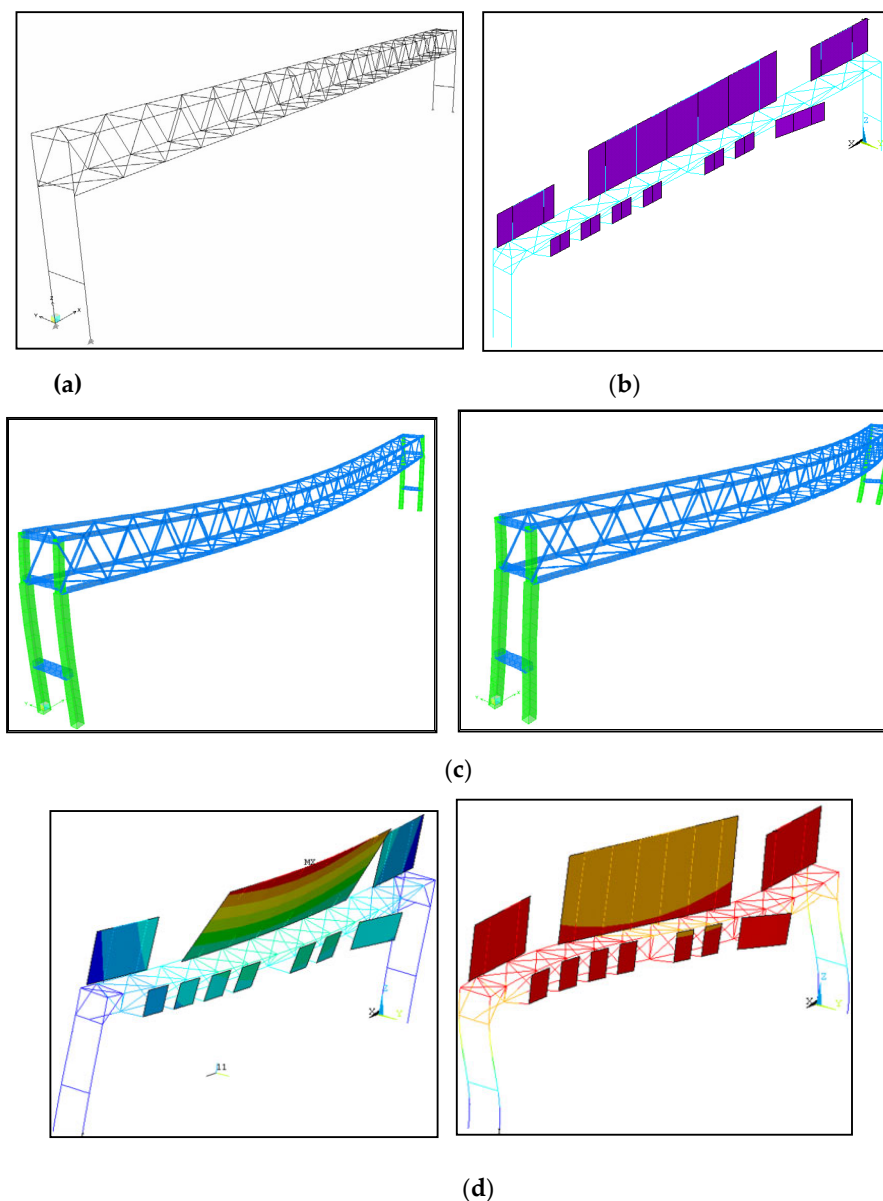


Figure 13. Global model of portal gantry (a) without and (b) with signs\signal boxes, and (c) gantry mode shapes without dynamic effects of traffic signs and (d) with traffic signs effects.

7.4. Environmental Wind

To add the effect of wind gust to the fatigue calculation and assess the fatigue life of structural joints based on combined stress ranges from vehicle buffeting and external wind, the European standard [45] can be used to start the calculation. For structural joints involving hollow cross sections, hot spot S–N curves from “CIDECT Design Guide 8” [46] were used to start the fatigue assessment postprocessing routine. The total fatigue damage due to a combined stress cycles (vehicle and environmental induced cycles) can be assumed to be the sum of the damage due to each cycle. As the fatigue damage due to one cycle with stress range “S” in most popular design codes is defined as $1/N$ times the total fatigue life of the structure at the particular location \joints, the total sum of stress cycles at different ranges (by linear Miner rules or rain flow counting scheme) can be used to inspect the fatigue life by estimation of the number of repetitions “N” from the S–N curve. Figure 14 shows the gantry structural joints and their FE simulations for fatigue hot spot estimations.

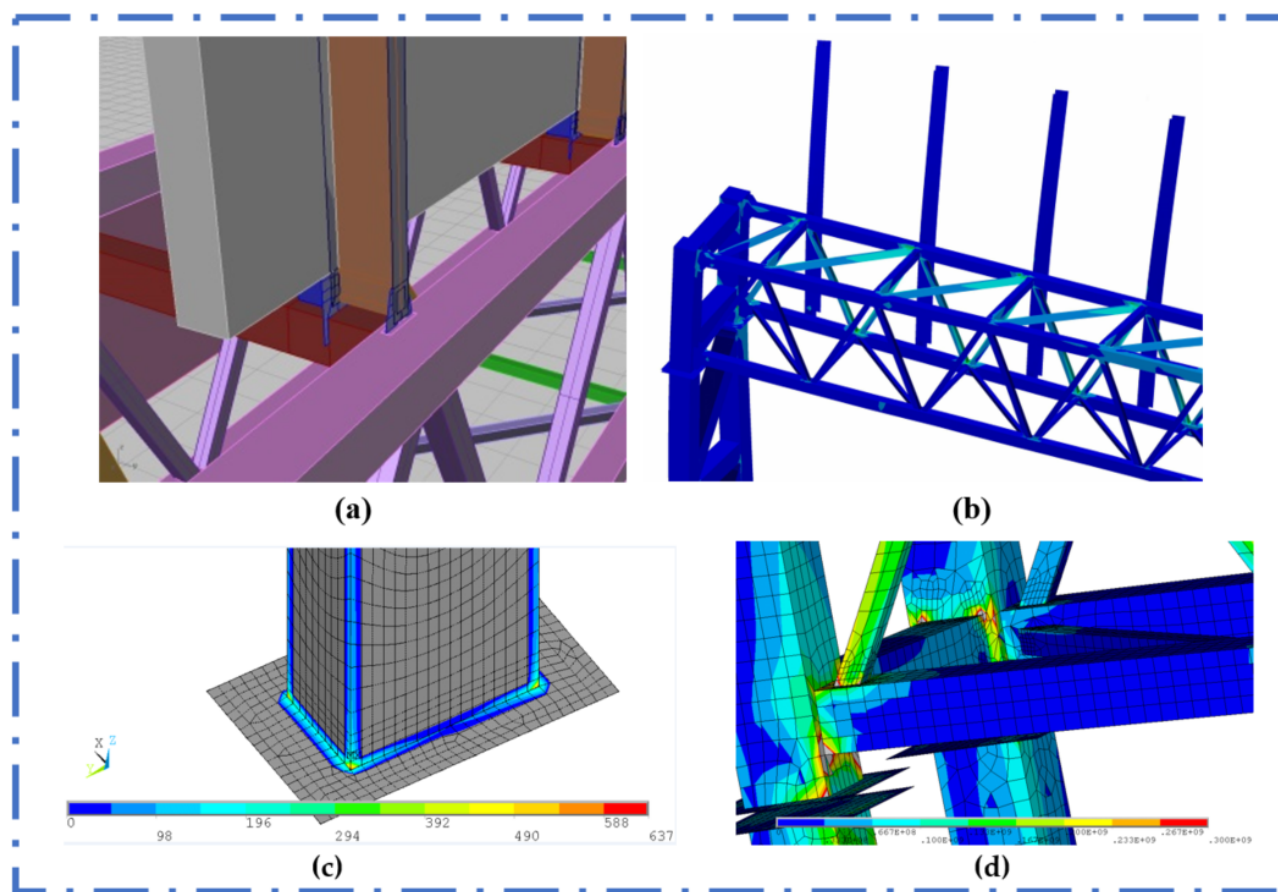


Figure 14. (a) Local/detailed CAD model of gantry boom, (b) its high-resolution zonal stress results, (c) fatigue calculation for baseplate welding, and (d) boom-leg joints.

Some initial assumptions can be made to start the fatigue life calculation under both environmental wind gust and HSV buffeting; namely,

- For stress cycles below the threshold limit $\Delta\sigma_D$, if all the stress ranges can roughly fall below the threshold (no large stress cycles), it can be assumed that no fatigue damage is considered to have been done in the joint zone (European standard [47] can be used to define the $\Delta\sigma_D$).

- For the stress cycles with a stress range less than $\Delta\sigma_L$, it is assumed that stress cycles can cause no fatigue damage and can be ignored ($\Delta\sigma_L$ can be defined as $\Delta\sigma_L = 0.549 \Delta\sigma_D$ according to the European standard [47]).
- For joints with exposure to stress cycles larger than $\Delta\sigma_D$, the damage from all service life cycles is summed. The damage from a cycle with stress range $\Delta\sigma$ is considered to be $1/N$ (times the joint failure damage), where N is obtained from the S–N curve for the joint.

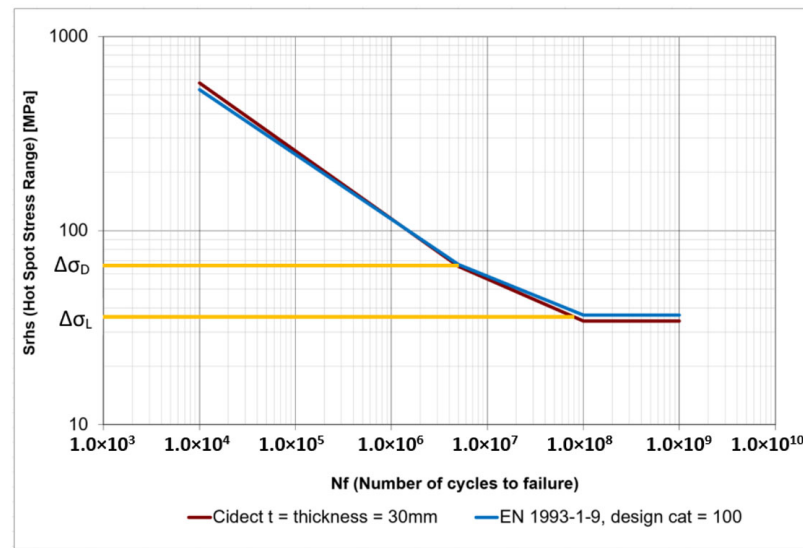
The fatigue life calculation can then be performed for each structural joint based on its own S–N curve. To account for the number of stress cycles for environmental wind gust, let us consider the equation [45]

$$\Delta S/S_k = 0.7 \cdot (\log(N_g))^2 - 17.4 \cdot \log(N_g) + 100 \quad (45)$$

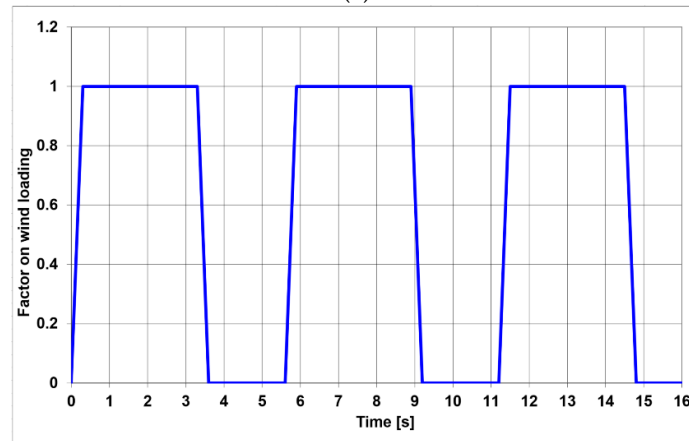
where $\Delta S/S_k$ is an effect from gust wind loading as a proportion (generally in percent) of the effect of the 50-year peak wind loading (the 50 year return period wind gust), while N_g is the number of times that this effect is expected to be exceeded in 50 years of service life (i.e., number of times a wind gust of each magnitude is expected to occur during 50 years). The pulse transient loading for these wind gust events can be defined using the 10 min wind mean speed according to the European standard [45]. The assumed gust pressure can be a constant multiple of basic wind pressure for the full wind exposure (without obstacles). A gust pressure factor of 3 can be used [45] for the gantry structure herein, which implicates the wind gust speed of $\sqrt{3}$ times the 10 min mean wind speed. Figure 15 shows typical S–N curves [46,47] for the reference stress of $\Delta\sigma_c = 100$ along with a graphical representation of the wind gust effect [45] and the cumulative 3 s transient pulse loadings for excitation scenarios.

The procedure for fatigue life assessment of the gantry systems for combined wind and vehicle dynamic loadings can be summarized as follows:

- Create digital geometries for both mechanical and CFD solvers (2D and 3D);
- Perform the CFD simulations and calculate the resulting pressure histories;
- Transfer the pressure histories to fast mechanical solver;
- Perform initial spectral modal analyses to flag out vulnerable natural modes to wind loading and vehicle buffeting;
- Perform mechanical simulation for cyclic gust pressure waves (three cycles and three HSVs) to excite the relevant modes;
- Calculate vehicle buffeting stress cycles from ML-fitted design graphs for HSVs with various speed/height and projected traffic data;
- Inspect critical joints/locations, and calculate local “stress ranges” from transient mechanical simulations;
- Calculate the number of cycles for wind gust from appropriate code of practice;
- Use the relevant code of practice to find the “reference stress, $\Delta\sigma_c$ ”, a measure of the fatigue strength, at each critical location;
- Calculate the fatigue damage and fatigue lifetime at each critical location.



(a)



(b)

Figure 15. (a) Typical S–N curves for fatigue calculation based on the European Standard [47] and Cidect guide [46]; (b) transient factors for pulse loading pattern representing wind gust loading.

For large gantry systems herein, at each structural joint, the detail weld category should be determined by looking up the relevant junction and weld type according to the European standard [47]. In some joints, the detail category can be different on the two sides of the weld and each welded edge shall get its own detail category. As the European standard [47] suggests that loading conditions other than those defined in [45] may be used, provided that an extra factor γ_{Fi} is applied to the stresses obtained, the factor can be used to stresses resulting from vehicle buffeting. If the detailed category is divided by $\gamma_{MF} = 1.1$ according to [47] to obtain the reference stress $\Delta\sigma_C$ at a joint location, an automated fatigue calculation [42] can be performed by creating a joint specific S–N curve using assumptions as [47]

- $\Delta\sigma_D = 0.737 \Delta\sigma_C$; $\Delta\sigma_L = 0.549 \Delta\sigma_D$;
- Starting point of graph as $N = 1 \times 10^4$, $\Delta\sigma_R = \sqrt[3]{200} \times \Delta\sigma_C$.

By introducing the alternative presentation of the S–N curve (in Figure 16a), the fatigue damage can be calculated based on the stresses from the numerical simulation runs. The detailed mathematical manipulation and automation processes for the calculation of fatigue life are not presented here owing to the excessive paper length, and the research work would be presented in a separate paper. Figure 16 also shows the in-house graphical

postprocessing tool for the fatigue calculation, which were used for final fatigue life assessment of large gantries.

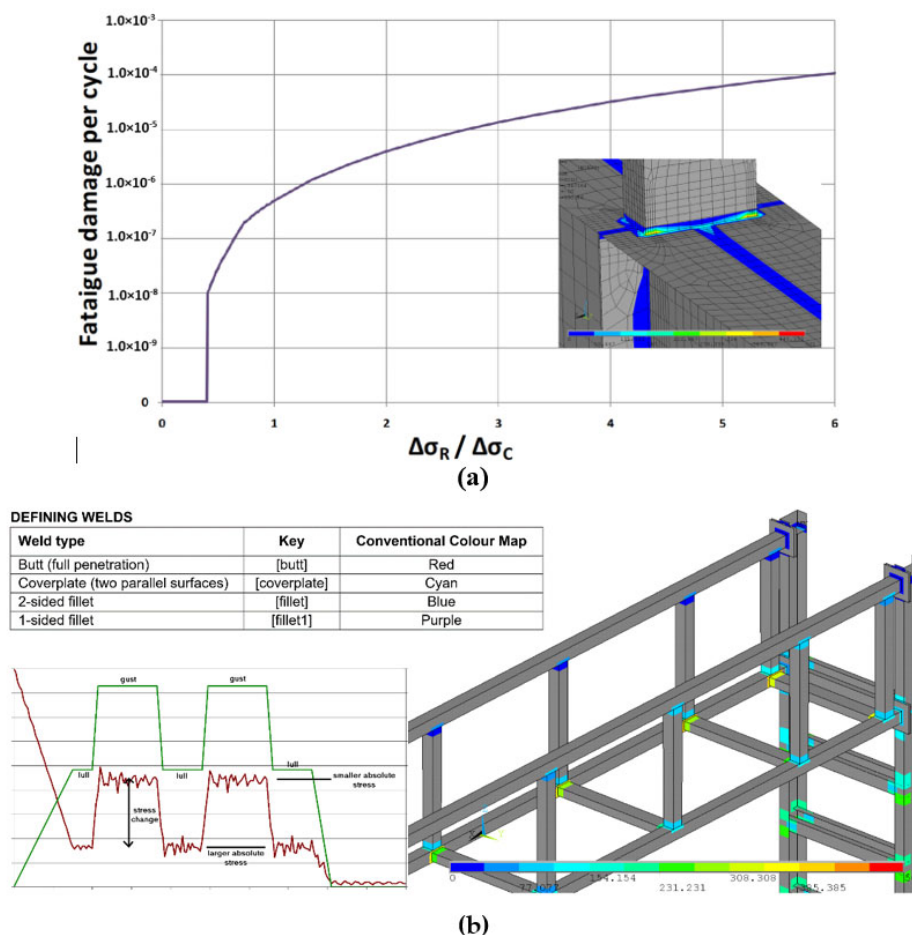


Figure 16. (a) Fatigue damage alternative mathematical representation for detailed stress cycles; (b) transient gust pressure loading pattern with structural response and results of graphical post-processing tool [48].

8. Conclusions

The integration of design and simulation has been a long-standing open challenge for scientist and practicing engineers in the area of complex engineering systems. In the research work herein, conventional simulation techniques and their discretization methods were scrutinized and the application of the new dynamic zone method for the large engineering systems was investigated. The technique has already made some design impacts in which design rules were extracted from the large simulation scenario tables using verified numerical results.

While in the conventional numerical techniques, it is hard to taken into account the effect of dynamic changes and their propagation within the domain, an alternative dynamic zone technique can be employed. The introduction of virtual boundaries, mathematical void zones, and genetic algorithm symbolic regression concepts can facilitate the formulation of the next generation of numerical techniques for practical design applications. In the research work herein, it is intended to identify and formulate the necessary vibrational aspects of the engineering system design and employ an innovative numerical solver technique using the full-parallel processing scheme.

In the first part of the paper, the basic concepts of the finite zoning technique and its discretization/interfaces schemes were briefly presented, while in the later sections, the faster spectral solver technology along with design-data handling using genetic algorithm for the dynamic design of large gantry systems were shown graphically. As results of this initiative research work, the combination of increasing available computational power along with more efficient discretization and solver technologies and smart data-driven and hybrid modelling can facilitate the future design of complex large systems under various external loadings. It can also be stated that, owing to extensive efforts required for modelling and design of large systems, to enable a faster and more systematic design procedure, more advanced numerical simulation tools are required (e.g., digital twin and virtual simulation-design tool).

On the other hand, the integration of the proposed simulation and design tools into mainstream engineering design offices has to be taken into account when developing sophisticated numerical schemes. It is preferable to set up a stepwise scheme where every step of the development can be customized/verified for more general application of mechanical design. The opportunity to investigate the consequences of the fatigue, obtained using the multi-resolution zoning technique, on the design of road/rail systems will be taken, and this will be the subject of a subsequent paper.

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References

1. Bazilevs, Y.; Takizawa, K.; Tezduyar, T.E. Challenges and directions in computational fluid-structure interaction. *J. Math. Models Methods Appl. Sci.* **2013**, *23*, 215–221.
2. Li, J.; Hao, H. Numerical study of structural progressive collapse using substructure technique. *J. Eng. Struct.* **2013**, 101–113.
3. Farhat, C.; Avery, P.; Chapman, T.; Cortial, J. Dimensional reduction of nonlinear finite element dynamic models with finite rotations and energy-based mesh sampling and weighting for computational efficiency. *J. Numer. Methods Eng.* **2014**, *98*, 625–662.
4. Blocken, B.J.E. Computational Fluid Dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations. *Build. Environ.* **2015**, *91*, 219–245, doi:10.1016/j.buildenv.2015.02.015.
5. Krack, M.; Panning-von; Scheidt, L.; Wallaschek, J. A method for nonlinear modal analysis and synthesis: Application to harmonically forced and self-excited mechanical systems. *J. Sound Vib.* **2013**, *332*, 6798–6814.
6. Besselink, B.; Tabak, U.; Lutowska, A.; van de Wouw, N.; Nijmeijer, H.; Rixen, D.J.; Hochstenbach, M.E.; Schilders, W.H. A comparison of model reduction techniques from structural dynamics, numerical mathematics and systems and control. *J. Sound Vib.* **2013**, *332*, 4403–4422.
7. Horr, A.M. Integrated material process simulation for lightweight metal products, computational methods and experimental. *WIT Trans. Model. Simul.* **2015**, *59*, 201–212.
8. Bathe, K.J.; Saunders, H. Finite element procedures in engineering analysis. *J. Press. Vessel. Technol.* **1984**, *106*, 421–422, doi:10.1115/1.3264375.
9. Clough, R.W.; Penzien, J. *Dynamics of Structures*; McGraw-Hill: New York, NY, USA, 1996.
10. Ferziger, J.H.; Peric, M. *Computational Methods for Fluid Dynamics*, 2nd ed.; Springer, Berlin, Germany, 1999.
11. Donea, J.; Giuliani, S.; Halleux, J.P. An arbitrary Lagrangian-Eulerian finite element method for transient dynamic fluid-structure interactions. *J. Comput. Methods Appl. Mech. Eng.* **1982**, *33*, 689–723.
12. Takashi, N.; Hughes, T.J.R. An arbitrary Lagrangian-Eulerian finite element method for interaction of fluid and a rigid body. *J. Comput. Methods Appl. Mech. Eng.* **1992**, *95*, 115–138.

13. Liu, W.K.; Belytschko, T.; Chang, H. An arbitrary lagrangian-eulerian finite element method for path-dependent materials. *J. Comput. Methods Appl. Mech. Eng.* **1986**, *58*, 227–245.
14. Lewis, R.W.; Navti, S.E.; Taylor, C. A mixed Lagrangian-Eulerian approach to modelling fluid flow during mould filling. *J. Numer. Methods Fluids* **1997**, *25*, 931–952.
15. Udaykumar, H.; Shyy, W.; Rao, M. ELAFINT-A mixed Eulerian-Lagrangian method for fluid flows with complex and moving boundaries. In Proceedings of the 6th Joint Thermophysics and Heat Transfer Conference, Colorado Springs, CO, USA, 20–23 June 1994.
16. Spurk, J.H.; Aksel, N. *Fluid Mechanics*, 1st ed.; Springer, Berlin, Germany, 1997.
17. Baines, M.J.; Hubbard, M.E.; Jimack, P.K. Velocity-Based Moving Mesh Methods for Nonlinear Partial Differential Equations. *J. Comput. Phys.* **2011**, *10*, 509–576.
18. Griebel, M.; Dornseifer, T.; Neunhoffer, T. *Numerical Simulation in Fluid Dynamics, a Practical Introduction*; SIAM: Philadelphia, PA, USA, 1998.
19. Horr, A.M. Computational evolving technique for casting process of alloys. *J. Math. Problem. Eng.* **2019**, *2019*, 6164092.
20. Horr, A.M. *Evolving Domain for Numerical Simulation of EM Semi-Continuous Casting Process*, Amoree Core Document; LKR, AIT: Vienna, Austria, 2015.
21. Horr, A.M.; Kronsteiner, J.; Mühlstätter, C.; Scheiblhofer, S. Recent advances in aluminium casting simulation: Evolving domains & dynamic meshing. In Proceedings of the Aluminium Two Thousand World Congress, 2017, Verona, Italy, 20–24 June 2017. Available online: <http://www.aluminium2000.com/index.php/en/event-profile/previous-congresses/previous-congress-verona-2017> (accessed on 13 January 2021).
22. Horr, A.M. Energy-efficient lightweight material processes for e-mobility applications. In Proceedings of the European Aluminium Congress, Body Structure & E-Mobility II session, Dusseldorf, Germany, 25 November 2017; Volume 2, pp. 1–12.
23. Doyle, J.F. *Wave Propagation in Structures. Spectral Analysis Using Fast Discrete Fourier Transforms*, 2nd ed.; Springer: New York, NY, USA, 1997.
24. Horr, A.; Schmidt, L.C. Dynamic response of a damped large space structure: A new fractional-spectral approach. *Int. J. Space Struct.* **1995**, *10*, 113–120, doi:10.1177/026635119501000204.
25. Horr, A.M.; Safi, M. Spectral dynamic analysis of power transmission towers using ANN imperfection simulator. *IEEE Power Delivery Trans.* **2004**, *19*, 1907–1912.
26. Horr, A.M. Energy Absorption in Structural Frames. Ph.D. Dissertation, University of Wollongong, Wollongong, Australia, 1995.
27. Horr, A.M.; Schmidt, L.C. Frequency domain dynamic analysis of large space structures with added elastomeric dampers. *Int. J. Space Struct.* **1996**, *11*, 279–289.
28. Horr, A.; Schmidt, L. Complex fractional-spectral method for space curved struts: Theory and application. *Int. J. Space Struct.* **1997**, *12*, 59–67, doi:10.1177/026635119701200201.
29. Horr, A.M.; Schmidt, L.C. Modelling of non-linear damping characteristic of a viscoelastic structural damper. *J. Eng. Struct.* **1996**, *18*, 154–161.
30. Doyle, J.F. A Spectrally formulated finite element for longitudinal wave propagation. *Int. J. Anal. Exp. Modal Anal.* **1988**, *3*, 1–5.
31. Bagley, R.L. Application of Generalised Derivatives to Viscoelasticity. Ph.D. Dissertation, Air Force Institute of Technology, OH, USA, 1997.
32. Flugge, W. *Viscoelasticity*, 2nd ed.; Springer: New York, NY, USA; Berlin/Heidelberg, Germany, 1975.
33. Koblitz, A.R.; Lovett, S.; Nikiforakis, N.; Henshaw, W.D. Direct numerical simulation of particulate flows with an overset grid method. *J. Comput. Phys.* **2017**, *343*, 414–431.
34. Horr, A.M. Designing safer lightweight road infrastructure using advanced simulation technology. *Transp. Res. Procedia* **2016**, *14*, 2458–2467.
35. Horr, A.M. Simulation of buffeting-induced vibrations using CFD grid to grid technology, invited keynote. In Proceedings of the 4th International Conference on Dynamic Simulation in Vehicle Engineering, Steyr, Austria, 16–18 December 2016; pp. 69–81.
36. Unterweger, K. CFD simulation of Moving Geometries Using Cartesian Grids. Master's Thesis, Technische Universität München Fakultät für Informatik, Diplomarbeit in Informatik, Munich, Germany, 2009.
37. Kassiotis, C. *Which Strategy to Move the Mesh in the Computational Fluid Dynamic Code OpenFOAM*; Laboratoire de Mécanique et Technologies (LMT), École Normale Supérieure de Cachan, Paris-Saclay University publishing, Gif-sur-Yvette, France, 2008.
38. Flint & Neill Partnership. *Buffeting of a Cantilever Mast by High Sided Vehicles*; Final Report; Gloucestershire, UK, company report, 2004.
39. Flint and Neill Partnership. *ATM Gantry Monitoring Task Report, Final Report*; Gloucestershire, UK, company report, 2006.
40. Wagner, S.; Affenzeller, M. HeuristicLab: A generic and extensible optimization environment, Adaptive and Natural Computing Algorithms; Springer, Wien, Austria, 2005; pp. 538–541.
41. Barbarino, S.; Kyncl, J.; Martinezavila, M.; Hiram, A. Performance measures and metrics for a hybrid on demand truck-trailer configuration: An end user perspective. In Proceedings of the Energy Systems Conference, London, UK, 24 June 2014.
42. Vaughan, D.; Horr, A.M. *Fatigue Assessment Report No. 127, Gifford Internal Report*; Advanced Engineering Team: Gifford, Southampton, UK, 2009.
43. BD 94/07. *Design Manual for Roads and Bridges Highway Structures: Design, Part. 1*; The Highway Agency, London, UK, 2007.
44. IAN 86/07. *Interim Advice Note Amendment to design requirements for Portal and Cantilever Sign/Signal. Gantries*; The Highway Agency: London, UK, 2007.

45. EN 1991–1–4: Eurocode 1: Actions on structures-Part. 1–4: General Actions-Wind actions, Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC; Brussel, Belgium, European Standard, 2005. (In English)
46. CIDECT Design Guide 8, Design Guide for Circular and Rectangular Hollow Section Welded Joints Under Fatigue Loading, Construction with Hollow Steel Sections; Köln, Germany, Versuchsanstalt für Stahl, Holz und Steine (VAKA) publishing, 2001; Volume 8.
47. EN 1993–1–9: Eurocode 3: Design of steel structures-Part. 1–9: Fatigue, Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC.; Brussel, Belgium, European Standard, 2005. (In English)
48. Horr, A.M.; Hartmann, M.; Kronsteiner, J. Advanced dynamic & crash simulation of lightweight profiles for design of road side infrastructure. *Transp. Res. Procedia* **2016**, *14*, 4180–4189.