Université de Mons
Faculté Polytechnique – Service de Mécanique Rationnelle, Dynamique et Vibrations
31, Bld Dolez - B-7000 MONS (Belgique)
065/37 42 15 – georges.kouroussis@umons.ac.be

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PREDICTING SENSITIVE BUILDING VIBRATION DUE TO RAILWAY EXCITATION

Giuliano Picariello, Georges Kouroussis
Department of Theoretical Mechanics, Dynamics and Vibrations, Faculty of Engineering, University of Mons, Belgium
email: Giuliano.Picariello@umons.ac.be

Laurent Van Parys
Department of Civil Engineering, Faculty of Engineering, University of Mons, Belgium

Antonio Formisano
Department of Structures for Engineering and Architecture, University of Naples Federico II, Italy

Due to the rapid development of urban railway networks, the problem of ground-borne vibration induced by railway traffic becomes important. For some buildings, these ground vibrations can induce cosmetic and structural damages and must be avoided according to the protection rules for old buildings. In the prediction of ground-borne vibration from railway systems, the amplification factor between each part of the building and the building foundation is not the only factor to take into account; the overall coupling between the building and the soil, as well as the nature of the excitation, remain important factors that must be mastered to reduce the vibration transmitted up through the buildings. The aim of this paper is to analyse the parameters that affects the vibration and to propose innovative solutions to help to reduce excessive vibration.

Keywords: cultural buildings, ground vibration, track dynamics, railway vibration, ground wave propagation

1. Introduction

For decades, traffic congestion, intense noise and air pollution were become a daily reality for populations living in most of urban centres, justifying public plans engaged by the end of the 20th century in order to improve the quality of urban life [1]. Embedded in sustainability reflection and mobilizing both time and space wide-scale frameworks, such interventions require a solid political background for establishing town areas dedicated to pedestrians and combining them urban equipments and public transportation lines intending at discouraging the use of cars [2] inside the city. Associated with urban revalorization, these operations improve life quality of “soft users” and are usually positive for touristic as well as health outlooks.

For related public transportations, high capacity solutions are often required. Although specific local characteristics open the way to alternative economical approaches like metrocable solutions studied for years and now installed in more and more South American cities like La Paz (Bolivia) or Meddelin (Colombia), metro, tramway and bus solutions are more classically encountered. The intrinsically high installation costs associated with metro-based solutions justify the current preference for tram- and bus-based solutions for medium size cities; the local area configuration revealing the highest interest of the one on the other as the robustness of the offer is often balanced with the flexibility. Balancing a high number of carried passengers with limited ecological impacts associated with the recourse to electrical power is often a key objective that counts better for tramways. Sacrificed in many places of Europe some 30 years ago when personal cars were seen as the unique way to exercise a freedom in mobility, tramway is now coming back in more and more urban landscapes.

In many parts of Europe, most of current cities are inherited from glorious ages. Enriched by their wealthy past, they suffer specific drawbacks as most of centres remain deeply impressed by their original urban structure with parcel divisions and street networks inherited from their origins (Fig. 1), linked through a trans-centuries relationship with building technical limitations and restricted transportations possibilities of early ages. Unless radical operations like area rehabilitations piloted by public authorities or rebuilding following war bombings, each building gave place to its successor.

Figure 1: Mons (Belgium) urban centre: ancient compared with current structure. The comparison (centre) between the 1777's situation (left) and the 2013's situation (right) outlines few modifications in the ground signature except the rehabilitation of a hollowed area near the principal market.

For railway components in motion, the transmission of vibrations to the environment is an undesired collateral effect. Ideally homogeneous and permanent, the wheel-rail contact, through which intense forces are permanently transmitted, can become disturbed due to the presence of localised defects affecting either the wheel or the rail surfaces. In practice, brand new systems can achieve excellent performances in terms of vibratory emissions. But problems may occur with time as the apparition of defects on the tracks and later the wheels, can hardly be prevented. Even if limited in localisation or duration, a loss of contact between the wheel and the rail will always induce bad consequences: the contact comeback (and the interfacial force comeback) will generate a localized vibratory wave through the rail, the track and later the ground and the neighbourhood. Unfortunately, the effects of a tramway passing along a building reveals nothing universal, considering simultaneously the specific characteristics of each tram model, the effective configuration of the track or even the local organisation of underground soil layers for anticipating vibratory impacts is not a trivial mission and requires considering the problem in its global complexity [3]. Facing the difficulties, the practitioners generally by-pass related questions by proposing artefacts like rubber-tired solutions in Padova city (Italy) [4] or by prescribing vibratory measurements, carried out a posteriori, and optionally coupled with the installation of specific components [5].

The present article aims at describing an integrated workflow that allows overcoming the enlisted difficulties. Its development has only been made possible by gathering and articulating skills from several specialities inside a unique tool that can be now considered as user-friendly. The innovative philosophy that is developed here brings the opportunity to answer objectively to questions addressed to urban planners from the very beginning of the process. In practice, it has been shown [6] a population can reveal very interested when a constructive discussion about urban evolutions is carried out and brings answers to its fears. In this way, it constitutes a robust ally for promoting the effective success of public transportation projects.

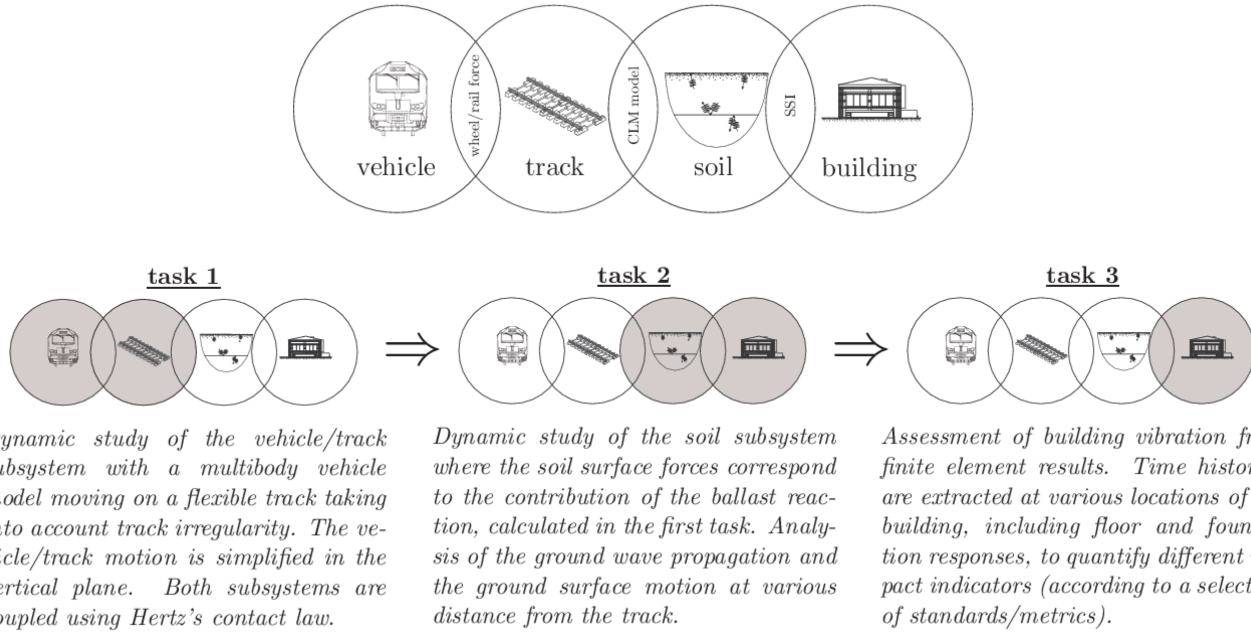

Figure 2: Sequential articulation of three tasks in the proposed integrated framework.

Based on data characterizing vehicle, track, soil and built environment, the proposed workflow will sequentially articulate three tasks (Fig. 2). The first one focuses on the mechanical behaviour of the light rail vehicle driven on the tracks under given conditions. Depending on the tramway type, its axle loading and its speed as well as the local configuration of the track, specific relative motions take place in the system. As people engaged in the mechanical design of tramway vehicles are concerned with the comfort of passengers, they developed tools likely to carry sharp studies. Relying on several published data, the authors proposed the development of complementary functionalities inside an existing modelling environment (EasyDyn, [7]), enabling in this way the efficient solving of the mechanical problem and delivering, for each point under the track, the force signal associated with the moving tramway in presence (or not) of a given defect. The second task concerns the excitation of the environment: the track/soil interface forces computed previously are transmitted on the ground through wave propagating on the medium, regarding its local configurations and properties and come into interaction with structures embedded in it. Depending on their material and/or morphologies, damping or resonance effects will take place and produce a response of the structure. For enabling a convenient replication of wave transmission, the greatest care should be brought for avoiding parasite effects associated with by-essence limited extension of the model. Relying on published data, the authors propose a commercially available finite-infinite element approach (Simulia software) that is likely to deliver time histories (displacement, velocity, acceleration) for any nodes considered in the discretization of a building or set of buildings. Finally, the third task concerns the user-related interpretation of the computed response. In fact, characterizing a vibratory impact requires considering effects-based lecture grids. Relying once again on published data, such signal processing operations have been implemented under the shape of a user-friendly tool in a well-known programming environment (MatLab).

2. Integrated workflow for vibratory impact anticipation

For each task of the workflow, the following subsections summarize a description of the context, a discussion concerning potential solving approaches with advantages and drawbacks as well as justifications of the retained proposition.

2.1 Ground excitation based on the study of vehicle-track subsystem

Any tramway vehicle can be considered as a set of interconnected masses disposed, to a first approximation, on carbodies, bogies and wheelsets. Depending on the accelerations, the decelerations and/or the configuration of the circuit, the bodies are submitted to relative and partially constrained motions. The EasyDyn modelling environment is typically dedicated to the efficient solving of such complicated mechanical railway problems. In practice, the EasyDyn modelling environment relies on the elementary theories of kinematics and dynamics of rigid bodies for enabling precise behaviour simulation of complicated multi-body systems. Based on the effective mass and geometry of every mechanical part implied in the motion and the nature of connections between them, the basic motion equations are automatically established under a symbolic formulation. Then, the entire (and consequently impressive) system of equations is solved and the time history of each degree of freedom of each body considered in the system may be outlined, whatever the motion scenario that has been imposed.

Due to the fact the EasyDyn environment is successfully used in daily railway engineering practices and it already embeds powerful modelling capabilities authorizing direct complements, the authors focussed their action on the development of specific fully embedded facilities for taking the track into account in the global calculation. The updated modelling environment is now likely to compute the transmission of forces (and subsequent vibratory waves) through the rail, sleeper and, ultimately the ground surface. The whole prediction scheme has been experimentally validated [8] and the method can be considered as valuable.

As such available time histories of forces under any sleeper may be predicted with regard to the speed, acceleration or deceleration noticed on a given circuit for even complicated railway vehicles, given repartitions of passengers and any track configuration, the first task in the sub-modelling approach may be easily carried out, even in presence of track and/or wheel defects [9].

2.2 Environment response based on the study of soil-building subsystem

The response of soils submitted to applied forces is more easily established for static loadings (e.g. permanent action of a building through its shallow foundation) than for dynamic ones (e.g. time histories characterised by quick and/or abrupt variations in force amplitude). In fact, further than basic grain-to-grain transmissions, constituting the fundament of usual engineering practices, time aspects should be complementarily taken into account for replicating realistic behaviours: the birth, propagation and fading of waves through the soil. Each wave is composed of body (primary and secondary) and surface components, each of them being associated with specific local strain types, dedicated propagation velocities and particular energy contents. For transportation problems, the motion of the vehicle still increases the complexity as series of wave sets are generated that are temporally (e.g. each wheel passing successively on the same part a damaged rail) and/or spatially (e.g. a damaged wheel whose defect part periodically hit the rail) offset.

For performing convenient predictions, the vibratory contributions brought to the system at given places and given times should be superimposed (resulting effect) while the weakening of signals (damping) should be taken into account for enabling any component to ultimately finish as faded.

Simulating wave birth, propagation and fade in such cases constitutes a challenge. The recourse to finite element modelling is recognized to be efficient as space and time aspects can be simultaneously mastered. By relying on a meshed discretization, it allows considering arbitrary loading shapes with even complex configurations for the propagation medium and provides time history of local strains and stresses for each node of the mesh. A severe drawback of classical modelling facilities concerns boundary management: by default, any non-zero wave component impacting a boundary of the modelled geometry will be affected by (partial) reflections with subsequent superimpositions. For ground propagation problems, the modelled geometry should present sufficient extension for enabling any wave contribution of the problem to propagate as far as in the reality and achieve its natural fade inside the modelled geometry without inducing parasite reflection likely to severely disturb the quality of results. Achieving such convenient spatial extension (in-plane and in-depth) often reveals so resource-demanding that it becomes then complicated to dispose of a computer (even most of the super-computers) likely to effectively solve the problem once the model has been established.

For overcoming this difficulty, the authors investigated the recourse to infinite elements coupled with a viscous boundary installed at the border of half-sphere finite element model (Fig. 3). This finite-infinite approach offers the opportunity to avoid disturbance in the propagation of wave components joining the boundaries of the finite element model. Its main characteristics and its validation have been discussed elsewhere [10].

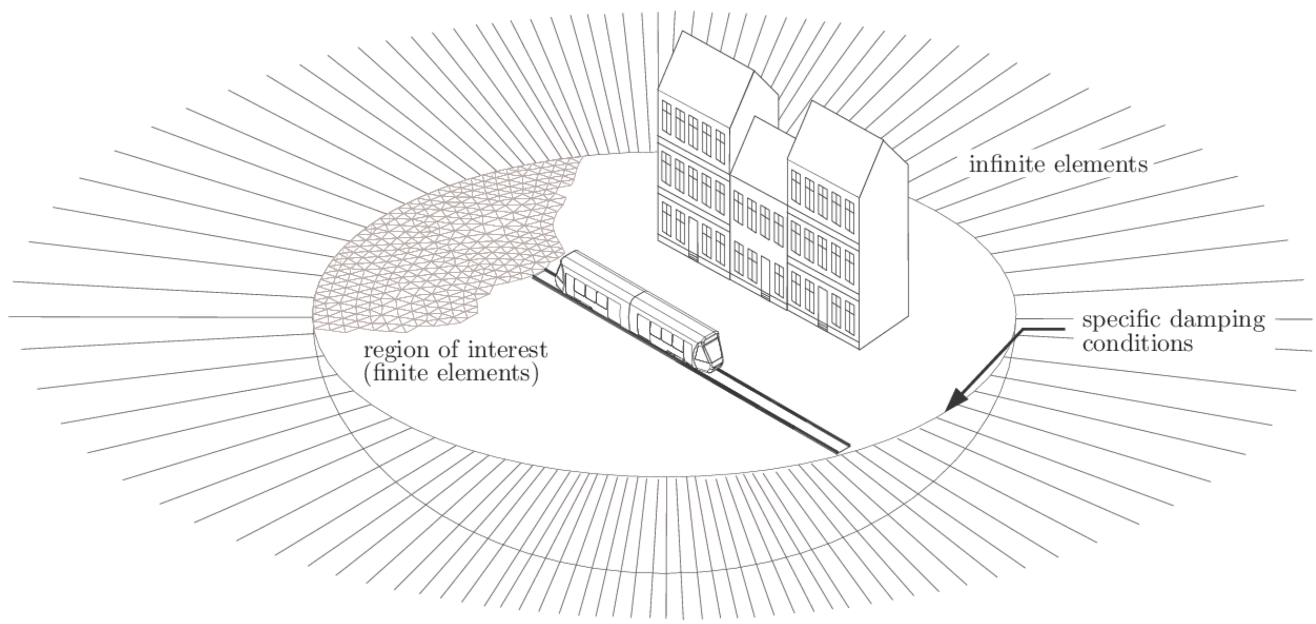

Figure 3: Finite-infinite approach for soil modelling. At the border of a half-sphere composed of finite element, radial infinite elements combined with specific damping conditions allow overcoming parasite reflection problems encountered at the boundaries of a classical finite element model.

In the finite element half-sphere, no particular restriction is required: it allows any usual engineering practice on area of reasonable size (~ 60 meter diameter, ~ 500,000 elements). The soil is considered as an elastic material and multi-layered configurations are supported whose parameters (layer organization, soil properties) may be derived from on-site geotechnical or geophysical campaigns. The ground excitation induced by the tramway is replicated by relying on series of forces applied at pertinent localization and whose time history of the amplitude is individually piloted based on the results of the previous EasyDyn modelling. An explicit integration scheme is followed and the calculations are carried out in the time-domain. This allows directly performing free field studies when the tramway is in motion in open space landscapes. A wide variety of complementary scenarios may be investigated. In particular, the direct insertion of any structure (building, tunnel, bridge) in conjunction with the soil model is straightforward, the interaction between soil and structures being manageable by relying on contact laws that will mobilize concerned degrees of freedom depending on the nature of the interface. The propagation of waves inside the structure is carried out in a classical manner by the finite element software. Based on preliminary modal analysis, the user is likely to take special care on a convenient replication (geometry, interactions and material properties) of structural members likely to be affected by resonance (frequency range of the excitation near eigen frequencies). For constitutive building materials, simplified elastic behaviours as well as more complicated ones may be considered.

2.3 Vibratory impact quantification

A finite element simulation provides nodal displacements and derived valuable information. In classical cases of buildings submitted to static actions, engineers are used to perform, based on stress-strain coloured maps, a direct interpretation and consequently design eventual structural interventions. The proposed coupled soil-building vibratory calculations provide, for each node of the calculation mesh, a time history of the degrees of freedom. The related signals, characterized by (quickly) varying amplitudes, express the local response of the building to the complicated set of mobile actions.

As in classical engineering frameworks, both ultimate and serviceability limit states must be considered. Ultimate limit states will essentially focus on integrity criteria with the occurrence of problems at the structure and/or the materials of the building. Building techniques used in contemporary projects are sufficiently developed for avoiding unexpected parasite actions to compromise the global safety of the system. It is not always the case in buildings integrating ancient materials and techniques (e.g. ancient masonries stacked with lime mortars). Although the proposed finite element approach allows direct damage to be taken into account in such cases, this will still increase the resource expensiveness and, if necessary, quick patterns transposed from other fields where similar threats concern ancient materials may be used for outlining impact indicators concerning the structural integrity. Besides these considerations, serviceability limit states will better focus comfort criteria adapted to the usage (housing, offices, shop,…) of the building or parts of it and the context (urban, peri-urban,…) in which it is implanted. Sometimes considered of less importance due to their non-technical character, such considerations however reveal of the greatest importance for people and then for politic decider. For various purposes in other disciplines, the comfort question has been widely studied. It focuses on phenomena and consequences that will be perceived by the human being and could be felt as uncomfortable like local velocities or accelerations of the medium. For the vibratory signal perceived at any location, both the amplitude and frequency content play a role and the recourse to Fourier analysis is required. The spectral decomposition of the response will allow outlining resonance phenomena affecting key structural parts. The establishment of impact indicators concerning the occupation comfort can rely on conventional indicators [11] derived from national or international standards (DIN, ISO, ANSI, OSHA) that take cognitive aspects into account.

For practical reasons (quantity of data), the authors developed an automatic post-processing facility inside the Matlab environment [12]. This computation environment is particularly well suited for the treatment of big data and presents native signal processing capabilities. In practice, the post-processing facility scans the response signal (acceleration and/or velocity) for each node of the meshed structure and computes an indicator value that may be compared with related boundaries. Three main aspects are investigated. The first one, based on ISO2631, will rely on the acceleration signal (square root of the integrated signal weighted by the elapsed time). It will outline total comfort for a_w values lower than 0,315 m/s² and major problems once higher than 2 m/s². The second one, based on DIN 4150-2, will rely on the velocity signal (after filtering, the signal is square elevated and multiplied by an exponential function before being integrated and weighted by the elapsed time). It will outline comfort for boundary values of KB_{Fmax} which depend on the fact the vibratory actions take place during the night or during the day. Finally, the third one, based on US593630-1, also relies on the velocity signal (square root of the integrated signal weighted by the elapsed time) that will be reported on a reference velocity and later translated into decibels. It will outline comfort for boundary values of V_{dB} which depend on the fact the solicitation will be more frequent (more than 70 occurrences a day: 72 dB allowed) or less frequent (less than 70 occurrences a day: 80 dB allowed).

3. SWOT analysis and potentialities

Based on preliminary usages of the presented method which have brought the evidence of its interest for predicting vibratory levels in buildings located along urban railway lines, a SWOT analysis gathering *Strengths*, *Weaknesses*, *Opportunities* and *Threats* associated to the proposition may be outlined, drawing the path to future developments.

The fundamental **strength** associated with the proposed approach is related to the fact it will effectively integrate each aspect playing a role in the problem, from the emission to the reception of the vibrations. Moreover, convenient results can be obtained without requiring hardly achievable data. The producer can deliver the mechanical data, basic geotechnical or geophysical survey can offer the soil data and classical building information allow replicating the structure to be studied. In cases where results obtained on a "rough" modelling outline the interest for higher precision concerning one or the other part of a sub-system, the initial model may be directly enriched. Besides these aspects, it is important to highlight that the proposed approach relies on existing methods and tools, developed for other purposes and recognized and robust, that have been here transposed (and eventually amended) for answering the considered question. Finally, the ultimate advantage concerns the fact that the proposed approach is not at all limited for what concerns the nature of the structure that can be studied: the recourse to classical Finite Element simulation opens the way to the classical day-to-day missions of civil engineering offices.

The most problematic **weakness** associated with the proposed approach concerns the CPU time that is required for solving the entire workflow. The second task is the main resource-demanding one with around 0.2 hours for task 1 and 3 while 30 hours are required for task 2. Up to now, considerable progresses have been obtained in soil modelling for offering the greatest freedom in structure modelling. A potential weakness may be pointed in relationship with the ease of structure modelling: a "classical" civil engineer should have trained basic skills in mechanical engineering if he needs to manage by himself the first task. Moreover, the increasing amount of high quality results will clearly require specific work to be brought for improving the manner these may be made interpretable to the practitioner. Finally, the occurrence of numerical instabilities being observed in some cases, the related aspects should be better taken into account for allowing the user not to waste time with useless runs. The recourse to a semi-implicit integration scheme should give encouraging results and will then be investigated.

The main **opportunity** associated with the proposed approach concerns the fact it is as "open-to-user" as "open-to-developer". In fact, even with the current level of development, any civil engineer will be likely to perform the work once the vehicle data will have been introduced in the workflow. In parallel, the workflow is totally likely to be improved with apartment logic: each task may be improved separately form the others and sharp specialists can then focus on parts they master the best [13].

When targeting ideal spread for the proposed workflow, an indirect **threat** concerns the CPU demand. For balancing important calculation times, recourse to supercomputers may be proposed. Nevertheless, such a solution is likely to limit the current usage to high added value cases, namely those associated with Heritage Preservation where general guidelines edited by international institutions like UNESCO or ICOMOS recommend careful studies to be carried out prior to any intervention on or in the neighbourhood of enlisted monuments and that are susceptible to induce damage or irreversible modifications to a part of the Heritage. Consequently, it is nowadays hardly reasonable to impose a systematic recourse to vibratory anticipation practices in any cases. In parallel, as EasyDyn is delivered as open-source and the development proposed in the Matlab environment could easily become exported to an open-source platform like Octave, the development of the second task is currently affected by commercial limitations: the proposed finite-infinite approach is only implementable in a limited number of commercial software.

Nevertheless, the intensive usage of finite element simulation in many fields of the daily engineering practice has initiated the development of non-commercial simulation platform that are quickly evolving. It is then possible that the recourse to proper boundary conditions mimicking soil infinity (and thus reducing the parasite reflection) could join such an open-source platform in a near future, allowing overcoming this commercial limitation.

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