The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 27.6
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.27.6

On the Development of Digital Twins for Condition Monitoring of Mechanical Systems

J. Ambrósio[1], J. Pagaimo[1], P. Millan[1], J. Costa[1],

[1]LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal

Abstract

The implementation of a condition-based maintenance policy for railway locomotives requires the development of models and methods to monitor the condition of bogie components using computer simulations, focusing on bogie frame damage and degradation of elements of the suspension system. First, the computational models are verified through the comparison of their results against the actual vehicle response, recorded in an experimental measurement campaign. The variability of the operating conditions and the parameter uncertainty are considered in the definition of the simulations using experimental design techniques. These strategies also contribute to solve the problem of the high computational cost associated with simulations of highly non-linear railway dynamics using detailed vehicle models. The post-processing involves a variety of methods including the analysis of signals in the frequency domain using the concept of transmissibility, in addition to the use of regression and statistical tools to model the vehicle response in the time domain. Condition classification methodologies are proposed to detect and locate damage on the bogie frame and the failure of suspension elements. The final result is the successful development of digital twins for the condition monitoring of the locomotive bogie structural heath and for the suspensions. In the process a methodological framework is presented to allow the use of the developments obtained in other applications for which the identification of physically based digital twins are of importance

Keywords: Multibody Dynamics; Railway Dynamics; Condition-Based Monitoring; Suspension Damage; Structural Damage.

1 Introduction

The online health monitoring of railway vehicles allows the optimisation of the maintenance strategies and, consequently, the reduction of the life cycle cost, with direct economic benefits for railway operators. In the framework of project LOCATE the development of tools and methodologies to implement a condition-based maintenance policy for railway locomotives is achieved [1]. The critical subsystems addressed in this work are the suspension system and bogie frame. This work is supported by models and numerical simulations that identify the nominal and abnormal behaviour of the locomotive and its subsystems, in conditions that are representative of the operational context of the vehicle. These simulations also allow not only the identification of simple predictive models of the vehicles, also referred to as digital twins, and the definition of thresholds for warning limits and the prediction of component degradation of these critical subsystems.

Two different approaches can be distinguished concerning the development of computational models for the prediction of component degradation [2]:

- Use of machine learning algorithms that provide predictive models based on large history datasets of faults and inspections. Such models are commonly black boxes, i.e. purely mathematical abstractions that do use any information on the physical processes of component degradation;
- Use of deterministic, or stochastic, models that depend on expert knowledge and are representative of the mechanics of failure and degradation, requiring the definition of the geometrical, material, and mechanical properties that describe the system.

Not only because the use data driven models do not include the physics of the problem but also due to the lack of a comprehensive operational history database to support the use of artificial intelligence approaches, the development and implementation of computational models based on expert knowledge of the system physics are preferred here. Models based on multibody dynamics for railway vehicles [3] are used to simulate the vehicle-track interaction [4] and the results contribute to generate a database of the vehicle behaviour considering different levels of component degradation. The measured behaviour recorded in on-track tests in the context the project LOCATE [5] are used to build, verify, and calibrate the database of the vehicle response.

2 Methods

The methodology developed here starts by identified suitable models for the vehicles and track and identifying the appropriate operation conditions in which sensor data sensitive to the vehicle condition can be extracted but which is basically insensitive to tack geometry. Next the models are validated in order to ensure their predictability. The third step involves the development of various models of the vehicle with varied levels of damage on the subsystems identified for maintenance. The final step on the methodology is the development of the physically based digital twins as a result of the simulation of the healthy and damaged vehicle models and the identification of thresholds of the key performing indices identified for the digital twins.

2.1 Models for the Vehicle, Track and Operation Scenarios

The objective of the work is the development of digital twins to appraise the condition of the locomotive bogie frame for structural integrity and suspension elements for performance degradation. Although the wagons are not the focus of the study, it is important to understand if the locomotive bogie conditions are sensitive, or not, to the operation conditions due to the pulling of the freight wagons. Therefore, multibody models of trains, with the locomotive and wagon models shown in Figure 1, are used to identify what is the less complex train model that can be used for the study.

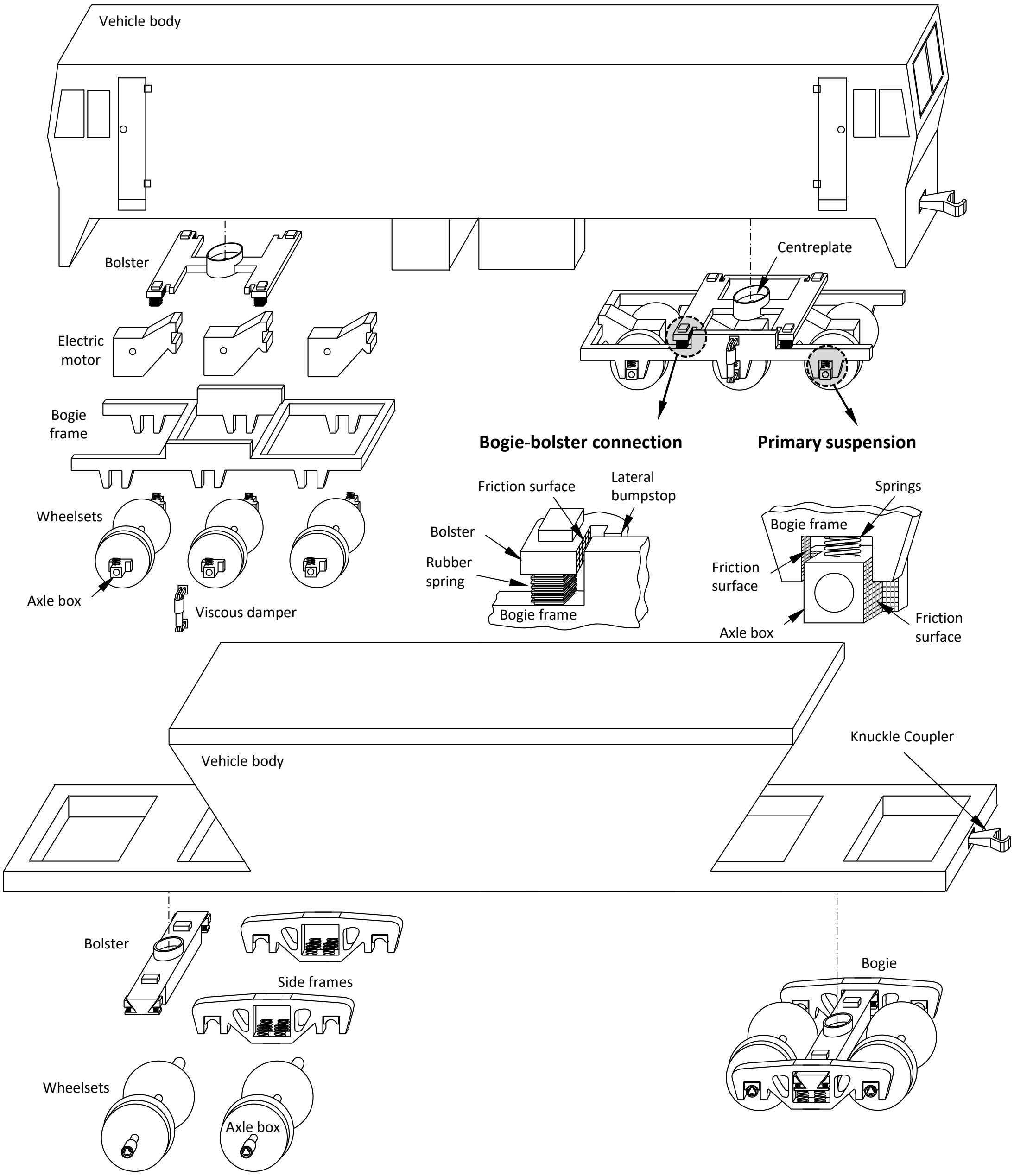

Figure 1 – Locomotive and wagon multibody models.

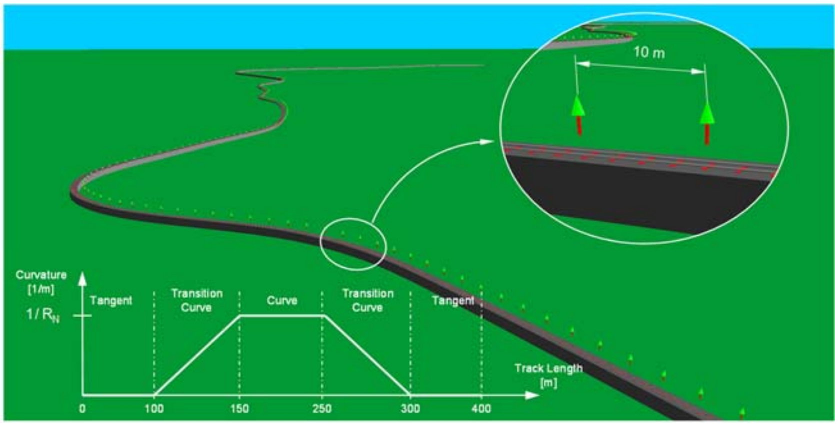

Figure 2 – Track section model for the operation of the freight train in a montanious railway.

Further details on the locomotive model are presented by Millan et al. [6]. Due to the need to handle the structural condition of the locomotive bogie frame, several components of the bogie are modelled with flexible multibodies, as described by Pagaimo et al. [7], for the purpose of modelling common structural defects.

The freight train is operated in a mountainous region in a track with a metric gauge. Several sections of the track, with 4 km each, are built to provide the reference operation scenarios. The track sections, such as that exemplified in Figure 2, are selected not only to allow the characterization of the operation but also because of their use during the experimental campaigns in which dynamic responses of the locomotive are acquired.

2.2 Vehicle and Track Models Validation

Before the train model, and those of those of the locomotive in particular, can be used for the developments that follow it is important that they can be trusted. The model validation process involves the fine tuning of selected mechanical properties for which the variability is very high and that can influence the vehicle dynamic behaviour. The procedure is highlighted in Figure 3 in which the model dynamics is compared against the experimental response acquired in track testing campaigns.

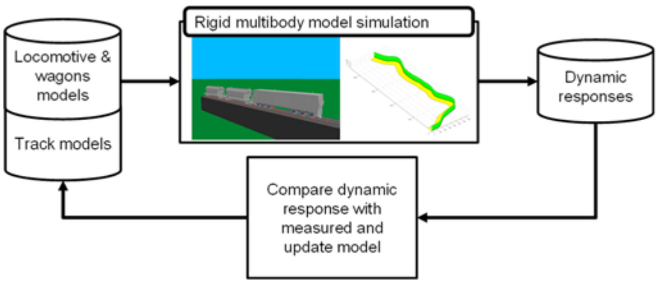

Figure 3 – Comparative study of the model behavior against experimentally acquired dynamic responses.

The signals are evaluated in different sections with constant radius, as suggested in the standard [8]. At each section the signals are filtered and processed to obtain the maximum and average values. In total, 10 straight sections and 10 curves are considered. This validation steps allows for two important conclusions: (1) the vehicle model dynamic response compares well with the experimental data, according to the metric used; (2) The presence of one or two freight wagons on the train, fully loaded or unloaded, do no influence the dynamic responses of interest to characterize the condition of the locomotive bogies. Therefore, not only the locomotive model is deemed as validated but also the less complex train includes the locomotive only.

2.3 Models of the Vehicle with Damage

With the locomotive model devised and the ability to represent selected components by flexible multibodies, several damaged models of the bogie frame, exhibiting crack in different location, generally at weld location, and with different depths are generated. A Finite Element model of the bogie frame is shown in Figure 4

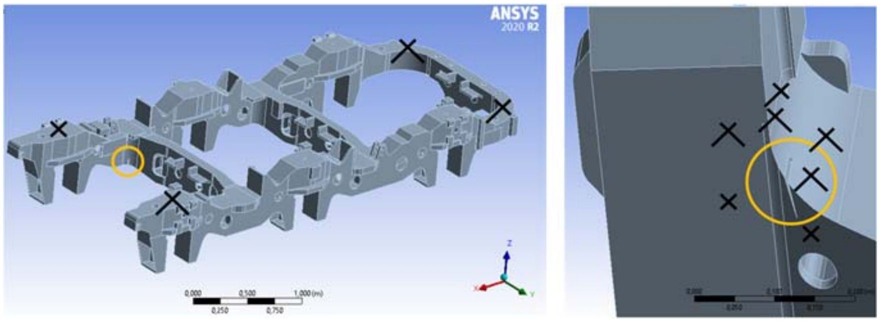

Figure 4 – Flexible multibody model (using the Finite Element Method) of the bogie frame with a crak modelled.

Different models for the suspension elements, i.e., springs and dampers, are also used in different locomotive models to appraise the effects on the dynamic response of different levels of suspension degradation. The use of Design-of-Experiment methods [9], and in particular of the Latin Hypercube Sampling, as pictured in Figure 5, provide the metric to devise the surrogate models (or meta-model) for each selected dynamic response with a minimal set of computer simulations.

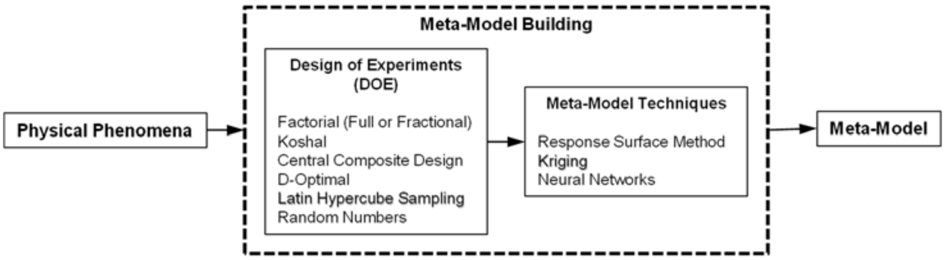

Figure 5 – Defining the computer experiments required to build the metamodel associated to each digital twin.

2.4 Digital Twins and Performance Thresholds for the Locomotive Bogie

These meta-models are in fact the digital twins in which for any given input to the system, i.e., mechanical conditions for the locomotive bogie, a dynamic response similar to that of the complex locomotive model is obtained immediately. The meta-model is in fact a surface response obtained via Kriging. The key issue is how to compare healthy dynamic responses, measured in terms of accelerations obtained in particular points of the bogie frame and suspension elements with those for damaged components. It is found that the natural frequencies of the damaged components are not sensitive enough to the level of damage. Instead, the use of the Transmissibility Damage Index (TDI) proposed by Maia et al. [10,11] shows a good sensitivity to the amount of damage with the extra benefit that it allows locating the defects in the bogie frame geometry. The process is illustrated briefly in Figure 6.

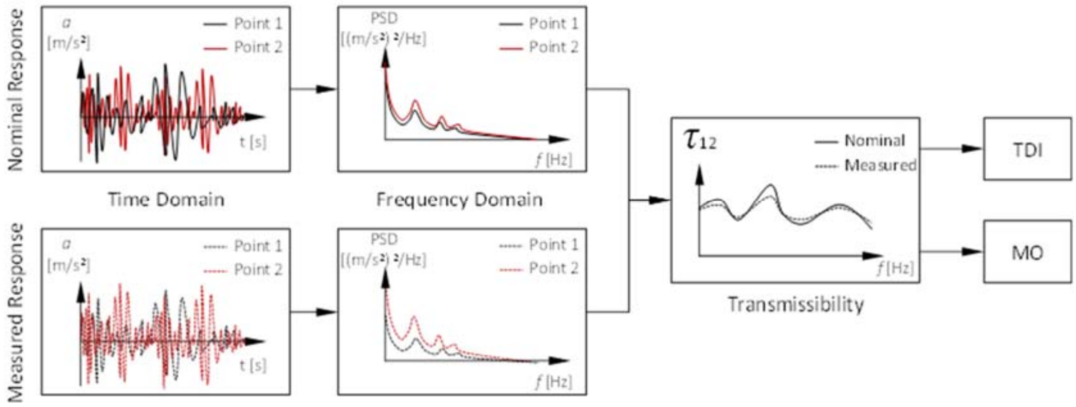

Figure 6 – Methodology for condition monitoring using the Transmissibility Damage Indicator (TDI).

3 Results

The key results for the developments described in this work are two digital twins for the condition-monitoring of two critical subsystems of the locomotive bogie, the bogie structure and the suspension elements. The flowchart of the digital twins, with the characterization of the inputs and their association to the sensoring system, are described in Figure 7. Computer simulations of the damaged locomotive and its components allow setting thresholds values for some of the studied quantities. The quantities identified are sensitive to cracks in the bogie frame, buckled or broken springs, and damaged dampers. However, note that these thresholds are defined for specific speed ranges using simulations. They must be reviewed and adapted using data from on-track measurement campaigns. Table 1 lists thresholds for the TDI, defined using the methods. The upper and lower thresholds for the standard deviation of the lateral accelerations of the bogie frame measured at different positions to detect damage are identified in the framework of Project LOCATE. It must be emphasized that the values reported here as they are specific for the particular locomotive studied. Other values must be identified for specific vehicles as their structure is also different.

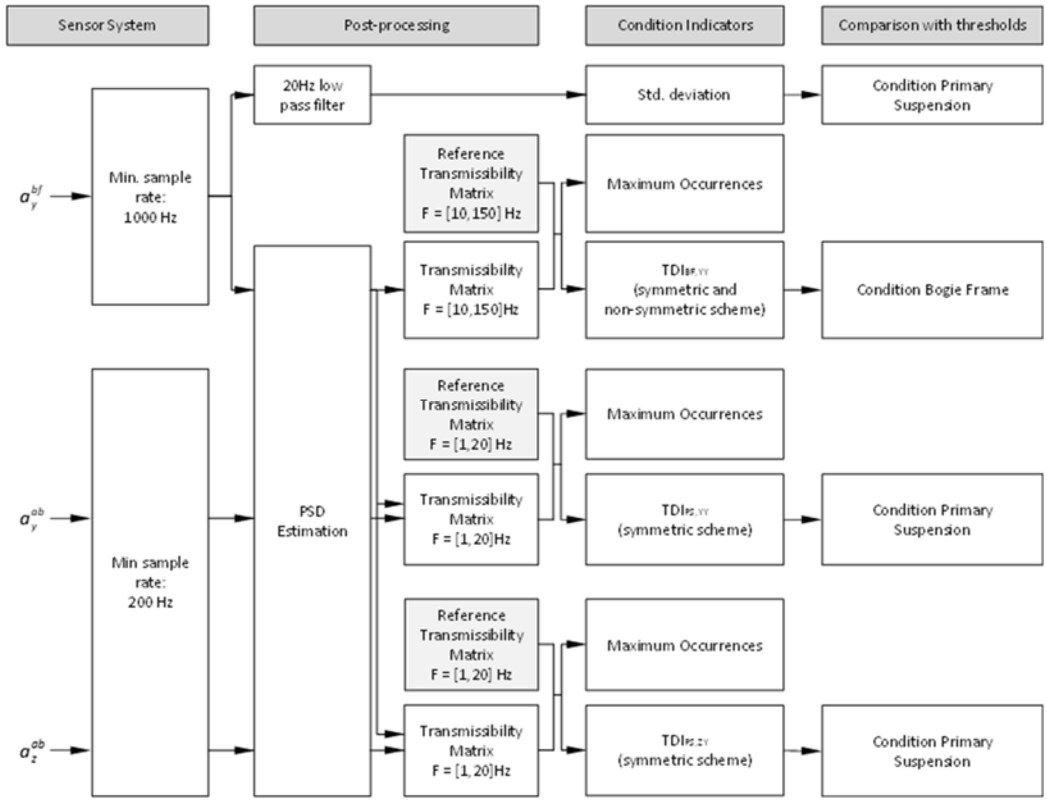

Figure 7 – Data flow for the condition monitoring methods.

Table 1 – Limit values for quantities used in condition monitoring.

System	Quantity	Description	Speed Range [km/h]	Limit value	Occurrence
Primary Suspension	$TDI_{PS,YY}$	TDI using lateral acceleration at axle boxes and lateral accelerations at bogie frame	25-70	0.85	Buckled/Broken Spring
	$TDI_{PS,ZY}$	TDI using vertical acceleration at axle boxes and lateral accelerations at bogie frame	25-70	0.95	Buckled/Broken Spring or Damaged Damper
Bogie Frame	$TDI_{BF,YY}$	TDI using vertical acceleration at axle boxes and vertical accelerations at bogie frame	57-63	0.7	Crack in Bogie Frame

4 Conclusions and Contributions

The development of physically based Digital Twins, aiming at exploring an alternative solution for the vehicle condition monitoring with a smart diagnostic approach, is demonstrated in this work. Instead of a comparison of the faulty and fault-free signals, this fault detection method takes the advantage of the relationship between the measured dynamic response and estimates for healthy conditions to identify directly the health parameters in a quantitative manner. In the process of the developments reported in this work it has been found that the use of the Transmissibility Damage Indicator Method, for the structural damage, and the Maximum Occurrences Method, with the aim of detecting damage in the springs and dampers of the primary suspension, provide the best metrics to allow differentiating healthy and non-healthy operating conditions. The transmissibilities between the Power Spectral Densities (PSD) of the accelerations measured at the virtual sensors in the axle boxes and bogie frame are employed extensively. The methodology proposed describes a framework for the development of physical based digital twins that can be easily replicated in other application cases.

Acknowledgments

The Portuguese Foundation for Science and Technology (Fundação para a Ciência e a Tecnologia) through IDMEC, under LAETA, project UIDB/50022/2020 and PhD grants BD/04939/2020 and UI/BD/151204/2021 are gratefully acknowledged. This work is part of the project LOCATE, under Shift2Rail Joint Undertaking, identified by the grant agreement 881805 – LOCATE –H2020-S2RJU-OC-IP5-01-2019. Ferrocarrils de la Generalitat de Catalunya and VibraTec are particularly acknowledged.

References

[1] Balouchi F, Bevan A. A Framework for Locomotive Bogie Condition-based Maintenance (LOCATE). WCRR22 - World Congr Railw Res. Birmingham, United Kingdom; 2022.

[2] Bruni S. INNOWAG D4.2 - Innovative Monitoring and Predictive Maintenance Solutions on Lightweight Wagon. Milan, Italy; 2018.

[3] Pagaimo J, Magalhães H, Costa JN, et al. Derailment study of railway cargo vehicles using a response surface methodology. Veh Syst Dyn. 2022;60:309–334.

[4] Magalhaes H, Marques F, Antunes P, et al. Wheel-rail contact models in the presence of switches and crossings. Veh Syst Dyn. 2022;1–33.

[5] Siwiak H, Bevan A, Santos M, et al. LOCATE Report D3.2 on List of Selected Sensors and Devices. Écully, Auvergne-Rhône-Alpes, France; 2021.

[6] Millan P, Pagaimo J, Antunes P, et al. Multibody Modelling of a Friction Damped Locomotive for Virtual Homologation. Railw 2022 - Fifth Int Conf Railw Technol Res Dev Maint. Montpellier, France; 2022. p. 1–8.

[7] Pagaimo J, Millan P, Magalhães H, et al. Influence of Damage on the Response of a Bogie Frame using a Flexible Multibody Methodology. Railw 2022 - Fifth Int Conf Railw Technol Res Dev Maint. Montpellier, France; 2022. p. 1–8.

[8] En BS, EN 14363. Railway applications - Testing for the acceptance of running characteristics of railway vehicles - Testing of running behaviour and stationary tests. Communities. 2005;3:CENELEC European Committee for Electrotechnical St.

[9] Santner TJ, Williams BJ, Notz WI. The Design and Analysis of Computer Experiments. 2nd ed. New York, US; 2018.

[10] Sampaio RPC, Maia NMM, Silva JM., et al. On the Use of Transmissibility for Damage Detection and Location. Eur COST F3 Conf Syst Identif Struct Heal Monit. Madrid, Spain; 2000. p. 363–376.

[11] Maia NMM, Almeida RAB, Urgueira APV, et al. Damage detection and quantification using transmissibility. Mech Syst Signal Process. 2011;25:2475–2483.