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Vehicle-Bridge Interaction and Structural Health Monitoring for Bridge Asset Management

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Abstract

Structural Health Monitoring of railway bridges is a widely researched topic, yet limited practical applications are found. This is partly due to the complexity of the problem. The dynamic response of the bridge is influence by various operational and environmental conditions. Vehicle-Bridge Interaction is another widely researched field, yet merely focusses on the dynamic effects itself and less on the applicability for Structural Health Monitoring systems. This paper provides a brief overview of the two topics Vehicle-Bridge Interaction and Structural Health Monitoring and shows how to link them. It is shown by an example of field experiments and modelling on the Boyne viaduct in Ireland that Vehicle-Bridge Interaction is an essential element of Structural Health Monitoring. It is also shown how the dynamic response can be converted into relevant features, the instantaneous resonance frequency and bridge free resonance frequency. The features are used in a pattern recognition step for the final judgement regarding the likelihood of damage.

Keywords: vehicle-bridge interaction, structural health monitoring, fault diagnosis, bridge condition, nonstationary dynamics, asset management.

1 Introduction

The crucial role of bridges in the railway infrastructure needs little explanation. Failure of a bridge can have catastrophic consequences, but even unexpected disruptions of the operation of the bridges have severe consequences. Aggressive maintenance policies will secure the safe operation and will prevent unexpected maintenance needs. However, it is costly, since a lot of redundant maintenance is done, and it negatively affects the availability of the track. Both aspect are undesirable in the context of the European ambitions to make the European rail network more efficient, cost effective, competitive and a green alternative for air transport.

The European rail network comprises of 212,000 km and 300,000 bridges, according to the information in the review of Vagnoli et al. [1]. Over 35% of these bridges are over 100 years of age. Not all of these bridge have reached their designed end of life, but a vast number of bridges possibly has reached the end of their lifetime. More importantly, many bridges will nowadays experiences loading conditions that were not foreseen in the design phase, as train designs and operation velocities have significantly changed over the course of time.

Keeping track of the need for maintenance, in other words monitoring the condition of bridges, is therefore of great importance: this knowledge allows to schedule maintenance in time and based on the actual condition of the asset. This will increase the availability and reliability of the track without compromising the safety. Moreover, it is more cost-efficient.

The main source of information to assess the condition of a railway bridge is the vibrations induced by passing trains. Although the relation between vibrations and passing vehicles is a general concept, the interaction between train and railway bridge is typically a special case: the mass of the train is relatively large compared to the mass of the bridge. This implies that the dynamic response of the system is that of a coupled system, where the dynamics of the passing vehicle interact with the dynamics of the bridge. In addition, a car or truck can be approximated by a point load or mass, while the length of the train cannot be considered small with respect to the bridge length, resulting in a distributed, moving dynamic load. Moreover, even more complex dynamics emerge in case of high-speed trains, since the velocity can be in the range of the critical velocity of the bridge.

The interaction is known as *Vehicle-Bridge Interaction* (VBI) and has been subject of a many researches. A literature search on Vehicle-Bridge Interaction reveals that most of the researches focus on the dynamic modelling aspects [2]. Indeed, the dynamic response – including the understanding of the sources of the response – is essential if it comes to the condition assessment. However, the response itself is not the assessment. This is illustrated in the flow chart in fig. 1 [3]. The dynamic response is the input for the diagnostic phase, with as main steps feature extraction and pattern recognition. An ideal feature is sensitive to the expected damage or degradation, while insensitive to operational and environmental conditions. The pattern recognition step essentially classifies whether or not the measured feature value (or pattern) is anomalous, to which extent and related to which type of damage or degradation. A prognostics step follows, if applicable and desirable, but is not considered in this paper.

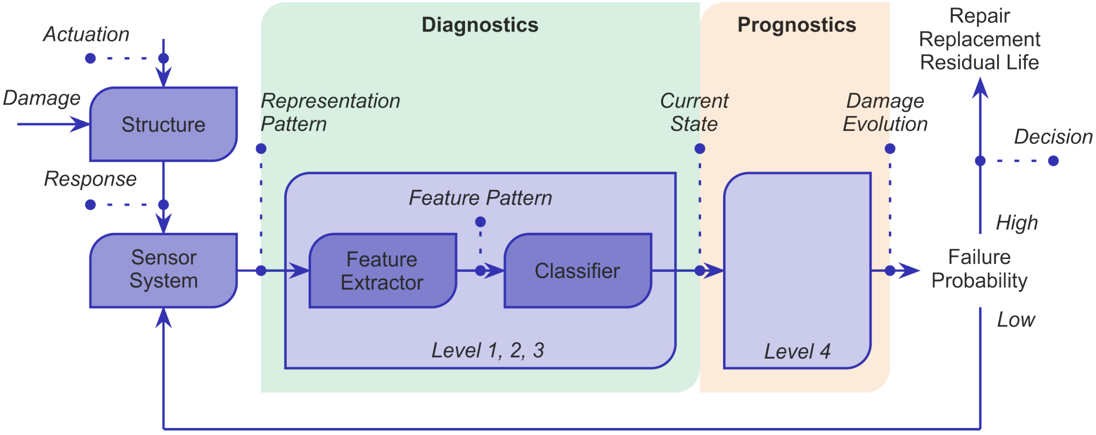

Figure 1: Flow chart of the Structural Health Monitoring process.

Searching for “railway bridge structural health monitoring” results in another large series of articles, too many to be listed. Vagnoli et al. collected a lot of relevant information in their review [1]. General concepts of Structural Health Monitoring, as also used in other fields of application, appear in these articles, but the link between VBI and SHM is not always evident. This paper addresses the several of the elements that need to be considered to develop the information of VBI systems and an SHM system to asset management information.

2 Methods

Using the flowchart of the Structural Health Monitoring process in fig. 1, a number of topics will be addressed in the following sections. The aim is to get an overview of achievements and challenges. The extent of this overview is limited by the limited length of the paper.

2.1 Vehicle-Bridge Interaction – Dynamical Models

The field of Vehicle-Bridge Interaction is broad and densely filled with research papers. However, the majority of the models is based on 2D models with one or multiple moving masses, connected by springs and dampers, over a beam structure. In some cases even the track dynamics are included, again by sets of spring-dampers. A solid foundation for this type of modelling is provided by Frýba [4], but many models, with varying complexity have followed since. One of the more complete examples is found in the work of Bowe et al. [5] and is shown in fig. 2.

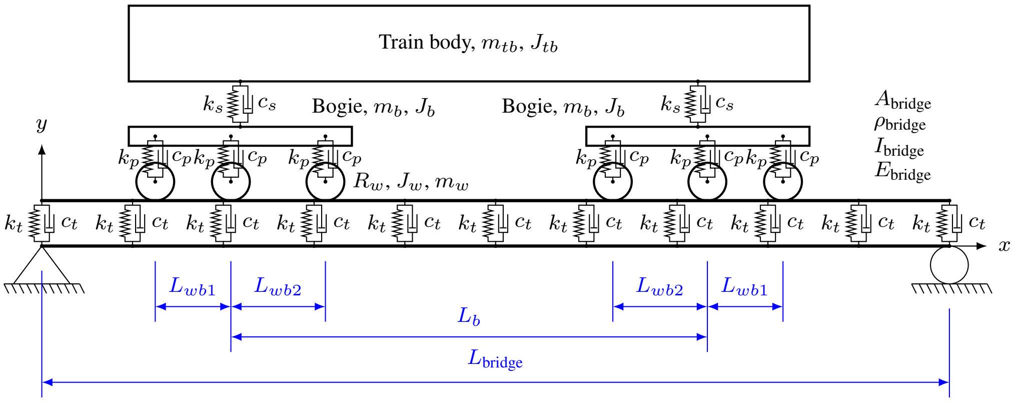

Figure 2: Schematic representation of a bridge and vehicle, both consisting of multiple sub-structures with each their own dynamics.

Analytical equations can be derived to describe the dynamic behaviour and calculate the response of the coupled system, such as, amongst others, described by Yang and Wu [6] and Wang et al. [7]. The general equation of motion is used as a starting point:

$$m\,\ddot{u}_y(x,t) + c\,\dot{u}_y(x,t) + k\,u_y(x,t) = f_y(x,t) \tag{1}$$

with $u_y(x,t)$ the displacement in time t in y direction along x direction, the mass m, damping c, stiffness k and $f_y(x,t)$ the force acting in y direction. A modal approach is chosen to solve the differential equation, describing the motion $u_y(x,t)$ of the bridge as a linear combination of the mode shapes ϕ_n:

$$u_y(x,t) = \sum_{n=1}^{N} \phi_n(x) q_n(t) = \sum_{n=1}^{N} \left(\sin\left(\frac{n\pi x}{L}\right) q_n(t) \right) \tag{2}$$

with $q_n(t)$ the modal coordinate of the n^{th} mode. The second part of the equation corresponds with the solution for the mode shapes of a simply supported beam of length L; bridges are commonly modelled as simply supported beams. The train induced moving force(s) $f(x,t)$ acting on the bridge are described employing a delta-Dirac operator:

$$f_y(x,t) = f_c(t)\delta\left(x - vt\right) \tag{3}$$

with $f_c(t)$ the forces resulting from the dynamics of the train (or vehicle in general) and v the velocity of the vehicle. The complexity of the force $f_c(t)$ evidently depends on the complexity of the vehicle model.

The existence of (semi-)analytical solutions for these models is a great benefit, but at the same time also a downside if it comes to damage modelling. Including damage, in terms of a locally reduced stiffness for example is not possible. Numerical models are needed to include the damage [8–10].

2.2 Updated Finite Element Models

As an alternative to the (semi-)analytical 2D models, more comprehensive models can be made. A Finite Element Model can be used to include more details of the bridge. However, as also clearly stated in the review of Vagnoli et al. [1], there is always a gap between the simulated response and the response measured in the field, compromising the validity of the model. This discrepancy originates from many sources. Precise modelling requires knowledge of a lot of details that are either not well defined or known. Material properties of older bridges may not be known precisely, the geometry and construction of elements may not be specified well, or not be exactly according to the technical drawing if those are available anyway. Modern technologies, such as point cloud based models [11], where drones are used to collect the images, necessary to create the model, only partly solve the problem: these methods are vision based and hence are inherently limited to (geometrical) features that are visible from the outside. This type of modelling is often referred to as “Digital Twinning”. The use of this term can be disputed as in many cases it only concerns a digital representation of the real asset.

A more fundamental problem is the poor ability of current dynamic models to include the complex behaviour in connection points. Model updating techniques are generally used to match the numerical model with the field observations. Limited possibilities exist to tune the model and these often concern global quantities, such as damping values. Model updating can be successfully applied to match the first modes of the numerical model with field measurements, but the more complex behaviour is more difficult to match and the link between the actual physical quantities and the values used in the model is gradually lost.

2.3 Data Collection

The data used to update numerical models, is collected by measurements. A clear distinction can be made between inspection and monitoring. Inspection is the activity in which a measurement device is brought to the object to be measured, while monitoring relies on integrated sensing systems. The advantage of the latter is that data can be acquired from more difficult to reach locations. Moreover, a more consistent and continuous data set is generated. At the same time it should be pointed out that a fully continuous measurement is typically not needed for structures such as bridges, as degradation processes are typically slow. Collecting continuous data generates large amounts of data, but not necessarily information. On the other hand, trends due to environmental conditions, such as the temperature fluctuation over the year, can be conveniently identified.

Typically, accelerometers are used to measure the dynamic response. Although these sensors have a strong track record, the downside is the wiring that is needed.

Wireless sensors only partly solve that issue, as dinstance over which the data needs to be transmitted can be large and energy resources for the wireless sensors to collect, process and transmit data are limited [12]. Optical fibre systems, mostly Fibre Bragg Graing based, are an upcoming and good alternative for accelerometers, since multiple sensors can be embedded in a single optical fibre (so-called *multiplexing*) [13]. However, the number of number of sensors available to monitor a complete bridge is in all cases relatively limited.

Other data source or data collection methods exist next to the direct measurement of the vibrations of the bridge structure. Firstly, the dynamic response of the vehicle-bridge system can also be captured by measurements on the train [5]. The advantage of such a measurement is that multiple bridge objects can be monitored with a single measurement system. A reasonable overview of the network can be acquired if multiple trains are equipped with a measurement system. However, the data analysis is in general more complex, although this also strongly depends on the location of the sensors. As close as possible to the track is best, but makes disclosure of the data more complex. These systems are often mounted on the bogie system, which makes sense in light of the dynamic properties of the bogie compared to those of the bridge – in the same range – and those of the train body – often different, with a lower resonance frequency, for reasons of passenger comfort.

Infra managers also measure data via way-side measurement systems. These systems provide predominantly operational data, such as the train velocity and tonnage passing a certain point. The data does not immediately provide insight in the condition of the rail system (or bridge for that matter), but it does give information on the loading of the system.

2.4 Feature Extraction & Pattern Recognition

Having collected data, either via field experiments or via models, does not imply that the condition of the bridge can immediately be determined. The identification and extraction of features in the signal that are sensitive to the damage of interest is key. According to Worden et al. [14], no baseline-free approach exists, since the response under investigation is always compared to some expectation, model, reference result and so on. Model-free approaches, however, do exist [1]. These approaches use no knowledge on the data and only rely on finding differences between two signals. These methods may be able to detect anomalies, possibly even the location of the anomaly, but not the extent and nature of the anomaly. Model-based approaches are needed for that purpose, implicitly referring to the use of physics-based models [9].

Physics-based models can be informative, but also become very complex, depending on the factors that need to be accounted for. Environmental effects are known to have a strong influence on the response, creating a large amount of variability in the results. The most common factor is temperature variation. Several field measurements that ran over a longer period show that the dynamic characteristic such as the eigenfrequency of a bridge vary with the temperature [15–17]. A clear pattern following the seasons of the year can be identified. The temperature itself shows a large amount of variability and other weather conditions can also influence the change of dynamics properties. Heat of the sun can even cause asymmetric modes, due the bridge being significantly warmer on one side than on the other side. The exact consequences of the different conditions are not sufficiently well understood.

In contrast to physics-based model, data-driven approaches are strong in recognising patterns in signals. Literature shows a lot of work is done on models based on for example Neural Networks, trying to identify the differences in the responses [1]. Most benefit is obtained when the variability in the physics-based models is dealt with by data-driven methods, creating so-called *hybrid* models [18]. Possibly the biggest hurdle here is that researchers work in different domains, are not familiar with each other's work and have problems appreciating the work of the other by lack of knowledge.

3 Results & Discussion

To illustrate at least part of the elements discussed above, the work done in a research project executed at the University of Twente is used. This work was done in the framework of the EU DESTinationRAIL project [19].

3.1 Field Experiments

A two-year measurement campaign was set up, centred around the Boyne viaduct near Drogheda in Ireland (fig. 3). The Boyne viaduct consists of a number of masonry arches and three steel girder spans. The centre span is of interest for monitoring. This sections spans 81 meters, with 10 truss based bays, and a curved top shape with a maximum height of 10.6 m. A single track runs over the bridge. Two different types of trains pass this bridge: a *Diesel Multiple Unit* (DMU) train with 4 to 8 carriages, with each their own diesel engine and equal dynamic properties, and a *Enterprise* diesel locomotive combined with up to 9 passenger wagons. Mass and suspension characteristics of the locomotive and wagons, and with that the train dynamics, are significantly different.

Four triaxial accelerometers and four strain gauge rosettes were installed on the bridge. The number of sensors is relatively small, due to costs of the sensor and data acquisition systems, but also the installation of the sensors. The data acquisition system is based on a Compact RIO (cRIO) system of National Instruments (NI cRIO 9068), a stand-alone unit to which dedicated acquisition units can be connected. To

Figure 3: Boyne Viaduct near Drogheda, Ireland. *Photo by R. Loendersloot.*

accommodate all channels, the following units are plugged in the base frame:

- One NI 9220 16 channel unit for the accelerometers (taking 4 slots)
- Three NI 9236 4 channel strain gauge units
- One NI 9191 4 channel temperature unit

The systems was installed for a period of well over two years, resulting in a data set of more than 2000 train passages and 500Gb.

3.2 Feature Extraction & Pattern Recognition

Data is a convenient asset, but not necessarily equal to information. Common approaches extract dynamic properties from the bridge out of signals recorded by the accelerometers. Subsequently changes are identified and correlated with for example environmental or operational conditions such as temperature or vehicle speed. If the change in dynamic properties can *not* be explained by any of the known variations, hence if it deviates from correlations found between for example resonance frequency and temperature, then it is assumed this change is attributed to damage.

However, this approach requires to first establish correlations between the dynamic characteristics and the various conditions under which the system operates. Moreover, it excludes in most cases the dynamic response during passage of the vehicle – the period to which Vehicle-Bridge-Interaction applies. The approach in this research is therefore to include the VBI response and as such to investigate the transient, non-stationary dynamics during the traverse phase and recognise patterns in the dynamic signature, inherently accounting for as many environmental and operational conditions as possible. The resulting signal pattern is one that can be compared with a reference case to judge whether or not damage is present. A numerical VBI model is used to develop this approach.

Vehicle bridge interaction learns that interaction between the bridge and the train depends on the resonance frequencies of the sub-systems. Mostafa et al. [10] showed that the interaction strength is high if the resonance frequency of the bridge and that of the bogie are close. In that case relatively strong added mass and added stiffness effects occur. This results in a specific pattern for the two close resonance frequency, as shown in fig. 4: one resonance frequency lowers and one rises, until the vehicle is halfway the bridge, after which they return to the resonance frequencies of the two individual sub-systems. The instantaneous frequencies for various bogie-bridge frequency ratio are shown.

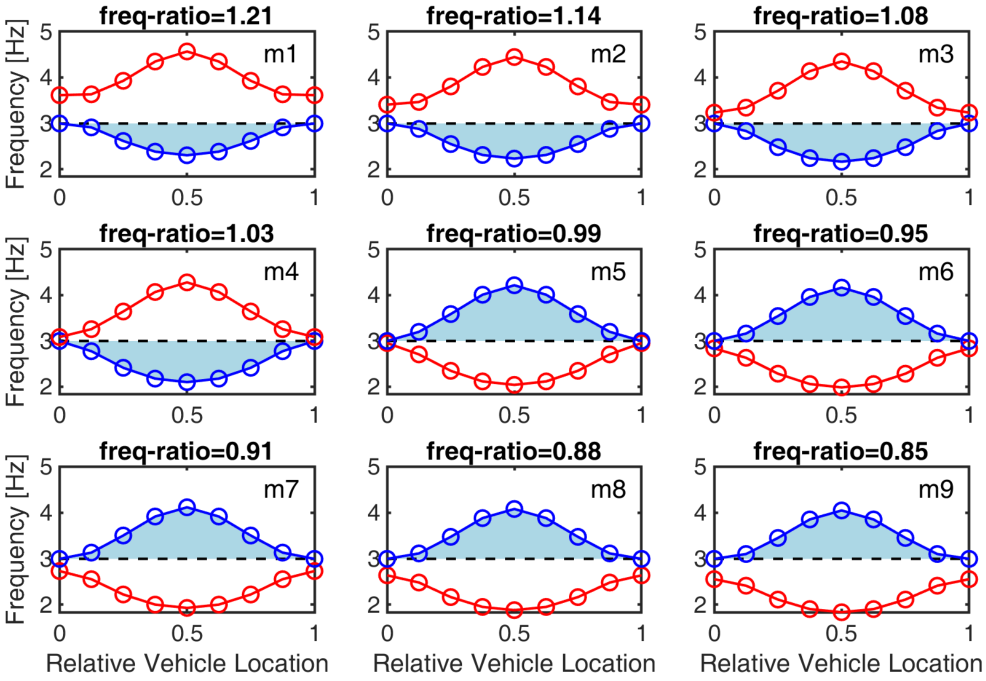

Figure 4: Typical instantaneous resonance frequency behaviour of a vehicle and bridge for varying ratios of the resonance frequencies, all relatively close to unity. Blue dots at relative position 0 and 1 correspond with the bridge resonance frequency, the red dots with the vehicle frequency.

Extraction of the instantaneous resonance frequencies is the first step in this analysis. Given the specific constraints of this case, the Wavelet Synchro-Squeezed Transform (WSST) was found to out perform other time-frequency based methods such as the Short Term Fourier Transform and the Wavelet Transform [8] in terms of accuracy of the instantaneous frequency. The WSST transform, for a time signal $x(t)$, wavelet function ψ with scaling parameters a and b is defined as:

$$T_x(\omega, b) = \sum_{\omega_j} \left(\frac{1}{\omega_j - \omega_{j-1}} \sum_{a_k} \left(\left(\int_{\Delta t} \frac{x(t)}{\sqrt{a_k}} \psi \left(\frac{t - a_k}{b} \right) \right) \frac{a_k - a_{k-1}}{a_k \sqrt{a_k}} \right) \right) \tag{4}$$

Subscripts j and k indicate a partitioning of the respective parameters in ranges. With this approach, the *shape* of the instantaneous resonance frequency is extracted as a feature. This shape-based feature can be made independent from the loading condition and the environmental conditions [20]. A different load will affect the maximum change of the resonance frequency, but not the shape itself. A change in temperature will cause a vertical shift of the instantaneous frequency, again not changing the shape itself. It should also be note that the actual bridge resonance frequency can be extracted from the remaining vibration just after the train has left the bridge (the free-vibration case).

The correlation between the shape of the instantaneous resonance frequency measured at a certain moment in time and the reference is the first step in the damage detection process. Any pattern recognition method can be used for this purpose, here the Pearson correlation coefficient ρ is used, which in discretised form reads:

$$\rho\left(\mathcal{F}_r, \mathcal{F}_m\right) = \frac{1}{n-1} \sum_{i=1}^{n} \left(\frac{\mathcal{F}_{r,i} - \mu_{\mathcal{F}_r}}{\sigma_{\mathcal{F}_r}} \right) \left(\frac{\mathcal{F}_{m,i} - \mu_{\mathcal{F}_m}}{\sigma_{\mathcal{F}_m}} \right) \tag{5}$$

with $\mathcal{F}$ the instantaneous resonance frequencies for the reference (r) and measured (m) case, and μ and σ the mean and standard deviations for n (time step) samples. A small damage may still result in a high correlation. Therefore a second measure, δ is introduced, which is defined as the deviation of the measured instantaneous frequency ($\mathcal{F}_m$) from the reference instantaneous frequency ($\mathcal{F}_r$):

$$\delta\left(\mathcal{F}_r, \mathcal{F}_m\right) = \frac{\sum\limits_{i=1}^{n-1} \left(\left(\mathcal{F}_{r,i} + \mathcal{F}_{r,i+1} \right) - \left(\mathcal{F}_{m,i} + \mathcal{F}_{m,i+1} \right) \right)}{\sum\limits_{i=1}^{n-1} \left(\left(\mathcal{F}_{r,i} + \mathcal{F}_{r,i+1} \right) - 2 f_r \right)} \tag{6}$$

where f_r refers to the bridge fundamental free resonance frequency. Equation (6) is the area enclosed by the two instantaneous frequencies $\mathcal{F}_r$ and $\mathcal{F}_m$ divided by the area enclosed by the instantaneous frequency of the reference case $\mathcal{F}_r$ and the free resonance frequency f_r (the blue areas in fig. 4). The combination of ρ and δ gives an indication of the presence of damage. A main issue is to determine when the combination of ρ and δ deviate sufficiently to conclude damage is present. A too strict threshold will result in a large number of false positives, undermining the trust in the added value of the monitoring system. A too loose threshold results in actual damage cases being missed, undermining the trust in the performance of the monitoring system.

An open question is how many reference signal will be needed in this approach. In principle, normalisation to the resonance frequency of the bridge, measured in the time span immediately after the train has left the bridge, compensates for temperature variations. Different magnitudes of loading does not result in a different shape. However, it may be necessary to compare the response of similar trains, since the response of for example the *Diesel Multiple Unit* trains and *Enterprise* trains do have a significantly different dynamic signature.

3.3 VBI-based SHM system

A flow chart, shown in fig. 5 can be constructed linking all elements mentioned in the previous section and hence linking Vehicle-Bridge Interaction with a condition assessment. The flow chart starts with a trigger event. The monitoring system is not collecting data continuously, but only in case of the presence of a train. Additional, randomly timed measurements can help to get an idea of the general noise levels and the functionality of the sensor system, but this is not included in the flow chart. The VBI response is collected after the trigger is issued. Information on the train type is collected in addition to the analysis of the measured signal (referred to with subscript m) on the lefthand side of the flow chart. This can be done using the same sensor readings as used in the VBI response analysis, but this information can also be retrieved via another wayside monitoring system.

Here, the VBI response is defined as the acceleration response $\ddot{x}_m(t)$. The first step is to separate the signal in two parts: the *traverse phase* ($\ddot{x}_m(t)\big|_{\text{TP}}$), during which the train passes the bridge, and the *leaving phase*, the free vibration response after the train has completely left the bridge ($\ddot{x}_m(t)\big|_{\text{LP}}$). The first is a non-stationary signal and the instantaneous resonance frequency $\mathcal{F}_m$ is extracted from this signal. Any other instantaneous, or non-stationary feature can be used in principle, as discussed in section 3.2. The leaving phase signal is used to extract the stationary features that provide information on the current environmental conditions, in this case the first bridge resonance frequency f_m is used as feature. Together with the identified type of train – and possibly weight of the train, via a *Weigh-In-Motion* system – the most suitable reference (instantaneous) frequencies $\mathcal{F}_r$ and f_r are selected. The measured instantaneous frequency $\mathcal{F}_m$ will be compared against this reference, obtaining first the (shape) correlation ($\rho(\mathcal{F}_r, \mathcal{F}_m)$) and if needed the deviation ($\delta(\mathcal{F}_r, \mathcal{F}_m)$). This last step is the *pattern recognition* step. If both thresholds are violated, then there is a high likelihood of damage. It is important to recognise that the outcome is a *likelihood* of presence of damage (or degradation). Uncertainty quantification methods and reliability engineering concepts need to be applied to translate the outcome to input for the

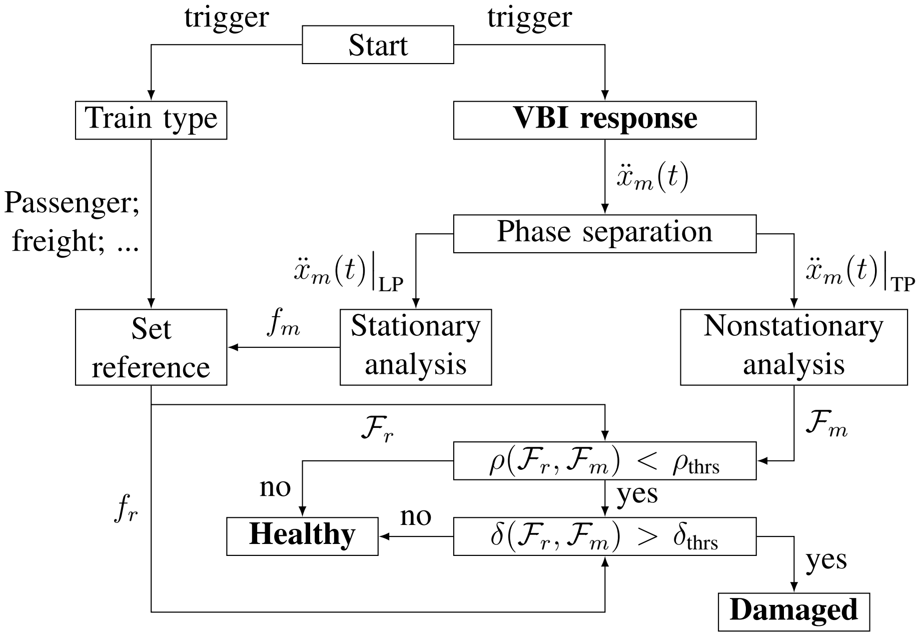

Figure 5: Flow chart of a VBI based SHM system for railway bridges.

risk assessment of an asset managers.

4 Conclusions & Future Work

This paper discussed the link between Vehicle-Bridge Interaction and Structural Health Monitoring. It has illustrated the elements that are important to make this link, be it in a somewhat superficial way as this is in fact a quite elaborate exercise with a lot of elements to take into account. The main messages of this work are that VBI by itself is insufficient to assess the structural integrity of a railway bridge, that SHM of railway bridges is made significantly more robust if the VBI response is taken into account and finally that the link can be made by selecting the right feature extraction (here the instantaneous resonance frequency, as well as the bridge free resonance frequency) and pattern recognition methods (here the Pearson correlation and the deviation function).

Although treated more implicitly, it can also be concluded that the implementation of a Structural Health Monitoring based asset management, can only be successfully implemented if physics-based, data-driven and data-science methods are combined. None of them by themselves will be sufficient for such a system.

The work presented here, is partly based on field experiments and partly on numerical models. Currently, there is still a gap between these. Closing this gap, by for example scaled, but realistic vehicle-bridge interaction experiments, is an essential step forward to be able to understand better how to analyse the field experiment data. This is one of the most important steps, but improvements, be it more in terms of fine-tuning and optimising, are needed in all aspects of the VBI based SHM system.

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