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## INVESTIGATION OF STRUCTURE BORNE NOISE FOR A STEEL RAILWAY BRIDGE

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### ABSTRACT

In this study the Equivalent Radiated Power (ERP) approach has been applied for assessment of structure borne noise radiated by a steel bridge subjected to train load (Klaerner, Marburg, & Kroll, 2014). Noise is defined as unwanted sound (Heutschi, 2016). In this paper noise and sound are used interchangeably. The main goal of this research effort is on introducing the ERP approach to classify the components of a specific steel bridge structure in terms of noise generated.

For this purpose a Finite Element (FE) model will be used to obtain structural vibrations of bridge components. Linearization of the fluid-structure-interaction yields the conclusion that the velocity of a radiating surface equals the velocity of fluid particles in vicinity. This notion represents the ERP approach, which is used in this study (i) to characterize modal noise contribution of noise radiating surfaces and (ii) to estimate the contribution of a vibration mode to the total noise generated. The ERP approach is computationally inexpensive, but it is restricted as discussed in the current study.

### 1. Motivation of the Research

When a train runs across a bridge, it is very likely that an amplification of excessive noise compared to the standard track will be observed (Thompson, 2009). This amplification

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varies with the type of the bridge structure and is frequent for ballastless steel railway bridges (Thompson, 2009). There are several reasons for increasing noise due to the presence of a bridge. Correspondingly, there are multiple possibilities to quantify noise. In the civil engineering community it is very common to characterize noise either based on the dominant sound generating source (for example, structure borne noise vs. vehicle borne noise) or on the frequency content of the sound pressure at the sensitive receiver. For instance, it is reasonable to consider a bridge as a ‘sounding board’, because of transmitting vibrations exposed by the train through the load bearing bridge structure to noise radiating surfaces. Therefore, this phenomenon is also referred to as structure borne noise, which is characterized by significant peaks in the low frequency domain. In contrast, rail fastening systems affect noise radiation in the high frequency region (Thompson, 2009). The punch line, however, is that the efficiency of acoustic design and/or noise mitigation systems strongly depends on the frequency content of the sound pressure at the sensitive receiver. In the current paper the ERP approach is used to approximate the radiated power by vibrating surfaces of a bridge. In other words, attention is on structure borne noise rather than on vehicle borne noise.

The main goal of the research is to classify the components of a specific steel railway bridge according to their noise generation potential. Based on this classification changes in the dynamic properties of the bridge could be assessed (that is tuning mitigation systems to structural performance) in order to achieve noise reduction (Wiechmann & Hiller, 2011).

This paper has the following structure: (i) briefly addressing the theoretical basis of the ERP approach, (ii) modelling of a representative bridge and the forcing function, and (iii) performing ERP analysis. Conclusions (iv) are drawn about the overall applicability of the method.

## 2. Fundamentals of the Equivalent Radiated Power Approach

Consider an elastic object with noise radiating surface  $S$  subjected to a forcing function in the frequency domain. The sound radiation of a vibrating object is estimated by the sound power  $P(f)$ , produced by its radiating surfaces:

$$P(f) = \int_S \vec{I}(f) \cdot \vec{n} \, dS . \quad (1)$$

In which  $f$  denotes frequency in units of Hz,  $\vec{I}(f)$  is the vector of sound intensity in accordance to Equation (3) (Heutschi, 2016), and  $\vec{n}$  is the orthogonal vector of the infinitesimal small surface  $dS$ . Let vector  $\vec{v}_f$  (subscript ‘f’ denotes ‘fluid’) be the vector of fluid velocity in adjacency to the sound radiating surface  $dS$ . Accepting that the fluid velocity is an adequate approximation of the velocity of the sound radiating surface,  $\vec{v}(f)$  represents the notion of ERP approach, which is equivalent to decoupling the fluid structure interaction (clearly this does not hold vice versa). Consequently, the fluid velocity can be estimated by dynamic analysis (actually representing a response quantity from dynamic train-load analysis):

$$\vec{v}_f(f) \approx \vec{v}(f) . \quad (2)$$

Subsequently, the sound intensity evaluated for any infinitesimal surface,  $dS$  for a given frequency is a vector proportional to the real part of the product of the scalar valued sound pressure,  $p(f)$ , and the velocity field,  $\vec{v}(f)$ , corresponding to  $dS$  :

$$\vec{I}(f) = 1/2 \Re[p(f)\vec{v}(f)]. \quad (3)$$

In linear acoustics, the relation between sound pressure,  $p(f)$ , fluid density,  $\rho_f$ , wave propagation velocity,  $c_f$ , and the fluid velocity,  $\vec{v}_f$ , reads:

$$p(f) = \rho_f c_f \vec{n} \cdot \vec{v}_f(f). \quad (4)$$

Substituting Equation (4) in Equation (3), considering Equation (2), and taking the norm yields a scalar field referred to as ERP density,  $ERP_d(f)$ , (that is, a scalar representing the radiated power at  $dS$ ), corresponding to sound intensity (Huang, Mhmed, & Rongfeng, 2011):

$$ERP_d(f) = 1/2 \rho_f c_f |\vec{v}(f)|^2. \quad (5)$$

The absolute ERP,  $ERP_{abs}(f)$ , is a scalar governed by the integral of the ERP density over the surface  $S$  of the vibrating object for a certain frequency  $f$ .

$$ERP_{abs}(f) = \frac{1}{2} \rho_f c_f \int_S |\vec{v}(f)|^2 dS. \quad (6)$$

### 3. Modelling and Simulating the Dynamic Response of the Bridge

#### 3.1. Finite Element Modelling

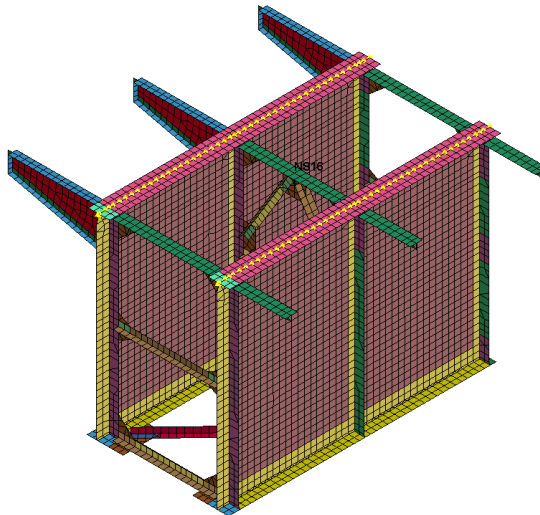


Figure 1. FE Model of the bridge structure

A FE model of a railway bridge near Vienna, Austria was built (Figure 1) (FCP – Fritsch, Chiari & Partner ZT GmbH, 2017). For reasons of demonstrating the *ERP* approach and studying structural behaviour, a sub-structure of the bridge has been modelled only. It is well-known that human perception of noise is associated with the frequency content of sound pressure between 20 Hz and 16 kHz (Heutschi, 2016) (sometimes referred to as *human hearing range*). The presented model of the sub-structure allows studying response quantities in the aforementioned frequency range as discussed in the following paragraphs.

### 3.2. Load Assigned to the Bridge Structure

The loading is applied as prescribed acceleration along the middle nodes of the top flange (Figure 1 – marked with yellow dots). The prescribed acceleration was obtained through measurement during a single train passage (FCP – Fritsch, Chiari & Partner ZT GmbH, 2017). This type of loading requires careful analysis of recorded signals and can be defended as outlined below:

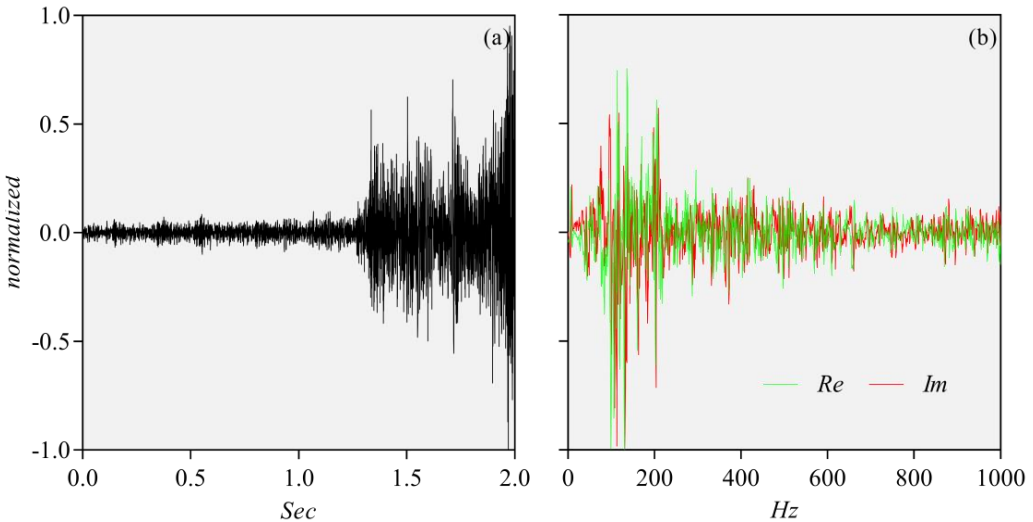
- **Stationary assumption:** It is of relevance to note that the duration of the excitation due to a train is relatively long compared to the periods of response quantities. Hence, it is reasonable to assume stationary conditions of the excitation, leading to simplified computational methods (FCP – Fritsch, Chiari & Partner ZT GmbH, 2017). That is, a stationary forcing function (in the frequency domain) will be assigned to the sub-structure rather than actual vehicle loads (in terms of rolling stock analysis in the time domain).
- **Load pattern:** The stationary assumption does not provide information regarding the load pattern. However, for representative sets of freight trains and passenger trains, the autocorrelation functions as well as cross correlation functions of the vertical component of recorded accelerations on the top flange have been evaluated (FCP – Fritsch, Chiari & Partner ZT GmbH, 2017). This led to the conclusion that the forcing function can be modelled by a zero mean normal stationary stochastic process with a linear spatial distribution on the top flange. In this paper results of deterministic simulation will be discussed in an effort to introduce the ERP approach. For stochastic dynamic analysis the reader is referred to (FCP – Fritsch, Chiari & Partner ZT GmbH, 2017).

Figure 2 (a) shows the first two seconds of normalized vertical acceleration measured during the train pass in the time domain, Figure 2 (b) depicts the corresponding signal in the frequency domain. With this data a ten point averaging of the time-history data was performed, since (i) the recording frequency was larger than required for the representation of the frequencies of interest (attention is on structure borne noise), and (ii) scope of the paper is on introducing the concept of ERP rather than presenting a comprehensive analysis. From Figure 2 (b) is clear that the frequency response is dominant in the region between 50 Hz and 300 Hz. Thus, it is expected that response quantities in the aforementioned frequency range will be amplified significantly since natural frequencies of the structure are tuned to the frequency content of the forcing function.

Notice, this hybrid strategy (FCP – Fritsch, Chiari & Partner ZT GmbH, 2017) consisting of measurement and numerical modelling allows separating the stochastic excitation from the deterministic structural model. For instance, geometric and material properties are readily available from shop drawings in an effort to assemble a reliable model. Uncertainty, however, is imposed to response quantities due to rail roughness, vehicle irregularities and

environmental conditions, among others. In other words, the uncertain part will be extracted from experimental data.

In summary the structural model shown in Figure 1 has been exposed to a linearly distributed stationary forcing function in terms of prescribed acceleration (see Figure 2 (b)) at the top flange. This comes with the benefit of performing analysis in the frequency domain, which is computationally relatively inexpensive compared to response history analysis (Clough & Penzien, 2003).



**Figure 2. Measured (prescribed) vertical acceleration in (a) the time domain and (b) in the frequency domain**

### 3.3. Steady-state Analysis of the Structure

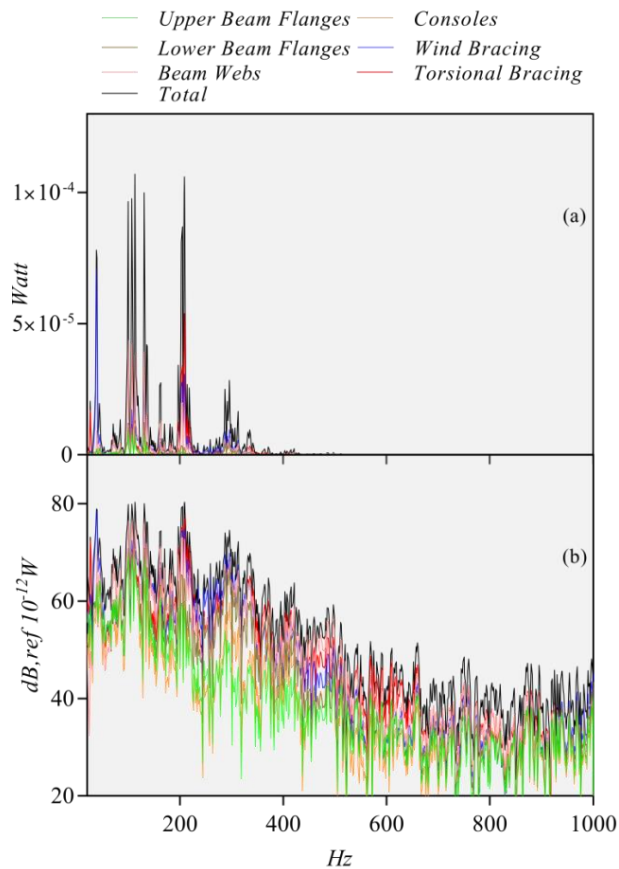
Response quantities, particularly Fourier amplitude spectra of structural velocities, have been extracted by means of steady-state analysis (SSA) (Clough & Penzien, 2003), which were required for ERP analysis as outlined below. In this study, steady-state analysis has been performed based on modal expansion. Therefore, in an initial step modal analysis has been used to decouple the system of equations leading to a set of modal equations of motion. For each modal Single-Degree-of-Freedom (SDOF) oscillator modal velocity spectra were determined. Finally, velocity spectra in physical coordinates have been computed by modal superposition (Chopra, 2011). To each modal SDOF oscillator a constant modal damping ratio of  $\zeta = 3\%$  as been assigned.

## 4. Evaluation of the ERP

From the vibration velocity obtained in the dynamic analysis of the bridge model the ERP density and absolute ERP are calculated according to Equation (5) and (6). From a practical point of view evaluation of ERP results should be separated in two stages (FCP – Fritsch, Chiari & Partner ZT GmbH, 2017):

- Extract spectra of the absolute ERP to identify sound radiating frequency regions based on the ERP magnitude provided by Equation (6).
- Plot the ERP density at the previously determined frequencies in accordance to Equation (5) in an effort to determine the distribution of sound radiation over the surface of the structure.

Figure 3 presents the absolute ERP of the sub-structure (black spectrum) and the relative contribution of different components (coloured spectra). It is interesting to see sharp spikes of the absolute ERP in the spectral region up to 300 Hz. This finding is consistent with the consideration explained in Section 3.2. Furthermore, the absolute ERP tends to zero as the frequency increases in the spectral region larger than 400 Hz. This behaviour indicates that for the sub-model of this particular bridge structure borne noise is dominant in the low frequency region with respect to the human hearing range.



**Figure 3. (a) Absolute ERP and (b) ERP in decibels**

Plots of the ERP density at these frequencies are required to identify sound radiating structural members. Representative plots of the ERP density for the vibration modes are presented in Figure 4 (39.6 Hz), Figure 5 (74.2 Hz), and Figure 6 (294.8 Hz). In Figure 4 and Figure 6 the wind bracing is expected to contribute most to the noise. In contrast,

Figure 5 shows that beam walls contribute significantly to the total radiated noise. Plot of the ERP density for the following members are not shown for the sake of brevity. However, torsional bracing contributes at frequencies around 26 Hz and at 225 Hz, the contributions of the lower and upper beam flanges are dominant at 120 Hz. The consoles are contributing at frequencies close to 100 Hz.

Based on these results various noise reduction provisions could be adopted, for typical application is referred to (Thompson, 2009). An important note is that since only a section of the bridge is modelled, the obtained ERP values correspond only to that section and not the entire structure. Nevertheless, these values are used as indicators for the noise generation mechanism of the entire bridge.

LS-DYNA keyword deck by LS-PrePost  
 Freq = 39.648  
 Contours of ERP density  
 min=3.89922e-12, at node# 62862  
 max=0.000229816, at node# 47533

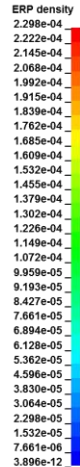
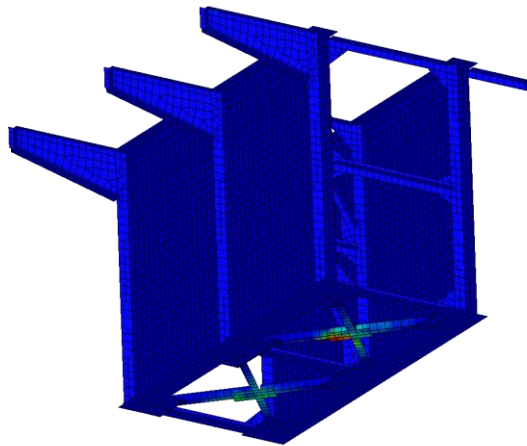


Figure 4. ERP density at 39.6 Hz

LS-DYNA keyword deck by LS-PrePost  
 Freq = 74.168  
 Contours of ERP density  
 min=1.8272e-13, at node# 51372  
 max=1.73817e-06, at node# 47549

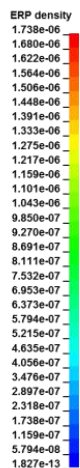
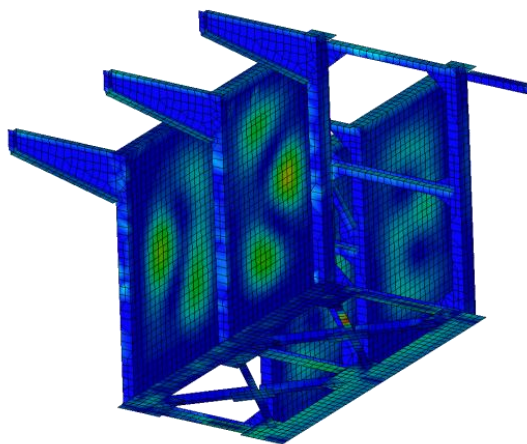


Figure 5. ERP density at 74.2 Hz

LS-DYNA keyword deck by LS-PrePost  
 Freq = 294.8  
 Contours of ERP density  
 min=1.00521e-12, at node# 51253  
 max=4.19099e-05, at node# 47778

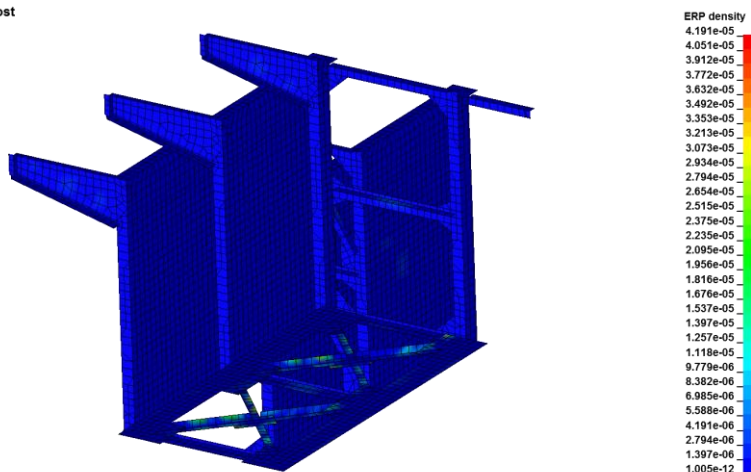


Figure 6. ERP density at 294.8 Hz

A restriction of the proposed ERP approach is the inability to obtain the spatial distribution of noise in the vicinity of the structure. The spatial distribution of noise would be useful when the goal is to reduce the noise levels for a residential area near the bridge structure.

Limitations of the proposed ERP approach could be overcome by the application of the Boundary Element Method (BEM). In this case BEM is used for the analysis of the sound wave propagation in the air medium. Boundary conditions are defined by the surface vibration of the bridge structure, obtained from the dynamic train-load analysis. The result is the pressure difference in the air medium as a function of time, which is perceived as sound. Further information on the application of the BEM for acoustic analyses could be found in (Huang, Mhmed, & Rongfeng, 2011), (Thompson, 2009); (Heutschi, 2016), (LS-DYNA Theory Manual, 2017).

## 5. Conclusions

The proposed ERP approach for bridge noise assessment is an effective procedure for gaining insight to the noise generation mechanism of a specific structure. Such insight would be used for analyses of noise reduction measures in both newly designed and existing structures.

The effectivity of noise reduction measurements can be analysed by changing dynamic properties of sound radiating members, by adding absorbing elements and/or changing support conditions of interconnected members (considering elastic pads, for instance). It is of essence to realize that changes in the dynamic properties of the bridge model would require modifications of the forcing function, since prescribed accelerations are part of the load bearing structure. This could be overcome by calculating the Transfer Function (TF) between the vertical distributed forces along the top nodes (Figure 1) and a vertical acceleration at a measurement point. Multiplying the measured acceleration by the TF would yield the distributed force in the frequency domain. The obtained force could be subsequently applied to the modified bridge model as it is less sensitive to changes in dynamic properties. However, this procedure is applicable as long as the effects of Train-Bridge Dynamic Interaction (TBDI) are not pronounced in the changed state of the bridge. This implies that the dynamic properties

of the bridge structure do not affect significantly the contact force between the structure itself and the passing train (Liu, De Roeck, & Lombaert, 2009). Therefore, the same input load could be applied to a model with changed dynamic properties. A procedure for the estimation of the TBDI significance is available in (Eurocode 1991, 2004).

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