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# A LABORATORY TEST BENCH TO SUPPORT PASSENGER COMFORT ASSESSMENT IN RAILWAY VEHICLES

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Ride comfort is assuming increasing importance for railway industry, from the very first stage of vehicle design up to the final on track tests. Reference standards define the measuring positions and the data processing techniques to experimentally assess ride comfort. The EN 12299 standard defines the $N_{MV}$ as the reference index for evaluating mean comfort, starting from acceleration measurements taken on the vehicle floor. However, passenger's perception is also influenced by the dynamic response of the seat, and by the consequent vibration levels at the interface with the human body. For this reason, additional indexes such as the $N_{VA}$ proposed by EN 12299 can be adopted. This paper presents a laboratory test bench which has been set up for investigating the relationship between the floor vibration and the actual comfort of a seated passenger. The test bench consists in a portion of floating floor on which a pair of seats is installed. The system is excited through an electro-hydraulic actuator and acceleration signals are collected in different positions, also including passenger-seat interface. The test bench can be used for analysing the effect of seat dynamics on passenger comfort and for supporting seat design optimization.

Keywords: railway vehicle, ride comfort, passenger, floating floor, seat dynamics.

## 1. Introduction

The ride comfort of railway vehicles has drawn increasing attention from the operators in the recent years, which is reflected by the efforts dedicated to improving it by means of active or passive methods [1-4]. The European standard EN 12299 defines the measurement and evaluation methods of railway vehicle ride comfort [5]. Acceleration signals measured on the floor and/or the seats are adopted to compute the ride comfort indexes. In particular, the standard defines the "Mean Comfort" index by the Standard Method as the reference index ($N_{MV}$), for which only the measurements on the floor are considered. In alternative, the "Mean Comfort" index can be evaluated by the Complete Method ($N_{VA}$ for seated passengers, $N_{VD}$ for standing passengers), starting from the measurements on seats or other interfaces. The Complete Method generally better correlates with the passenger's perception of comfort, especially in the case of seated passengers. This implies that the transmissibility of the seats is fundamental for the passenger's perception. Other standards, such as ISO 2631 [6] that evaluates the human exposure to vibration in a more general context, consider only the whole-body vibration, and the importance of the passenger's whole-body vibration is widely acknowledged by researchers [7-10]. Most of the studies on ride comfort rely on numerical models or on-track test data [11]. The precision of the numerical model predictions depends on its complexity (vehicle only or coupled vehicle-track), and the ability to reproduce the dynamic characteristics of the various sub-systems (e.g., suspensions, vehicle body, seats) as well as the connections between them. The on-track test results are the most representative for the passenger perception but are subjected to a few limitations for a more detailed analysis. For instance, the effects of the various sub-systems cannot be distinguished and, hence, it is difficult to understand which sub-system should be tuned to improve the ride comfort. On the contrary, if appropriately designed, laboratory tests can be carried out to study the influence of a single sub-system taking into account the actual dynamics of the same (also including the connections between the various sub-systems, thus replicating the actual configuration on the vehicle).

The current work presents a laboratory test bench designed to support passenger comfort assessment. The test bench consists in a portion of floating floor of a railway vehicle on which a pair of seats are installed and is used to study the effects of the dynamics of the floor and seats on a passenger. Specifically, the relationship between the floor vibration and the passenger's perception is investigated by comparing the $N_{\mathbf{MV}}$ and $N_{\mathbf{VA}}$ comfort indexes. It is worth stressing that the excitation applied to the floor and seats is deemed as representative of that received by the same components during the train commercial service in terms of the spectral content, because the adopted signals are derived from on-track measurements.

## 2. Laboratory test bench and test procedure

In the first part of the current section, the test bench is illustrated followed by its experimentally identified frequency response. In the second part, the test procedure for the investigation of the relationship between the floor vibration and the passenger's perception is described. In addition, the method adopted to derive the excitation equivalent to that generated during on-track tests is explained in detail.

The laboratory test bench is set up at the Department of Mechanical Engineering of Politecnico di Milano. The test bench is shown in Fig. 1. A portion of an actual floating floor of a vehicle is reproduced, where a pair of seats are installed. The test bench consists of floor panels, extruded aluminium profiles, and isolators (between the previous components and the supporting beams). An electro-hydraulic actuator is positioned in front of the seat, rigidly connected to the floor to excite the floor-seat system by means of the inertial force transmitted to the ground. A mass of 5 kg is placed on the top of the actuator to increase the applied force. A triaxial accelerometer is installed on the floor, under the seat (point A in Fig. 1). Two triaxial seat pad accelerometers are positioned on the seat pan and the backrest.

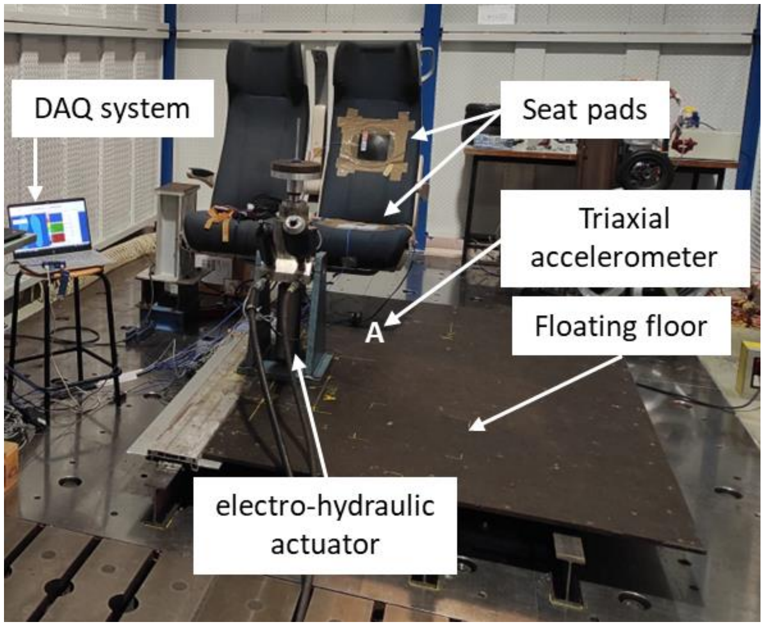


Figure 1: laboratory test bench.

The dynamic characteristics of the test bench are studied by computing the frequency response function (FRF) of the floor. The transfer inertance evaluated at point A (see Fig. 1) is derived and presented in Fig. 2 as a function of frequency. A slow sine sweep (5-40 Hz) is applied by the actuator; the input force, for the FRF computation, is estimated starting from the acceleration measured by the transducer mounted on the oscillating mass connected to the actuator's rod. A passenger is seated on the instrumented seat during the test.

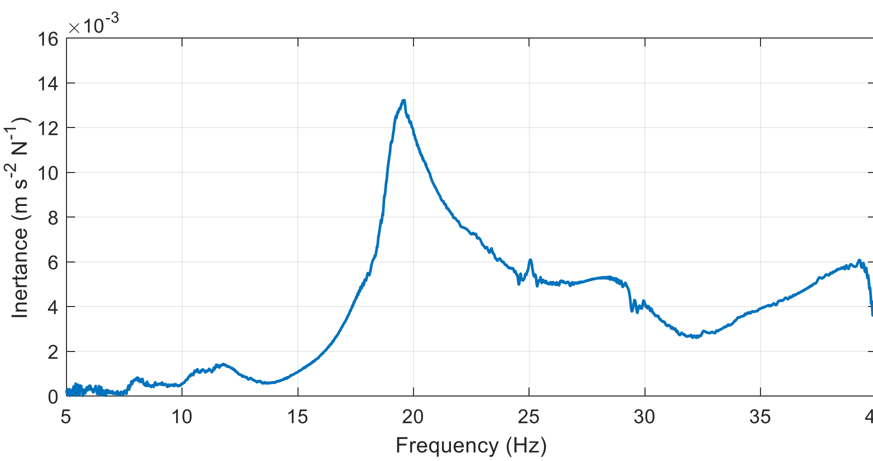


Figure 2: floor transfer inertance evaluated at point A (see Figure 1).

The dynamic amplification effect is evident above 15 Hz and a peak of the FRF is located at 19 Hz, which is associated to a resonance of the floor-seat system. The result implies that the ride comfort can be significantly influenced by the dynamics of the floor and seats. It should also be pointed out that the influence is the consequence of the floor-seat coupled system, rather than of the individual sub-systems.

Once the experimental characterization of the test bench was carried out, the test procedure for the investigation of the relationship between the floor vibration and the passenger's perception is explained. To accomplish the task, acceleration data representative of those reached during the train commercial service should be considered. To this end, reference is made to data previously measured during an experimental campaign carried out by the Department of Mechanical Engineering on the same vehicle considered in this work. During the on-track tests, accelerometers were placed in different locations along the vehicle floor, respectively in correspondence of two sections of the vehicle: the front bogie and the mid-section of the coach, referred to as $F_Z$ and $C_Z$ in the following. For each measuring section, sensors were installed in positions analogue to the point A in Fig. 1 (i.e., under the seat). This choice is made to perform a comparative analysis of the passenger perception at different positions in the vehicle, given on the one hand the dynamic amplifications that may rise due to the excitation of the carbody modes [12], and on the other hand due to the effect of the suspension transmissibility in proximity of the bogie [13]. The experimental acceleration data $F_Z$ and $C_Z$ have then been processed according to the block diagram presented in Fig. 3, aiming to identify actuator strokes representative of such conditions.

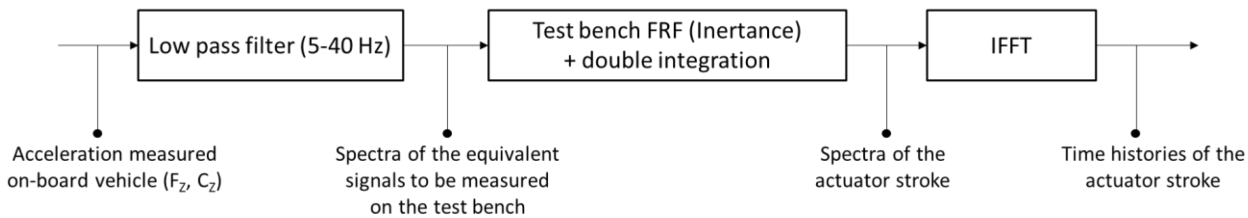


Figure 3: procedure to convert the on-track floor acceleration measurements to the signals adopted by the actuator for dynamic loading in laboratory tests.

At first, the acceleration signals are filtered to be consistent with the frequency range under analysis, and their spectra are calculated. Then, they are divided by the FRF presented in Fig. 2 (representative of the floor-seat dynamic response), to identify the spectrum of the actuator force (and, eventually, that of the actuator stroke) to be imposed during the tests to obtain the same acceleration measured on-board. Finally, the stroke time history is evaluated by the Inverse Fast Fourier Transform (IFFT), assuming random phases for each signal generated.

In this way, the test bench will allow imposing signals that are representative of those perceived by the passengers during on-track tests, although the signals will be scaled due to the technical limitations of the considered actuator. In particular, time histories 300 s long have been realized and the corresponding accelerations have been processed in accordance with the reference standard EN 12299 to compute the $N_{\mathbf{MV}}$ and $N_{\mathbf{VA}}$ comfort indexes, as discussed in the following section.

## 3. Results: comfort indexes evaluation

In the current section, the relationship between the floor vibration and the passenger's perception is investigated by comparing the $N_{\mathbf{MV}}$ and $N_{\mathbf{VA}}$ values computed based on the test results.

Once that the test bench has been assembled and characterized so as to allow simulating on-track tests, the evaluation of the passenger comfort has been carried out in compliance with the reference standard EN 12299, which defines the $N_{\mathbf{MV}}$ (Standard Method) and the $N_{\mathbf{VA}}$ (Complete Method) comfort indexes as follows:

$$N_{\boldsymbol{MV}} = 6\sqrt{\left(a_{X\,P95}^{W_d}\right)^2 + \left(a_{Y\,P95}^{W_d}\right)^2 + \left(a_{Z\,P95}^{W_b}\right)^2} \tag{1}$$

$$N_{\boldsymbol{VA}} = 4\left(a_{Z\,P95}^{W_b}\right)^2 + 2\sqrt{\left(a_{Y\,S95}^{W_d}\right)^2 + \left(a_{Z\,S95}^{W_b}\right)^2} + 4\left(a_{X\,B95}^{W_c}\right)^2 \tag{2}$$

Considering the generic term $a_{k\ j95}^{W_i}$, the following notation is adopted:

- $a$ is the rms acceleration value in (m/s$^2$) computed over time windows of 5 s;
- $W_i$ accounts for the weighed curves prescribed by the standard;
- $k$ is the measuring direction;
- $j$ refers to the measuring position, being P the floor, S the seat pan and B the backrest;
- 95 stands for the 95$^{th}$ percentile of the distribution of the 5 s weighted rms values.

Starting from the available spectra, 12 time histories have been realized to provide statistical relevance, adopting random phases. Moreover, both the $F_Z$ and $C_Z$ inputs have been considered, for a total of 24 test cases. These signals have been used to compute the corresponding comfort indexes $N_{MV}$ and $N_{VA}$, which are shown in Fig. 4. Blue dots stand for the couple $N_{MV} - N_{VA}$ realized from the $F_Z$ input, whilst red dots identify the $C_Z$ input.

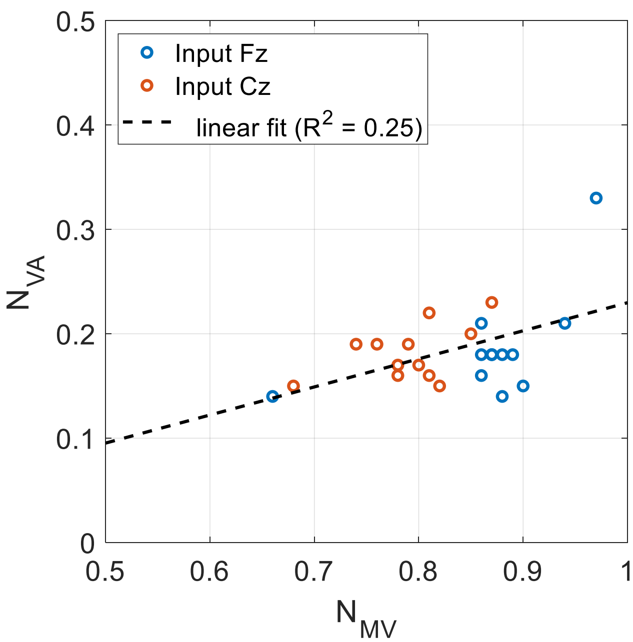


Figure 4: comfort index evaluation: comparison between $N_{MV}$ and $N_{VA}$ indexes computed with the same input signals. $F_Z$ and $C_Z$ input considered for the analysis, respectively shown as blue and red dots. Linear best fit of the data shown as a dashed line ($R^2$ = 0.25).

The linear best fit of the available samples has been first realized, showing a correlation coefficient $R^2$ equal to 0.25. This parameter is usually adopted to infer the degree of correlation between the variables of a model, assuming a value of 0 in case of null correlation and 1 in case of complete correlation. Thus, $N_{MV}$ and $N_{VA}$ comfort indexes show very poor correlation. For instance, it can be observed that a higher $N_{MV}$ value does not always correspond to a higher $N_{VA}$ value. This suggests the importance of including the human-seat interface measurement for a detailed investigation of the passenger comfort. In fact, dynamic amplifications may be perceived by the passenger in case the vibration modes of the seats will be excited during the train trip.

Ahead with the discussion of the experimental results, it can be noted that the $F_Z$ input is generally associated to higher values of the $N_{MV}$ comfort index (blue dots belonging to the top-right part of the diagram, exception made for one single value). This result agrees with the spectra adopted to realize the signals, and with the results of an experimental campaign carried out during passenger service on the same vehicle reproduced in the laboratory test bench. Being closer to the suspension connections, the carbody ends are indeed more excited by the rail unevenness during the train trip.

As a final comment, note that the values assumed by the $N_{\mathbf{MV}}$ index are significantly small if compared to the semantic scale proposed be the EN 12299 standard (thus suggesting highly comfortable perception). Actually, although the input signals are derived from on-track tests, their amplitudes result to be significantly reduced to comply with the test bench characteristics. Therefore, in the project follow-up, the possibility to update the test bench architecture to allow reaching higher acceleration levels can be pursued, so as to better reproduce on-track tests.

## 4. Conclusions

The current work presents a laboratory test bench designed to support passenger comfort assessment. The test bench consists in a portion of floating floor of a railway vehicle on which a pair of seats are installed and is used to study the effects of the dynamics of the floor and seats. The frequency response of the test bench shows an evident dynamic amplification effect in the 5-40 Hz frequency range, which is of interest for the ride comfort. Dynamic forces are applied to the realised test bench through an electro-hydraulic actuator and the acceleration of the floor and seats are measured. The dynamic force signals are derived from on-track measurements and are hence deemed as representative of that received by the same components during passenger service, in terms of the spectral content. Comfort indexes, $N_{\mathbf{MV}}$ and $N_{\mathbf{VA}}$, are computed according to the standard EN 12299 to investigate the relationship between the floor vibration and the passenger's perception. The two indexes are proved to be unrelated, which suggests that it is fundamentally important to include the human-seat interface measurements for a detailed investigation of the passenger comfort, since the dynamics of the seat-floor coupled system can play a significant role.

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