XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 – September 4, 2015, Prague, Czech Republic

MEASUREMENT OF TRAIN SPEED BASED ON THE CROSS-CORRELATION OF ACCELEROMETERS SIGNALS

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Abstract – One of the most important tasks to evaluate the reliability and safety of railway transportation in terms of derailment risk, is monitoring the infrastructure condition. Several on-board high-performance devices are used in order to accomplish this task, among which accelerometers mounted on axle-box are recently gaining an increasing interest. Aim of this paper is to identify a numerical procedure able to reconstruct the instantaneous forward speed of a rail vehicle from axle-box acceleration measured data collected by mean of the gravitational accelerometer sensors. The preliminary validation of the proposed method has been carried out on a set of virtual accelerometer recordings generated by a numerical multi-body simulation code. It is believed that, within a more extended modelling framework, the speed profile reconstruction so far obtained will help in detecting critical locations with respect to the derailment risk.

Keywords: train speed, accelerometers, cross-correlation.

1. INTRODUCTION

The recent increase of railway track has implied a renewed interest in railway safety issues. As far as the derailment risk is concerned, the monitoring of the railway infrastructure plays a critical role in the railroad safety. To this purpose, Railway Companies are employing several monitoring devices: instrumented trailers, on-board equipment or specially devoted instrumented vehicles [1]. However, most of monitoring devices used are proprietary and small railway administrator may not afford their costs. Moreover, frequency of inspection can be somehow low and therefore there is the need to develop additional and cost-effective diagnostic units able to integrate the infrastructure framework for data collection.

A promising technology may be represented by low-cost accelerometer that are widespread diffused and that have been often used in the past in order to monitor railway vehicle dynamics [2]-[7]. The novel aspect that it is intended to be investigated in this paper is the use of a set of accelerometers mounted on the each axle-box in order to derive relevant information on wheel-rail dynamic interaction. Within a more extended research framework that it is going to be undertaken, the basic idea is to combine the use of accelerometer acquisitions with a simplified mathematical model of rail vehicle in order to estimate the vertical (Q) and lateral wheel load (Y) at the wheel-rail interface. It will be so possible of characterizing the dynamic behaviour of a rail vehicle against the risk of derailment in terms of the Y/Q derailment coefficient.

In this connection, a relevant aspect is represented by the evaluation of train instantaneous speed, since this value can play a critical role in rail vehicle dynamics and stability.

In order to tackle this problem, a preliminary investigation has been carried out by means of a Multi-Body (MB) approach able to provide a set of realistic -although artificial- acceleration records that will be analysed in order to develop and calibrate an optimal procedure to estimate the rail vehicle speed. In other terms, the MB environment has used as a virtual laboratory in order to analyse acceleration records obtained under controlled conditions.

2. MODELLING OF THE RAILWAY-VEHICLE SYSTEM

Multi-Body modelling is a very powerful simulation tool developed in Mechanical Engineering and it is currently used in vehicle design in order to capture the essential dynamic behaviour of vehicle travelling on road and/or track [8]. A multi-body approach allows simulating the dynamic performance of integrated railway systems that are essentially composed of a vehicle, a track and a wheel-rail contact interaction, including the masses and inertias of the structural elements and the suspensions characteristics.

The vehicle is usually modelled with rigid and/or flexible bodies interconnected by means of springs, dampers and more complex rheological or interaction models describing suspension levels and wheel-rail interface. A comprehensive multi-body model of a four-axle passenger rail vehicle by mean of the SIMPACK simulation software has been developed and implemented. [8]

2.1. Rail vehicle model

The model of the rail vehicle consists of a carbody supported by two bogies through the secondary suspension. Each bogie consists of a frame ad two wheelsets, connected by primary suspension; both the primary and secondary suspensions include spring and damper components.

Also, the secondary suspension is equipped with one anti-roll bar per bogie in order to counteract roll motion of the carbody. The detailed parameters regarding the moment of inertia and mass of essential components of the vehicle model are given in Table 1.

Tab.1. Inertial properties of the vehicle model components.

Type of component	Mass [kg]	Jxx Inertia [kgm^2]	Jyy Inertia [kgm^2]	Jzz Inertia [kgm^2]
Carbody	$32.00x10^3$	$56.80x10^3$	$1.97x10^6$	$1.97x10^6$
Bogie	$2.62x10^3$	$1.72x10^3$	$1.48x10^3$	$3.08x10^3$
Wheelset	$1.81x10^3$	$1.12x10^3$	$1.12x10^3$	$1.12x10^3$

Fig.1 shows the full vehicle model used to simulate different scenarios of train running. The UIC 60 rail profile with an 1/20 inclination and S1002 wheel profile are assumed without defects.

In order to measure and record continuously the acceleration during the vehicle running simulation, eight gravitational accelerometers have been mounted on the each axle-box of the four wheelsets.

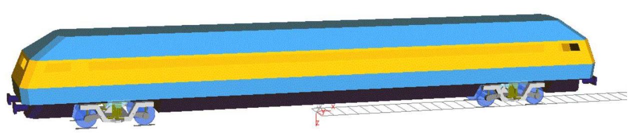

Fig. 1. Full vehicle model (SIMPACK).

2.2. Track model

A general geometric description of a spatial track is required for the Multi-Body simulation of a rail vehicle.

The track geometry can be described by the nominal geometry and irregularities. As far as the nominal track geometry concerns, it consists of vertical curvature, horizontal curvature, gradient, track gauge and cross level (cant). In this study, the implemented track geometry consists of a first straight segment followed by one left curve opposite to one right curve, both with same radius (275 m); then the track continues with a second straight segment. Between all these elements, the transition curves with continuously changed radii are interposed. The total length of the track is 1344 m and its schematic representation of track geometrical properties is reported in the Fig. 2.

Also, the assigned cant changes gradually over the transition length from the zero value (at the straight track) to the nominal cant (160 mm) on the curve.

As far as the track irregularities concerns, they are defined as deviation of the actual track geometry from the nominal (or designed) track geometry, according to EN 13848-1. They influence the motions of the vehicle due to excitations of the wheelsets and have generally great impact on the wheel-rail forces and ride comfort.

As input data for analysis of vehicle dynamics, the track irregularities as function of distance have to be known or assumed. In this simulations, four different kinds of track irregularities are obtained in according to ERRI B-176 and they are implemented in SIMPACK environment as given in the Fig. 2.

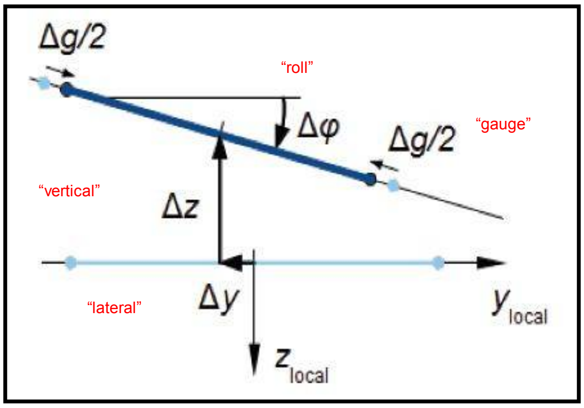

Fig. 2. Track related irregularities.

2.3.Experimental design

Several simulations have been carried out by varying the sampling frequency. In detail, two sampling rate for output results have been considered: 160 Hz and 640 Hz. For each one of these, two set of simulations, with and without track irregularities, have been carried out.

In all simulations, it was possible to control the speed of the train assuming the realistic speed profile reported in the Fig. 3 where the maximum value of 100 km/h has been reached.

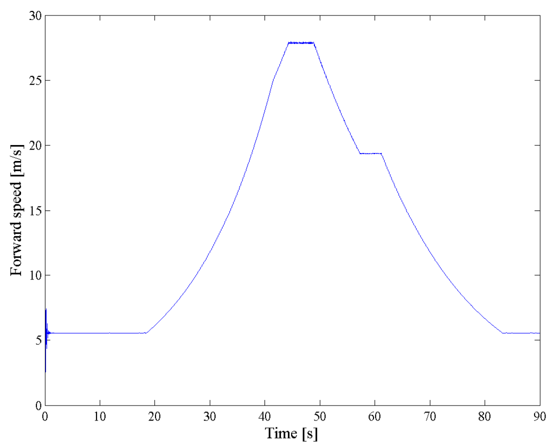

Fig. 3. Evolution versus time of the nominal simulated speed profile.

3. PROPOSED METHOD

Aim of the paper is the measurement of train forward speed by means of the acceleration samples acquired through a set of suitable sensors. With no loss in terms of generality, let us consider eight accelerometers [9] mounted according to what shown in Fig.4; in particular, each wheel of a wheelset is equipped with a tri-axial sensors [10].

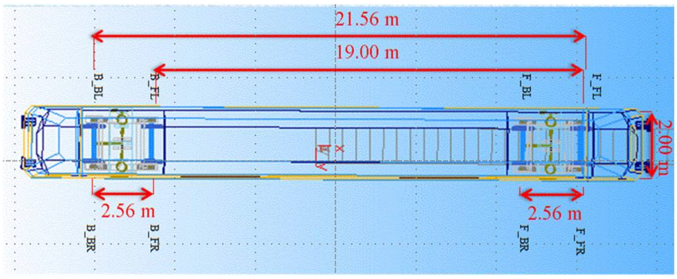

Fig. 4. Sensors arrangement on the car body; in the acronym X_YZ, X stands for the truck (F=Front, B=Back), Y stands for the axle, (F=Front, B=Back) and Z indicates the train side (L=Left, R=Right).

The key idea underlying the proposed method is measurement of the time delay $\Delta\tau$ between the transits of couple of wheels located on the same side of the train and pertaining to different axles of the same or different trucks. Once known the distance d between the wheels of the considered couple, the train speed s is straightforwardly evaluated as

$$s = \frac{d}{\Delta\tau} \quad (1)$$

For the sake of the clarity, the method will be described in the following with reference to the block diagram of Fig.5, considering only two sensors of the same truck; similar considerations hold whatever the couple of wheels of the same train side.

Let us assume that the signal incoming from the sensors are simultaneously digitized with a sample period equal to t_c; moreover, let $x_1[nt_c]$ and $x_2[nt_c]$ represent the samples acquired from the two sensors, n varying within the range from 0 up to N-1 to cover the whole acquisition interval Nt_c.

As it can be expected, noisy signals generated from rails irregularity and jerks associated with rail interconnections or turn entries give rise to highly correlated signals on each wheel of the train. This way, the abovementioned time delay between wheels transits can be estimated through the maximum of the cross-correlation function of the associated acquired signals. To assure the right trade-off among computational complexity, real-time operation and proper signal-to-noise ratio, observation intervals covering about 1s have been exploited to calculate the cross-correlation. The longer the observation intervals, the better, in fact, the readability of the maximum correlation spike (especially in the case of uniform train speed) to the detriment of processing time and the possibility of exploiting the speed information for real-time operations.

The first step of the proposed method accounts for a preliminary estimation of the time delay between the acquired signals. To prevent harmful artefacts due to the limited signal-to-noise ratio usually affecting the considered

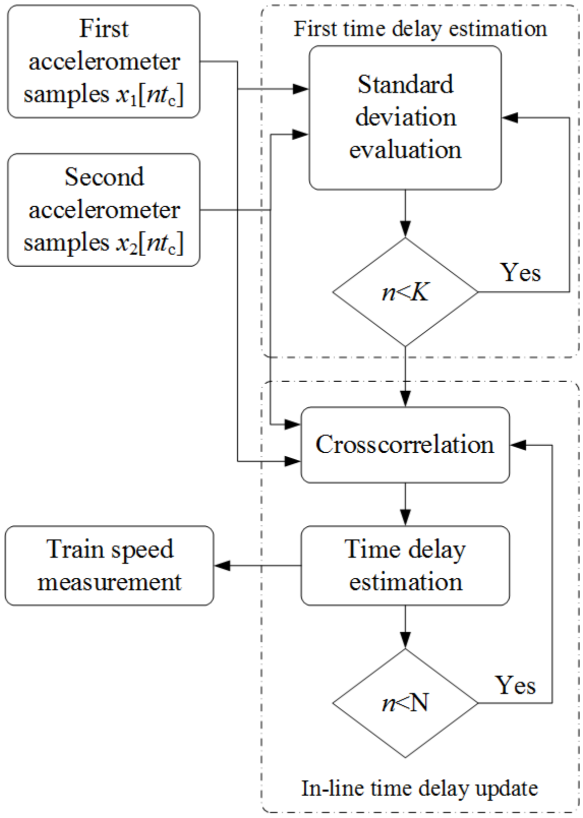

Fig. 5. Block diagram of the proposed measurement method.

acceleration signals and maintain reduced the duration of the observation interval, the time delay is roughly evaluated as:

$$\Delta\tau_0 = \min_{k=0,\ldots,K} \sqrt{\frac{1}{M-1}\sum_{n=0}^{M-1}(x_2[(n+k)t_c] - x_1[nt_c])^2} \quad (2)$$

where M is the number of samples covering the 1 s observation interval and K stands for the upper bound index within the minimum search has been carried out (currently set to 5 s). In other words, the first time delay is determined as the minimum of the experimental standard deviation of the differences between the samples accounting for the first second of the first sensor and those associated with the other accelerometer, suitably slid up to 5 s.

Once determined the value of $\Delta\tau_0$, the corresponding index, namely k_0, is adopted as first lag for the evaluation of the cross-correlation between x_1 and x_2. Moreover, due to the reduced dynamics of the train motion, the new value of time delay $\Delta\tau$ can be updated by taking into account only a limited range of lags (empirically set to 41 for the considered sample rate values) in cross-correlation sequence.

$$\Delta\tau[nt_c] = \max_{k\in[-20,20]} \sum_{m=0}^{M-1}(x_1[(m+n)t_c]x_2[(m+n+k)t_c]) \qquad n \in [k_0, N] \quad (3)$$

It is so possible to gain new values of the desired speed with a very reduced computational burden, thus making it possible to assure real-time operation in actual measurement conditions.

Finally, the train speed measurement is achieved applying eq.(1) to the obtained estimate of time delay

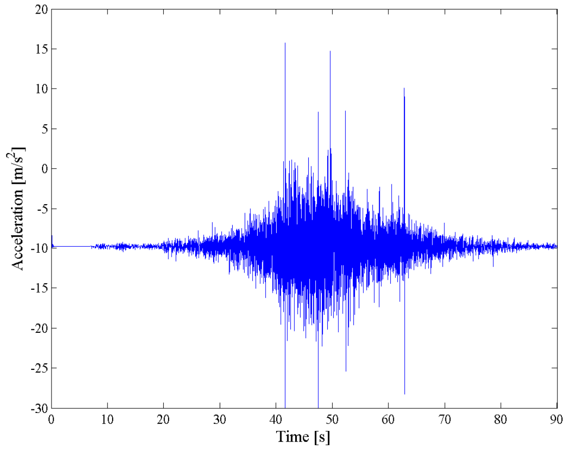

Fig. 6. Example of signal generated by an accelerometer oriented along z-axis.

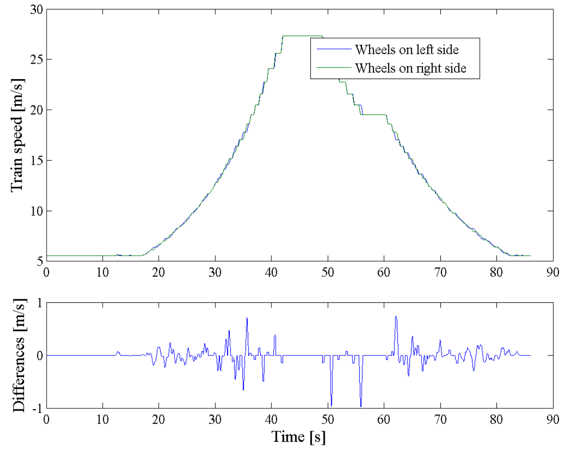

Fig. 8. Train speed measured by means of the proposed method (top) and point-by-point differences of the results obtained on wheels couple of different sides of the train (bottom).

4. NUMERICAL RESULTS

To assess the performance of the proposed method, a number of tests have been carrying out in both simulated and actual measurement conditions. As an example, preliminary results obtained in numerical tests are presented in the following; in particular, they refer to time delay and speed measured from the four couples of wheels included in the same truck (i.e., with reference to Fig.3, the couples F_FL-F_BL, F_FR-F_BR, B_FL-B_BL and B_FR-B_BR). The corresponding acceleration signals have been digitized at a sample rate equal to 160 Hz.

As an example, a typical signal generated by a simulated accelerometer is shown in Fig.6; it refers to the sensor mounted on the left side of the front truck, front axle and oriented along the z-axis. In principle, each axis can be used to measure the train speed; as a matter of practice, z-axis turns out to be the most feasible. Other axes, in fact, suffer from harmful artefacts associated with the train acceleration that is simultaneously sensed by each accelerometer, thus preventing the cross-correlation operator to successfully work.

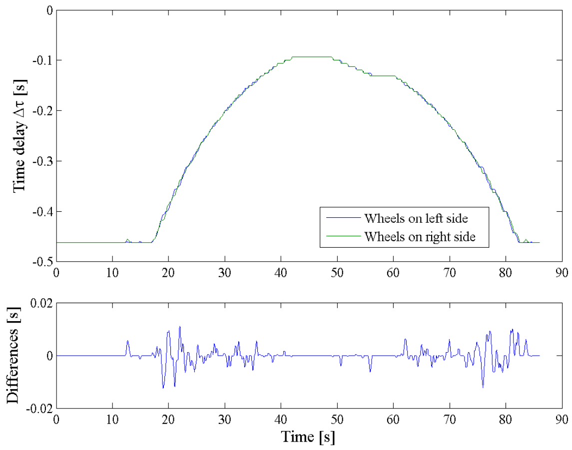

Fig. 7. Time delays measured by means of the proposed method (top) and point-by-point differences of the results obtained on wheels couples mounted on different sides of the train (bottom).

For the sake of the readability, the time delay obtained by applying the proposed method to the wheels of the front truck are shown in Fig.7; notable results concurrence has been experienced also for the other considered couples. To further appreciate the performance of the proposed method, point-by-point difference between the measured time delays has also be reported in Fig.7; values never greater than 1% have been encountered.

Similar considerations can be drawn if the train speed, plotted in Fig.8 is taken into account; speed measurements obtained on the wheels couple of the left side highly match with both those achieved on the right side and the nominal values (Fig.3). Differently from the results of Fig.7, low resolution issues are evident for speed values higher than 20 m/s; they are related to low values of time delay and associated with the limited time resolution (equal to 6.25 ms) granted by the adopted sample rate.

4. CONCLUSIONS

The paper presented underlines the possibility of greatly reducing costs of train safety monitoring, through an innovative approach that makes use of cheap accelerometer sensors. In detail, it highlighted a method to evaluate train instantaneous speed, since its value can play a critical role in rail vehicle dynamics and stability. It has been shown how it is possible to estimate the rail vehicle speed with promising results, by means of a set of realistic (although artificial) acceleration records and the proposed approach. However this procedure is generic and it doesn't require strictly simulated acceleration records. In particular, preliminary performance assessment showed differences between measured and nominal speed never greater than 1%, thus confirming the feasibility of the proposed measurement method.

Ongoing activities are focused on the execution of tests in actual measurement conditions. To this aim, a prototype car body has been equipped with eight triaxial accelerometers mounted on the journal box of each axle.

Moreover, to suitably enhance the measurement resolution, authors are working on a revised version of the cross-correlation operator capable of estimating the time delay of wheels couple mounted on different trucks. Due to the different speeds associated with the transit of the wheels in the same rail location, the acceleration signal of the second wheel, in fact, turns out to be the time scaled version of that generated by the first one. In such operating conditions, the traditional cross-correlation does not work with success. Obtained results will be presented in the final paper.

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