Acoustic-signature-based determination of railway vehicle speed - application to tramways

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Introduction

When characterizing the acoustic emission of a transportation vehicle, acoustic parameters must be linked with the vehicle's kinematics and its speed in particular. In the field, speed information is often retrieved from a radar device. Unfortunately, the recorded speeds for tramways are often quite low and the standard devices tend to become unreliable below 30 km/h.

It is demonstrated in the present paper that, in the case of a railbound vehicle, speed information can be retrieved from a pass-by acoustic recording taken close to the axis the investigated vehicle moves along. This is made possible by events in the vehicle's acoustic signature - expressed in short leq time series - that give unambiguous spatial information. After some background information, two post-processings are investigated below. The first one is based on auto-correlation properties of the leq signature, the second one is based on a simple emission model and a pattern matching approach involving global optimization. Both principles are outlined and evaluated on in situ measurements.

Background

At the close proximity of the railway a typical signature for a tramway looks like on figure 1. For a tramway with *n* cars, one can see *n+1* peaks in the signature. Each of them corresponds to a bogie. It is then possible to link a time instant to a given position of the tramway whose accurate dimensions can be obtained from the manufacturer or the operating company.

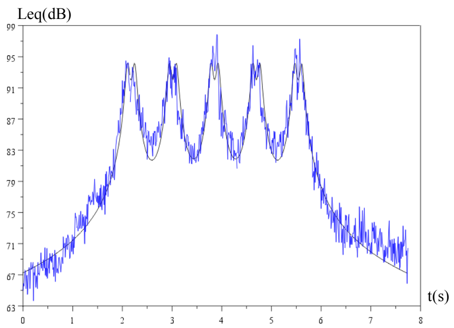

Figure 1: a typical tramway signature (blue/grey), and the adjustment of the energetic emission model (black) (cf equations 1 and 2.

There are however some fast fluctuations over the average curve with slower variations. The former induce uncertainty on the position of each peak. These fluctuations appear to be wide-band on the original pressure signal. So they can not be filtered out. Another source of problems is the use of the vehicle's klaxon which sets potential decoys on the signature.

If one tries to retrieve speed directly form the signature by locating two peaks, the uncertainty on the obtained information is too high, and too human-operator-dependent in general. So this procedure is not reliable enough [1] for measurements of the acoustic emission.

A model that fits very well on measured tramway signatures (cf figure 1) can be defined as follows :

$$Lp(t) = 10\log\sum A_i^2/(d^2 + x_i^2(t)) \qquad (1)$$

where A_i is the source amplitude, d the distance to the railway axis, $x_i(t)$ the position of source *i* at instant *t* and

$$x_i(t) = x_o + e(i-1) + vt \qquad (2)$$

where x_o is the initial position of the vehicle, e the spacing between bogies, v the speed of the vehicle.

Speed by auto-correlation

In the absence of strong parasitic noises, a typical auto-correlation curve of the experimental signature is shown on figure 2. The spacing of peaks is proportional to the one between bogies. The auto-correlation removes the fast fluctuations efficiently.

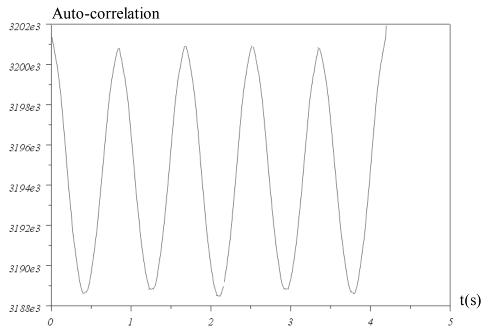

Figure 2: a typical auto-correlation curve for a signature.

The procedure for calculating speed by auto-correlation is the following :

1. Extract the “quasi-periodic” part of the signature,
2. Compute the auto-correlation,
3. Find the local maxima and average duration between two neighbour local maxima,
4. Compute speed from the average delay between 2 peaks obtained from step 3 and the inter-bogie distance .

This procedure gives good results for low speeds, as shown in the last section. Unfortunately it appears difficult to formalize step 1 and the procedure remains somewhat operator-dependent.

Speed by pattern matching

It has been shown that a simple model of signature (equations 1 and 2) fits visually very well with experimental data (cf figure 1). The approach adopted here to extract the speed of the vehicle is to minimize a proper cost function expressing the agreement between a signature and the model described above. One assumes that $A_i = A$ in Eq. 1. The parameters to optimize are A, v and x_o.

The cost function is inspired by the Bayesian point of view as it is composed of 2 parts : one „a priori“ part and one „a posteriori“ part. For more details on this approach, the reader shall refer to [2]. The first part estimates the relevance of the parameters without reference to a given measurement. For each parameter X, one defines a interval of relevance $I_X = [X_{min}, X_{max}]$. A value outside this interval is judged irrelevant. For example, speed must be positive and lower than 70 km/h for a tramway.

A „valley“ function V is associated with each interval $I_X, X \in [v, x_o]$. It is defined in equation 3 :

$$\begin{aligned} &X < X_{min}, V(X) = (X - X_{min})^2 \\ &X \in I_X, V(X) = 0 \\ &X > X_{max}, V(X) = (X - X_{max})^2 \end{aligned} \qquad (3)$$

Function V is designed to insert a penalty when parameter X is outside the interval of relevance. The farther, the higher the penalty. The same valley function was also used twice for A but the boundaries are signature dependent. So the resulting terms can not be regarded as „a priori“ terms. The choice of quadratic slopes was obtained by experience.

The „a posteriori“ part is a norm based on the difference between measurement (*meas*) and simulation (*model*), as expressed in equation 4 :

$$W = \sum_{i=i_{min}}^{i=i_{max}} \left| L_{Aeq,meas}(t_i) - L_{Aeq,model}(t_i) \right|^2 \qquad (4)$$

The resulting cost function f is given in equation 5 :

$$\begin{aligned} &f(A, x_o, v) = W(measurement, model) \\ &+ V(A, -\infty, max(meas)) \\ &+ V(A, min(meas), +\infty) \\ &+ V(x_o, x_{omin}, x_{omax}) \\ &+ V(v, v_{min}, v_{max}) \end{aligned} \qquad (5)$$

Experience shows that the minimization of f over the search space is a global optimization problem. Therefore, the simulated annealing algorithm was used for this task [3]. The computation time is somewhat longer than for the auto-correlation but remains a matter of minutes on a standard personal computer. Experimental results are given in the next section.

Results on pass-by measurements

In this section, both procedures described above for the estimation of the speed of a railbound vehicle are applied to in situ measurements. These measurements have been carried out in 2000 and 2003 on the tramway of Strasbourg [1]. The reference equipment for speed estimation is a Mesta 208 radar [4]. As mentioned, this equipment is not designed for low speeds and often fails to give a result in this range. When missing, the speed information was obtained from the tramway speedometer.

Speed / Range	***Number of signatures***	***Auto-correlation***	***Pattern matching***
10 km/h	8	-1.1(0.4)	-0.6(0.3)
20 km/h	6	-1.1(0.9)	-1.4(0.7)
30-40 km/h	8	5.8(1.1)	2(1.2)
41-50 km/h	2	6.2	1

Table 1: Application to tramway pass-by recordings. Columns 3 and 4 displayed in km/h the average and the standard deviation of the difference between the speed obtained by the quoted principle (head of column) and the reference speed.

Table 1 gives a summary of the results. It appears that both procedures work well at low speeds but that auto-correlation is no longer valid at higher speeds whereas pattern matching still gives satisfying results.

Conclusions

Two procedures for retrieving the speed of a tramway from its acoustic signature have been described. The pattern matching approach appears to be the best if we consider its range of application. A possible extension of the pattern matching approach on the same topic is the computation of acceleration.

References

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