RAILWAY INFRASTRUCTURE SYSTEM DIAGNOSIS USING EMPIRICAL MODE DECOMPOSITION AND HILBERT TRANSFORM

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ABSTRACT

This paper introduces a diagnosis scheme of a railway infrastructure component based on a combined use of empirical mode decomposition (EMD) and Hilbert transform. This component is dedicated to track/vehicle transmission referred as track circuit. The aim is to detect its working state from one measurement signal which can be viewed as a superposition of several oscillations and periodic patterns called intrinsic mode functions (IMFs). For this application, it will be shown that physical meaning can be assigned to each mode that EMD tries to extract. Furthermore, when the Hilbert transform of the IMFs is performed, we show that the changing of instantaneous frequency can be linked to the existence of defect. The performances are illustrated on both simulated and experimental signals.

1. INTRODUCTION

The diagnosis of a complex system consists in detecting and identifying its working state from one or more inspection measurements. When a pattern recognition method is adopted [1], the goal is to assign any measurement signal represented by a feature vector to one of the predefined classes listed as "normal" or "abnormal". This method involves two steps : a parametrization procedure of the measurement signal, followed by automatic classification phase.

Another approach for the complex system diagnosis consists in detecting abrupt changes in the measurement signals. In this case, various detection algorithms have been proposed and successfully applied to solve different problems [2]. We choose to design the diagnosis with this kind of approach based on signal change detection, but rather than using the original measurement signal, the main idea is to decompose it into different waves by EMD and then, look for the change occurred on these elementary waves. Hilbert transform is performed on the obtained modes in order to highlight modifications of instantaneous frequencies due to the presence of defect.

EMD has been recently proposed and is widely used both in signal and image processings [3] [4]. Even if the method does not have an analytical description and is purely algorithmic, reliable results are obtained on many applications for non-stationary signal analysis. Different works compare this approach and well-known methods such as wavelet transform [5]. When the EMD is combined with Hilbert transform, it gives a time-frequency representation of the signal without involving any choice of analyzing functions. This method called Hilbert-Huang transform allows to define an instantaneous frequency of each mode, which can be relevant for diagnosis problem.

In this paper, we explore the use of this approach to achieve a diagnosis task of track/vehicle transmission system. In the French high speed line (LGV), signalling information as maximum speed is transmitted through the rails as modulated electrical signals which are picked up by antennas placed under the train. The information is then processed and displayed to the driver. The different parts of this system, called track circuit, are subject to dysfunctions that are necessary to detect as soon as possible in order to maintain the required safety and availability levels. For this purpose, an inspection car is able to deliver measurement signal linked to electrical track circuit characteristics. Because of the non-stationary behaviour of the signals, the use of EMD combined with Hilbert transform seems to be suitable to this kind of analyse.

At first, we will present the basics of EMD and Hilbert transform. Then, we detail the track circuit principle and we give some leads for its diagnosis. Section 4 gives the performances of the approach obtained on simulated and experimental signals with and without defect and summarizes the conclusions and future works of this study.

2. EMD AND HILBERT TRANSFORM BASICS

2.1. EMD description

Introduced by Huang & al in 1998 [6], the EMD method is widely applied to non-linear and non-stationary processes analyzing in different fields of real-world applications. Its principle consists to iteratively decompose an initial signal into a sum of finite and small number of components so called intrinsic mode functions (IMFs). This decomposition is an auto-adaptative process, performed on the only local properties of the signal. The original signal $s(t)$ is split up in K modes $d_k(t)$ and a residual term $r(t)$ relating to signal trend. The signal expression can be written as

$$s(t)=\sum_{k=1}^{K} d_k(t) + r(t) \quad (1)$$

The EMD algorithm consists of the following steps :

1. start with the signal $d_1(t)= s(t)$, $k=1$
Sifting process $h_j(t)=d_k(t)$, $j=0$
   2. identify extrema of the signal $h_j(t)$
   3. compute the upper and the lower envelopes by cubic spline lines interpolation of the maxima and the minima
   4. calculate the mean envelop $m(t)$ of the lower and upper envelopes
   5. extract the detail $h_{j+1}(t) = h_j(t)-m(t)$
   6. if $h_{j+1}(t)$ is an IMF, go to step 7, else, iterate steps 2 to 5 upon the signal $h_{j+1}(t)$, $j=j+1$
7. extract the mode $d_k(t)=h_{j+1}(t)$
8. calculate the residual $r_k(t) = s(t)-d_k(t)$
9. if $r_k(t)$ has less than 2 minima or 2 extrema, the extraction is finished $r(t)=r_k(t)$. Else iterate the algorithm from step1 upon the residual $r_k(t)$, $k=k+1$.

We note that the algorithm includes a sifting process leading to the IMFs. The definition properties of an IMF are : the number of extrema and the number of zero-crossing must differ at must by 1 and the mean envelope must be close to zero according to some stopping criterion. Standard deviation criterion computed from two consecutive sifting results is often used [6]. Here, we use another criterion based on 2 thresholds that ensure globally small magnitudes but allow locally large excursions [7].

2.2. EMD and Hilbert Transform

The analytic signal associated to a signal $s(t)$ is defined by

$$s_a(t)=s(t)+i\,y(t)=a(t)\,e^{i\theta(t)} \quad (2)$$

where the amplitude $a(t)$ and the phase $\theta(t)$ are given by

$$a(t)=\sqrt{s^2(t)+y^2(t)} \quad (3)$$

$$\theta(t)=A\tan\left({y(t)}/{s(t)} \right) \quad (4)$$

$y(t)$ can be defined as Hilbert transform of the signal $s(t)$. The instantaneous frequency is given by

$$\omega(t)=\frac{d\theta(t)}{dt} \quad (5)$$

By applying Hilbert transform to each mode according to (1), we obtain

$$\mathrm{H}\left[s(t)\right]=\sum_{k=1}^{K} H\left[d_k(t)\right] + H\left[r(t)\right] = \sum_{k=1}^{K+1} H\left[d_k(t)\right]$$

The expression of the analytic signal can be written as

$$s_a(t)=\sum_{k=1}^{K+1} d_k(t) + i\,H\left[d_k(t)\right]$$

$$s_a(t)=\sum_{k=1}^{K+1} a_k(t)\,exp^{iq_k(t)} = \sum_{k=1}^{K+1} a_k(t)\,exp^{\,i\int w_k(t)dt} \quad (6)$$

Once extracting the IMFs, we use the Hilbert transform to each IMF and compute the instantaneous frequency and amplitude according to equations (3) and (4). Unlike Fourier transform, the a_k and θ_k coefficients are function of time; their time evolution can highlight modifications induced by the presence of defect.

3. TRACK CIRCUIT DIAGNOSIS

3.1. Track circuit principle

Track circuit is an essential element of automatic train control. Its main function is to detect the presence or absence of a train on a given railway section of track. For the French high speed lines, track circuit is also a fundamental element of track/vehicle transmission system. It is used to transmit, over a specific carrier frequency, coded data to the train such as the maximum authorized speed on given section with safety constraints. A track circuit, associated to a specific section, consists of:
- a transmitter which supplies a FM alternating current
- a transmission line constituted by the two rails
- a receiver that is connected to opposite end from the transmitter. It detects the specific emitted signal.
- trimming capacitors connected between the two rails at constant spacing to compensate inductive behaviour of the track. An electric tuning is then achieved that limits the attenuation of the emitted current and improve the transmission level. The number of capacitors depends on the carrier frequency and the length of the track section.

The presence of a train in a given section induces the loss of track circuit signal due to shorting by train wheels. The drop of the received signal below a preset threshold indicates that the section is occupied.

3.2. Diagnosis purpose

Characteristics of track circuit equipment may change because of ageing or atmospheric conditions, either as result of track maintenance operations. That induces an attenuation of the transmitted signal which can be, in a major defect case, responsible of signalling failures. The loss of the track circuit signal due to failure will be interpreted as an indication that the section is occupied even if it is not. The operating of trains is greatly disturbed. The purpose of the system diagnosis is to inform maintainers on major track circuit defects, thus ensuring a good quality of the transmitted information. Inspection car equipped with induction sensors measures the short-circuit current (Icc) at each position of the train when the track is shunted by the first axle (cf. figure 1).

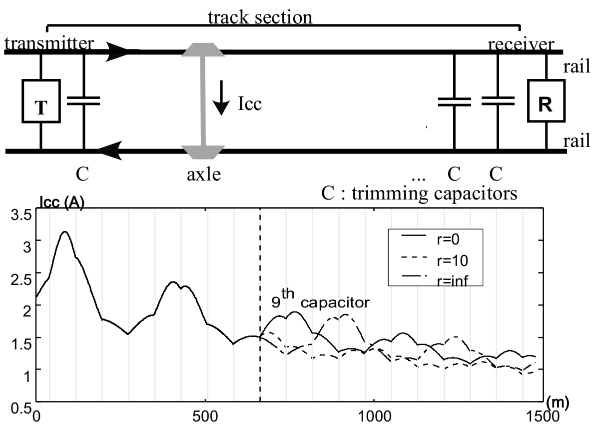

Figure 1. Track circuit representation and example of simulated Icc without defect (r=0Ω) and with the 9th capacitor defective (r=2Ω and r=∞).

In this paper, we will focus on a defect class that concerns the existence of capacitor internal resistance. An electrical model has been developed and allows to perform realistic simulations of the system including large variety of dysfunctions [8]. Figure 1 shows three examples of Icc curve simulated along a 1500m track circuit : one is obtained when the system is reliable (without defect), while the two others are simulated when the 9th capacitor is medium or large defective. The signal has the following properties :

- the signal amplitude is function of both the axle position and the distance from the transmitter. It decreases when the vehicle goes from the transmitter to the receiver.
- a principal waviness (λ≈400m) is due to electrical detuning of the track relatively to the carrier frequency.
- each position of a trimming capacitor coincides with a discontinuity of the derivative curve.

The main idea is to extract different modes linked to each of these listed behaviours.

4. RESULTS

The diagnosis approach starts with a pre-processing block (section locating, signal denoising…). The EMD is then performed to decompose the signal in different modes of which Hilbert transform is computed. Instantaneous amplitudes and phases are also calculated and analysed.

4.1. Simulated signals

With the simulated signals of the figure 1, the EMD decompositions are presented in figure 2 :
- the first mode is constituted by local arches (parabola) between trimming capacitors.
- the second mode corresponds to the principal waviness of the Icc curve due to the natural frequency of the trimming track. An exponential decay of its amplitude is observed.
- the residual expresses the global exponential decay of the signal amplitude along the track circuit.

It can be noted that each mode is differently affected by a defect. For the first IMF, the influence of the defect is effective on the arches localised at the base of the defect. In the extreme case of removed trimming capacitor (r=∞), the corresponding arch disappears. The second IMF is modified through its instantaneous phase.

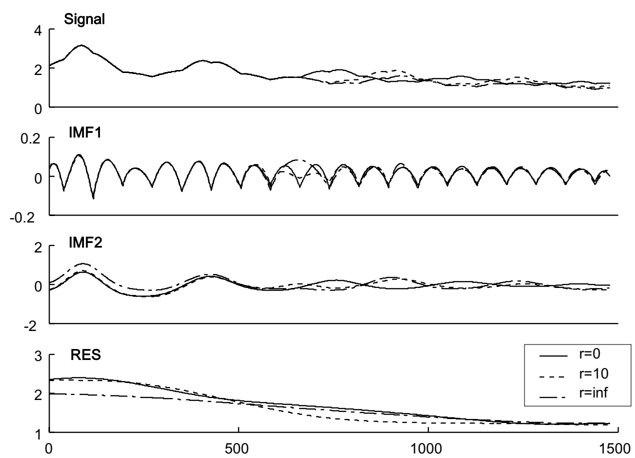

Figure 2. Decomposition of 3 simulated signals with and without defect

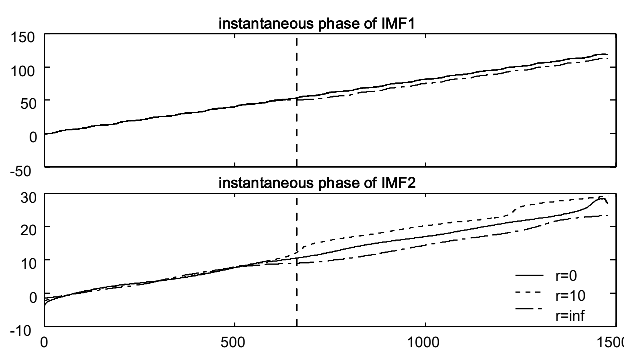

Figure 3. Instantaneous phases of hilbert transform of the two IMFs

The instantaneous phases are shown in Figure 3. The IMF2 phase highlights the presence of defect. On the IMF1 phase, only a removed capacitor defect induces a notable modification.

4.2. Experimental signals

The same processing is applied to experimental signals recorded for two working states of a track circuit : without defect and with one removed capacitor at the position mentioned by dotted lines (figure 4). The presence of the defect affects principally the instantaneous phase of the IMF2 as it is shown in figure 6 and identically to the simulated tests. However, the IMF1 does not reproduce the simulated case (the local arch does not disappear)

5. CONCLUSION

In this paper, we investigate the application of EMD and Hilbert transform to diagnostic a railway infrastructure component. Reliable results are obtained on both simulated and experimental signals that show a real interest of the method. The signal decomposition allows to perform the diagnosis task on the different IMFs. Further studies are carried out to use EMD for both denoising phase and signal decomposition. This must leads to efficient results only if a prior information about noise and signal models is coupled with the sifting process.

6. REFERENCES

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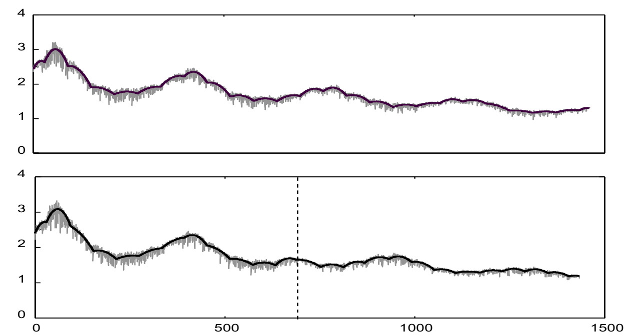

Figure 4. Experimental signals recorded for a track circuit without defect and with a defect (removed trimming capacitor)

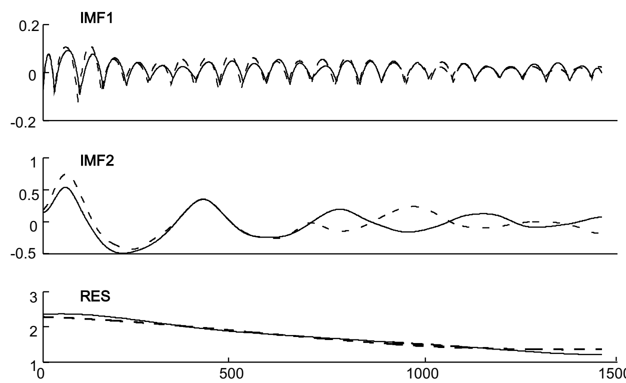

Figure 5. EMD of 2 experimental signals recorded for a track cicruit wihout defect and with one defective trimming capacitor.

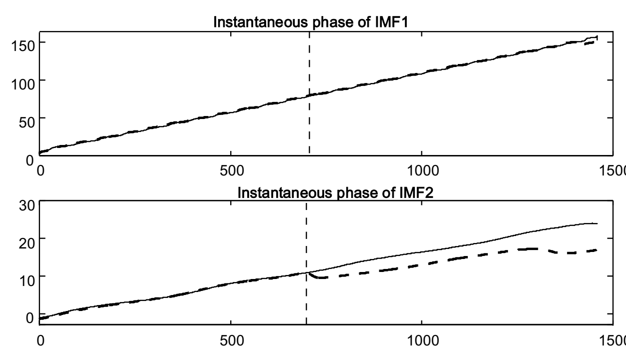

Figure 6. Instantaneous phases estimated from hilbert transfrom