

ON THE UNCERTAINTY OF THE BANDPASS FILTER METHOD FOR THE EVALUATION OF INTERFERENCE ON TRACK CIRCUITS

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Abstract: The problem of the evaluation of the interference to signalling track circuits is considered and the specifications appearing in the recently issued European standard discussed. A broad class of track circuits is simulated by means of a band-pass filter and the focus is on the uncertainty related to its implementation.

Keywords: Analog filters, Digital filters, Guideway Transportation Systems, Conducted Interference

1. INTRODUCTION

When a new locomotive is introduced on existing lines it is essential to ensure that the locomotive and the signalling systems are compatible under normal operation and exceptional conditions. A key point is the evaluation of the interference mechanism, where the locomotive is the source of the disturbance (and new locomotives equipped with electronic static converters have pushed the spectrum of disturbances at higher frequency), the signalling circuit is the victim (new signalling systems operate in a wide frequency range at power frequency and audio-frequency up to some tens of kHz) and the line and track are the means of propagation. Several are the relevant parameters and the degrees of freedom, related to:

- the infrastructure parameters that modify in terms of transfer function and impedance the return path of the current leaving the train axles (called “cold path”) and the supply path feeding current to the pantograph (called “hot path”) [1]-[3];
- the complex architecture of the on-board converters and drives, for traction and auxiliaries, related static and dynamic operations, depending in particular on transient conditions [4][5];
- the susceptibility of the victim track circuits, not only for steady conditions (that can be simulated at manufacturer’s workshop), but also including various types of transients and the variability of the characterizing parameters [2][3][6].

Also the contribution of different units absorbing current in the same supply section may be relevant and the return current components (flowing in the analyzed track circuit section) may be led back (and apportioned in terms of limits) to the respective sources with different summation rules (depending on the degree of synchronization of the sources) [7].

This evaluation process is particularly important if the exigency of a high degree of reproducibility and repeatability is considered, in particular to ensure the interoperability of rolling stock and the equivalence of the test results by different operators and manufacturers, to ensure in turn the cross-acceptance of rolling stock on existing traction lines in Europe. The focus of this paper is on the processing circuits and algorithms indicated by the European standards to model the susceptibility of the victim circuits and applied to the recorded pantograph current and its spectrum. It is underlined that they can be also applied in real time, while the train or locomotive is subject to the tests or even later on in normal service to monitor normal service.

2. PROBLEM DESCRIPTION

The problem as considered in this paper is reduced to two elements, the victim (represented by the signalling circuit and by its susceptibility) and the source (represented by the rolling stock, the characteristics of its conducted emissions and the variability of their properties).

2.1 Signalling circuits

The considered signalling circuits are track circuits (TCs), all based on a common operating mechanism, that of transmitting a modulated signal from a transmitter (TX) to a receiver (RX) over the track, and sensing track occupation by measuring the amount of signal that reaches the RX. The track is detected as occupied, if the rails are shunted by the low resistance axles of the entering rolling stock and the RX signal drops below a given threshold. The TCs frequency interval ranges from some tens of Hz for power frequency TCs up to about 20 kHz for audio-frequency TCs, with only a few exceptions. The longitudinal voltage drop along the track is mainly inductive and is thus roughly proportional to the frequency; for this reason, to maximize the amount of signal reaching the RX in free conditions, some techniques are normally adopted (capacitive compensation of the track impedance, matching of TX impedance to track impedance, directionality of TX signal towards the respective RX by use of track bonds) [8]. The signal is nowadays always modulated to increase the robustness against the superimposed conducted disturbance of circulating rolling stock, that may occur in the operating band of the TC itself. Moreover, the RX has an intrinsic band-pass behavior determined, first, by the electrical coupling method itself often obtained by using resonant circuits tuned including the

track itself, and, second, by additional analog or digital filters to increase noise rejection. The so-called relays connected to the RX output cable in the interlocking cabin are responsible for additional processing, since they often include a delay, to filter out transient components (such as in motor relays or slow pick-up relays) or a phase/frequency matching circuit between the track and a “clean” parallel cable between TX and RX (such as for vane relays). The modern relays are digital implementations on an interlocking computer and their functions are even more extended; however, the continuity with respect to “traditional functions”, often required by railways, has led to a standardization on old functionalities.

An entire TC is a complex, potentially non-linear, system, that can be characterized with a black box approach by a series of curves of susceptibility, only if a certain degree of approximation is acceptable. Susceptibility tests with steady signals are easier, in that swept sinusoidal signals are applied first, and then followed by multi-sine signals, all of variable amplitude, until the effects of interference are detected. If transient signals are considered too, the characterization is very complex, since the time-frequency behavior of the signal and of the TC are strongly related, and the identification of the suitable subspaces, indexes and mathematical representations is still under investigation [3]. Pragmatically, in this paper, the band-pass approach followed by the cited standards is considered, thus fixing the method of evaluation, while the uncertainty related to the variability of the applied transients is analyzed.

2.2 Rolling stock

The rolling stock (i.e. a locomotive or electrical multiple units) represents the source of disturbance as the return current leaving its axles and coupling along the track with the victim TC. Coupling is conductive and occurs mainly in differential mode, while the return current leaves in principle symmetrically the axles, so representing a common mode variable. A certain amount of asymmetry exists in the rail-wheel contact resistances, in the rail self and mutual impedance and in the grounding electrical terms, and represents a first important assumption for an administration or standardization committee, while fixing the safety margins for the evaluation methods and limits.

Moreover, the pattern of conducted emissions is basically determined by the characteristics of the on-board converters and of the adopted modulation schemes. Even in perfectly steady conditions, modulations can change in an attempt of optimization, depending on the motor speed and torque, or even pantograph voltage level. Normal rolling stock operations are divided into acceleration, coasting and braking; acceleration and braking may occur at different rates, and for braking a regenerative action is possible up to a maximum allowed line voltage, then dissipative electric braking is applied; below a certain speed, on the contrary, braking is normally pneumatic. Coasting at a fairly constant speed may occur at different line slopes, positive and negative, so with different amounts of however small absorbed power.

Transient conditions may be various, such as pantograph bounce, wheel slip and slide and input transformer and filter

inrush current. The former causes a series of electric transients in the input circuitry, in particular transformer and filters, influencing also traction and auxiliary converters. The second may be quite complex, in particular if an anti-skidding mechanism is implemented, quickly changing the traction converter modulation. The latter occurs when the rolling stock is stationary and raises its pantograph (or more properly closes its main circuit breaker), or while passing neutral sections (similar to pantograph bounce). In the presence of transients (thus non-stationary signals) a Fourier based analysis may be inadequate and unsatisfactory, taking into account in particular the trade-off between the time duration of the transient, the desired frequency resolution and the time constants of the RX and relays.

2.3 Track circuits and supply systems

Rolling stock may circulate on different supply systems: dc systems at 1500 and 3000 V rated voltage and ac systems at 16.7 Hz / 15 kV rated voltage (used in German speaking countries and also Sweden and part of Norway) or at 50 Hz / 25 kV rated voltage (for many railway systems, high speed or not). While in the past a given rolling stock was bounded to one or few countries with the same supply system, several modern locomotives and EMUs can be supplied by two (or even three, very recently) different supply systems.

The situation for the track circuits is even more articulated: while there are evident impediments for the use of a 50 Hz track circuit under a 50 Hz supply system, track circuits and supply systems combinations are all possible, even if for historical reasons and opportunities only a subset of them is really implemented [6].

3. REFERENCE SETUP

Test methods generally assess receiver immunity through signal processing of the recorded variables. A distinction may be made between type tests performed on reference railway tracks with the mentioned test methods and on-line monitoring of traction return current to prevent signalling interference. On-line monitors usually implement the same algorithm for type testing and they are aimed at detecting possibly critical interference situation in real time.

The considered track circuit receivers have all a band-pass behavior. The band-pass function may be obtained with different solutions: an analogue filter, a digital filter or a Discrete Fourier Transform (DFT). To operate on previously recorded data the analogue solution is not satisfactory. The CLC/TS 50238-2 [3] proposes the digital band-pass filter solution and this will be considered here, against a set of synthetic and real test signals. In the 50238 standards also the use of DFT is considered, as dictated by some national standards, but not recalled explicitly in the last issue [3].

The standardized filter for the evaluation of interference has some degrees of freedom in its specifications, also depending on the specific target track circuit:

- attenuation or frequency response and filter order are the most relevant and obvious; attenuation is normally given in one or two frequency points on the sides of the filter band, thus defining its

bandwidth (at -3 dB points) and its roll-off (e.g. adding another point at -6 or -10 dB);

- filter type is sometimes specified, that fully identifies the filter behavior and in particular the phase response, that is particularly relevant for transients and for the correct combination of the sinusoidal components occurring in the filter band.

The block diagram of the interference evaluation system (IES) includes an input band-pass filter (BPF) followed by a routine for the computation of the total rms in the filter band (RMS detector), and is shown in Figure 1. The signals are indicated there as continuous time signals, even if they are in reality discrete time signals.

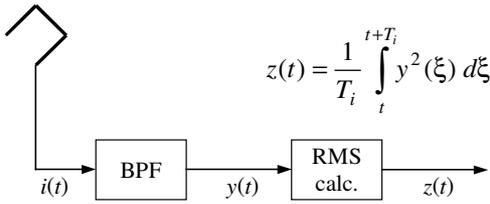


Figure 1. Block diagram of the IES with the BPF and the RMS calculation block (the possible implementations in the time or frequency domain are outlined in the upper right position)

RMS computation of the BPF output y may be in general performed in two ways: in frequency domain the root of the sum of the squared DFT components is used; in time domain the exact definition of rms is used, taking the average of y^2 . The latter is preferred because it's closer to the rms definition and the integration time T_i specified in [3] can be readily implemented (modified Simpson rule over a moving integration window of amplitude T_i).

The test signal that will be used in the following is the absorbed pantograph current $i(t)$. Real signals are the result of past recordings on various locomotives and trains and cover real situations, including any type of transients as they occur in normal circulation conditions. Synthetic signals are conceived to be similar to known already observed spectral signatures, but with controllable parameters, to test the sensitivity of filter response to their variations.

The band-pass filter, lacking a precise specification, may be implemented in any of Infinite Impulse Response (IIR) architectures, provided that the requisites on attenuation, roll-off and number of poles are met [9].

4. TEST RESULTS

Several tests were made using both synthetic and real signals. A synthetic noise signal was used with a flat power spectral density in the filter band to derive the basic BPF properties. Then real recorded absorbed current waveforms are used to show the BPF operation.

A set of victim TCs is defined (see Table 1). Since in some cases there is no indication of the type of filter, the BPF transfer functions were analyzed for three different architectures, Bessel (BS), Butterworth (BW) and Chebyshev (CB), for simplicity all in analog implementation; the filter order is the same and the bandwidth is adjusted for equivalence (see below the two

criteria used) and to comply with the attenuation specifications of Table 1.

Table 1. Reference TCs at power and audio frequency used in the foregoing analysis

TC	f_0 [Hz]	Δf [Hz]	T_i [s]	order N	Limit [A]
UGSK 3	208.75	6.5 @ -3 dB 14 @ -20 dB	0.5	2×3	4
	222.45	6.5 @ -3 dB 14 @ -20 dB	0.5	2×3	4
	242.15	6.5 @ -3 dB 14 @ -20 dB	0.5	2×3	4
TI 21	1549	12 @ -3 dB 60 @ -20 dB	2.0	unspecified	0.09
	1699		2.0		0.09
	1848		2.0		0.09
	1996		2.0		0.09
	2146		2.0		0.09
	2296		2.0		0.09
	2445		2.0		0.09
	2593		2.0		0.09

4.1 Synthetic noise signals and BPF benchmarking

In the first example (focusing on UGSK 3), the three BPF architectures have all the same number of poles ($n = 3$) and the same central frequency ($f_c = 208.75$ Hz). Concerning the definition of filter bandwidth and the equivalence between the three architectures, two criteria were followed (the equivalence is established either for equal -3 dB attenuation or for equal Equivalent Noise Bandwidth) and two series of tests were performed. The ENBW difference for the -3 dB criterion is 2.83% between BS and BW and 1.14% between CB and BW, the BW always taken as reference. The condition of -3 dB bandwidth is imposed when the band-pass filter is created from the low-pass prototype: it is evident that the BW architecture meets also the specification at -20 dB, thus indicating the BW as the underlying filter architecture for the UGSK 3 specification.

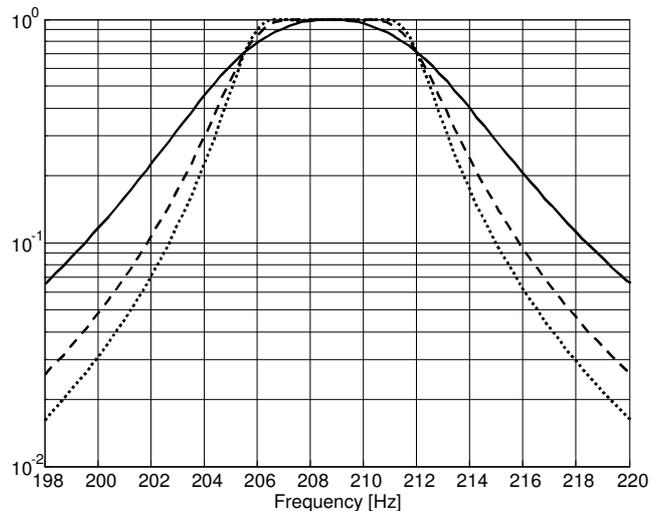


Figure 2. Frequency response of the three BPF implementations for UGSK 3: BS (solid), BW (dashed), CB (dotted)

The difference in $z(t)$ for -3 dB and ENBW criteria was evaluated as the rms deviation over average value of $z(t)$ for a set of random test sequences (see Figure 3): while there is a general agreement between the curves (accounting for not so much different rms values over the 5 s records), there are some small parts of the traces showing an amplitude discrepancy (like the second one between 2 and 2.5 s, with a spread of up to 20% for the three architectures and a negligible difference for the two criteria).

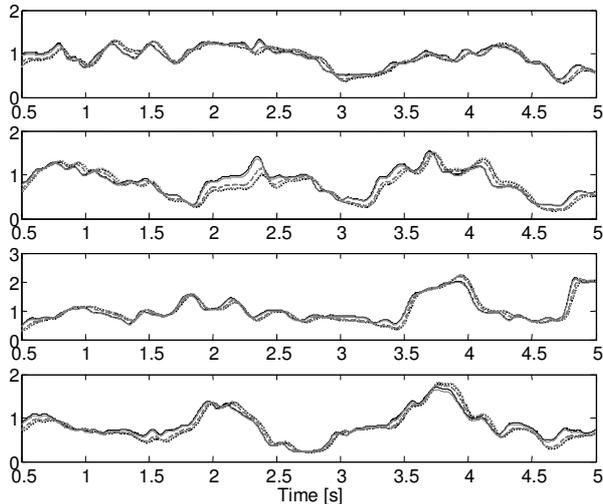


Figure 3. Calculated rms signal $z(t)$ for UGSK 3 and four random sequences: “ -3 dB criterion” (black) and “ENBW criterion” (gray); BS (solid), BW (dashed), CB (dotted)

In Table 2 the results for twenty test sequences are shown in aggregate form: maximum deviation δz_{max1} and δz_{max2} and rms deviation δz_{rms1} and δz_{rms2} between BS/BW and CB/BW.

Table 2. Statistical analysis of deviations of signal $z(t)$ for the BPF architectures with respect to Butterworth: rms value over 5 s records and maximum value over the average $z(t)$ of Butterworth.

parameter	Bessel	Chebyshev
$\delta z_{rms}/z_{av(Butt.)}$	0.1075	0.0538
$\delta z_{max}/z_{av(Butt.)}$	0.5144	0.2810

Being the difference between the three BPF in terms of ENBW less than 3% (2.83% and 1.14%, as said above), the larger rms variability is to be explained with differences in the phase response, that for a random test signal are particularly relevant.

The test is repeated for the TI 21 track circuit, whose frequency response is peculiar and cannot be led back to one of the three architectures (as shown in Figure 4).

In this case there is no underlying assumption for the BPF architecture and the fulfilment of frequency response specifications is reached with a high order FIR filter, synthesized with the inverse DFT technique [9] (see Figure 5). Some different filter lengths (i.e. number of filter taps) were considered and the approximation is satisfactory for our tests beginning with $N = 3072$.

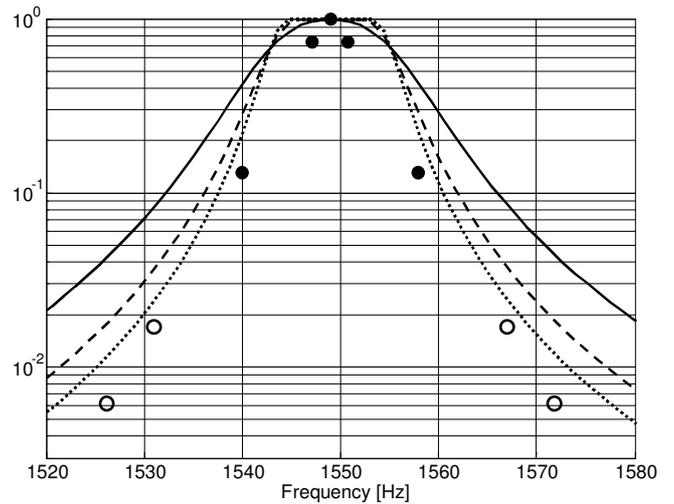


Figure 4. Frequency response of the three BPF implementations for TI 21: BS (solid), BW (dashed), CB (dotted); frequency response specifications (solid circles) and additional points (hollow circles)

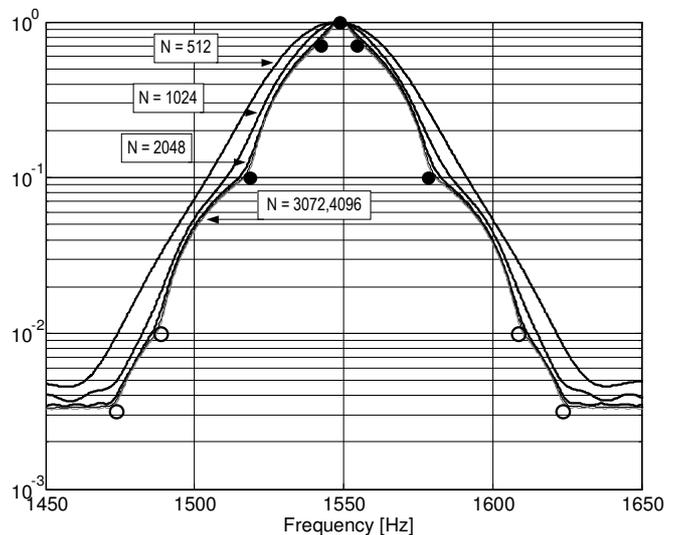


Figure 5. Frequency response of the FIR implementation for TI 21

4.2 Real pantograph current

Some recordings of pantograph current absorbed by different types of locomotives in real operating conditions over different networks are considered for a practical assessment of the variability due to filter architecture. The results are shown in Figure 6 for a German and a French train taken as an example with respect to some sample filters: the response of the UGSK3 filters working at the lower frequency is always characterized by the larger uncertainty to the filter implementation. The upper traces (the first three of Figure 6(a) and the first one of Figure 6(b)) exhibit a variability between the red, the blue and the black waveforms of up to 100%. This represents a large variability that is to be accounted for in similar analysis.

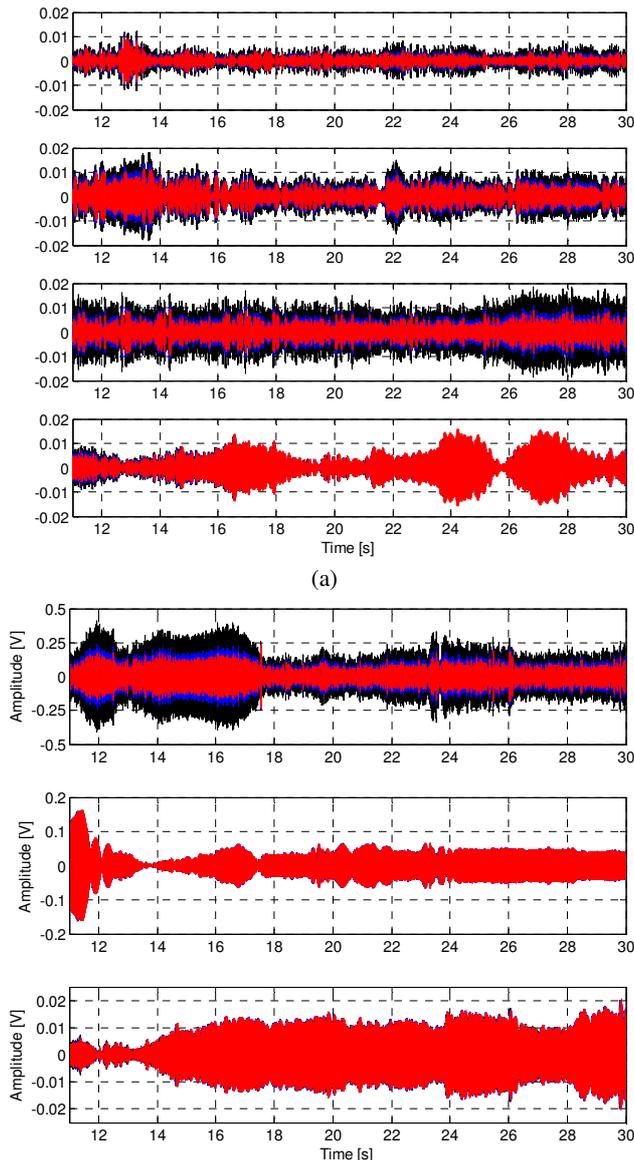


Figure 6. Frequency response of the three BPF implementations for (a) Germany (UGSK3 with 208.75 Hz, 222.45 Hz and 242.15 Hz channels, and TI21 with 1549 Hz channel) and (b) France (TI21 with 1549 Hz, 1699 Hz and 1848 Hz)

5. CONCLUSIONS

The focus of this work was the evaluation of the uncertainty related to the choice of the band-pass filter implementation and its use for the evaluation of conducted disturbance produced by rolling stock in the track circuit operating bands. The tests were carried on using a synthetic noise sequence and real pantograph current waveforms.

This uncertainty, related to the post-processing of the recorded signal in order to assess possible interference to the safety relevant track circuit systems, is one of the terms of the uncertainty budget of the whole measurement chain and is not negligible, if compared to the usual specifications of one or few % uncertainty for the current probe and acquisition system.

The rms variability of the output $z(t)$ measured with respect to the Butterworth response using synthetic test

signals gave 10.8% and 5.3% for Bessel and Chebyshev architectures respectively.

The application to real time waveforms of recorded pantograph currents have shown a variability in the output response of the three BPF implementations of up to 100%, in particular for the low frequency implementations (the UGSK3 track circuit has been used as an example)

6. REFERENCES

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