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A SIMPLE METHOD FOR CABLE COMPENSATION WITH FAST PULSE TRANSMISSION APPLICATIONS

J.M. Seixas^{*†}, L.P. Caloba[†] and M.N. Souza ^{†‡}

Abstract

A simple method for compensating signal cable effects on fast pulse transmission is described. The effects which are here compensated are mainly the long tail, that appears when fast signals are transmitted through cables, and the deterioration on the rise time. The method described is rather general and suitable for many applications, including circuit design and off-line analysis. It characterizes cables by a summation of exponentials, which has proved to be an accurate and relatively easy to implement representation. The compensation network is then implemented in the frequency domain by means of pole-zero cancellation.

The computer simulation results are presented and a modular active filter topology and design procedure are discussed. Experimental results using commercial cables are also included. The method has been used for acquiring and processing signals from the Spaghetti Calorimeter which is currently being developed at CERN.

^{*}CERN, Geneva, Switzerland

[†]COPPE/EE/UFRJ, Rio de Janeiro, Brazil

[‡]IF/UFRJ, Rio de Janeiro, Brazil

1 Introduction

The distortion effects due to signal cables are present in different fields of applications. These effects have been analyzed in some details in the literature [1, 2, 3, 4, 5]. Specifically, in particle detectors, the long tail, introduced by rather long cables used for transmitting signals from the detector to the data acquisition system, may provoke serious pileup problems [6, 7, 8]. For fast signal transmission applications, this long tail and the deterioration in the rise time of the signal to be transmitted pose severe restrictions in the experiments.

To avoid these problems, some methods for compensating cable effects have been developed [8, 9, 10]. In particular, [8] has described one method using a time-domain approach and passive filter implementation of the compensating network. It uses a finite sum of exponentials to approximate the so called “complementary step response”, which simplifies the compensating network design. The results obtained were quite good but the passive design poses some limitations, due to the use of inductors and to difficulties in tuning the filter for massive applications. In [9] a passive filter approach was also used and in [10] an amplifier with a gain that increases as $\sqrt{f}$ was used in order to compensate the attenuation curve of the cable.

In what follows, a new compensating method is described. It simplifies the ideas developed in [8] but still uses a summation of exponentials to fit the desired signal. The method is developed in the frequency-domain and the cable is treated like a system, for which we would like to approximate the impulse response. We do this using exponentials and, thus, the compensating filter design becomes easy and compact. An active filter realization is developed to overcome the passive design limitations mentioned above.

The method can be applied for general cables and the filter topology, being modular, can suit a large sort of applications. The long tail effect is shown to be compensated and the rise time is reduced by a factor of 10 or more, which stress the capability of this compensating filter to recover the high frequency information present in the original signal, after being transmitted by the cable.

In the next sections, the method is described in details. Computer simulation of some experimental data is shown in order to exhibit what we can expect from the compensating network performance. Finally, a modular filter architecture is presented and experimental results are obtained for

general coaxial commercial cables. Also, applications for the new Spaghetti Calorimeter [13] are presented.

2 General Formulation

Let's consider the cable to be compensated as a general system [11, 12]. Our aim is to find a representation of its impulse response in order to deconvolute it from the signals that should be transmitted through the cable itself. Thus, the presence of a compensating network in the output of the main system, for which the cable transmits signals, unfolds the undesired effects introduced by the cable system (see Figure 1).

In order to characterize the cable's impulse response, we need to measure it. This is achieved in practice by the measurement of the step response of the system [8]. The system's step response can be measured with a fast step (square wave) generator, with a rise time much shorter than the one from the system signal (which means to be in the range of a few hundred picoseconds for the applications we're showing next), fast settle-time and, preferably, no overshoot. The output of the cable can then be digitized by a fast digital storage oscilloscope (DSO) and the data can be sent to a computer system, to be analyzed and to have the cable parameters extracted. If a DSO is not available, a fast analog oscilloscope can also be used for the system step response acquisition. However, with analog scopes, additional care is then required, as the measurements taken near the steady state part of the step response are less accurate than the ones performed on the beginning of the transient part. Therefore, measurements based on a logarithmic time scale proved to be a good solution in these cases.

Hence, to obtain the cable's impulse response $h(t)$ we measure its step response

$$r(t) = \int_0^t h(x)dx \quad (1)$$

and, thus, we can get the so called complementary step response $c(t)$, defined as

$$c(t) = [1 - r(t)]u(t) \quad (2)$$

with $u(t)$ being the step function.

Moving the analysis to the frequency-domain, we get [12]

$$C(s) = \frac{1}{s} - R(s) \quad (3)$$

and

$$R(s) = H(s)/s \quad (4)$$

with the capital letters representing here the Laplace transform of the respective original time function.

Using 3 and 4 we have

$$H(s) = 1 - sC(s) \quad (5)$$

Now, let's consider some design goals. We would like to approximate the impulse response of the cable with a time function that should be simple and generate an easy to implement compensating network. Also, we're interested to preserve the high-frequency components of this impulse response for fast signal transmission applications. One requirement for the latter consideration can be translated in

$$h(0) = 0 \quad (6)$$

and, in frequency-domain, using the Initial Value Theorem [11, 12], this can be stated as

$$\lim_{s \rightarrow \infty} sH(s) = 0 \quad (7)$$

If we consider $H(s)$ as a rational function

$$H(s) = N(s)/D(s) \quad (8)$$

this means that the degree of the polynomial in s , $N(s)$, should be two orders less than the one of $D(s)$.

Now consider the approximation of $h(t)$. It's been tried [8] the exponential sum as a good candidate, leading to simple and compact circuit design. Here, we also take this approach. As we have measured the step response and, thus, the complementary function $c(t)$, we use an exponential sum with n terms to approximate $c(t)$, that is

$$c(t) = \left(\sum_{i=1}^n k_i e^{-a_i t} \right) u(t) \quad (9)$$

which gives

$$C(s) = \sum_{i=1}^n \frac{k_i}{s + a_i} \quad (10)$$

or in terms of a rational function

$$C(s) = P(s)/Q(s) = \frac{\sum_{i=0}^{n-1} p_i s^i}{\sum_{i=0}^n q_i s^i} \quad (11)$$

In terms of the polynomial $N(s)$, using 5 we get the following

$$N(s) = \sum_{i=0}^n q_i s^i - \sum_{i=0}^{n-1} p_i s^{i+1} = q_0 + \sum_{i=1}^n (q_i - p_{i-1}) s^i \quad (12)$$

and, as $D(s) = Q(s)$, we have

$$D(s) = \sum_{i=0}^n q_i s^i \quad (13)$$

If we now apply the conditions obtained for the relationship between numerator and denominator polynomial orders of $H(s)$, we have in terms of p_i and q_i

$$q_i = p_{i-1} \quad , i = n-1, n \quad (14)$$

Expressing these conditions in terms of polynomials of $C(s)$, when we use the exponential sum approximation procedure, we get

$$Q(s) = \prod_{i=1}^n (s + a_i) \quad (15)$$

From this it's easy to show that the values for q_n and q_{n-1} are

$$q_n = 1 \quad (16)$$

$$q_{n-1} = \sum_{i=1}^n a_i \quad (17)$$

For the coefficients of $P(s)$ we have

$$P(s) = \sum_{i=1}^n k_i \prod_{\substack{j=1 \\ j \neq i}}^n (s + a_j) \quad (18)$$

from which we extract

$$p_{n-1} = \sum_{i=1}^n k_i \quad (19)$$

$$p_{n-2} = \sum_{i=1}^n k_i \sum_{\substack{j=1 \\ j \neq i}}^n a_j \quad (20)$$

Hence, the conditions stated in 14 are translated into the following design constraints:

$$\sum_{i=1}^n k_i = 1 \quad (21)$$

$$\sum_{i=1}^n k_i \sum_{\substack{j=1 \\ j \neq i}}^n a_j = \sum_{i=1}^n a_i \quad (22)$$

Consequently, $H(s)$ comes to be given by

$$H(s) = \frac{q_0 + \sum_{i=1}^{n-2} (q_i - p_{i-1}) s^i}{\prod_{i=1}^n (s + a_i)} \quad (23)$$

from which we can determine its zeros in order to design the compensating network.

Hence, we got so far, an impulse response represented by a sum of n exponentials. However, for fitting $c(t)$, obtained from the measurements, we have only $n - 2$ degrees of freedom, according to conditions 21 and 22. This means that the parameters k_n and a_n can be obtained as follows. k_n we get directly from 21:

$$k_n = 1 - \sum_{i=1}^{n-1} k_i \quad (24)$$

On the other hand, a_n can be calculated from the expression 22, using the above relation 24 for k_n . Hence, we get:

$$a_n = \frac{-\sum_{i=1}^{n-1} k_i a_i}{1 - \sum_{i=1}^{n-1} k_i} \quad (25)$$

Putting together the above relations 9, 24 and 25 , one can fit the complementary function, obtained from the measured step response. In practice, in order to keep low the order of the filter used for compensating cable effects and its tuning process feasible, we should try 2 or 3 exponentials to do the job. Also, depending on the sampling rate of the digital storage oscilloscope used during data acquisition, or when an analog oscilloscope is being used, another parameter can be used to set the initial time of the step response. This means to add an additional degree of freedom to the fitting, leaving free the time t_0 , for which $c(t_0) = 1$.

Once the poles and zeros have been obtained for the compensation network, the compensation performance can be checked with a simulation program which can filter the cable components out from the measured step response. Moreover, the compensation scheme can be applied successively in order to improve the compensated step response, as one can consider the compensated response from the first filtering action as a response from a faster cable that one would like to compensate for. This successive compensation scheme has proved to be very helpful in the off-line analysis, as we describe below.

3 Computer Simulation Results

We have acquired data from two different cables using a 1 GSa/s digital storage oscilloscope (with 500 MHz of bandwidth) and a 400 MHz analog scope. One of the cables selected was a fast signal cable (type C-50-6-1) which has been used in tests for the Spaghetti Calorimeter [13] at CERN and the other a slower signal cable (type RG-58 C/U) which could also simulate applications with fast signal cables that impose long cable length. We used a fast step pulse (rise time less than 1 ns) for taking data and measured the cables' step response. Then we fitted their impulse response, according to the method described above, using a sum of 3 exponentials, which revealed to be a good compromise between cable characterization accuracy and practical filter design considerations.

We have used digital filter programs in order to simulate our cable compensation method. The results for the fast cable can be seen in Figure 2, where the step response measured for the cable and the output of the compensating network are shown. As can be seen, the expected step function is

quite well obtained at the output of the filter. Unfortunately, the generator we used exhibited an undesirable overshoot at its signal output which reappears when the fast cable is being compensated for. For slower cables this effect is less noticeable due to the fast settling-time of this generator.

For the second cable, a two phases compensation scheme has been tried, the obtained results being showed in Figure 3. The original step response measured for this cable revealed a rise time of 66 nanoseconds. Applying the compensation procedure to this step response, it was possible to speed up the cable response achieving 6.4 ns, a 10 fold reduction. A further application of the compensation procedure to the compensated step response obtained in the first phase was able to reduce the rise time to 2.3 ns, which means a total reduction of about 30 times.

It should be stressed that each stage of the compensating filter acts on different components of the cable system. Therefore, if one only desires to compensate the long tail introduced by the cable, a single section can be used. This is exemplified in Figure 3 (d), where the response of a one-section filter for the slower cable is shown, allowing the tail to be compensated and achieving a 18 ns rise time. Hence, in many applications a single section filter can be quite effective.

4 Filter Design

For realizing the cable compensating filter, we should have in mind that high frequency components are present in cable characterization, moreover in applications where a fast signal cable is desired. Hence, the topology to be selected should behave well in the range of hundreds of Megahertz and should be modular in order to accommodate different sort of applications that require a different number of pole-zero compensation sections.

We chose a differential modular structure in order to have pole-zero compensation either in the emitter or in the collector without disturbing the DC biasing when tuning the filter and providing good high-frequency matching. Moreover, this structure has a fast recovery from overloading pulses. The circuit diagram can be seen in Figure 4, where up to 4 pole-zero sections can be realized.

The transistors used are selected due to their high f_T and good driving current capability. The input stage is a NPN to provide good 50Ω cable

matching. As the zeros of the pole-zero sections have lower values than poles, we use RC networks in the emitters to realize these sections [14]. The tuning process is done varying the values of R and C without interfering in the DC circuit and is achieved in steps, going from the lowest pole to the highest one. This filter provides two complementary $50\ \Omega$ matched outputs.

In Figure 4 is also shown the DC stabilizing circuit. There are three of these circuits, shown at the top of the figure. Offset adjustment is provided for each operational amplifier and another adjustment keeps the low-frequency gain flat, avoiding further tails to be introduced. The operational amplifier *A1* takes care to maintain the input at the input stage at zero. The other two act on the output stage. *A2* guarantees that the DC level in both outputs are equal and *A3* provides the zero output at the non-inverting output. The DC stabilization circuit does not affect the signal shaping and is independent on the number of shaping stages used.

5 Experimental Results

The circuit in Figure 4 was tested with both cables referred to in Section 3. In the case of the fast signal cable, we can see in Figure 5 the output of the spaghetti calorimeter (SPACAL) for incoming electrons of 150 GeV after 30 meters of cable without filtering and with our cable compensating filter. It can be seen how the tail introduced by the cable is compensated by the filter action, as the return of the filtered signal to the baseline is done much faster.

The application of the cable compensation method to SPACAL pulses was extended, with the compensation filter becoming a block in a discrimination system foreseen to provide a fast triggering on electrons [15]. This system exploits subtle differences in electron and hadron signal structures in order to supply a very fast and accurate electron identification. Unfolding the cable effects on the signals, a better electron identification was achieved. Moreover, the hadronic signals cleaned by the compensating filter revealed the neutron component that contributes to the hadronic shower signal in the calorimeter [15, 16].

For the slow cable, we achieved a very good tail compensation too. This approximately 60 meters long cable was used during the measurement of the charge collection time for SPACAL [17] and we applied the compensation scheme in the off-line analysis, allowing the fast charge collection performance

of this detector to be recovered (see Figure 6). The effects of the cable slower response on the charge curve were deconvoluted using digital filtering and we used the successive compensation scheme as described in section 3. The results obtained in this case show that even when a measurement is realized without using any cable compensating filter, still one can unfold the cable effects on the measurement done during the off-line analysis.

Therefore, the cable compensation scheme revealed to be not only a matter of circuit design to achieve the desired compensation in hardware, but also a helpful tool for off-line analysis.

6 Conclusions

A simple method for signal cable compensation was described. It uses a sum of exponentials to fit the impulsive response of the cable to be compensated and thus preserves the high-frequency information to be transmitted. The accuracy of cable characterization with up to three exponentials revealed to be quite good for different types of cables. Hence, simple filter design procedure and topology can be achieved, even for fast pulse transmission applications.

A modular filter topology was also described and its performance was investigated. It was shown that the long tail introduced by cables on signals is compensated and rise time can be improved by up to a factor of ten or more. The tuning procedure is relatively easy, as each zero-pole section can be adjusted separately.

Applications to detectors were also shown, taking the Spaghetti Calorimeter being developed at CERN as an example. Cleaner and shorter signals (coming from the filter output) can allow better particle discrimination and shower structure recognition. On the other hand, the compensating scheme can be applied in the off-line analysis to unfold the cable effects on a measurement done having no cable compensation circuit installed.

Therefore, applications that impose long cable length and fast signal transmission can be accomplished using the technique described for a compact compensating network.

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Figure Captions

1. General idea of a compensating filter for unfolding cable effects on transmitted signals. The main system is the system that generates the signals that should be transmitted.
2. The step response of a fast signal cable (a) and the same response after the compensating filter (b). The desired step function is quite well obtained apart the observed overshoot that comes in fact from the step function generator used in this tests. The generator output signal (c) exhibits overshoot and the compensation filter action, which brings the rise time of the fast cable step response to the range of a few hundreds of picoseconds, recovers clearly this overshoot from the cable step response.
3. Successive compensation scheme. The step response of the slower cable (a) and the same response after compensation (phase 1) (b). Considering the signal in (b) as the new step response to be compensated for and applying the compensation scheme again, the compensated response (phase 2) is obtained (c). The tail compensation realized with a single filter section is quite well obtained (d).
4. The cable compensating filter diagram. Resistors are in Ohms. The NPN transistors are of the type BFR90, the PNP ones of the type BFQ23 and the operational amplifiers are LM 301A.
5. The output signal of the Spaghetti calorimeter for incoming electrons of 150 GeV (a) and the same signal after unfolding the cable effects in these fast signals (b).
6. The charge collection curves from SPACAL as varying the gate width (in nanoseconds) of a charge ADC (a). The curves shown are for 80 GeV electron and pion beams. During off-line analysis, the cable effects were unfolded, which represented a recovery better than a factor of 2 in the rise time of the measured curves (b). The risetime achieved after cable compensation was 37.5 ns, for electrons. The actual curve is even faster than this last one, as other subsystems used during the data acquisition still limit the overall performance [17].

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6