OPTIMIZATION OF A RLC SHAPING CIRCUIT FOR NAI(TL) SCINTILLATION DETECTORS

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The problems arising when the output signal from a current pulse detector is further shaped by a RLC circuit are considered. The amplitude dependence of the output signal is derived as a function of the incoming charge. The energy-code transfer function is logarithmic which is a precondition to achieve a wide energy range (more than three decades). The influence of the ratio T_0 / τ_0 (T_0 being the period of the RLC circuit's free oscillations and τ_0 being the decay constant of the incoming pulse) on the signal shaping accuracy is investigated.

Keywords: scintillation detectors, optimal processing of signals

1 INTRODUCTION

Scintillation detectors are widely used for ionizing radiation measurements due to their high sensitivity, good energy resolution, high performance and moderate price.

However, the signal processing has to satisfy some conflicting requirements in order to achieve both high performance and good energy resolution [1]:

a) full collection of the anode charge from the photomultiplier tube (PMT);
b) linear charge-amplitude dependence in a wide range of amplitudes;
c) fast recovery of the shaping circuit characteristics;
d) large amplitude of the output signal.

2 INFLUENCE OF AN INDUCTANCE IN THE PMT LOAD CHAIN (RLC-SHAPING)

The presence of an inductance in the anode chain of the PMT yields slowly fading oscillations which deteriorate the pulse shaping conditions. So, some efforts are normally taken to reduce the hum inductance.

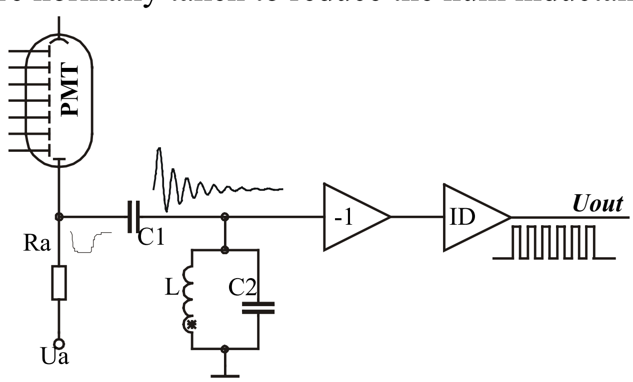

Fig. 1

However, it is possible to use these oscillations advantageously if the RLC-shaped signal is subsequently discriminated (Fig.1). Then the count of the standard pulses can be used as a digital code for the incoming charge, bypassing sophisticated shaping amplifiers, peak detectors, spectrometric ADC etc. This technique has been developed in the 60ies and 70ies [2], [3], [4].

3 ANALYSIS OF THE RLC-SHAPING

The equivalent scheme for the anode chain is shown in Fig.2. The capacitance C accounts for the combined capacitance of the PMT's anode chain, that of the LC circuit, the input capacitance of a subsequent amplifier and the montage capacitance. The resistor r stays for the output resistance of the PMT chain and the input resistance of the amplifier. L is the inductance of the RLC circuit and R is its active resistance.

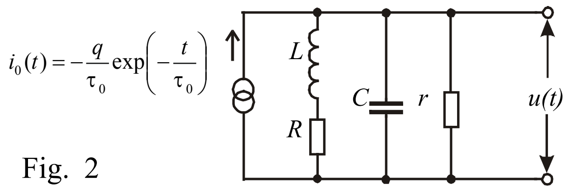

Fig. 2

The following equations describe the current and voltage behavior of the system:

$$L\frac{di_{LR}}{dt} + Ri_{LR} = u(t) \text{ and}$$

$$i_{LR} + C\frac{du}{dt} + \frac{u}{r} = i_0(t) \tag{1}$$

The PMT output current can be described in a good approximation by [1]:

$$i_0(t) = -\frac{q}{\tau_0}\exp(-\frac{t}{\tau_0}) \tag{2}$$

where q is the charge generated in the PMT and τ_0 is the decay constant of the PMT pulse.

Equations (1) can be transformed to the following non-homogeneous equation:

$$\frac{d^2u}{dt^2} + 2\alpha\frac{du}{dt} + \omega_0^2\left(1 + \frac{R}{r}\right)u = \omega_0^2\left(L\frac{di_0}{dt} + Ri_0\right) \tag{3}$$

where $\omega_0^2 = \frac{1}{LC}$, $\alpha = \frac{1}{2}\cdot\frac{1}{LC}\left(RC + \frac{L}{r}\right) = \frac{R + (\omega_0 L)^2/r}{2L}$ (4)

The solution of (3) is:

$$u(t) = a\exp\left(-\frac{t}{\tau_0}\right) + A\cdot\exp(-\alpha t)\sin(\omega t + \varphi) \tag{5}$$

The constants A (the maximal amplitude of the induced oscillations) and φ (the initial phase of the oscillations with respect to the PMT signal beginning) are determined by the initial conditions in the form:

$$A^2 = a^2 + \left(\frac{Ca - q - C\tau_0 a\alpha}{C\omega\tau_0}\right)^2$$

$$\varphi = arctg\frac{-aC\omega\tau_0}{Ca - q - C\tau_0 a\alpha} \tag{6}$$

where $a = \frac{\omega_0^2\beta}{\frac{1}{\tau_0^2} - \frac{2\alpha}{\tau_0} + \omega_0^2\left(1 + \frac{R}{r}\right)}$, $\beta = -\frac{qR}{\tau_0} + \frac{qL}{\tau_0^2}$. (7)

So, the shaped voltage is a sum of two terms: a transient component $U_{tr}(t) = a\exp\left(-\frac{t}{\tau_0}\right)$ corresponding to the input perturbation, and a stationary component $U_{st}(t) = A \cdot \exp(-\alpha t)\sin(\omega t + \varphi)$ which describes the free oscillations of the RLC circuit.

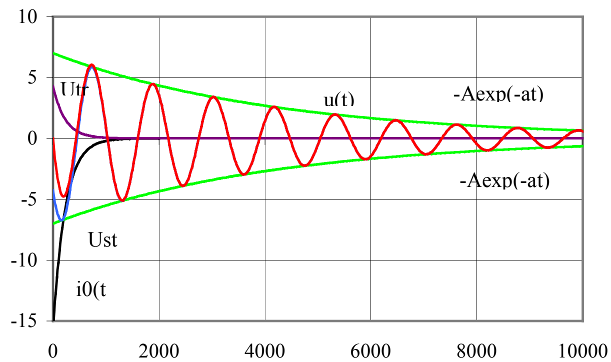

Fig. 3

The functions $i_0(t)$, $U_{tr}(t)$, $U_{st}(t)$ and $u(t)$ are shown in Fig.3. The first semiperiod of $u(t)$ has smaller amplitude than the second one. This is physically explained by the continuing action of the perturbation $U_{tr}(t)$; therefore, energy is being saved in both L and C. After the end of the transient process only the free oscillations of the RLC circuit remain, when the saved energy is periodically exchanged between L and C. Energy loss is described by the enveloping curve $\text{Aexp}(-\alpha t)$.

The following conclusions can be derived from the analysis, which are important for the optimal RLC shaping of the signal:

1. *u(t)* is strictly proportional to the anode charge q, i.e. the oscillations amplitude is proportional to the energy deposited in the scintillator volume.

2. The transient process $U_{tr}(t)$ decays with a time constant τ_0, determined by some external factors (the decay time of the scintillator and the PMT transfer function).

3. The stationary term $U_{st}(t)$ has oscillating form with a time constant T_0 determined only by the RLC circuit parameters.

4. There is no zero level shift after the end of the transient process (this is of importance for the subsequent signal processing).

Hence, ***the optimal pulse shaping strategy*** is:

- to achieve a minimal conversion time (i.e. to decrease the transducer's dead time aiming at a higher performance), and
- in the same time to keep the decrement factor of the oscillations as low as possible (in order to achieve larger code/charge ratio and, hence, a better energy resolution).

Three factors limits the metrological possibilities of the RLC shaping method:

- maximal amplitude of the RLC circuit oscillations which does not overload either the amplifier or the discriminator;
- the minimal threshold of the integral discriminator which still preserves its sensitivity to noise pulses;
- the minimum achievable decrement factor of the RLC circuit.

4 ENERGY-CODE DEPENDENCE

The time t_b necessary for the oscillations having initial amplitude A to fade down to a fixed threshold U_{th} is:

$$t_b = \frac{1}{\alpha} \ln \frac{A}{U_{th}} \tag{8}$$

If the fading oscillations are further processed by an integral discriminator having threshold U_{th} , then a pulse burst would appear at its output. The number of pulses n in the burst will be:

$$t_b = nT_0 = \frac{2\pi \cdot n}{\omega} \tag{9}$$

Or, combining (8) and (9):

$$n = \frac{\omega}{2\pi\alpha} \ln \frac{A}{U_{th}} \tag{10}$$

Taking into account (4), we obtain:

$$n = \frac{1}{\pi\omega\left(RC + \frac{L}{r}\right)} \ln \frac{A}{U_{th}} \tag{11}$$

The following conclusions results from (11):

1. The function $n(A)$ is logarithmic. Since the amplitude A is a linear function of the charge q, generated in the PMT, therefore the code-energy function by RLC shaping is also logarithmic.

2. The upper amplitude registered by the system can be controlled by the PMT amplification factor.

3. The desired energy range can be achieved by the integral discriminator's threshold U_{th}.

4. The number of channels in the useful energy range can be adjusted by choosing proper values for R, L and C.

The energy-code function for a RLC shaping circuit is shown in Fig.4. It is calculated for $\omega_0 = 1MHz$ and quality factor of the RLC circuit $Q = 62$.

5 OPTIMAL CHOICE OF THE RESONANT FREQUENCY

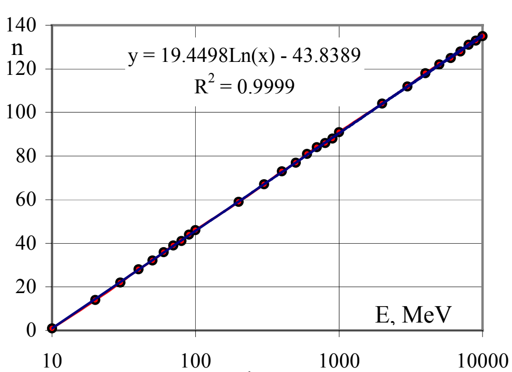

Fig.4.

The resonant frequency ω_0 of the LC circuit influences directly the dead time of the charge-code transducer (as higher the resonant frequency so lower the dead time). On the other hand, the maximal value of the resonant frequency is limited by the time constant of PMT pulse decay τ_0, since no full charge collection is possible if $T_0 = 2\pi / \omega_0 \cong \tau_0$.

Fig.5. shows the relative amount of the

collected charge *vs* the resonant frequency (measured by T_0/τ_0). At first sight, it seems somewhat unusual that T_0/τ_0 should be greater than 12 in order to achieve a full charge collection. Indeed, it should be taken into account that some energy can be transferred from a current generator into the RLC circuit only during the first quarter of the oscillations period.

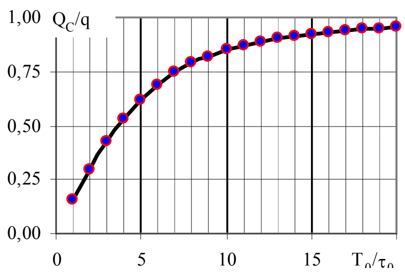

Fig. 5

If one strictly requires a full charge collection, then the resonant frequency should be limited to about 200 kHz for NaI(Tl) detectors ($\tau_0 = 230ns$) and the subsequent dead time would be too large. So, it is interesting to investigate whether the proportionality $n \cong \ln(E)$ is still valid in a partial charge collection mode.

Some additional criterion can be the energy saved into the RLC circuit. It is defined as the sum of the energy collected in the capacitance and that collected in the inductance:

$$E_{CL} = E_C + E_L = \frac{1}{2}\left(Cu_C^2 + Li_L^2\right) \qquad (12)$$

Energy is introduced into the RLC circuit only during the transient process, so Figs.6a-d show E_{CL}, E_C, E_L and $u(t)$ for different values of T_0/τ_0.

It is seen from Fig.6a ($T_0 = \tau_0$) and Fig.6b ($T_0 = 2\tau_0$) that there is a moment after

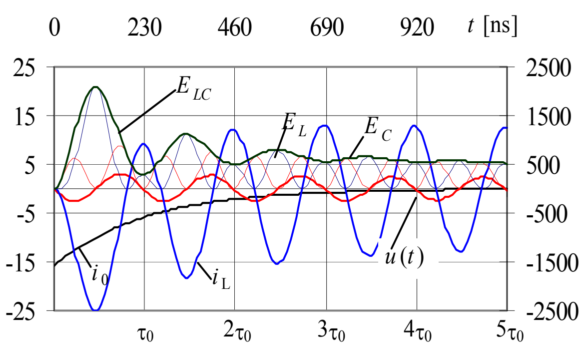

Fig.6a - $T_0=\tau_0$

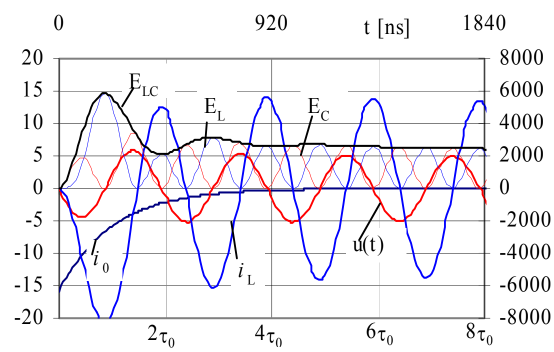

Fig.6b - $T_0=2\tau_0$

that the input signal decreases the energy saved in the circuit instead to further increase it. This is due to the fact that if a zero voltage is reached on the capacitor then the current coming from the magnetic energy saved into the inductor is opposite to that of the incoming signal. Hence, a smaller energy will be saved in the circuit and a faster fading of the voltage below the threshold level occurs. Moreover, the amount of energy saved into the circuit is strongly dependent on T_0/τ_0. So, a minimal change of decay time of the scintillator (e.g. due to a change in the ambient temperature) will produce different code at the same energy of radiation deposited in it.

If $T_0 = 5\tau_0$ (Fig.6.c) then the minimum in the time diagram of the saved energy is no more significantly pronounced. Probably, this is the point for a compromise solution when the full charge collection requirement is still not fulfilled but the proportionality charge-amplitude is already reached.

The picture shown in Fig.6.d ($T_0 = 8\tau_0$) is no more significantly different from that for $T_0 = 5\tau_0$, i.e. a still better charge collection does not more improve the shaping

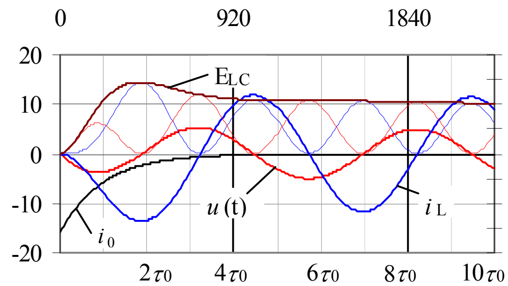

Fig.6c $T_0=5\tau_0$

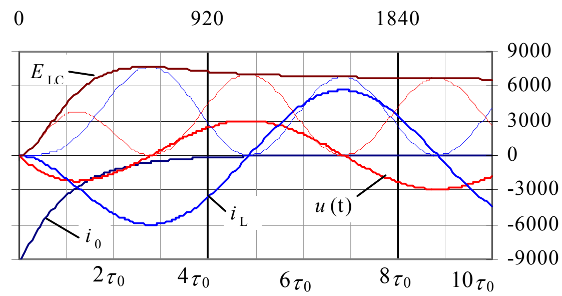

Fig.6d $T_0=8\tau_0$

circuit parameters (except the increasing of the dead time).

Therefore, we conclude that a compromise solution for optimal choice of the resonant frequency by RLC shaping is that ***the period of the RLC circuit oscillations should be at least 5 times greater than the decay time of the used scintillator***.

6 CONCLUSION

It is possible to use RLC circuit for shaping the charge output from a charge output detector, taking into account the following special features:

1. RLC has larger dead time than RC shaping.
2. The generated code is strongly dependent on the decay constants (that of the incoming perturbation and that of the free oscillations).
3. The amplitude of the oscillations excited into the RLC circuit depends linearly on the incoming charge.
4. The number of periods necessary for the free RLC oscillations to decrease under a predefined threshold voltage (i.e. the generated digital code) is logarithmic function of the incoming charge. This makes possible to use a larger dynamic range of the transducer.

7 ACKNOWLEDGEMENTS

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