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Unity direct chain with feedback series impedance based innovative negative group delay circuit

Blaise Ravelo

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ABSTRACT

An innovative negative group delay (NGD) circuit theory on unity direct chain (UDC) topology is developed in this paper. The NGD UDC cells are based on the operational amplifier adder with feedback series impedance. Innovative topologies of high-pass NGD UDC cell composed of RL-series network, all-pass RC-parallel network and low-pass RC-series network are identified. It is a first time that all-pass NGD original topologies are defined. NGD analyses and synthesis methods of each NGD UDC cells are provided. The UDC cell based NGD functions are validated with SPICE simulations. The proofs-of-concept (POC) of UDCs behave as all-pass and low-pass NGD functions with group delay equal to −1 ms at very low frequencies. The low-pass NGD cut-off frequency is 424 Hz. The high pass NGD circuit generates −1 μs at the optimal NGD frequency of about 5.15 kHz. Further analysis of the operational amplifier gain and bandwidth effects is performed. The operational amplifier gain affects significantly the NGD level and bandwidth for the all considered UDC cells. Nevertheless, only the RC-parallel feedback based UDC cell is particularly sensitive to the operational bandwidth.

1. Introduction

Theoretical and experimental investigations illustrate that certain electromagnetic and optical media as atomic coherence effect media are susceptible to produce the negative group delay (NGD) phenomenon [1]. By analogy between transfer function, the equivalent electronic circuit topology based on the amplifier classical function generating NGD function was established in 1990s [2]. It was pointed out that the NGD phenomenon does not forbid the causality principle [3,4]. At the beginning, the occurrence of the NGD phenomenon was initially explained with the anomalous dispersion [5,6]. This effect was understood from theoretical study on the abnormal media with negative group velocity [1,5,6]. It was shown that at certain wavelengths, these media are capable to present refractive group index ng can be negative. The theoretical demonstration of the NGD can be illustrated with the following simple mathematical analysis. First of all, it is well-known that the group velocity v_g is linked to the speed of light in the vacuum c by the expression $v_g = c/n_g$. Obviously, if ng is negative, the group velocity v_g is also negative. It means that when using a physical medium with geometrical length d, the group delay, which is by definition, expressed as $\tau_g = d/v_g$, can also be negative. The NGD phenomenon is produced by the inherent fact of the wave reshaping or the combination of the constructive and destructive interferences at the edge of the abnormal dispersive passive medium [5]. In time-domain, the NGD function enable to exhibit innovative physical function by generating an output signal with wave fronts propagating in advance of its input under certain conditions [7,8]. The time domain demonstration was performed with low frequency signals enabling naked eyes observation of time-advance [7,8] and arbitrary shape audio signal advance [9]. Counteractively to the ordinary medium, in this case, the time delay can be assumed as negative [2–9].

The initial electronic circuit NGD topologies are mainly built with relatively complex operational amplifier-based topologies [2–9]. The initial NGD topologies are mainly built with passive network in feedback with operational amplifier. Potential application of NGD function has been introduced for the electrical interconnect delay cancellation [10,11]. In 2000s, a complex NGD circuit with feedforward amplifier has been introduced [12]. Despite the limitations of NGD circuits [13,14], RF/microwave feedback topologies have been developed based on the low noise amplifier [15–17]. A systemic approach on the NGD feedback topology is proposed in [18]. The influence of the feedback delay on the NGD function is characterized. Investigation on NGD function based on delay induced system has been introduced [19–21]. It was reported that the NGD function can be an alternative solution compared to the technique proposed in [22,23] respectively for the signal behavior prediction and self-correction. Another potential application of the NGD function is the electronic system delay cancellation [24–26]. The NGD technique can also be envisaged as the development of communication channel effect equalizer as alternative of solution proposed in [27]. Basically, the system equivalent transfer function has been considered to characterize the NGD function. However, it acts as a typically distributive high-order system and rather

E-mail address: blaise.ravelo@esigelec.fr.

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difficult to implement with classical circuit. Simpler topologies of NGD function have been identified in [28]. It was emphasized that the NGD function behaves similarly to the filter function [28]. Typically, low- and high-pass NGD canonical forms have been established [29,30].

The present paper is focused on the analysis of the family of typically unit direct chain (UDC) feedback topology. The paper is organized in three main sections. Section 2 presents the UDC NGD cell identification methodology fundamentally based on the voltage transfer function (VTF). The NGD analyses will be elaborated. Then, the synthesis method enabling to calculate the circuit parameters is presented. Section 3 is focused on the investigation the identified topology validations. Comparisons between the analytical models and SPICE simulations are described. It enables to verify the established NGD topologies theory efficiency. Then, the conclusion of the paper will be presented in Section 4.

2. Theory of unity direct chain (UDC) NGD topologies

The present section describes the UDC topologies under study. The NGD identification topology is provided. Identified innovative NGD UCD cells will be analyzed and characterized.

2.1. General description of the UDC topologies with feedback series impedance

Fig. 1(a) represents the general UDC system with feedback transfer function denoted $F_0(j\omega)$ ($j\omega$ is the angular frequency variable). The general input and output are respectively denoted $V_i(j\omega)$ and $V_o(j\omega)$. The simple idea of the paper is to use R-parameter based operational amplifier adder and the feedback chain $F_0(j\omega)$ by series impedance $Z(j\omega)$. The inspired UDC topology family is shown in Fig. 1(b).

The UDC topology associated voltage transfer function (VTF) is expressed as:

$$T(j\omega) = 2[1 + R/Z(j\omega)]. \tag{1}$$

Intuitively, simplest NGD cell should be built with a first order feedback impedance. The practical solution consists of using associated resistor R_x and a reactive component (inductor L or capacitor C). So, the different configurations of feedback impedance RL-series network $Z(j\omega) = R_x + jL\omega$, RL-parallel network $Z(j\omega) = jL\omega R_x/(R_x + jL\omega)$, RC-series network $Z(j\omega) = R_x + 1/(jC\omega)$, and RC-parallel network $Z(j\omega) = R_x/(1 + j\omega R_x C)$ are developed in this paper. The following paragraphs characterize the NGD aspect of these different elementary UDC cells.

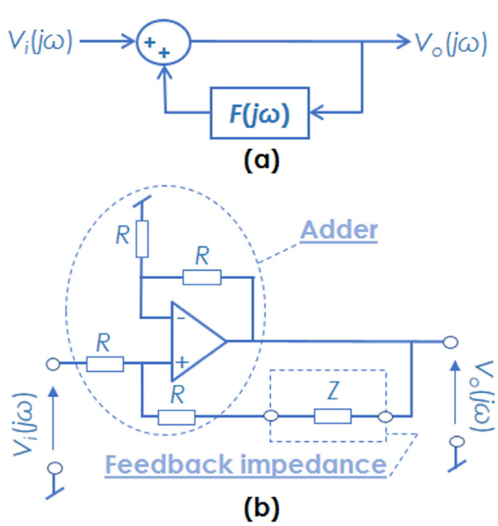

Fig. 1. General configuration of UDCF topology under study.

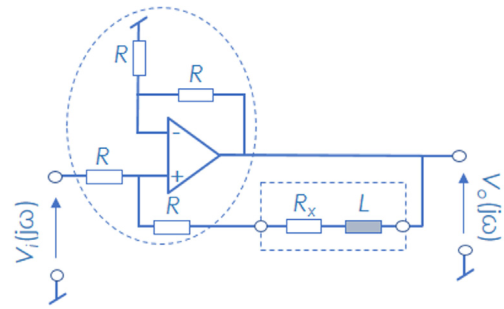

Fig. 2. RL-series network feedback UDC cell.

2.2. NGD analysis of RL-series impedance feedback UDC cell

Fig. 2 introduces the RL-series impedance feedback UDC cell.

2.2.1. Frequency response analyses

The VTF magnitude, phase and the associated group delay of the circuit proposed in Fig. 2 are written as:

$$\begin{cases} T(\omega) = |T(j\omega)| = 2\sqrt{[(R + R_x)^2 + (L\omega)^2]/[R_x^2 + (L\omega)^2]} \\ \varphi(\omega) = \arctan[L\omega/(R + R_x)] - \arctan(L\omega/R_x) \\ \tau(\omega) = -\frac{\partial\varphi(\omega)}{\partial\omega} = \frac{LR[R_x(R+R_x) - (L\omega)^2]}{[R_x^2 + (L\omega)^2][(R+R_x)^2 + (L\omega)^2]} \end{cases}. \tag{2}$$

It can be remarked that this group delay can be negative under the condition:

$$R_x(R + R_x) < (L\omega)^2. \tag{3}$$

It means that the cell depicted in Fig. 2 generates the NGD function.

2.2.2. NGD analyses

At very low frequencies $\omega \approx 0$, the VTF magnitude and group delay are respectively equal to:

$$T_0 = T(\omega \approx 0) = 2(1 + R/R_x), \tag{4}$$

$$\tau_0 = \tau(\omega \approx 0) = RL/[R_x(R + R_x)]. \tag{5}$$

As the group delay at low frequencies is positive, the UDC cell behaves as high pass NGD function. The cut-off angular frequency is:

$$\omega_c = R\sqrt{2T_0}/[L(T_0 - 2)]. \tag{6}$$

At this cut-off frequency, the VTF magnitude is equal to:

$$T_c = T(\omega_c) = \sqrt{2T_0}. \tag{7}$$

The NGD minimal value is equal to:

$$\tau(\omega_o) = \sqrt{2T_0}(2 - T_0)(\sqrt{T_0} - \sqrt{2})^2/[\omega_c(T_0 + 2)], \tag{8}$$

at the optimal angular frequency:

$$\omega_o = \omega_c\sqrt{(T_0 + 2)/\sqrt{2T_0} + 1}. \tag{9}$$

The corresponding VTF magnitude is equal to:

$$T(\omega_o) = 2^{3/4}T_0^{1/4}. \tag{10}$$

By denoting $x = R/R_x$, the UDC cell VTF magnitude flatness in the NGD bandwidth can be evaluated with the ratio:

$$y = T(\omega_o)/T(\omega_c) = 2^{1/4}T_0^{-1/4} = (1 + x)^{-1/4}. \tag{11}$$

2.2.3. NGD synthesis method

Acting as a high pass NGD function, the UDC cell synthesis can be performed by inverting the NGD $\tau_m = \tau(\omega_o) < 0$ written in (8) and the VTF magnitude $T_m = T(\omega_o)$ expressed in (10). Knowing T_m and τ_m, the following R_x and L synthesis formulas can be derived, respectively: