LC Ladder Filter Emulation by Structures with Current Conveyors

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Abstract: Active network structures emulating LC ladder structures are presented. Design process based on state variable description is shown in detail. Various types of current and voltage conveyors are used as active network elements so that a number of different topologies were obtained. A new universal circuit device named UCCX containing universal current conveyor UCC and CCII+- is described and its real properties are evaluated. Selected structures are designed and simulated.

Key-Words: Signal processing, current and voltage conveyors, UCC, UCCX

1 Introduction
Passive LC ladder filters are known to have several advantages when compared with other passive structures. They have simple structure and their design is described in many books in very detail, e.g. [4]. But the most important advantage is very low sensitivity to the variations of its component. When active circuit elements like operational amplifiers became available, no wonder that scientists and filter designers tried to simulate these LC structures by the active ones to replace bulky inductors but to preserve advantageous properties of former LC structures. Two main approaches have been found:

- element simulation,
- operational simulation

In the first case inductors can be simulated by
- impedance converters, e.g. by GIC,
- impedance inverters, e.g. by gyrators,
- general active structure

In the second case the original LC ladder structure is described by current and voltage expressions. The voltages and currents are state variables of the network, i.e. voltages over capacitors and currents via inductors. It corresponds to the network description by SFG (signal-flow graphs). Obtained equations are transformed then into a suitable form that can be simulated by active circuit blocks.

2 Simulation principle
Let us consider resistively terminated LC prototype depicted in Fig. 1.

电压传输函数的网络从图 1 a) 由下式给出

\[ K_v = \frac{R_L}{b_3 s^3 + b_2 s^2 + b_1 s + R_L + R_S}, \]

\[ b_3 = R_i R_S L C_3, \]

\[ b_2 = R_i L C_1 + R_i L C_3, \]

\[ b_1 = R_i R_S (C_1 + C_3) + L_2. \]

The current transfer function of the network from Fig. 1 b) differs only in the numerator where \( R_i \) is replaced by \( R_S \). The prototype from Fig. 1 b) can be described by a set of equations derived using Kirchhoff's voltage and current laws

\[ V_i = \frac{1}{sC_1 + C_S} (I_i - I_2), \]

\[ I_2 = \frac{1}{sL_2} (V_i - V_3), \]

\[ V_3 = \frac{1}{sC_1 + G_i} I_2. \]

This step is very often viewed as SFG description, [1]. In the past the designers used operational amplifiers in active blocks and the voltage mode was the only choice,
e.g. [1], [2], [3]. At present a number of additional active
circuit elements are available. More and more a current
mode is being preferred. So that a designer has to solve
two basic problems:

- **type of active element** – OpAmp, OTA, CFA, CC
  (current conveyor), VC (voltage conveyor),
- **operation mode** – voltage or current.

Either voltage or current mode is selected, it is necessary
to do some modifications of equation set (2). According
to the mode of the designed circuit, current or voltage,
all the equations have to be converted either to the
voltage formulas or to the current ones respectively. An
auxiliary scaling resistor \( R_p \) is used for these
conversions. Eq. (3) shows conversion for voltage mode,
while eq. (4) becomes starting point for design for
current mode network.

\[
V_i = \frac{1}{sC_1R_p + G_1R_p} (R_p I_i - R_p I_2) = \frac{R_i}{R_p} \frac{1}{sC_1R_1 + 1} (V_i - V_2),
\]

\[
R_p I_2 = V_2 = \frac{1}{sL_2/R_p} (V_i - V_3),
\]

\[
V_3 = V_o = \frac{1}{sC_3R_p + G_3R_p} R_p I_2 = \frac{R_i}{R_p} \frac{1}{sC_3R_1 + 1} V_2.
\]

\[
I_{V_1} = V_i / R_p = \frac{R_i}{R_p} \frac{1}{sC_1R_1 + 1} (I_i - I_2),
\]

\[
I_2 = \frac{1}{sL_2/R_p} (I_i - I_{V_3}),
\]

\[
I_{V_3} = V_o / R_p = \frac{R_i}{R_p} \frac{1}{sC_3R_1 + 1} I_2.
\]

When we look at these equations we found that lossless
and lossy integrators with two summing or
differentiating inputs are the basic building blocks for
filter realization. Resulting structures are called LF
(Leap Frog) structures.

Design procedure when opamps are used is described in
a number of books dealing with active filters, like [1],
[3], [5] and others. Also LF structures with OTA devices
are common [3].

### 3 LF structures with current conveyors

Current conveyors become more and more common
because of current mode of their operation. Their
advantages like wider operation frequency range, good
dynamic range, low- voltage operation, possibility of
voltage, current and mixed mode operation and others
were presented in many publications, e.g. in [5], [6], [7].

A number of types of current conveyors have been
designed, three-port groups of four CCI, four CCII, four
CCIII, four-port conveyors like CCII+/− or DVCC and
five-port conveyor DVCC+−. Recently a new current
conveyor has been developed and realized in our Faculty
– the UCC (Universal Current Converter) [10]. The UCC
is eight-port element that contains three high-impedance
voltage inputs \((y^+, y^-, y^-)\), one low-impedance current
input and four high-impedance current outputs, see Fig.
2. The UCC was developed due to its capability to
simulate many types of particular current conveyors
because it is known that only a few devices containing
separate current conveyor is on the market.

![Fig. 2 Universal Current Conveyor UCC](image)

The simplest solution for current-mode structure is to
use CCII+/− conveyor because this device contains two
output currents with opposite polarities and no other
modifications are necessary. Fig. 3 shows lossless and
lossy current integrators – building blocks for LF
structure.

![Fig. 3 Lossless and lossy current integrators with CCII+/−](image)

Final solution can be seen in Fig. 4. Only three active
elements (CCII+/−) are required and all passive
components are grounded.

![Fig. 4 Current mode LF structure with CCII+/− elements](image)

The transfer function of this network has form (5).

\[
K_i = \frac{R_3}{b_2 s^3 + b_2 s^2 + b_2 s + R_3 R_4 / R_3 + R_8},
\]

\[
b_2 = R_1 R_3 R_2 C_1 C_2 C_3,
\]

\[
b_2 = R_2 R_3 C_1 (R_4 C_1 + R_6 C_1)
\]

\[
b_1 = R_1 R_3 (C_3 + C_1 R_1 / R_3) + R_4 C_2.
\]

When \( R_3 = R_{L} \) the current flowing from the \( z^+ \) output of
\( ^3\text{CCII+/−} \) has the same value as the current flowing
through the load \( R_{L} \).
It is possible to design LF structure where three-port current conveyors are used. For this purpose it is necessary to modify the set of current formulas (4) to the form (similarly like the LF structures with opamps):

\[-I_{V1} = V'_1/R_p = -\frac{R_s}{R_p} \frac{1}{sC_1R_s + 1} \left(I_1 + (-I_2)\right),\]

\[-I_2 = \frac{1}{sL_2/R_p} \left(I_{V3} + (-I_{V1})\right),\]

\[I_{V3} = V_3/R_p = -\frac{R_i}{R_p} \frac{1}{sC_3R_i + 1} \left(-I_2\right).\]

The only difference is that the transfer function becomes negative because of second formula in set (6).

In addition to the inverting integrators also non-inverting ones are required. Interesting structure is shown in Fig. 5 a), that provides not only positive integration but it also reduces the influence of parasitic impedances of “x” inputs of both current conveyors. The principle is described in [8].

The number of passive elements of any active structure is higher than in the prototype, so this freedom can be used to select identical capacitors, to scale the circuit to obtain reasonable values of passive elements and to maximize the dynamic range of the whole circuit [1].

In the Faculty of Electrical Engineering and Communication of Brno University of technology in cooperation with AMI Semiconductors company an integrated circuit UCCX-0349 was designed and samples were manufactured. The UCCX device was designed on technology CMOS 0.35 µm and contains one UCC and one CCII+/− conveyor. Its parameters can be found e.g. in [11].

A LF structure was designed according to the third-order lowpass filter prototype from Fig. 1. Butterworth approximation was chosen with bandwidth 1 MHz.

When we return to the network from Fig. 4 we can see that only one output current in the first and the last CCII+/− conveyors is used. Therefore when we replace CCII+/− by CCII+ conveyors according to Fig. 5 b), we can save one CCII when compared with network from Fig. 6. Fig. 7 shows the result.

Six conveyors CCII+ are used to build this structure. CCII+ No. 4 is necessary to copy the output current of CCII+ No. 3. Matching of the resistors R2 and Rx2 is required for correct operation of the circuit.

Fig. 8 shows usage of UCCX device in the structure from Fig. 4. Two ICs are required. One half of the second IC remains unused or it can be used as a voltage or current follower to allow additional load.

4 Design verification

Fig. 9 shows the results of the designed structure with the UCCX-0349 IC.
The current-mode structure from Fig. 4 was designed and analyzed. Source and load resistors $R_S$ and $R_L$ were chosen 50 $\Omega$ both for the prototype and the active structure. Calculated values of other passive elements were $R_1 = R_3 = 100 \Omega$, $R_2 = 159.1 \Omega$, $C_1 = C_3 = 3.18 \text{nF}$, $C_2 = 1\text{nF}$. PSpice simulation tool was used for the analysis. The circuit was simulated with ideal models of CCII+/- devices, with macromodels, see Fig. 10, and with a model of UCC that was used to simulate all CCII+/-s. Results can be seen in Fig. 11.

4 Conclusion
Active filter structures using current conveyors and simulating RLC ladder networks were presented. Current-mode was preferred. Selected structure was designed and simulated. Results proved good properties of active structures derived from RLC prototype. Analyzed network will be built with the UCCXs and measured. Results will be compared with theoretical and simulation outputs and presented at the conference.

Acknowledgement
This paper was supported by the Grant Agency of the Czech Republic, grants No. 102/02/P067 and No. 102/03/1465

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