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Simulation of a mutually coupled circuit using plus-type CCIIs

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A new CCII-based circuit for the simulation of mutually coupled circuits is presented. The circuit uses six commercially available plus-type second-generation current conveyors (CCII+s), six resistors and two grounded capacitors. The primary self-inductance, the secondary self-inductance and the mutual inductance can be independently controlled using three different resistors. SPICE simulation results are included.

Keywords: Current conveyors; Coupled circuits

1. Introduction

Mutually coupled circuits are widely used in communication, instrumentation and control. A mutually coupled circuit comprises a primary self-inductance L_1, a secondary self-inductance L_2 and a mutual inductance M. A literature survey reveals that several approaches have been reported for simulating a mutually coupled circuit using operational amplifiers (Atiya 1978, Soderstrand 1978, Higashimura and Fukui 1985), bipolar junction transistors (Higashimura and Fukui 1991, Shigehiro *et al.* 1991), second-generation current conveyors (CCIIs) (Higashimura 1991, Higashimura and Fukui 1991a) and the operational trans-conductance amplifier (OTA) (Higashimura and Fukui 1991a,b). Of these, the CCII-based realizations are more attractive. This is attributed to their higher signal bandwidths, greater linearity, wider dynamic range, simple circuitry and low power consumption (Roberts and Sedra 1989). However, while the available CCII-based realizations can provide independent tuning of the three inductances L_1, L_2 and M, plus-type and minus-type current conveyors (CCII+2 and CCII−) are required for their implementation. Since the CCII− is not commercially available, a practical implemenation would require two CCII+s to replace each CCII−. Thus, practical implementation of the CCII-based circuits reported in Higashimura and Fukui (1991a) and Higashimura (1991) would require an excessive number of current conveyors.

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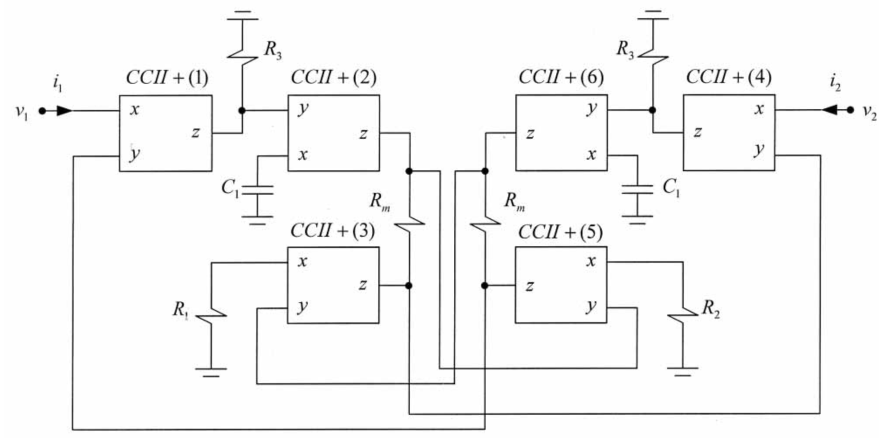

Figure 1. Proposed circuit for simulating a mutually coupled circuit.

The major intention of this paper is to present a new CCII-based realization for the mutually coupled circuit. The proposed implementation uses only six CCII+s and can provide independent tuning for the three inductances.

2. Proposed circuit

The proposed circuit is shown in figure 1. Assuming ideal, the terminal characteristic of the CCII+ can be described by $i_x = i_z$, $i_y = 0$, $v_x = v_y$. Routine analysis shows that the voltages v_1 and v_2 can be expressed as

$$v_1 = sC_1R_1R_3i_1 + sC_1R_3R_mi_2 \tag{1}$$

and

$$v_2 = sC_1R_3R_mi_1 + sC_1R_2R_3i_2 \tag{2}$$

Inspection of equations (1) and (2) shows that these are the equations describing a mutually coupled circuit with

$$L_1 = C_1R_1R_3 \tag{3}$$

$$L_2 = C_1R_2R_3 \tag{4}$$

and

$$M = C_1R_mR_3 \tag{5}$$

Under the open-circuit condition, that is $i_2 = 0$, the ratio between the output and input voltages can be expressed as

$$\frac{v_2}{v_1} = \frac{M}{L_1} \tag{6}$$

Inspection of equations (3)–(5) shows that the inductances L_1, L_2 and M can be independently controlled using the resistors R_1, R_2 and R_m respectively. Moreover, by controlling the resistance R_3 the three inductances can be simultaneously controlled. Equation (6) clearly shows that, assuming ideal current conveyors, under the open-circuit condition the ratio between the output and input voltages is constant and independent of frequency.

Current conveyors are non-ideal devices. It is therefore essential to study the effect of the current-conveyor non-idealities on the performance of the proposed mutually coupled circuit. Assuming that a non-ideal CCII+ can be characterized by $i_z = \alpha i_x$, $v_x = \beta v_y$, where $\alpha = 1 - \varepsilon_i$, $|\varepsilon_i| \ll 1$ and $\beta = 1 - \varepsilon_v$, $|\varepsilon_v| \ll 1$, denote the current and voltage tracking errors, re-analysis yields

$$v_1 = s(C_1 R_1 R_3 \alpha_1 \alpha_2 \beta_1 \beta_2 / \alpha_3 \beta_3) i_1 + s(C_1 R_3 R_m \alpha_4 \alpha_6 \beta_1 \beta_6) i_2 \tag{7}$$

and

$$v_2 = s(C_1 R_3 R_m \alpha_1 \alpha_2 \beta_2 \beta_4) i_1 + s(C_1 R_2 R_3 \alpha_4 \alpha_6 \beta_4 \beta_6 / \alpha_5 \beta_5) i_2 \tag{8}$$

Inspection of equations (7) and (8) shows that these are the equations that describe a mutually coupled circuit with

$$L_1 = C_1 R_1 R_3 \alpha_1 \alpha_2 \beta_1 \beta_2 / \alpha_3 \beta_3 \tag{9}$$

$$L_2 = C_1 R_2 R_3 \alpha_4 \alpha_6 \beta_4 \beta_6 / \alpha_5 \beta_5 \tag{10}$$

$$M_1 = C_1 R_m R_3 \alpha_4 \alpha_6 \beta_1 \beta_6 \tag{11}$$

and

$$M_2 = C_1 R_m R_3 \alpha_1 \alpha_2 \beta_2 \beta_4 \tag{12}$$

From equations (9) and (12) it appears that the self- and mutual inductances L_1, L_2, M_1 and M_2 will be slightly affected by the current- and voltage-tracking errors of the current conveyors. However, unless the current conveyors are identical, the mutual inductances M_1 and M_2 will not be equal. This will result in a slight error in the performance of the mutually coupled circuit.

On the other hand, the current conveyors have parasitic impedances at terminals x, y and z. For example, for the widely used AD844 CCII+, the parasitic impedances are $R_x = 50\,\Omega$, $R_y = 10\,\mathrm{M}\Omega$, $C_y = 4.5\,\mathrm{pF}$, $R_z = 3\,\mathrm{M}\Omega$ and $C_z = 4.5\,\mathrm{pF}$. From figure 1 it is easy to see that the effects of R_{x3} and R_{x5} can be easily absorbed into the resistors R_1 and R_2 respectively. Taking the effects of parasitic resistances R_{x1} and R_{x4} into consideration, equations (1) and (2) reduce to

$$v_1 = (R_{x1} + sC_1 R_1 R_3) i_1 + sC_1 R_3 R_m i_2 \tag{13}$$

and

$$v_2 = sC_1 R_3 R_m i_1 + (R_{x4} + sC_1 R_2 R_3) i_2 \tag{14}$$

Under the open-circuit condition, that is $i_2 = 0$, the ratio between the secondary and the primary voltage can be expressed as

$$\frac{v_2}{v_1} = \frac{sM}{R_{x1} + sL_1} \tag{15}$$

Equation (15) clearly shows that under the open-circuit condition the ratio between the output and input voltages will be frequency dependent. For example, if the frequency is sufficiently small that $R_{x1} \gg sL_1$, then this ratio will be linearly changing with frequency. However, if the frequency is sufficiently large that $R_{x1} \ll sL_1$, then this ratio will be equal to M/L_1 and will be independent of frequency. This means that under the open-circuit condition the ratio between the output and the input voltages approaches the ideal value as the frequency increases. Inspection of equations (13) and (14) shows that, considering the effects of R_{x1} and R_{x4}, the inductances L_1 and L_2 will be associated with relatively small series resistances. This will not affect the operation of the mutually coupled circuit. At relatively low frequencies with $R_{x2} \ll 1/\omega C_1$ and $R_{x6} \ll 1/\omega C_1$, the effects of the parasitic resistances R_{x2} and R_{x6} can be ignored. Thus, these parasitic resistances will limit the high-frequency operation of the circuit. Inspection of figure 1 also shows that the parasitic components R_{z1}, R_{y2}, C_{z1} and C_{y2} will be in parallel with the resistance R_3. Thus, if we choose R_3 much smaller than the parallel combination of these parasitic components, then, except at relatively high frequencies, the effect of these parasitic components can be ignored. A similar argument applies to the parasitic components R_{z4}, R_{y6}, C_{z4} and C_{y6}. Similarly, the parasitic components R_{z5}, R_{y1}, C_{z5} and C_{y1} will be in parallel and the parasitic components R_{z6}, R_{y3}, C_{z6} and C_{y3} will be in parallel. Thus, unless the frequency is sufficiently high, with R_m sufficiently smaller than these parallel combinations of parasitic components, the currents i_{z5} and i_{z6} can be assumed equal, and the performance of the proposed mutually coupled circuit will not be affected by the parasitic components. A similar argument applies to the parasitic components R_{z2}, R_{y5}, C_{z2} and C_{y5}, and the parasitic components R_{z3}, R_{y4}, C_{z3} and C_{y4}. Thus, one can conclude that the effect of the parasitic components of the current conveyors will manifest itself only at relatively high frequencies.

3. Experimental results

The proposed mutually coupled circuit of figure 1 was bread-boarded and experimentally tested using the AD844 CCII+ and discrete components. The results obtained with a $1\,\text{M}\Omega // 20\,\text{pF}$ impedance connected to terminal 2, a dc supply voltage of $\pm 7.5\,\text{V}$, $R_1 = R_2 = 5.0\,\text{k}\Omega$, $R_3 = 10.0\,\text{k}\Omega$, $C_1 = 1.0\,\text{nF}$ and $R_m = 2.2\,\text{k}\Omega$ are shown in figures 2 and 3. This corresponds to $L_1 = L_2 = 0.05\,\text{H}$, $M = 0.022\,\text{H}$, $k = 0.44$ and an ideal ratio between output and input voltages $(v_2/v_1) = 0.44$ under the open-circuit condition. It appears from figure 2 that the measured value of (v_2/v_1) is not equal to the ideal value of 0.44 and changes with the frequency. This is to be expected from a bread-board realization where the effect of the parasitic capacitances cannot be avoided. From figure 3 it appears that, for a fixed working frequency, the ratio between the output and input voltages is almost constant with variations of the input voltage. Again, as expected, the ratio between the output and input voltages is not equal to the ideal value of 0.44. Thus, it appears from figures 2 and 3 that the measured results are in fairly good agreement with the presented theory.

4. Conclusion

A new CCII-based circuit for simulation of mutually coupled circuits has been presented. Compared to the available CCII-based realizations, the proposed circuit uses a smaller number of active and passive elements. Moreover, the proposed circuit uses only the commercially available CCII+. This simplifies its practical implementation. Similar to the available realizations, the proposed circuit

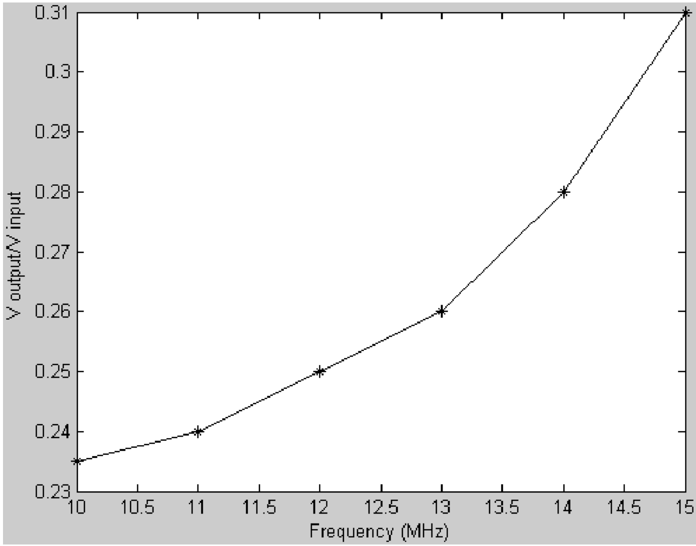

Figure 2. Variation of the ratio between output and input voltages of the proposed mutually coupled circuit with frequency.

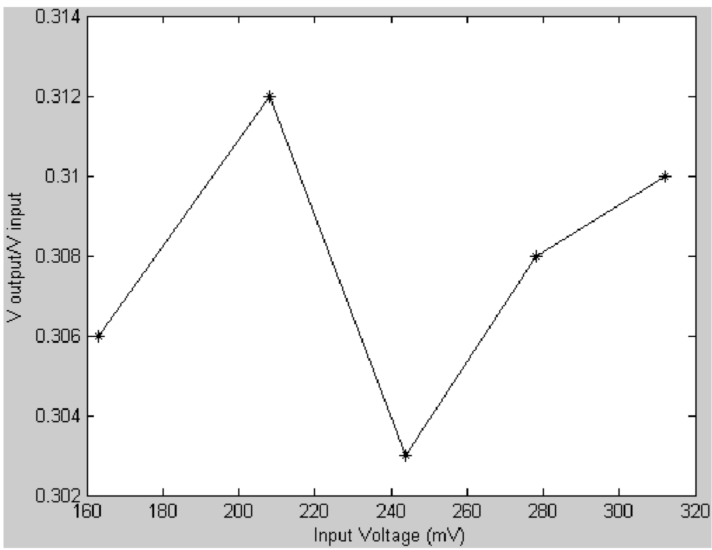

Figure 3. Variation of the ratio between output and input voltages of the proposed mutually coupled circuit with the input voltage.

enjoys the independent tuning of the self-inductances and the mutual inductance and the additional advantage of simultaneous tuning of the three inductances. Also, it uses grounded capacitors, which makes it suitable for integration. The experimental results obtained confirm the validity of the proposed circuit for simulating double-tuned circuits widely used in communication, instrumentation and control.

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