the example shown in Figs. 1 and 3. Specifically, they should be useful for checking computer and other approximate solutions to such problems, particularly since it is usually difficult to fabricate economically the class of inhomogeneous conductors under discussion for experimental comparisons, evaluation, and general explorations.

Acknowledgment

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The *Current Conveyor**—A New Circuit Building Block

***Abstract*—A new circuit concept applicable to a basic building block in a variety of instrumentation and communication systems is introduced. The new concept is called *current conveying* and its implementation a *current conveyor*.**

This letter introduces a new circuit concept applicable to a basic building block in a variety of instrumentation and communication systems. The new concept is called *current conveying* and its implementation a *current conveyor*. According to this concept, current is conveyed between two ports at extremely different impedance levels. An elementary implementation is found in the well-known common-base transistor configuration.

Fig. 1 is a black box representation of the current conveyor in its simplest form. If input terminal y is connected to a potential v, an equal voltage will appear on the other input terminal x. In a dual manner, if a current I is forced through input x, an equal current will flow through input y. The same current I is also conveyed and supplied through output terminal z at a high impedance level in the manner of a current source. Moreover, the potential of input x, being fixed by that of y, becomes independent of the current I forced through x. In a dual manner, the current I through input y, being fixed by that through x, becomes independent of the voltage v applied to y. Thus the device exhibits a virtual short-circuit input characteristic at port x and a dual virtual open-circuit input characteristic at port y. It should be noted that if the circuit is examined between input port x and output port z, it can be considered as a dual to the idealized emitter follower.

Adopting the hybrid-h two-port notation, the relationship between terminals x and y is represented by

$$H_{xy} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

with z grounded, and that between terminals x and z is represented by

$$H_{xz} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$$

with y grounded. The corresponding incremental model is shown in Fig. 2.

Fig. 3 is a first-order circuit implementation of the current conveyor principle. Assuming that all correspondingly marked transistors and resistors are matched and that all transistors have high common-base current gain (both dc and incremental), it can be shown that all transistors carry the same current, I. Thus it follows that x and y track each other in potential. It should also be noted that the operation is independent of the absolute values of resistors and supply voltage as long as linear operation of the transistors is ensured throughout the operating range.

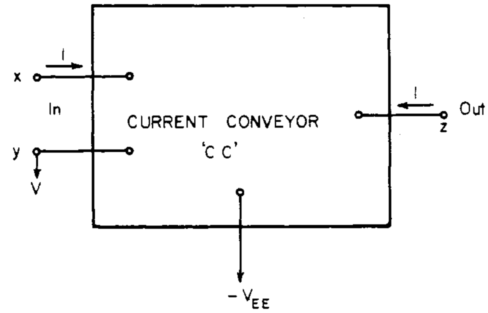

Fig. 1. Black box representation of the basic *current conveyor*.

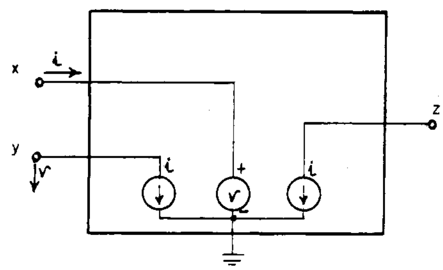

Fig. 2. Incremental circuit model of the basic *current conveyor*.

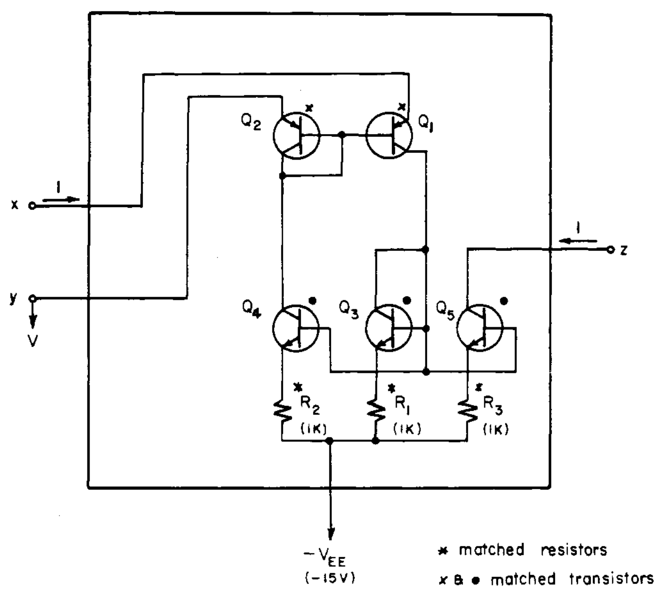

Fig. 3. First-order circuit implementation of the basic *current conveyor*.

On closer observation of Fig. 3, one sees that there will be slight differences in the currents carried by different transistors due to nonunity common-base current gains. However, these differences can be corrected by a suitable addition of transistors in a positive-feedback connection. This connection also serves to raise the output impedance. Further, by a repetition of the current conveying principle, additional output terminals providing complementary currents and currents at different voltage levels can be made available.

The terminal properties of the current conveyor outlined above, together with the incremental transfer characteristics described by matrices H_{xy} and H_{xz}, suggest a variety of applications. The transfer characteristic between ports x and z is clearly that of a current-controlled current source with several special applications in instrumentation and communication systems [1]. The virtual control of the potential of the input

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* Patent applied for.

terminal x (or, alternatively, the virtual short-circuit characteristic at input x) leads to several other applications including simple voltage-to-current conversion [2], digital-to-analog conversion with current source output [3], and dc offset control of wide-band signals [4]. The transfer matrix H_{xy} relating x to y corresponds to that of an ideal negative impedance converter (NIC), with x as the open-circuit stable (OCS) port and y as the short-circuit stable (SCS) port.

Other applications still under investigation include an ideal voltage follower, an electronically gain-controlled amplifier, and a high-speed logic gate. In general, the current conveyor is a new circuit configuration which appears to be useful in many linear and some digital applications, providing reasonable accuracy and high speed. The latter stems from the fact that in many applications currents alone are varied, hence little effect of stray capacitances on speed is observed [5].

In conclusion, a new circuit concept has been introduced, an implementation for it described, and its properties and applications outlined. Further publications will consider design details, analysis of performance under both small and large signal conditions, and the large numbers of applications clearly available.

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On Uniform Distributed Amplifiers

The structure for uniform distributed amplification that Jutzi considers in his recent letter [1] is a generalization of that proposed by McIver [2]; my earlier letter [3] gave an alternate approach to McIver's analysis.

Jutzi remarks that my approach (neglecting reflected waves) cannot be used for a stability analysis "because a perfect match is impossible." This is certainly true in practice, particularly if one hopes for a broadband device. However, the question of whether a perfect match for both modes is *theoretically* possible is an interesting one; I shall return to this point shortly.

A complete analysis of the device with reflections requires an approach somewhat different than that supplied in [1]. First of all, Jutzi conceives of the fast and slow waves as existing essentially independently on the two separate lines. In particular, he associates a reflection coefficient with each wave on each line at each end, for a total of eight coefficients. However, the fast and slow waves are normal modes of the system, and exist on both lines simultaneously. (Elliott and I have emphasized this in a recent paper [4].) There is a unique reflection coefficient for each mode at each end, or a total of four coefficients. Thus Jutzi's (6) is not only true "in most practical cases," but inherent in the concept of fast and slow waves.

Of greater significance is the fact that Jutzi has neglected the mode conversion that will take place at the terminations. For example, if the fast mode is not completely absorbed at the load, it will set up two reflected waves—one fast and the other slow—which is not surprising since this is the characteristic behavior of a multimode propagating system at a discontinuity. Therefore, the fast and slow modes are coupled at the terminations, and Jutzi's (7) cannot be valid. By continuing the transmission line analogy, one can compute the mode-conversion coefficients, but I doubt the accuracy of this procedure, as explained below.

Before further meaningful work on the analysis of the distributed amplifier can be accomplished, we must clarify the nature of the electromagnetic waves on the structure. The existing analyses use transmission line parameters, with the implicit assumption of TEM waves. This cannot be completely correct, for two reasons: 1) An active structure (such as that proposed by McIver) cannot support a pure TEM wave; 2) TEM waves travel with a single velocity, so that "fast" and "slow" waves cannot occur. It is probably true that TEM waves are a good approximation to the actual field configurations, but the errors contained in this approximation should be evaluated. For example, Amemiya has proved [5] that it is possible to match perfectly two TEM modes supported by two lines; is this a reasonable approximation for a distributed amplifier? Such questions need to be explored before design criteria for second-order effects (such as stability) can be obtained.

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Author's Reply[1]

I appreciate Kopp's comment on my letter [1], as he emphasizes several essential points. But since I cannot agree with some of these, I should like to give an explanatory reply.

The system I analyzed is defined with differential equation (2) and Fig. 1 of my letter. The system is chosen to compromise the requirement for a good approximation of actual structures and handy formulas. Once the astonishingly simple results of the system are available, and the degree of accuracy of the transmission line analogy is checked, the formulas constitute a useful tool for interpreting measurements on particular devices.

Starting from the differential equations and the boundary conditions assumed, the given formulas are not assumed but derived rigorously. The solution of the differential equation is well known as "a superposition of two wave pairs" (see [1]):

$$\begin{aligned}
U_1(z) &= A\cdot e^{-\gamma_f z} + B\cdot e^{+\gamma_f z} + C\cdot e^{-\gamma_s\cdot z} + D\cdot e^{+\gamma_s\cdot z}\\
U_2(z) &= (A\cdot e^{-\gamma_f z} + B\cdot e^{+\gamma_f z})\frac{\gamma_f^2 - a}{b} + (C\cdot e^{-\gamma_s z} + D\cdot e^{+\gamma_s z})\frac{\gamma_s^2 - a}{b}\\
I_1(z) &= \frac{1}{Z_{f1}}(A\cdot e^{-\gamma_f z} - B\cdot e^{+\gamma_f z}) + \frac{1}{Z_{s1}}(C\cdot e^{-\gamma_s\cdot z} - D\cdot e^{+\gamma_s z})\\
I_2(z) &= \frac{1}{Z_{f2}}(A\cdot e^{-\gamma_f z} - B\cdot e^{+\gamma_f z})\frac{\gamma_f^2 - a}{b}\\
&\quad + \frac{1}{Z_{s2}}(C\cdot e^{-\gamma_s z} - D\cdot e^{+\gamma_s z})\frac{\gamma_s^2 - a}{b}
\end{aligned} \tag{1}$$

in which A, B, C, D are determined with the boundary conditions. The terms $e^{\pm\gamma_f z}$ and $e^{\pm\gamma_s z}$ describe the fast and slow waves, where γ_s and γ_f are the propagation constants according to (3) in [1]. Characteristic impedances $Z_{s1}, Z_{s2}, Z_{f1}, Z_{f2}$ are defined quite formally as abbreviations during the derivation. Only in the mentioned special case of no induction coupling, $M=0$, do they considerably reduce to the very simple formulas (4) and (5) in [1] (see also [6]). The reflection coefficients are defined formally, too; for instance,

$$\rho_{\substack{f\\s}2l} = \frac{R_{2l}/Z_{\substack{f\\s}2} - 1}{R_{2l}/Z_{\substack{f\\s}2} + 1} \quad \text{or} \quad \rho_{\substack{f\\s}1l} = \frac{R_{1l}/Z_{\substack{f\\s}1} - 1}{R_{1l}/Z_{\substack{f\\s}1} + 1}. \tag{2}$$

The first index of ρ refers to the wave type, the second to the input or output line, and the last to the near or far end. This reflection coefficient definition has nothing to do with the fact that fast and slow waves exist on both

[1] Manuscript received May 31, 1968.