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Cascadable Current Mode Multipurpose Filters Employing Current Differencing Buffered Amplifier (CDBA)

Sadri Özcan, Hakan Kuntman and Oğuzhan Çiçekoğlu

Abstract **In a recent work, a new active building block, CDBA: current differencing buffered amplifier is introduced to provide new possibilities in the circuit synthesis and to simplify the implementation. The basic aim of this paper is to present a CDBA-based multipurpose filter topology which realises LP, BP, and HP transfer functions simultaneously. The performance of the circuit has been tested experimentally by using the bipolar realization of the CDBA. It has been demonstrated in the frame of this work that large output swings even at high frequencies is possible due to current-mode operation.**

Keywords **Analog signal processing, Analog integrated circuits, Active filters, CDBA-based filters.**

1. Introduction

As an active building block, operational amplifier played a predominant role in the last two decades and an enormous number of publications exist in the literature on various circuit examples so that the design engineer can make choice of them. However, opamp-based circuits exhibit several drawbacks in their performance arising from the limited bandwidth and slew-rate of these active elements. Therefore, current-mode approach has been increasingly recognized as a way to overcome the opamp drawbacks and to realize high speed systems. In the last decade and especially in recent years new current-mode active building blocks like second generation current conveyors (CCII+ and CCII−), current-feedback opamps (CFOA) received considerable attention due to their larger dynamic range and wider bandwidth [1, 2]. In addition, different types of active elements like electronically controlled current-conveyor (ECCII), differential voltage current conveyor (DVCC), differential difference current conveyor (DDCC), third generation current conveyor (CCIII), dual output operational transconductance amplifier (DO-OTA) and four terminal floating nullor (FTFN) are presented in the literature [3–8].

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In a recent work, a new active building block, CDBA: current differencing buffered amplifier is introduced by Acar and Özoğuz to provide further possibilities in the circuit synthesis and to simplify the implementation [9, 10].

The basic aim of this paper is to present a CDBA-based multipurpose filter topology which realizes LP, BP, and HP transfer functions simultaneously. In this study a single CDBA is used as the starting point.

Most cascadable current mode filters permit cascadability due to their high output impedances. But most of them do not exhibit low input impedance, except [11]. The proposed circuit however permits low input impedance due to unconditionally grounded input pin of the CDBA. This will bring further advantages, for example there will be no loading problem for the current mode signal source.

2. Current Differencing Buffered Amplifier (CDBA)

The circuit symbol of the CDBA is shown in Figure 1a, where p and n are input, w and z are output terminals. The equivalent circuit of the CDBA is given in Figure 1b. The current differencing buffered amplifier is characterized by Eq. (1) [9].

$$\begin{bmatrix} i_z \\ v_w \\ v_p \\ v_n \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_z \\ i_w \\ i_p \\ i_n \end{bmatrix} \tag{1}$$

According to the above matrix equation and equivalent circuit of Figure 1b the current through z-terminal is the difference of the currents through p-terminal and n-terminal, hence, the z-terminal is called current output; p- and n-terminals are noninverting and inverting input terminals, respectively. Since the voltage at the w-terminal

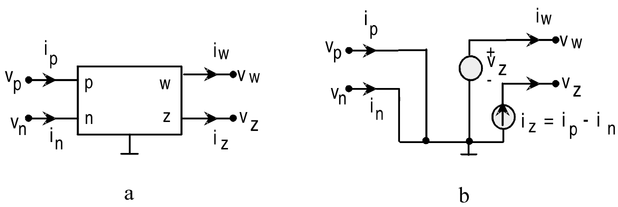

Fig. 1. a) Circuit symbol of CDBA. b) Equivalent circuit of CDBA.

follows the voltage of z-terminal, it is called voltage output. Note that the input terminals, through which i_p and i_n flows, are internally grounded. CDBA can easily be implemented with bipolar and CMOS technologies [9, 10].

3. Proposed filter topology

The current mode filter topology proposed is illustrated in Figure 2. Transfer functions from the input to i_{o1}, i_{o2} and i_{o3} outputs are respectively given by

$$\frac{i_{o1}}{i_{in}} = \frac{\frac{G_2}{C_2}s}{s^2 + \frac{G_1+G_2+G_3}{C_1}s + \frac{G_1G_2}{C_1C_2}} \tag{2}$$

$$\frac{i_{o2}}{i_{in}} = \frac{\frac{G_2G_3}{C_1C_2}}{s^2 + \frac{G_1+G_2+G_3}{C_1}s + \frac{G_1G_2}{C_1C_2}} \tag{3}$$

$$\frac{i_{o3}}{i_{in}} = \frac{s^2 + \frac{G_1+G_2+G_3}{C_1}s}{s^2 + \frac{G_1+G_2+G_3}{C_1}s + \frac{G_1G_2}{C_1C_2}} \tag{4}$$

where the pole frequency and the pole quality factor are defined as

$$\omega_p = \sqrt{\frac{G_1G_2}{C_1C_2}} \tag{5}$$

$$Q_p = \frac{1}{G_1+G_2+G_3}\sqrt{\frac{G_1G_2C_1}{C_2}} \tag{6}$$

From Eqs. (2)–(3) it can be easily observed that the output currents i_{o1} and i_{o2} yield BP and LP filter functions, respectively.

The passive $\omega_p$and Q_p sensitivities are determined as

$$S_{G_1}^{\omega_p} = S_{G_2}^{\omega_p} = 1/2 \qquad S_{G_3}^{\omega_p} = 0$$

$$S_{C_1}^{\omega_p} = S_{C_2}^{\omega_p} = -1/2$$

$$S_{G_1}^{Q_p} = \frac{G_2 - G_1 + G_3}{2(G_1+G_2+G_3)}$$

$$S_{G_2}^{Q_p} = \frac{G_1 - G_2 + G_3}{2(G_1+G_2+G_3)}$$

$$S_{G_3}^{Q_p} = -\frac{G_3}{G_1+G_2+G_3}$$

$$S_{C_1}^{Q_p} = 1/2$$

$$S_{C_2}^{Q_p} = -1/2$$

In this form the circuit represents a dual function filter where Q_p can be adjusted independently. Furthermore, the circuit is easily cascadable and no additional active element is needed to pick-up the signals on the passive elements, since the input of the next stage is grounded.

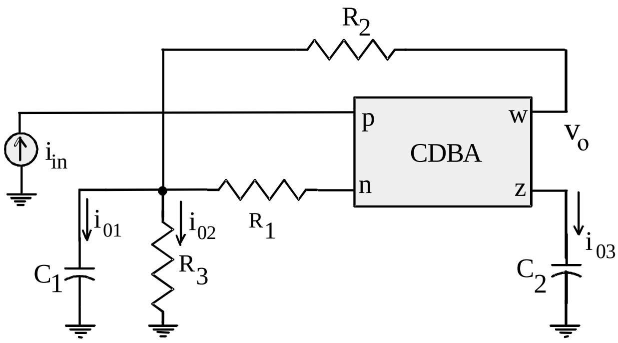

Fig. 2. The proposed filter topology.

In this circuit (Figure 2) the high-pass filter function can be obtained by means of the i_{o3} output. But as it is observed from Eq. (4), the transfer characteristic represents the sum of high-pass and band-pass functions; therefore the HP filter characteristic must be extracted from Eq. (4), which will be described next.

Realization of high-pass filter: To obtain HP characteristic two modifications must be made on the circuit proposed as described below.

The first realization circuit of the HP filter is obtained by subtraction Eq. (2) from Eq. (4) which yields

$$\frac{i_{o3} - i_{o1}}{i_{in}} = \frac{s^2 + \frac{G_1+G_2+G_3}{C_1}s - \frac{G_2}{C_2}s}{s^2 + \frac{G_1+G_2+G_3}{C_1}s + \frac{G_1G_2}{C_1C_2}} \tag{7}$$

As it can be clearly seen from Eq. (7), we get only HP filter characteristic if the coefficients of the s-terms are set equal to each other, which results in the relation between passive components as

$$\frac{C_2}{C_1} = \frac{G_2}{G_1+G_2+G_3} \tag{8}$$

This can be easily achieved by introducing an additional CDBA and applying the currents i_{o3} and i_{o1} to its *p* and *n* inputs, respectively. The resulting circuit is illustrated in Figure 3a.

On the other hand, Eq. (6) gives the relation between the quality factor Q_p and the element values as

$$\frac{C_2}{C_1} = \frac{G_1G_2}{Q_p^2(G_1+G_2+G_3)^2} \tag{9}$$

Combination of Eq. (8) and Eq. (9) yields the condition which must be satisfied by the values of conductances G_1, G_2 and G_3. This condition is given by

$$Q_p^2 = \frac{G_1}{G_1+G_2+G_3} \tag{10}$$

From Eq. (10) it is easiliy observed that this realization of the HP filter is only suitable for low Q applications. Note that there are many parameters and element values to be determined which causes difficulties in the circuit design. To overcome these difficulties, the conditions to be satisfied can be simplifed by choosing $G_3 = 0$ which reduces Eqs. (10) and (9) to

$$Q_p^2 = \frac{G_1}{G_1 + G_2} \tag{11}$$

$$\frac{C_2}{C_1} = \frac{G_1 G_2}{Q_p^2 (G_1 + G_2)^2} \tag{12}$$

with adequate choice of values the desired filter function is obtained.

The second realization circuit of the HP filter: Another simple realization of HP filter is also possible by setting the conductances G_1, G_2 and G_3 equal to each other and adding extra capacitor to the circuit. In this case the quality factor which is given in the Eq. (6) is modified to

$$Q_p = \frac{1}{3}\sqrt{\frac{C_1}{C_2}} \tag{13}$$

which gives the relation between capacitor values as

$$\frac{C_2}{C_1} = \frac{1}{9Q_p^2} \tag{14}$$

On the other hand, similar to Eq. (7), for obtaining HP characteristic subtraction of the BP characteristic from Eq. (4) is necessary which results in

$$\frac{i_{o3} - k i_{o1}}{i_{in}} = \frac{s^2 + \frac{3G}{C_1}s - k\frac{G}{C_2}s}{s^2 + \frac{G_1+G_2+G_3}{C_1}s + \frac{G_1G_2}{C_1C_2}} \tag{15}$$

where k is a multiplier satisfying the condition

$$k = \frac{3C_2}{C_1} = \frac{1}{3Q_p^2} \tag{16}$$

This can be provided by splitting the capacitor into two components such as

$$C_{1A} = kC_1$$
$$C_{1B} = (1-k)C_1 \tag{17}$$

and injecting the current through the C_{1A} to the n input of the second CBDA in Figure 3a while the capacitor C_{1B} is a grounded capacitor. Note that $C_1 = C_{1A} + C_{1B}$. The resulting circuit is illustrated in Figure 3b. The circuit is similar to the circuit of Figure 3a. Note that the HP realization circuit of Figure 3b is more suitable than Figure 3a for high-Q applications in expense of large component spread due to the flexibility provided by the multiplier k.

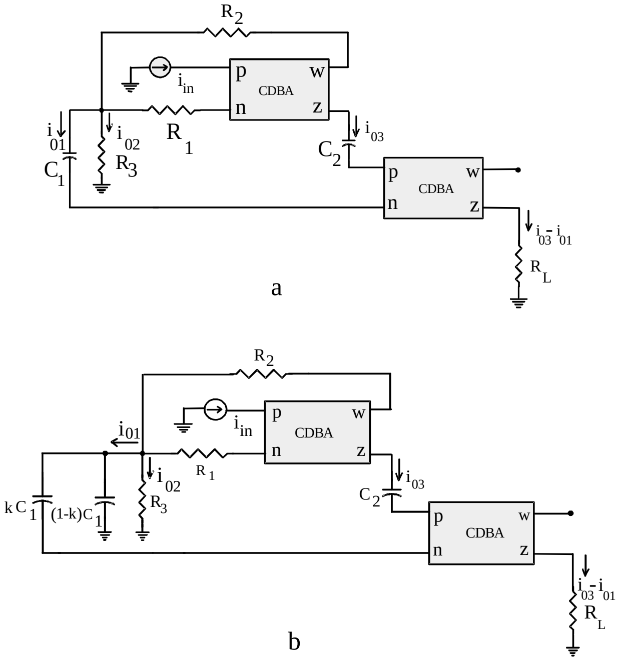

Fig. 3. Realization of HP circuits a) First realization, Eqs. (7)–(12). b) Second realization, Eqs. (13)–(17).

4. Influence of the non-idealities

In case of non-ideal CDBA voltage and current tracking-errors arising from the active element can seriously influence the circuit behaviour. It is necessary therefore to give the effect of the non-idealites on the circuit performance. Including the voltage and current tracking errors the current differencing buffered amplifier is characterized by Eq. (1) [9, 10].

$$\begin{bmatrix} i_z \\ v_w \\ v_p \\ v_n \end{bmatrix} = \begin{bmatrix} 0 & 0 & a_p & -a_n \\ b & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_z \\ i_w \\ i_p \\ i_n \end{bmatrix} \tag{18}$$

where a_p and a_n are the tracking coefficients for i_p and i_n, respectively; b represents the voltage tracking coefficient. Including these non-idealites into the transfer function the pole frequency and the pole quality factor are modified as follows.

$$\omega_p = \sqrt{\frac{a_n b G_1 G_2}{C_1 C_2}} \tag{19}$$

$$Q_p = \frac{1}{G_1 + G_2 + G_3}\sqrt{\frac{a_n b G_1 G_2 C_1}{C_2}} \tag{20}$$

The active sensitivities are calculated as

$$S_{a_n}^{\omega_p} = S_{b_n}^{\omega_p} = 1/2$$
$$S_{a_n}^{Q_p} = S_{b_n}^{Q_p} = 1/2$$

5. Experimental verification

The performance of the circuit is tested experimentally by using the bipolar realization of the CDBA shown in Figure 4 consisting of two CFOAs, namely AD844 of Analog Devices. The supply voltages were taken as $V_{CC} = +12$ V and $V_{EE} = -12$ V. The elements values were chosen as

$$R_1 = 1\,\text{k},\ R_2 = 1\,\text{k},\ R_3 = 1\,\text{k},\ C_1 = 4.5\,\text{nF},\ C_2 = 1\,\text{nF}$$

which results in an universal filter with a pole frequency of $f_p = 100$ kHz and with a quality factor of $Q_P = 0.707$. To obtain HP filter characteristic the k coefficient is calculated as $k = 1/3\,Q_p^2$. For $Q_P = 0.707$, k is obtained as $k = 2/3$. As a result, the capacitance values of C_{1A} and C_{1B} are obtained as $C_{1A} = k\ C_1 = 2/3 \times 4.5\,\text{nF} = 3\,\text{nF}$ and $C_{1B} = (1-k)\ C_1 = 1/3 \times 4.5\,\text{nF} = 1.5\,\text{nF}$.

The resulting frequency characteristics obtained from experiments are illustrated with ideal frequency responses in Figure 5. It can be easily observed from Figure 5 that the frequency response of the proposed filter is in good agreement with theoretical ideal results in the operating region. The deviation in the actual bandpass and highpass characteristics at low-frequencies is caused by the finite output impedances of the active elements. The limited band-widths of CDBA result in the deviations from the ideal filter frequency responses at high frequencies.

From Figure 3 it is obvious that the HP output can be also obtained from the low-impedance w terminal of the second CDBA. Note that the currents i_{o1} and i_{o2} realising BP and LP filters can be similarly picked-up and obtained at an low-impedance output by the use of an additional CDBA.

The dependence of the output signal level on the load resistance R_L is determined experimentally and illustrated in Figure 6. Note that signal amplitude increase linearly with increasing load resistance and signal amplitudes up to 10 V is possible at the output for appropriate resistance values.

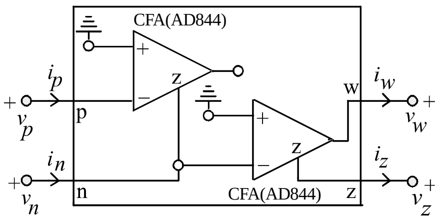

Fig. 4. Realization of CDBA with CFOAs of AD844.

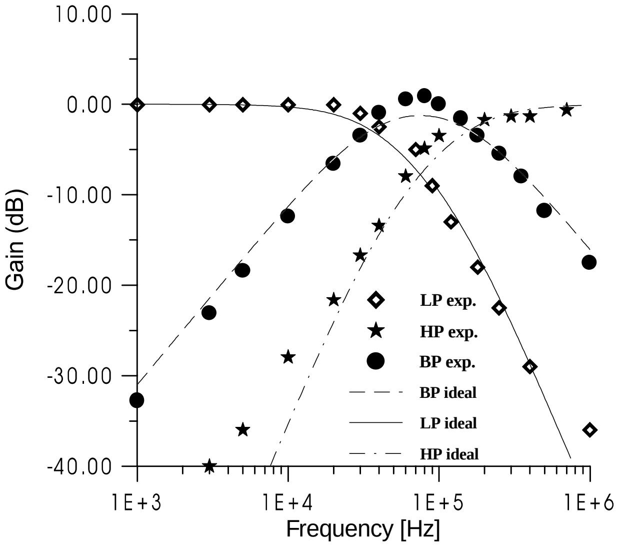

Fig. 5. Theoretical and experimental frequency response of proposed filter topology.

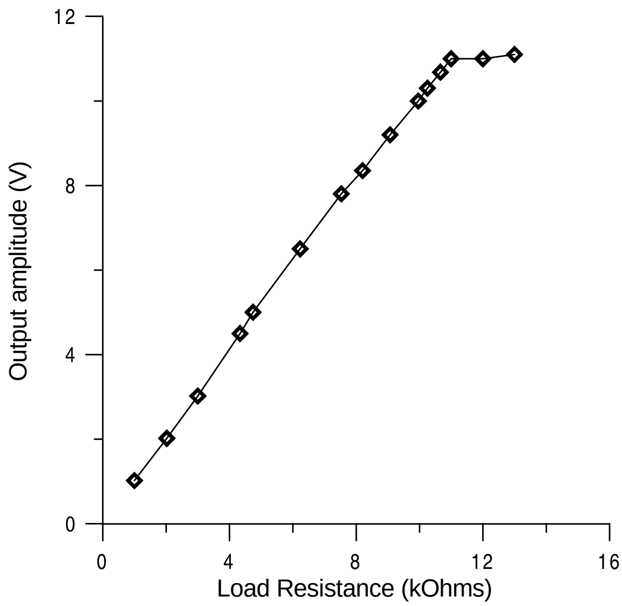

Fig. 6. Dependence of the output voltage at z-terminal of CDBA2 on the load resistance R_L for a sinusoidal 100 kHz input signal of 1000 µA.

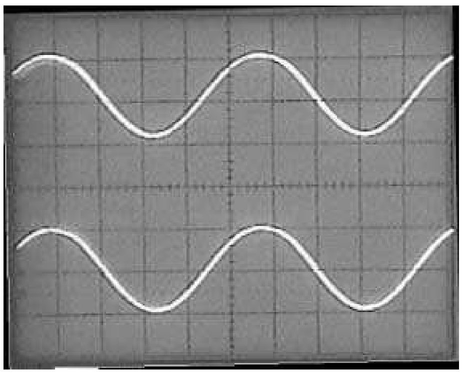

Fig. 7. Output waveforms for a sinusoidal 100 kHz input signal of 1000 µA and for a load resistance of $R_L = 10$ kOhm. Lower trace w-output, upper trace z-output (voltages) of CDBA2. Vert.: 10 V/div, Hor.: 2 µs/div.

The large signal behaviour of the circuit is demonstrated by applying an input signal amplitude of 1000 μA and picking-up the current i_{o1} realizing BP filter with a second CDBA. The resulting output waveform obtained at z and w outputs for a load resistance of $R_L = 10\,k\Omega$ is shown in Figure 7. The results prove that the circuit operates even at larger signal levels of the order of 1000 μA properly. Note that w-terminal provides a low impedance BP output which is a further advantage provided by the circuit. From Figure 7 it is obvious that a maximum output swing of 20 V_{PP} is possible even at a frequency of 100 kHz.

The maximum value of the input signal I_{in} depends on the realization topology of CDBA and can be increased by appropriate design of the active element which results in an improved large signal behaviour. The CFOA-based realization of the CDBA used for the experiments exhibits an input resistance value of 64.65 Ohm and an input capacitance value of 4.6 pF for p and n terminals; the output resistance and capacitance of the z-terminal are specified as $R_z = 2.2$ MOhms and $C_z = 5.5$ pF. The output resistance of the w-terminal is determined as $R_W = 15$ Ohm. The related capacitance to the w terminal exhibits very low values and can be easily neglected. To reduce the influence of the device parameters and the load impedance on the circuit behaviour, wideband and high impedance building blocks for the realization of the z terminal and low impedance structures for the realization of the input stages can be used in the design of high performance CDBA topologies.

A design example of a fourth-order Butterworth BP filter with a center frequency of $f = 100$ kHz is chosen to demonstrate that the proposed filter topology can be easily cascaded by connecting the terminal of the corresponding element to the input of the next stage. The filter is realized by cascading two similar topologies illustrated in Figure 2. The pole frequencies and the pole quality factors of the first and second stages are specified as $f_{p1} = f_{p2} = 100$ kHz, $Q_{p1} = 1.315$ and $Q_{p2} = 0.543$, respectively. All of the resistance values are taken as 1 kΩ. For the specified pole frequencies and pole quality factors the capacitance values are calculated as $C_{11} = 6.3$ nF, $C_{21} = 403$ pF for the first stage and $C_{12} = 2.59$ nF, $C_{22} = 977$ pF for the second stage. The cascade connection is provided simply by connecting the lower terminal of the capacitor C_{11} of the first stage to the input of the second stage. The CDBAs are realized again with CFOAs (AD844 of Analog Devices) as shown in Figure 4 and supplied with symmetrical voltages of ±12 V. SPICE simulation results are given in Figure 8 with the ideal frequency response of the 4th. order Butterworth filter. It can be observed from Figure 8 that the performance of the actual circuit is in good agreement with the ideal presponse which demonstrates clearly that two similar stages can be easily cascaded to achieve a high-order filter. The deviations in the passband gain and in the high-frequency region arises from the non-idealites of the active elements and can be overcomed by the adequate design of the CDBAs.

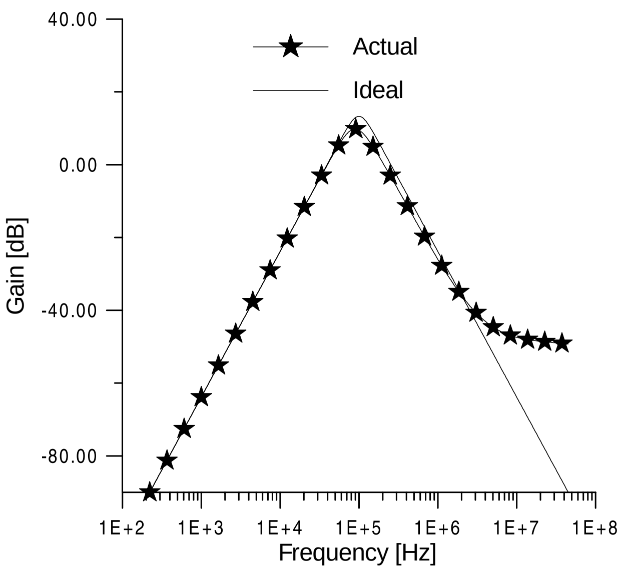

Fig. 8. Frequency responses of ideal and actual fourth-order Butterworth BP filters with a center frequency of $f = 100$ kHz; filters obtained by cascading two biquad sections.

6. Conclusion

In this paper a new CDBA based multipurpose filter is presented. The basic filter cell is a dual-function filter realizing LP and BP transfer functions. For this realization no element matching is necessary. The filter permits independent adjustment of Q exhibits low input impedance and a good large signal behaviour. Due to the low input impedance provided by the active element, CDBA, the proposed filter topology can be easily cascaded by connecting the terminal of the corresponding element to the input of the next filter stage. The passive ω_o and Q sensitivities are shown to be low. Using an additional CDBA and matching conditions, the realization of a HP filter is also possible. Due to current-mode operation large output swings even at high frequencies is possible. Furthermore, the LP and BP filter functions can be picked-up and obtained at low-impedance output by the use of an additional CDBA, similar to HP filter.

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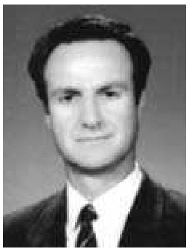

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