Response to Michael Kiwanuka's "Current Feedback and Voltage Feedback Fallacies" as appearing in *AudioXpress,* June 2017

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In the above article, it appears that Michael Kiwanuka's pretension is to dismantle a well-established three-decade analysis of current-feedback amplifiers (CFAs). We cannot help but view this as wrong. In contrast to this MK position, an example of the analysis he contests is outlined within the ISCAS invited paper "Analytical Foundations of Current-Feedback Amplifiers," below, referenced for convenience. **[R1]** We substantiate our claims on the basis of the following points 1) -5) enumerated below:

> 1) The analysis provided in **[R2]** below (Ref [1] of the MK article) starts out with the simplifying assumption that the voltage buffer appearing across the CFA's inputs be ideal. (Reference is made here to resistances R1 and R2 of Figure 1 within the MK article, on page 33). So, if you ground the CFA's noninverting input, break the loop at the CFA's output, and inject a test signal into the feedback network to see what comes back to the CFA's inverting input, you see just a current; no voltage is fed back. This is due to the current being injected into a node of zero impedance. In other words, the input buffer keeps the CFA's inverting input fixed at 0 V, for all current levels. So, you can only refer to this state of affairs as "current feedback". Hardly any "fallacy" here.
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> 2) Next, if one turns to the more realistic case in which the input buffer exhibits non-zero output impedance (r_E in MK's notation), then of course there will be also some nonzero voltage feedback at the CFA's inverting input. The IC CFA designer strives to keep r_E as low as possible, so as to approach idealized current-feedback operation. So, it stands to reason to continue referring to the amplifier as a CFA type, and analyzing it as such. This has formed the basis of countless successful applications over the last three decades, so MK's claim that this analysis is fallacious is plain wrong. References **[R1 - R3]** support this. See the additional bibliography **[B1 - B12]** on CFAs, below. While not all-inclusive, this follows a rough developmental timeline.

3) In his "Conclusion," MK claims that his analysis holds "irrespective of the workings of the internal circuitry". Ironically, this can readily be shown to be fallacious. (Reference again to MK's Figure 1). In fact, it is precisely the unique CFA circuit topology that accounts for its distinguishing features:

- Fast dynamics, due largely to the *current-on-demand* behavior of the CFA input stage. This feature essentially removes slewing limitations due to finite tail current, as is typified by a voltage feedback amplifier (VFA). The CFA will provide small-signal response to input signals over a broader dynamic range than will a VFA, for comparable drive conditions. This absence of slew-rate limiting makes the CFA a good candidate for low-THD applications (such as audio). In fact, the good linearity of the CFA architecture allows low distortion for both video and audio applications. Low CFA video differential gain and phase operation was an early performance hallmark.

- CFAs perform with relatively constant closed loop bandwidth, regardless of closed loop gain. Intuitively, one can say that R1 and Ceq form an R-C network in which the current drawn by R1 is not supplied to Ceq directly, but rather through the inherently fast current-processing current mirrors. So, the dynamics of the CFA are specified in terms of the time-constant tau = R1 * Ceq in the time domain, and by the closed-loop bandwidth of 1/(2 * pi * tau) in the frequency domain. This implies a number of things that MK's dismissal of the internal workings fails to point out.

    (a) In application, the CFA user selects feedback resistor R1 to fix the CFA's dynamics, as consistent with device recommendations. Note that since R1 determines bandwidth, it should not deviate far from the nominal.

    (b) The CFA user then selects resistor R2 to set the desired closed-loop gain. R1 and R2 work together, according to the relation below, under point 5).

    (c) With R1 in the k-Ohm range and Ceq in the pF range, tau is in the ns range, implying a typical rise-time of 2.2 * tau. This equates to a few ns, providing a bandwidth on the order of 100 MHz.

4) Equation (1) of the article is wrong, as it implies [V] = {[Ohms]/[Ohms]} * [A], or [V] = [A], which is dimensionally impossible. MK does a disservice to Ref **[R2]** by claiming it is the origin of this equation. *This is simply not true.*

> ***Update of July 11, 2017:*** *As originally printed, the article included an incorrect Equation (1), which the above analysis addresses. At the urging of this document's authors, AudioXpress has subsequently fixed this expression, as shown in this errata note. (Note that within this expression the "//" should be interpreted as in parallel).*

5) Equation (2), based on wrong premises, gives absurd results. For instance, at dc (s = 0), it gives, in the idealized limit of r_E tending to zero,

$$A_V = Req/(R1 \parallel R2)$$

instead of the well-known and correct result for voltage gain,

$$A_V = 1 + R1/R2.$$

Evidently MK doesn't bother to either check the dimensionality of his equations, or to verify well-known limits. Yet, he aims to subvert well-accepted and successfully applied analyses, and *AudioXpress* publishes his claims without bothering to verify how preposterous they are.

CFA References:

[R1] S. Franco, "Analytical Foundations of Current-Feedback Amplifiers", **IEEE International Symposium on Circuits and Systems,** 1993. (Download Link:)

[R2] Sergio Franco, **Design With Operational Amplifiers and Analog Integrated Circuits, 4th Ed.,** McGraw-Hill, 2014.

[R3] Walt Jung (Editor), **Op Amp Applications**, Analog Devices Seminar Notes, ISBN-0-916550-26-5). (Download Link:)

CFA Bibliography References:

[B1] R. H. Baker, "The Diamond Circuit", **ISSCC Digest**, February 1963, pp. 80, 81

[B2] R. H. Baker, "Gatable Bridge Network Having Power Gain", **US Patent 3,302,039,** Filed February 17, 1964, Issued January 31, 1967.

[B3] David A. Nelson, "Wideband Feedback Amplifier", **US Patent 4,628,279,** filed December 26, 1985, granted December 9, 1986.

[B4] David A. Nelson, “Settling Time Reduction in Wide-Band Direct-Coupled Transistor Amplifiers,” **US Patent 4,502,020**, Filed October 26, 1983, Issued February 26, 1985.

[B5] Comlinear Corporation, "A New Approach to Op Amp Design", **Application Note 300-1**, March 1985.

[B6] Wyn Palmer, Barry Hilton, “A 500 V/µs 12-Bit Transimpedance Amplifier,” **ISSCC Digest**, February 1987, pp. 176–177, 386.

[B7] David Potson "Current Feedback Op Amp Applications Circuit Guide", **National Semiconductor OA-07,** May, 1988. (Download Link Rev C:)

[B8] “Op Amps Combine Superb DC Precision and Fast Settling,” **Analog Dialogue**, Vol. 22, No. 2, pp. 12–15.

[B9] Barry Harvey, "Practical Current Feedback Amplifier Design Considerations", **Intersil Application Note AN1106,** March 24, 1998. (Download Link) see also, "Take Advantage of Current-Feedback Amps for High-Frequency Gain, *EDN*, March 18, 1993.

[B10] Elantec, "EL2020 Data Sheet", ©1989. (Download Link Rev G:)

[B11] Elantec, "EL2003 Data Sheet", Rev. F, September 1998.

[B12] Sergio Franco, "Current-Feedback Amplifiers Benefit High-Speed Designs", *EDN*, January 5, 1989. See also, Sergio Franco, “Current-Feedback Amplifiers,” Chapter 25 within *Analog Circuit Design*, Jim Williams, Butterworth-Heinemann, 1991.