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TRANSCONDUCTANCE FEEDBACK AMPLIFIERS

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Abstract. Gain-bandwidth independence over a wide range of voltage gain levels is available by employing feedback around a transconductance amplifying element in place of a voltage amplifying element. It is shown that only minor changes are required to the architecture of standard 3-stage voltage operational amplifier circuits to obtain all the advantages of this new configuration, which also include improved voltage slew rates, whilst retaining two high-impedance input terminals.

Key words: transconductance amplifier, feedback, gain-bandwidth product, slew rate, operational amplifier architecture.

1. INTRODUCTION

General-purpose voltage operational amplifiers (VOAs) with internal dominant-pole compensation are widely used to obtain voltage gain, but suffer reduced bandwidth at higher gain through the well-known restriction of a constant gain-bandwidth product [1,2]. In contrast, current feedback amplifiers (CFAs) offer constant-bandwidth operation and significantly increased slew rates compared to standard VOA designs, but have not become commercially popular, possibly because of their asymmetrical input terminal impedances and relatively low loop gain due to fewer gain stages [3]. This paper introduces a new kind of operational amplifier, the transconductance feedback amplifier (TFA), in which the normal 3-stage VOA architecture is modified to produce gain-bandwidth independence and improved slew rates, in addition to the standard attributes of two high-impedance input terminals and internal compensation.

2. THEORETICAL

Stabilization of an amplifier's overall transfer function is governed by both the feedback network and the nature of the gain element employed to provide the forward path gain, since it influences the overall pattern of bandwidth behaviour, particularly in regard to source and load sensitivity [4,5]. As there are four possible amplifier target configurations (voltage, current, transimpedance, and transconductance), then employing all four amplifying element types in turn to provide the forward gain results in 16 possible combinations. Examination of loop-gain equations then permits the detailed behaviour of each particular amplifier and feedback network combination to be studied. Focusing on the case of stabilized voltage amplification utilizing feedback via the familiar potential divider arrangement of R_1 and R_2, (Fig. 1), results in the four cases listed in Table 1 for the four different types of amplifying element. The term G_V represents the asymptotic closed-loop voltage gain at high loop gain, given by $1+R_2/R_1$ in all four cases.

Table 1. Bandwidth behaviour for different amplifying element types when configured as voltage amplifiers

Active element	Loop gain	Bandwidth	Input resistance
VCVS	A_V/G_V	GBP constant	High
CCCS	A_i	BW always constant	Low
CCVS	A_Ω/R_2	BW potentially constant	Low
VCCS	$A_s R_1$	BW potentially constant	High

We see from Table 1 that employing a voltage-controlled voltage source (VCVS) as the active gain element results in the well-known combination of a loop gain involving the inverse of the demanded closed-loop gain G_V, thus producing a constant gain-bandwidth product. Adopting a current-controlled current source (CCCS) as the amplifying element has previously been shown to generate a constant loop gain and a constant bandwidth, but at the expense of modest input impedance due to the necessarily low input impedance of the

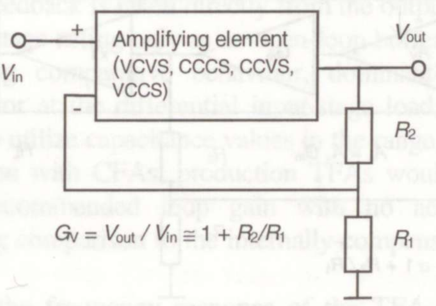

Fig. 1. Stabilized voltage gain using different amplifying elements.

current amplifying element [6]. In general, either input or output impedance levels will be mismatched for constant-loop-gain operation and so require input or output buffers. Input matching is preferable, as additional circuitry at the input will adversely affect noise performance, whereas output buffers operate at higher signal levels and detract less from overall performance. Of the remaining two cases (current-controlled voltage source CCVS and voltage-controlled current source VCCS), both will give rise to gain-bandwidth independence when one of the gain-defining component values is held constant to produce a constant loop gain. However, adoption of a VCCS active element will result in a much higher input impedance, making it an ideal formulation for a constant-bandwidth voltage amplifier. A similar approach using a current amplifying element in a transimpedance configuration to achieve gain-bandwidth independence through to the microwave region was recently reported by the author [5].

Figure 2 illustrates how the basic structure of the TFA maps directly onto a standard 3-stage VOA architecture, in which the differential input stage and single-ended second stage together provide the required transconductance gain. For a transconductance gain A_s between input and feedback connection, the closed-loop voltage gain G_V of the configuration will be

$$G_V = \frac{\text{Forward gain}}{1+\text{Loop gain}} = \frac{A_s(R_1+R_2)}{1+A_s R_1} \cong \frac{R_1+R_2}{R_1}, \tag{1}$$

for high loop gain, given by $A_s R_1$. Keeping R_1 constant and defining closed-loop voltage gain by varying R_2 will therefore result in constant loop gain and hence gain-bandwidth independence. Unlike a CFA, the new connection presents two high-impedance input terminals and functions by generating a truly constant loop gain without introducing variable input attenuation [7].

Constant-loop-gain amplifiers differ from constant gain-bandwidth-product amplifiers in respect of their forward gain behaviour. As shown in Fig. 3, the level of forward gain $A_s(R_1+R_2)$ increases to accommodate the higher

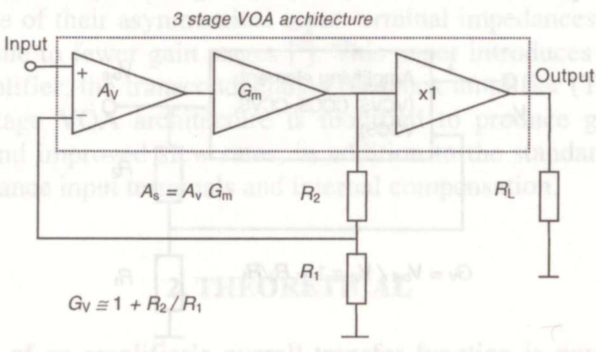

Fig. 2. Voltage amplifier configured from a transconductance amplifying element.

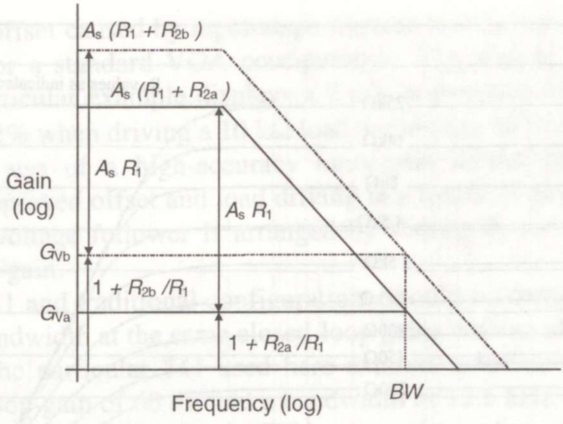

Fig. 3. Gain levels in a constant-loop-gain amplifier.

demanded closed-loop gain, leaving the loop gain $A_s R_1$ constant. As a consequence, the overall 3 dB bandwidth *BW* remains constant as long as elevated values of gain-defining resistors and parasitic capacitance at the feedback node do not form a limiting secondary pole, causing reversion to a constant gain-bandwidth product for *further* gain increase.

As closed-loop stability is determined by loop-gain behaviour, the new configuration is advantageous in that only the (lower) level of loop gain itself needs to be dominant-pole compensated, rather than the whole of the available forward gain, as for the traditional configuration. This avoids over-compensation at low gains and permits the TFA loop-gain breakpoint to be set at a much higher frequency than otherwise, requiring a smaller compensation capacitance and also producing a significantly increased slew rate.

3. CIRCUIT SIMULATION

The new TFA has been investigated by 'SPICE' simulation using a standard 741 VOA circuit model [8], but with an updated symmetrical output stage for improved offset performance. Feedback is taken directly from the output of the 2nd stage, with the unity-gain output stage acting only as an open-loop buffer to isolate the load. For purposes of exploring comparative behaviour, dominant-pole compensation is provided by a capacitor at the differential input-stage load, whereas final designs would be optimized to utilize capacitance values in the range available in monolithic fabrication. In common with CFAs, production TFAs would have pre-determined compensation and recommended loop gain with no access to compensation components, validating comparison to the internally-compensated 741 from which it is directly derived.

Figure 4a shows the frequency response of the TFA-connected 741 with a low-frequency loop gain set at 55 dB ($R_1 = 250\,\Omega$) driving a load of 1 kΩ in

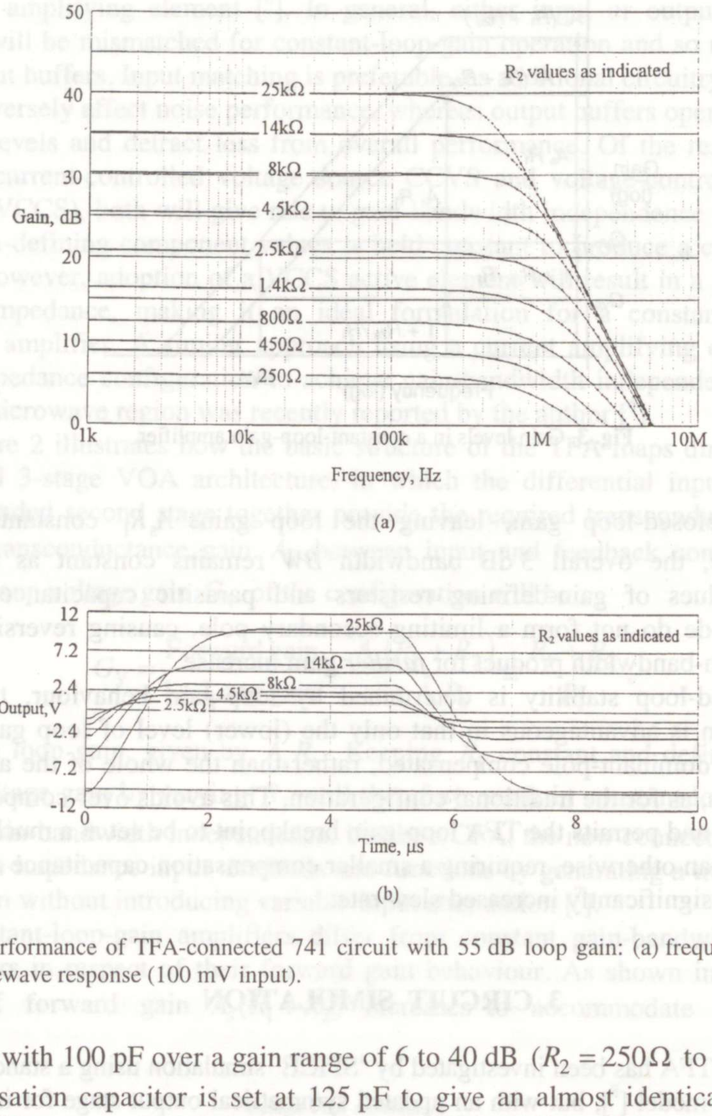

Fig. 4. Performance of TFA-connected 741 circuit with 55 dB loop gain: (a) frequency response; (b) squarewave response (100 mV input).

parallel with 100 pF over a gain range of 6 to 40 dB ($R_2 = 250\Omega$ to 25 kΩ). The compensation capacitor is set at 125 pF to give an almost identical unity-gain bandwidth to a standard 741. We see that the TFA-741's 3 dB bandwidth remains very close to 1 MHz up to gains of 30 dB, beyond which it becomes influenced by the feedback-node pole and starts to revert back to constant gain-bandwidth-product operation. At a gain of 40 dB the new configuration has a 3 dB bandwidth of 400 kHz, in contrast to a 741 circuit in conventional mode, which displays a bandwidth of only 12.5 kHz at this level of gain, but with a very slightly greater loop gain. Figure 4b shows the well-controlled transient response, where the output swings through 20 V in 2 μs with a maximum slew rate of 12 V/μs, a twentyfold improvement over the very same devices and circuit when employed as a standard 741. Operation in the inverting mode produces substantially similar performance.

Output DC offset caused by input-stage mismatch is nulled out in exactly the same way as for a standard VOA configuration. The simple open-loop buffer used in this particular example displays a 2 mV zero-signal offset coupled to a gain error of 0.2% when driving a 10 kΩ load, increasing to 1% for a 250 Ω load, suggesting the use of a high-accuracy unity-gain output buffer with 100% feedback for improved offset and load driving in a finalized design. Operation of the TFA as a voltage follower is arranged by setting R_2 to zero, with R_1 still setting the loop-gain.

The TFA-741 and traditional configurations should be compared on the basis of operating bandwidth at the same closed-loop gains with an identical loop-gain. For example, the particular 741 used here exhibits a forward gain of 100 dB, resulting in a loop-gain of 60 dB and a bandwidth of 12.5 kHz when operating at a closed loop gain of 40 dB. For the TFA connection, when setting an identical loop-gain (LG) of 60 dB the dominant pole will be at 800 Hz (effective compensation capacitance of 325 pF), resulting in a bandwidth for 40 dB closed-loop gain of 350 kHz, as shown in Table 2.

Table 2. Performance comparison for new TFA topology and standard VOA

Gain, dB	Bandwidth, kHz		
	TFA-741 40 dB LG	TFA-741 60 dB LG	Standard 741
40	800	350	12.5
35	1200	480	20
30	2300	570	35
26	3500	650	60
21	4600	700	100
17	5000	700	150
12	5000	700	250
9	5000	700	350
6	5000	700	550

Reducing the TFA loop gain to 40 dB (compensation capacitance 6 pF) results in a low-gain bandwidth of 5 MHz (limited by the 741 secondary poles), contracting to 800 kHz at a gain of 40 dB and 85 kHz at 60 dB closed-loop gain, in contrast to the standard 741 circuit which can only achieve a bandwidth of 12.5 kHz under identical conditions of 60 dB gain with 40 dB loop gain. An additional consequence of the TFA configuration is that the whole of the loop gain is available for feedback action up to a much higher frequency than the standard configuration under identical conditions; here 800 Hz for 60 dB loop gain, as against typically 5 Hz for a 741.

4. CONCLUSIONS

Configuring a standard VOA as a TFA results in both gain-bandwidth independence and increased slew-rates from the very same devices and an otherwise identical design. For example, the new TFA-741 produces a bandwidth of 350 kHz for a closed-loop gain of 40 dB and loop gain of 60 dB, dramatically outperforming the standard VOA-741 which only returns a bandwidth of 12.5 kHz under identical conditions. The new approach offers significant opportunities for upgrading many classical operational amplifier designs.

REFERENCES

1. Franco, S. Analytical foundations of current-feedback amplifiers. In *IEEE International Symposium on Circuits and Systems*. Chicago, 1993, 1050–1053.
2. Harvey, B. Current-feedback opamp limitations: State of the art review. In *IEEE International Symposium on Circuits and Systems*. Chicago, 1993, 1066–1069.
3. Bowers, D. F. The so-called current-feedback operational amplifier – technological breakthrough or engineering curiosity. In *IEEE International Symposium on Circuits and Systems*. Chicago, 1993, 1054–1057.
4. Payne, A. and Toumazou, C. Analog amplifiers: Classification and generalisation. *IEEE Trans. Circuits Syst.I*, 1996, **43**, 1, 43–50.
5. Wilson, B. and Drew, J. D. Transimpedance formulation exhibits gain-bandwidth independence at microwave frequencies. *Electron. Lett.*, 1997, **33**, 5, 410–411.
6. Allen, P. E. and Terry, M. B. The use of current amplifiers for high performance voltage applications. *IEEE J. Solid-State Circuits*, 1980, **SC-15**, 2, 155–162.
7. Bruun, E. Feedback analysis of a transimpedance operational amplifier. *IEEE Trans. Circuits Syst.I*, 1993, **CAS-40**, 4, 275–278.
8. Gray, P. R. and Meyer, R. G. *Analysis and Design of Analog Integrated Circuits. 3rd ed.* J. Wiley, New York, 1993, Chapter 7.

TAGASISIDEGA LÄBIJUHTIVUSVÕIMENDID

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Võimendi ribalaiuse sõltumatus võimendusest laias võimendusdiapasoonis on realiseeritav tagasiside rakendamisega pingevõimenduselemendi asemel läbijuhtivuselemendile. On näidatud, et vaid väikesed muudatused standardse kolmeastmelise pingevõimendi lülituse arhitektuuris võimaldavad ära kasutada uue struktuuri kõiki eeliseid, kaasa arvatud suuremat väljundpinge muutumise kiirust, säilitades samas kaks kõrgeoomilist sisendterminali.