increased by the application of any degree of feedback. This may well be due to parasitic effects or internal resonances caused by input and output impedance mismatches due to the additional circuitry.

**Feedforward system simulated results: A comparison by simulation of the two gain response control methods applied within an octave-band feedforward network yielded the results shown in Fig. 2. The network was designed to operate over the frequency range 1–2GHz. Measured S-parameters of all subcomponents were used in the simulation to provide meaningful results. It can be seen here that direct RF feedback offers better performance in both of the primary network parameters of gain and distortion suppression. Taking 20-dB distortion suppression as our benchmark, isolated-zero gain compensation offers around 42% bandwidth at 1.4GHz whereas direct RF feedback offers 98% bandwidth at 1.7GHz (nearly three octaves). The applicability of the feedforward technique to octave-band linearisation has been demonstrated and work is currently underway to implement this simulated hardware.**

**Conclusion:** The applicability of the feedforward technique to octave-band amplifier linearisation has been demonstrated by simulation based on measured sub-component S-parameters.

The components within an octave bandwidth feedforward network must be controlled to exhibit wideband gain flatness and linear phase. Two methods of amplifier transfer characteristic control were discussed, linear compensation and direct RF feedback. The result of the application of the latter to an MMIC amplifier is presented showing that careful design can increase stationarity whilst maintaining feedback stability margin.

The two amplifier control methods have been compared within the context of an octave-band feedforward linearisation network. Direct RF feedback is shown to offer better performance in both of the primary network parameters — gain and linearity.

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**References**


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**n-scroll chaos generators: a simple circuit model**

M.E. Yağcı, S. Özoğuz, J.A.K. Suykens and J. Vandewalle

n-scroll attractors which are generated from a generalised and simple circuit model are presented. The nonlinear characteristics can be systematically designed by adding comparators. A 5-scroll attractor circuit realisation is shown, which has been experimentally verified using current feedback opamps.

**Introduction:** The use of chaotic signals in communications has recently attracted much interest. An important part in chaos-based analogue/digital communications systems [1] is the choice of the chaotic oscillator. Chua’s circuit [2] is probably the most well-known and commonly used chaotic oscillator in this field. Among the many generalisations of Chua’s circuit, more complicated attractors have been proposed by Suykens and Vandewalle [3] by introducing additional breakpoints in the nonlinearity of Chua’s circuit, leading to so-called n-scroll scroll attractors. A more complex family of n-scroll instead of n-scroll scroll attractors has been obtained from a generalised Chua’s circuit reported in [4]. Experimental confirmations of 2-scroll scroll and 5-scroll scroll attractors have been given in [5, 6], respectively. The same generalisation idea has been applied to the so-called hyperchaotic attractors proposed by Yağcı, Suykens and Vandewalle [7].

The design of chaos generators has received considerable attention and a novel and simple model for chaos generation has recently been proposed [8]. A double scroll-like attractor has been observed from this circuit. In this Letter, we show how the simple model proposed in [8] can be generalised to generate n-scroll attractors in a somewhat similar fashion as the original Chua’s circuit has been generalised to obtain such a family of attractors.

Because of the well-known advantages of the current feedback opamps (CFOAs) over the conventional opamps, i.e. much higher slew rates and constant bandwidth almost independent of the gain, researchers have attempted to use CFOAs in the implementation of chaotic oscillators to improve high-frequency performance, e.g. [9, 10]. As a possible implementation of the proposed generalised model, we present a circuit, the core of which is implemented using CFOAs.

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**Fig. 1 Simulation of 8-scroll attractor**

*a* 8-scroll attractor (*N* = 4, *M* = 4, *α* = 0.4)  
b Nonlinearity f(x)

**Chaos generator with hard limiter and its generalisation:** The following chaos generator with hard limiter has been proposed [8]

\[
\dot{x} = \begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1 \\
-a & -a & -a \\
\end{bmatrix} x + \begin{bmatrix}
0 \\
0 \\
1 \\
\end{bmatrix} f(x_1)
\]

\[
f(x_1) = \begin{cases}
1 & x_1 \geq 0 \\
1 & x_1 < 0 \\
\end{cases}
\]

where \(x \in \mathbb{R}^3\). It has been observed that the proposed model (eqn. 1) exhibits a double-scroll-like attractor by setting \(a = 0.8\).

In this Letter, the main idea is to modify the nonlinear characteristic \(f(x_1)\) into

\[
f(x_1) = \sum_{i=1}^{N} a_i f_m(x_1) + \sum_{j=1}^{M} b_j (f_m(x_j) - 1)
\]

where

\[
f_m(x_1) = \begin{cases}
1 & x_1 \geq m \\
0 & x_1 < m \\
\end{cases}
\]

and \(N, M\) denote natural numbers, and

\[
a_i = \begin{cases}
1 & i = 1 \\
2 & i > 1 \\
\end{cases} \\
b_j = \begin{cases}
1 & j = 1 \\
2 & j > 1 \\
\end{cases} \\
p_i = 2(i - 1) \\
n_j = -2(j - 1)
\]

In [8], the special case of \(N = 1, M = 1\) has been investigated for this generalised characteristic. In the generalised nonlinearity, the core function \(f_m()\) is a comparator which is a useful aspect for circuit realisation. The set of equilibrium points of the generalised system is given by \(-2M+1, ..., -2j+1, ..., -1, 1, ..., 2-1, ..., 2N-1\). The Jacobian matrices evaluated at each of these equilibrium points are the same. The scrolls are located around these equilibrium positions and the number of scrolls generated from the gen-
eralised nonlinearity is equal to $N + M$. A computer simulation for the 8-scroll attractor is shown in Fig. 1, corresponding to $N = 4$, $M = 4$, $a = 0.4$.

![CFOA-based Chaotic Oscillator](image1)

**Fig. 2 CFOA-based chaotic oscillator**

be verified that the circuit realises eqns. 1 and 2 for $M = 3$ and $N = 2$. Using this circuit, the 5-scroll attractor can be observed. It should be noted that systematic generation of a higher number of scrolls is possible by using additional comparators.

The circuit in Fig. 2 is verified experimentally using the commercial CFOA, AD844 [11] supplied under ±10 V and LM331 type comparators. The passive component values have been chosen as $R_1 = R_2 = 1k\Omega$, $R_3 = 1.9k\Omega$ corresponding to $a = 0.53$, $R_{d1} = 2R_{d2} = 2R_{d3} = 2R_{d4} = 15k\Omega$, $C_1 = C_2 = C_3 = 1nF$ and also $V_{CC}$ is taken as 10V. The controlling voltages at the comparators’ non-inverting inputs, i.e. $V_{R1}$ and $V_{R2}$, are taken as adjustable. The observed $(V_{R1}, V_{R2})$ trajectory corresponding to the $(x_1, x_2(x_N))$ trajectory from which a 5-scroll attractor can be observed is shown in Fig. 3.

**Conclusion:** We have introduced a generalisation of a simple circuit model for double-scroll-like chaos generation, which results into more complicated n-scroll attractors. A circuit realisation has been made using CFOAs, which is expected to offer a good high-frequency performance.

**Acknowledgments:** This research work was carried out at the ESAT laboratory and the Interdisciplinary Center of Neural Networks of the Katholieke Universiteit Leuven, in the framework of the the Belgian Programme on Interuniversity Poles of Attraction, initiated by the Belgian State, Prime Minister’s Office for Science, Technology and Culture (IUAP P4-02), the Concerted Action Project MEFISTO of the Flemish Community and ESPRIT IV 27077 (DICTAM). J. Suykens is a postdoctoral researcher with the National Fund for Scientific Research FWO, Flanders.

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