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Low-Distortion, Low-Noise Composite Operational Amplifier

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A composite operational amplifier is presented that is optimized for building low frequency ($\leqslant$ 100 kHz) signal paths with very low distortion and noise. It consists of a cascade of two monolithic operational amplifiers and additional RC components for frequency compensation. The open-loop response is designed for conditional stability, such that a very large gain-bandwidth product at signal frequencies can be achieved. This leads to very good distortion performance in the audio frequency range. A numerical optimization procedure is introduced that is used to derive the frequency compensation, based on specific stability criteria. Monte Carlo simulation results are presented that estimate the worst case deviation from the nominal stability margins. Measurement results confirm the predicted high gain-bandwidth product (10 GHz at 100 kHz) and excellent distortion performance (< -180 dB). Furthermore application notes considering various implementation issues such as large-signal stability are given. Applications for the new composite operational amplifier include, e.g., audio frequency distortion measurement equipment.

0 INTRODUCTION

There are two fundamental limitations to the dynamic range achievable for a signal path: noise and distortion. Noise sets a lower, and distortion an upper, limit for the processible signal level. Reducing noise below a certain limit is impractical because of cost, complexity, and power consumption. Hence it is desirable to improve the distortion performance of a signal path in order to achieve higher dynamic range.

An application of particular interest to the authors is harmonic distortion (THD) and total harmonic distortion and noise (THD+N) instrumentation circuitry at audio frequencies. In state-of-the-art implementations a single amplifier stage may be required to provide a THD figure of better than -140 dB for a 5 V_{RMS}, 20 kHz signal in order to support a total instrument dynamic range of 120 dB in a 80 kHz measurement bandwidth. Currently it is not possible to achieve this performance level using available commercial monolithic operational amplifiers in a standard configuration. Audio recording, processing or playback equipment claiming particularly high performance may also demand unusually low distortion and noise not achieved by monolithic amplifiers.

A particularly authoritative approach to improve the distortion performance is to merge two (or sometimes even more) operational amplifiers—usually one with low noise and the other with high speed—in one amplifier stage. Such topologies are typically called *composite operational amplifiers* as the combination of the standard amplifiers effectively forms a new self-contained operational amplifier (with two input and one output terminal). Usually they employ a higher order, conditionally stable open-loop response that allows for a very high gain-bandwidth product at signal frequencies. The improved distortion performance of composite operational amplifiers is a direct result of their increased gain-bandwidth product.

A detailed description of the basic concepts and advantages of composite operational amplifiers is found in [1]. A systematic family of composite operational amplifier topologies, each using two to four individual amplifiers and a number of resistors, is presented in [2] [3]. A special composite operational amplifier topology that uses the offset trim ports of one operational amplifier as summing node to derive the combined amplifier response is shown in [4] [5]. Further approaches are described, for example, in [6] [7].

The composite operational amplifiers presented in the mentioned references all have particular disadvantages that limit their usefulness. More specifically, some are not unity gain stable [1] [2] or degrade the noise performance [2] [7]. Others depend on the availability of trim ports [4] [5], achieve only modest open-loop gain improvement [1] [2] or have high complexity [7].

The novel composite operational amplifier presented in this paper is unity gain stable and avoids any significant

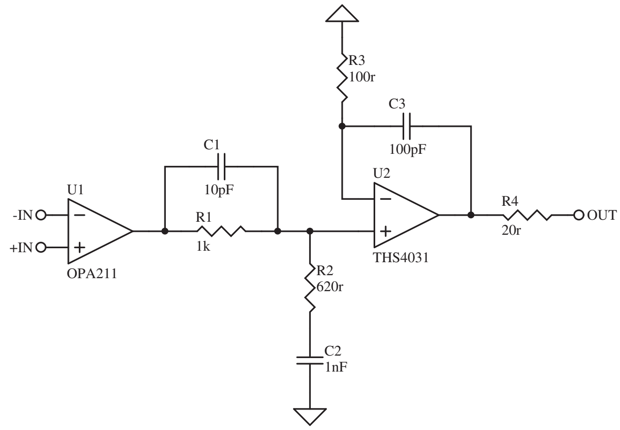

Fig. 1. Proposed composite operational amplifier.

degradation of the noise performance. Furthermore, it attains very high open-loop gain und thus very low distortion at modest circuit complexity.

In Sec. 1 the basic topology is described. Secs. 2 and 3 deal with the compensation to achieve unity gain stability. Subsequently some measurement results are shown (Sec. 4). In Sec. 5 a few application notes for the novel composite operational amplifier are given.

1 CIRCUIT DESCRIPTION

The proposed composite operational amplifier consists of a cascade of two monolithic operational amplifiers (OPA211 [8] and THS4031 [9]) as shown in Fig. 1. The first operational amplifier U_1 is a precision type that offers very low voltage noise (1.1 nV/$\sqrt{\text{Hz}}$ typical at 1 kHz) along with low offset and drift ($\pm$125 μV and $\pm$1.5 μV/°C maximum for the standard grade). The operational amplifier of the second amplifier stage (U_2) is a high-speed type. It provides high slew-rate (100 V/μs typical), unity gain frequency (about 170 MHz), and output current ($\pm$90 mA typical) while still operating on $\pm$15 V supplies.

Between these two amplifiers a compensation network (R_1, R_2, C_1, and C_2) is arranged. It consists of a passive lead-lag network and is used to shape the high-frequency open-loop response to provide unity gain stability. The second operational amplifier U_2 is configured with a frequency-selective feedback network (R_3 and C_3). This network effects that the second amplifier operates as follower at high frequencies. Thus the second amplifier stage degrades the phase margin as little as possible. At signal frequencies, it provides additional open-loop gain that improves the distortion performance of the overall composite operational amplifier.

R_4 is used to isolate capacitive loading from the local feedback loop of U_2. Due to the high bandwidth of U_2, the local feedback loop is much more sensitive to capacitive loading than the feedback loop of the overall composite amplifier. Including R_4 within the overall feedback loop has the advantage of minimizing the wiring at the output of U_2.

At signal frequencies where the attenuation of the lead-lag compensation network is insignificant, it is easily seen that the input referred characteristics (in particular noise) of the second operational amplifier U_2 are reduced by the open-loop gain of U_1 and thus not significant. In turn, the output related characteristics (such as large signal bandwidth) of the first amplifier U_1 are improved because the additional gain provided by the second amplifier stage reduces the output voltage swing of U_1.

2 FREQUENCY COMPENSATION

The implementation of a composite operational amplifier with the presented topology requires the dimensioning of six passive components for frequency compensation. This parameter set can be represented by four time constants ($\tau_1 = R_1C_1$, $\tau_2 = R_2C_2$, $\tau_3 = R_3C_3$, $\tau_{12} = R_1C_2$) and two impedance levels (e.g., by fixing R_1 and R_3). Analytical modelling of this dimensioning problem is difficult because there appears to be no simple solution for the optimum. Hence a heuristic approach is followed. Also it was found that available simulation models for the used operational amplifiers are usually not accurate enough to serve as basis for the design process. Thus it must be based on actual measurement data. Furthermore, the component values are discretized by the choice of standard part values (typically the E6 series for the capacitors and the E24 series for the resistors). Resulting rounding errors were found to be significant and must thus be taken into account. Therefore a numerical routine is used to dimension the component values.

For further discussion we define the following quantities:

- $H_{U_1}(s)$, the open-loop response of U_1;
- $H_{U_2}^{[\mathrm{CL}]}(s)$, the closed-loop response of U_2 in a unity gain follower configuration;
- $H_{CN}(s)$, the transfer function of the compensation network.

$H_{U_1}(s)$ and $H_{U_2}^{[\mathrm{CL}]}(s)$ can be measured, while the transfer function of the compensation network is given by:

$$H_{CN}(s) = \frac{(1 + s\tau_1)(1 + s\tau_2)}{(1 + s\tau_1)(1 + s\tau_2) + s\tau_{12}}. \tag{1}$$

By neglecting the finite DC gain and finite input and output impedances of the amplifiers the open-loop response of the overall composite operational amplifier is then approximated by:

$$H_{COA}(s) \approx H_{U_1}(s)H_{CN}(s)H_{U_2}^{[\mathrm{CL}]}(s)\left(1 + \frac{1}{s\tau_3}\right). \tag{2}$$

The presented composite operational amplifier achieves its exemplary performance mainly because of the additional open-loop gain provided by the second amplifier stage. Besides ensuring sufficient stability margins, the dimensioning of the passive components should thus also maximize the overall open-loop gain $|H_{COA}(s)|$. However, it is not clear at which frequency the open-loop gain shall be maximized;

while the context of a particular application may suggest a specific optimization frequency, a more general approach is desired. This was found in the following optimization criterion:

$$\arg\max_{\tau_1,\tau_2,\tau_3,\tau_{12}} f_c(\tau_1, \tau_2, \tau_3, \tau_{12}), \tag{3}$$

where f_c is the crossover frequency at which the composite operational amplifier has the same open-loop gain as U_1 (i.e., where f_c satisfies $|H_{COA}(2\pi \boldsymbol{i} f_c)| = |H_{U_1}(2\pi \boldsymbol{i} f_c)|$). In essence Eq. (3) states that the overall composite operational amplifier should have higher open-loop gain than U_1 at the highest possible frequency. At frequencies below f_c, the benefit of additional loop gain sets in. Maximizing f_c thus extends the frequency range with improved performance as much as possible.

To guarantee sufficient stability margins, a boundary condition for the above maximization problem is necessary. Usually, stability margins of an operational amplifier are characterized at two points only, namely the phase and gain margin. This Bode stability criterion is only applicable to systems with restricting additional properties. These are not necessarily fulfilled for the more complex transfer function of the composite operational amplifier with its higher degrees of freedom. Degenerated and potentially instable cases (e.g., where the open-loop gain crosses unity multiple times) were found when using such a simple two-point stability model. Also it was desired to widen the frequency range with sufficient phase margin around the unity open-loop gain frequency to lower the sensitivity to component tolerances.

Such a more robust approach was found by the use of a stability function F_s. This function defines the minimum required phase margin for all frequencies where the open loop gain is near unity as follows:

$$F_s(|H_{COA}(2\pi \boldsymbol{i} f)|) \leq \pi + arg(H_{COA}(2\pi \boldsymbol{i} f)) \quad \forall f : A_{min} \leq |H_{COA}(2\pi \boldsymbol{i} f)| \leq A_{max}, \tag{4}$$

where A_{min} and A_{max} define the minimum and maximum open loop gain where the stability function is applied.

For the design of the presented composite operational amplifier a second order polynomial is used for F_s with coefficients that are determined by fitting it to three points. The fitting points are 45° phase margin at +6 dB, 70° phase margin at 0 dB, and 0° phase margin at −8 dB open-loop gain. The second and third points correspond to the traditional phase and gain margin specifications. A_{max} is set to the amplitude of the first, and A_{min} to the amplitude of the last fitting point.

An additional boundary condition was found beneficial to avoid solutions where the attenuation of the compensation network is excessive:

$$\alpha \frac{1}{2\pi\tau_3} \leq f_0, \tag{5}$$

with f_0 the unity open-loop gain of the composite operational amplifier and $\alpha > 1$ a heuristically chosen constant. Values of $\alpha = 3$ were found suitable. This boundary condition prevents that the second amplifier stage applies significant gain near the unity open-loop gain frequency, which would need to be compensated by increased attenuation of the compensation network.

The optimization problem as stated by Eqs. (3), (4), and (5) shows many local maxima. To estimate the global maximum evaluation over a set of input intervals is required. The following intervals were empirically found suitable:

$$\tau_1 \in \left[\frac{0.1}{2\pi\hat{f}_0}, \frac{10}{2\pi\hat{f}_0}\right];$$
$$\tau_2 \in \left[\frac{1}{2\pi\hat{f}_0}, \frac{100}{2\pi\hat{f}_0}\right];$$
$$\tau_3 \in \left[\frac{2\alpha}{2\pi\hat{f}_0}, \frac{20\alpha}{2\pi\hat{f}_0}\right];$$
$$\tau_{12} \in \left[\frac{\hat{A}_0}{2\pi\hat{f}_0}, \frac{100\hat{A}_0}{2\pi\hat{f}_0}\right], \tag{6}$$

where $\hat{f}_0$ is an estimate of the unity gain frequency of the composite operational amplifier:

$$\hat{f}_0 : \pi + arg(H_{U_1}(2\pi \boldsymbol{i} \hat{f}_0) H_{U_2}^{[CL]}(2\pi \boldsymbol{i} \hat{f}_0)) = F_s(1) \tag{7}$$

and

$$\hat{A}_0 = \left| H_{U_1}(2\pi \boldsymbol{i} \hat{f}_0) H_{U_2}^{[CL]}(2\pi \boldsymbol{i} \hat{f}_0) \right|. \tag{8}$$

The optimization problem is solved for all suitable combinations of E6 (capacitor) and E24 (resistor) values, where the corresponding time constant falls within the intervals given by Eq. (6). The resulting optimum component values are those shown in Fig. 1.

3 SENSITIVITY ANALYSIS

To estimate the sensitivity of the open loop response and thus stability margins to component tolerances Monte Carlo simulation was used. With common tolerances for discrete resistors (1%) and capacitors (5%) their contribution to deviations from the nominal open loop response was found to be insignificant. The influence of the operational amplifier gain-bandwidth product is substantially higher, but also more difficult to predict quantitatively because of the absence of detailed statistical manufacturing data. For the THS4031, a minimum (100 MHz) and typical (120 MHz) figure is quoted in the data sheet [9]. As there is no data available for the OPA211, we estimated that the expected deviation is in a similar range. A worst case deviation of 30% was finally chosen for the Monte Carlo simulation in order to conservatively estimate the effects. The resulting maximum gain deviation at 30 MHz (the nominal unity gain bandwidth) was found to be −3.6 dB and +2.6 dB. The worst case phase deviation at the same frequency is +5.7° and −6.6° respectively. These figures are sufficiently low to not cause stability problems and allow for temperature and aging effects, which can be expected to be lower than the initial tolerances.

The gain-bandwidth product of the monolithic operational amplifiers is also dependent on the power supply voltage. By comparing measurements of the open loop response with ±5 V and ±15 V supplies it was found that

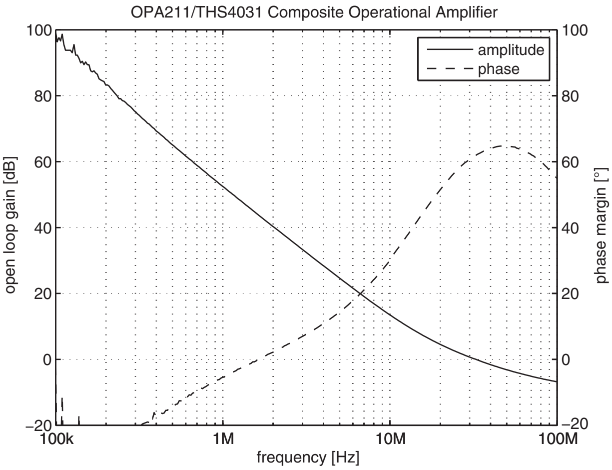

Fig. 2. Measured open-loop gain for the proposed composite operational amplifier.

these effects are negligible for the presented composite operational amplifier.

4 MEASUREMENT RESULTS

Fig. 2 depicts the measured open-loop gain and phase of the presented composite operational amplifier. At unity gain, the phase margin is larger than 60°. At 100 kHz the open-loop gain is 100 dB, corresponding to a gain-bandwidth product of 10 GHz. This is two orders of magnitude higher than for either U_1 or U_2 alone. Below 100 kHz, the open-loop gain is not directly measurable with the setup available to the authors (based on a Hewlett Packard 4195A network analyzer) but is expected to increase considerably above 100 dB.

Fig. 3 demonstrates the distortion performance of the novel composite operational amplifier. Shown is the spectral magnitude of the input-referred harmonic distortion voltage at 10 kHz for an inverting configuration at 7.746 V_{RMS} (+20 dBu) output level into a 600 Ω load.[1] It can be seen that the distortion improvement is presumably more than three orders of magnitude, with the harmonics not resolvable in the noise floor for the composite operational amplifier. This represents a very significant step in the state of the art of low distortion amplification.

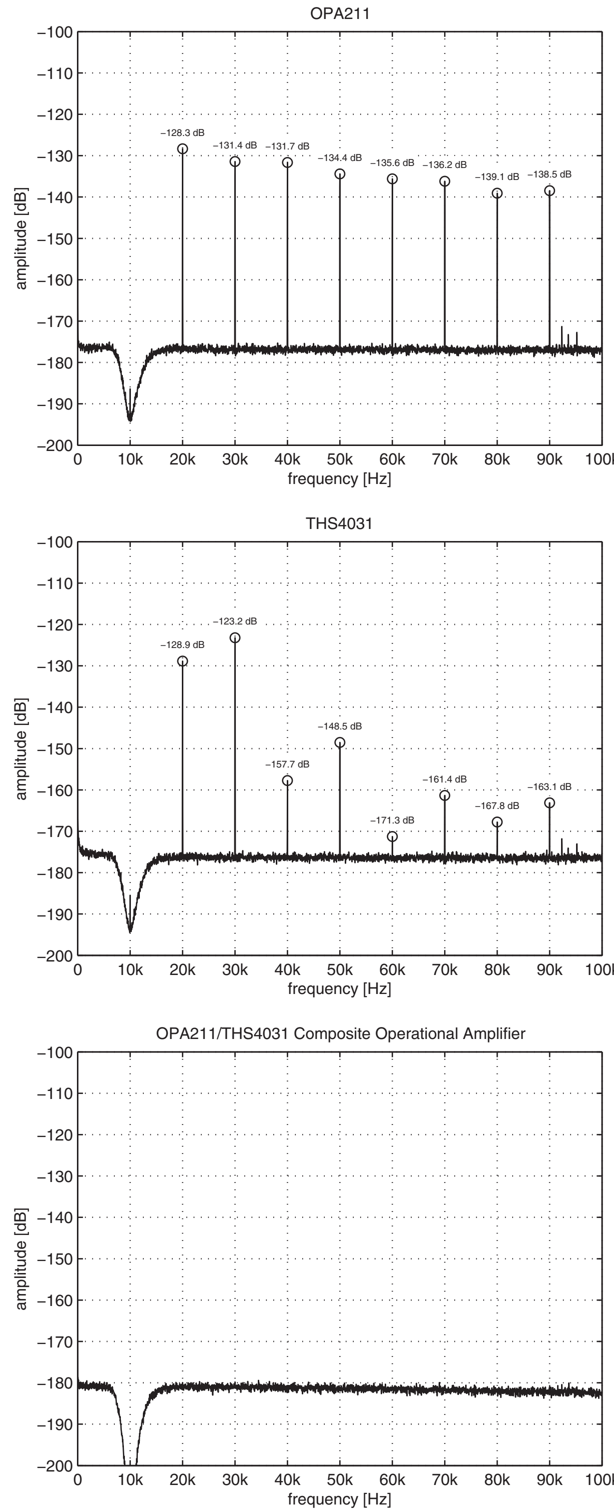

Fig. 3. Measured input-referred harmonic distortion voltage at 10 kHz for the OPA211, THS4031, and resulting composite operational amplifier.

5 APPLICATION NOTES

While the presented composite operational amplifier easily provides a significant distortion performance

[1]The used distortion analyzers (Audio Precision SYS-2722) is limited to about −120 dB usable resolution at a 10 kHz fundamental frequency. Thus it is necessary to operate the operational amplifier under test at high noise gain. For the single operational amplifiers a noise gain of 40 dB was used, whereas for the composite operational amplifier 60 dB was needed to avoid distortion contribution from the analyzer. The different noise gain configurations result in slightly different noise contribution from the feedback network, which is seen in the spectral magnitude plots. Note that this measurement method has reduced sensitivity to distortion from nonlinear amplifier input currents. These should be negligible for inverting configurations, and all other distortion mechanisms attributable to the amplifier directly are accurately captured.

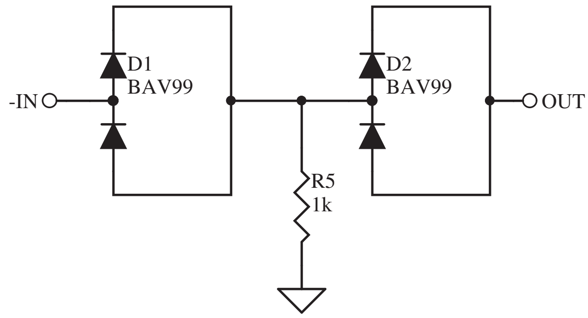

Fig. 4. Clamping network connected to U_1.

improvement over standard amplifiers, it has some pitfalls that must be taken into account.

First and foremost, it should be appreciated that the novel composite operational amplifier is conditionally stable only. Sufficient phase margin is (except at very low frequencies) only available near the unity open-loop gain frequency. The composite operational amplifier must thus be operated with a unity loop gain frequency close to the unity open-loop gain frequency. In many cases this implies the use of an additional feedback capacitor instead of a purely resistive feedback network. Large-signal overload conditions such as output voltage clipping, output current limiting or slew-rate limiting can trigger instability. Similar effects may occur during power-up and power-down.

This behavior can be considerably improved by clamping the output voltage of U_1 to a few hundred millivolts. Without clamping, the output of U_1 may rise to either supply voltage during overload conditions. The finite slew-rate of U_1 then causes a long overload recovery time that may trigger relaxation-type oscillation. For a noninverting amplifier configuration, possible implementations include the network shown in Fig. 4. It is connected from U_1 inverting input to U_1 output. As at signal frequencies and under normal operating levels the voltage swing at the output of U_1 is very low, this clamping circuit does not add significant distortion.

In order to realize the potential distortion performance of the presented composite operational amplifier, attention to several implementation details is necessary. While U_1 operates with very low output voltage and output current, it may see significant common-mode input voltage swing. The increased open-loop gain of the composite operational amplifier cannot reduce nonlinear input currents resulting from common-mode swing. These will cause significant distortion if the source impedance is high [10]. Therefore amplifier configurations with low common-mode voltage swing (e.g., inverting amplifiers) are recommended wherever possible. Furthermore, distortion injected from power supply ripple should be considered. This mechanism is most effectively avoided by powering U_1 from a separately filtered or regulated power supply. Obviously the feedback network must be built from components with very low voltage and power coefficient. Also extensive attention to layout effects (e.g., mutual inductance to the power supply [11]) is mandatory.

6 CONCLUSION

A unity gain stable composite operational amplifier has been presented. It consists of a cascade of two operational amplifiers, an intermediate compensation network, and a frequency-selective feedback network for the second amplifier. This configuration achieves very high open-loop gain (100 dB at 100 kHz) and thus shows exceptionally good distortion characteristics. Furthermore the noise characteristics of the first operational amplifier is preserved, such that the composite operational amplifier supports the design of signal paths with very high dynamic range.

A numerical optimization procedure is proposed to design the compensation and frequency-selective feedback network for arbitrary operational amplifier combinations. By the use of a boundary condition, sufficient stability margins for the composite operational amplifier are ensured.

Finally, a brief application note covering some stability, large signal, and low distortion implementation considerations is given.

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