

Low Distortion Sine Wave Generator for Analog IC Testing: Harmonics Cancellation, Digital Predistortion and Analog Filter

Student Paper

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With the advent of the IoT era, analog and analog-digital mixed signal (AMS) circuits are becoming increasingly important. Their high-quality mass production tests must be performed at low cost [1-3]. Measurement instruments such as audio analyzers used in bench-top are not suitable for mass production testing due to their high cost and long measurement time. In this paper, a low distortion sine wave generator is investigated for the AMS circuit mass production testing, its three technologies are described.

(i) The first one is its implementation using logic circuits followed by relatively simple analog filter [4]. The circuits cancel HD3 (3rd-order harmonic distortion) and HD5 (5th-order harmonic distortion) by summing multiple rectangular waveforms of fundamental and higher frequencies (Fig. 1). These rectangular waves are generated by dividing the rectangular of 15ω frequency by 15 for ω one, by 5 for 3ω one and by 3 for 5ω one. These are summed by three resistors with weights of 1, $-1/3$ and $-1/5$, respectively. Notice that Fourier series of the rectangular signal with angular frequency of ω is given by Eq. 1. Then the rectangular wave HD3 (shown in Eq. 2) and HD5 (shown in Eq. 3) are cancelled (Eq. 4) and the other higher order odd harmonics can be removed by the following simple analog band-pass filter (BPF). The 15ω frequency rectangular is provided from a digital automatic test equipment (ATE) and the frequency divisions can be realized by simple logic circuits (Fig. 1). We have implemented its prototype with discrete components, and its measurement evaluation shows that it generates a sine wave with harmonics of less than -95 dBc (Fig. 2). Since this circuit is very simple, the low-cost testing system can be realized.

$$V_{\text{rect1}}(t) = \sin(\omega t) + \frac{1}{3}\sin(3\omega t) + \frac{1}{5}\sin(5\omega t) + \frac{1}{7}\sin(7\omega t) + \dots \quad (1)$$

$$V_{\text{rect3}}(t) = \sin(3\omega t) + \frac{1}{3}\sin(9\omega t) + \frac{1}{5}\sin(15\omega t) + \frac{1}{7}\sin(21\omega t) + \dots \quad (2)$$

$$V_{\text{rect5}}(t) = \sin(5\omega t) + \frac{1}{3}\sin(15\omega t) + \frac{1}{5}\sin(25\omega t) + \frac{1}{7}\sin(35\omega t) + \dots \quad (3)$$

$$\begin{aligned} f(t) &= V_{\text{rect1}}(t) - \frac{1}{3}V_{\text{rect3}}(t) - \frac{1}{5}V_{\text{rect5}}(t) \\ &= \sin(\omega t) + \frac{1}{3}\sin(3\omega t) + \frac{1}{5}\sin(5\omega t) + \dots \\ &\quad - \frac{1}{3}[\sin(3\omega t) + \frac{1}{3}\sin(9\omega t) + \frac{1}{5}\sin(15\omega t) + \dots] \\ &\quad - \frac{1}{5}[\sin(5\omega t) + \frac{1}{3}\sin(15\omega t) + \frac{1}{5}\sin(25\omega t) + \dots] \\ &= \sin(\omega t) + \frac{1}{7}\sin(7\omega t) + \frac{1}{11}\sin(11\omega t) + \dots \end{aligned} \quad (4)$$

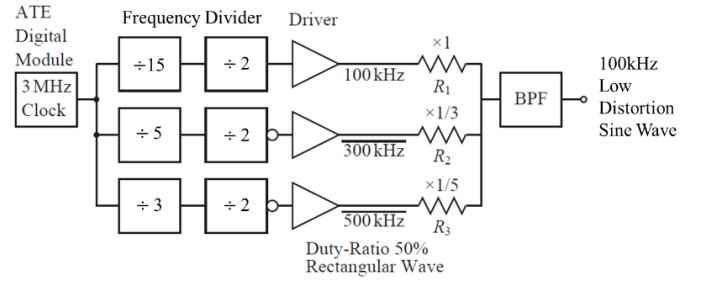


Fig. 1 Investigated low-distortion sine wave generator.

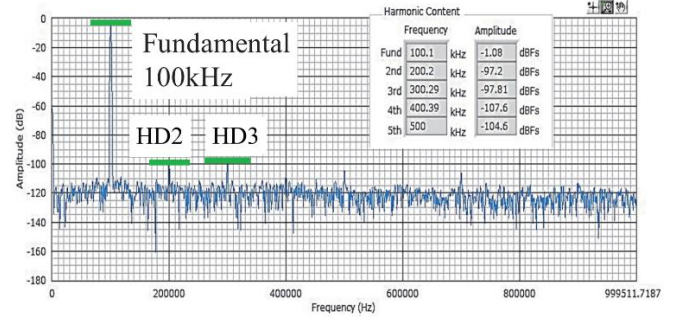


Fig. 2. Measured output power spectrum of the circuit in Fig. 1.

(ii) The second one is the digital predistortion technique to reduce the harmonics further for audio application IC testing. The output of the sine wave generation circuit in Fig. 1 is digitized by a high-resolution ADC and its fundamental and harmonic components are calculated by FFT so that the amplitudes of the second and third harmonics are obtained. The simple direct digital synthesizer generates a two-tone signal with the same amplitudes of the second and third harmonics respectively, but their phase shifts of π respectively. This two-tone signal is added to the sine wave generator output using an instrumentation amplifier and a few resistors. We obtained very low distortion sine wave in simulation and experiment, and further investigation is underway.

(iii) The third one is two design considerations of LCR analog filter design for AMS IC test systems [5]. We investigated an

inductor equivalent series resistance compensation technique. Fig. 3 (a) shows an ideal LCR analog BPF. However, in reality, the inductor L has an ESR. Fig. 3 (b) shows an LCR BPF with the ESR compensation, and Fig. 4 shows its simulation results; Q is enhanced and the gain is attenuated by the proposed ESR compensation. There ESR is cancelled by a negative resistor realized by an operational amplifier and a resistor. These were verified with simulation and measurement results. The other one is the coupling effects of the two inductors; we found in simulation and experiment that mutual inductance between two inductors in the analog filter degrades its stop band characteristics and quality factor (Q), and this problem can be alleviated by the perpendicular placement of the inductors (Fig. 5).

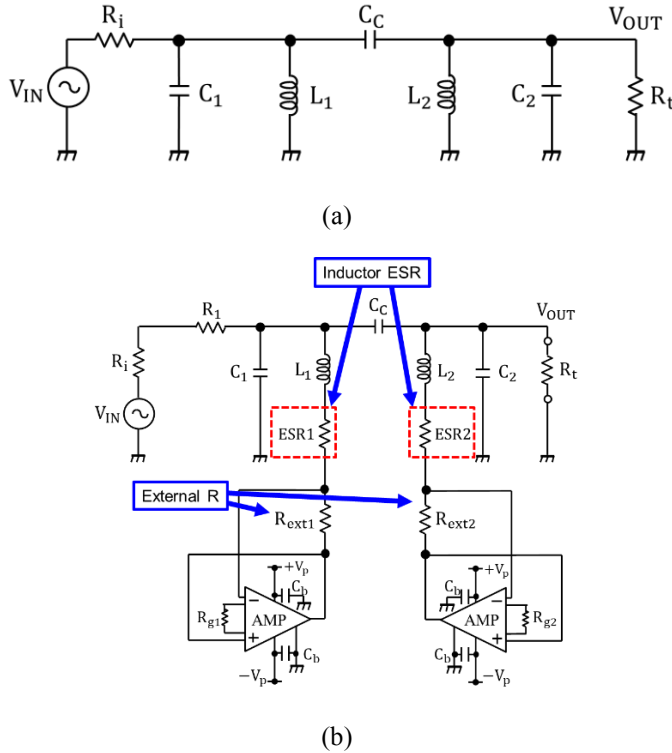


Fig. 3. Analog LCR bandpass filters. (a) Ideal one. (b) With inductor ESR compensation.

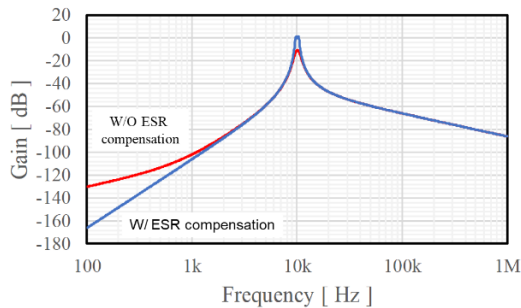


Fig. 4. Simulated BPF gain characteristics with (blue line) and without (red line) the inductor ESR compensation.

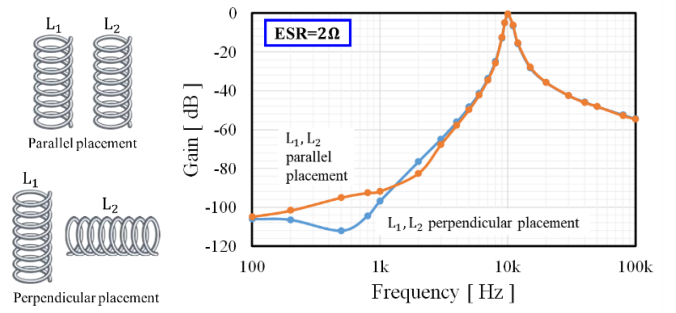


Fig. 5. Measured BPF gain characteristics for L_1 , L_2 perpendicular or parallel placement.

In this paper, we have described a low-distortion sine wave generator for analog device testing application. It can be composed of logic circuits and simple low-order analog filter circuits; expensive high-order filter with special fabrication in [6] is not required. Also an expensive mixed-signal ATE is not required, but only an inexpensive digital ATE is enough. The digital ATE provides a rectangular wave to the proposed sine wave generator where the frequency dividers produce different frequency rectangular waves so that HD3 and HD5 are cancelled and they are summed. Then it passes through a relatively simple analog filter and the low-distortion sine wave is obtained. For further low distortion, the digital predistortion method has been investigated as preliminary experiment, which may be comparable performance to the one described in [7]. We also presented two design considerations of an analog LCR filter implemented with discrete components.

REFERENCES

- [1] G. W. Roberts, *et al.*: *An Introduction to Mixed-Signal IC Test and Measurement*, Second Edition. Oxford University Press (2011).
- [2] G. W. Roberts: "Mixed-Signal ATE Technology and its Impact on Today's Electronic System", IEEE International Test Conference (2016).
- [3] H. Kobavashi, *et al.*: "Analog/Mixed-Signal Circuit Testing Technologies in IoT Era", IEEE 15th International Conference on Solid-State and Integrated Circuit Technology (Nov. 2020).
- [4] S. Katayama, *et al.*: "Low Distortion Sine Wave Generator With Simple Harmonics Cancellation Circuit and Filter for Analog Device Testing" IEICE Electronics Express, vol. 20, Issue 1, Pages 20220470. (Jan. 2023).
- [5] M. Takagi, *et al.*: "Design Consideration for LC Analog Filters: Inductor ESR Compensation, Mutual Inductance Effect and Variable Center Frequency", 8th International Congress on Information and Communication Technology (Feb. 2023)
- [6] T. Komuro, *et al.*: "Total Harmonic Distortion Measurement System for Electronic Devices up to 100MHz with Remarkable Sensitivity", IEEE Trans. on Instrumentation and Measurement, vol. 56, Issue 6, pp. 2360 - 2368 (Dec. 2007).
- [7] G. Castro: "High Performance Source for ADC and Audio Test with Novel Digital Predistortion", ADI Technical Article.