A Novel Distortion Analysis Method for Amplifiers Considering Frequency Characteristics

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ABSTRACT

This paper proposed a novel distortion analysis method for amplifiers considering frequency characteristics. In this method, a frequency-dependent nonlinear amplifier is represented with a model, which consists of a frequency-independent nonlinear amplifier and input/output filters. Time-domain analysis using Single-Carrier method, which uses single-carrier amplitude and phase distortion of an amplifier, is done for the frequency-independent amplifier, and frequency-domain analysis is applied to the filters. We calculate the third-order intermodulation of a GaAs MESFET amplifier with this method and Harmonic Balance method. The results are in good agreement.

INTRODUCTION

For distortion analysis of nonlinear amplifiers, several methods have been reported. Single-Carrier method [1]-[2], which uses single-carrier amplitude (AM-AM) and phase (AM-PM) distortion of an amplifier, has been widely used because of its simplicity and easiness to calculate. However, this method supposes that the bandwidth of the input signal is negligibly narrow compared with the amplifier's bandwidth. Therefore, it is not effective for analyzing distortion of broadband signal, such as multi-carrier or CDMA modulated signals. Volterra Series method [3]-[7] is able to analyze frequency dependent distortion of nonlinear amplifiers, however it became difficult to solve the equations with increasing non-linearity and complexity of modulated signal. Harmonic Balance (HB) method [8] is another method. However it is not power-full tool for broadband signal because of limitation of computational memory and time.

This paper proposed a novel distortion analysis method for amplifiers, which is able to consider frequency dependence of an amplifier. In this method, a frequency-dependent nonlinear amplifier is represented with a model, which consists of a frequency-independent nonlinear amplifier and input/output filters. The filters explain frequency characteristics of the amplifier. Time-domain analysis using Single-Carrier method is done for the frequency-independent amplifier, frequency-domain analysis is applied to the filters. In this method, it becomes possible to calculate a frequency dependent distortion of a nonlinear amplifier with broadband signal such as multi-carrier and CDMA modulated signals.

In the following, we describe the principle of the method. Then, we calculate third-order intermodulation (IM3) of a GaAs MESFET amplifier with this method and HB method in order to verify the effectiveness of the proposed method. Finally, we give the comparison of this method and Volterra Series.

ANALYSIS METHOD

In general, non-linearity of amplifiers is derived from DC characteristics of active devices such as FET and BJT, and frequency characteristics of amplifiers are derived from passive-reactive elements. Therefore, we can suppose that a frequency-dependent nonlinear amplifier (H) is represented with an equivalent circuit which consists of a frequency-independent nonlinear amplifier (G) and input/output filters (A and B) as shown in Fig. 1.

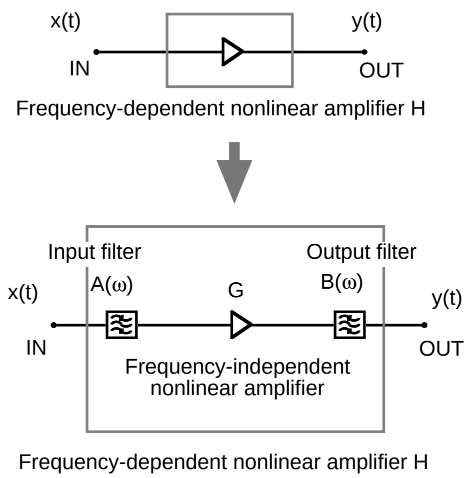

Fig.1 Equivalent circuit of an amplifier

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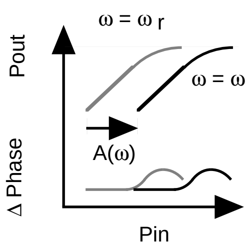
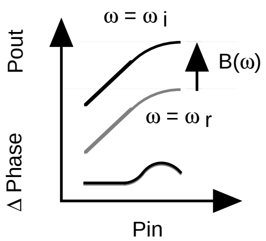
By the way, the frequency-dependent nonlinear amplifier has frequency-dependent AM-AM/PM distortion at each frequency. Fig. 1 means that AM-AM/PM distortion of the amplifier (H) at an arbitrary frequency of ω_i can be represented by the one at the reference frequency of ω_r and values of the filter A (ω) and B (ω) as shown in Fig. 2.

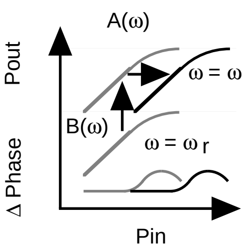
From another viewpoint, if we have data of AM-AM/PM distortion at each frequency, we would treat the amplifier as shown in Fig. 1. First of all, we have to obtain coefficients of A (ω) and B (ω) before calculating distortion of the amplifier. A frequency-dependent nonlinear amplifier has different AM-AM/PM distortion at each frequency. That is, the amplifier has frequency deviation of small-signal gain (Gs), saturated power (Psat) and phase distortion (Δphase). @A(ω) and B(ω) can be given from the frequency deviation of Gs, Psat and Δphase, as shown in the Fig.2.



(a) Only Gs has frequency deviation



(b) Gs and Psat have the same frequency deviation



(c) Gs and Psat have frequency deviation

Fig.2 Frequency deviation of Gs, Psat, and ΔPhase

1) If Gs has frequency deviation and Psat has no frequency deviation, A(ω) can be obtained, as shown in Fig.2 (a).
2) If both Gs and Psat have the same frequency deviation, B(ω) can be obtained, as shown in Fig.2 (b).
3) If both Gs and Psat have frequency deviation, both A(ω) and B(ω) can be obtained, as shown in Fig.2 (c).
We assume that frequency deviation of ΔPhase is corrected by using A(ω) .

Fig. 3 shows a flow chart of the calculation. The input signal is generated in frequency-domain. The frequency-domain output signal of A(ω) is transformed to time-domain signal using Inverse Fast Fourier Transform (IFFT). The signal is input to the nonlinear amplifier (G) and the output signal is calculated applying Single-Carrier method. Furthermore, we obtain the frequency-domain signal with Fast Fourier Transform (FFT). Finally, we calculate distortion from frequency-domain output signal of B (ω).

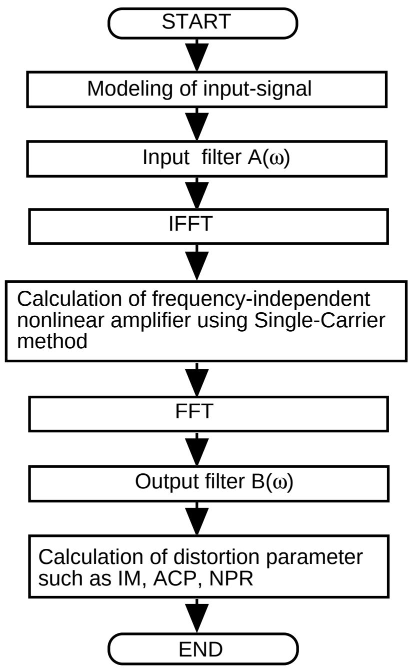


Fig.3 Flow chart of the calculation

SIMULATION RESULT

In this section, we show the effectiveness of the proposed method. The third order intermodulation (IM3) of a GaAs MESFET power amplifier is calculated using the proposed method and the HB method. The results are in good agreement.

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Fig. 4 shows the schematic diagram of the GaAs FET amplifier considered in the simulation. We have obtained calculated data of the single-carrier AM-AM and AM-PM distortion with HB method. The Curtice cubic large-signal FET model was employed in this calculation. Calculated results at ω_i $(i = 1, ..., 5)$ are shown in Fig. 5.

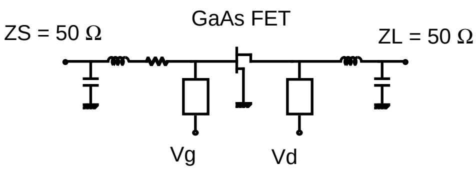

Fig.4 Schematic diagram of the amplifier

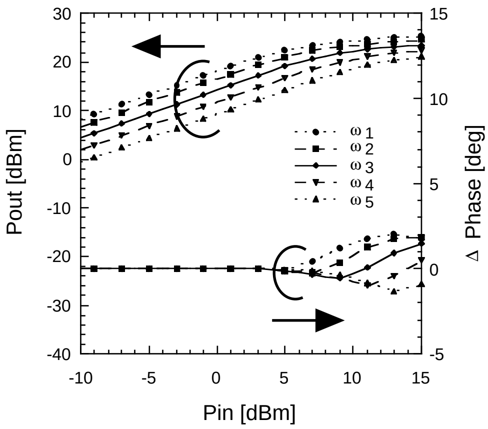

Fig.5 Calculated AM-AM and AM-PM distortion using Harmonic Balance method

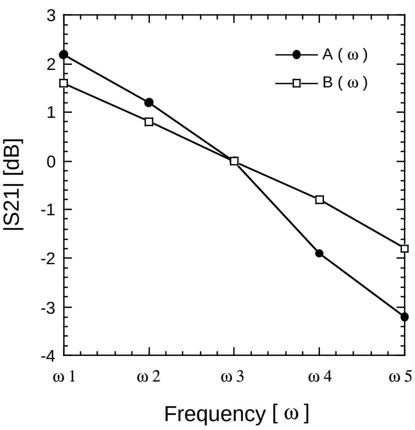

Fig.6 Calculated transmitting characteristics of A(ω) and B(ω)

Filters of A(ω) and B(ω) can be determined by using the technique shown in Fig. 2. The calculated transmitting characteristics of A(ω) and B(ω) are shown in Fig. 6. The frequency of ω_3 is the reference frequency (ω_r) . Frequencies of the input two-tone signals are $\omega_\alpha = (\omega_2 + \omega_3)/2$ and $\omega_\beta = (\omega_3 + \omega_4)/2$. Thus, the third order intermodulation signals (IM3L,IM3H) appear at frequency of $(\omega_1 + \omega_2)/2$ and $(\omega_4 + \omega_5)/2$, respectively. Fig. 7 shows the calculated output power and IM3 of the amplifier using the proposed method and HB method. The HB calculation was done on the circuit of Fig. 4 with two-tone input signal. Calculated results are in good agreement over a wide dynamic range. The effectiveness of the proposed method is verified.

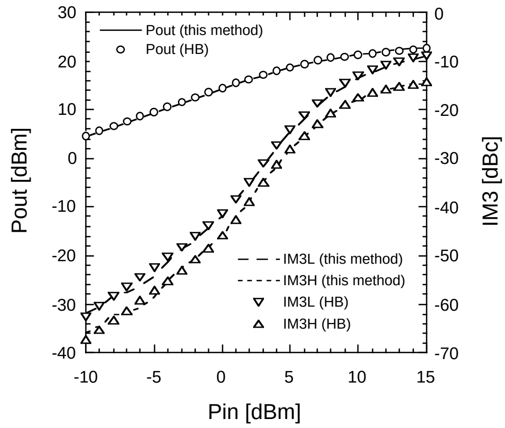

Fig.7 Calculated results of output power and IM3 using the proposed method and HB method

THE COMPARISON OF THE PROPOSED METHOD AND VOLTERRA SERIES

In this section, we consider the comparison of the proposed method and Volterra Series.

If an input signal $x(t)$ has a discrete spectrum, it can be expressed as a sum of sinusoids

$$x(t) = \frac{1}{2} \sum_{a=-p}^{p} X_a \exp(j\omega_a t) \qquad (1)$$

where

$$X_0 = 0, \quad X_{-a} = X_a, \quad \omega_{-a} = -\omega_a \qquad (2)$$

Using Volterra Series representation, the relation between the output signal $y(t)$ and the input signal $x(t)$ in a nonlinear amplifier can be written as

$$y(t) = \sum_{n=1}^{\infty} \frac{1}{2^n} \sum_{a1=-p}^{p} ... \sum_{an=-p}^{p} X_{a1} ... X_{an} H_n(\omega_{a1}, ..., \omega_{an}) \cdot \exp\{j(\omega_{a1} + ... + \omega_{an})t\} \qquad (3)$$

where $H_n(\omega_{a1},...,\omega_{an})$ is the *n*th-order nonlinear transfer function, and both nonlinear and frequency characteristics of the amplifier are shown by this transfer function in Volterra Series.

On the other hand, the approximation assumed in the proposed method can be expressed by a product of a frequency-independent non-linear function and linear functions of input/output signal frequency. Thus, the *n*th-order transfer function of this method can be given by

$$H_n(\omega_{a1},...,\omega_{an}) = G_n(\omega_r)A(\omega_{a1}-\omega_r)...A(\omega_{an}-\omega_r)B(\omega_i-\omega_r) \quad (4)$$

and

$$H_n(-\omega_{a1},...,-\omega_{an}) = H_n^*(\omega_{a1},...,\omega_{an}) \quad (5)$$

where $G_n(\omega_r)$ is the *n*th-order transfer function, $A(\omega_{a1}-\omega_r)...A(\omega_{an}-\omega_r)$ is the transfer functions of input signal frequency (ω_a), and $B(\omega_i-\omega_r)$ is the transfer functions of output signal frequency (ω_i).

In the following, we show that Eq. (4) corresponds to the assumption employed in the proposed method as described in previous section. Substituting Eq. (4) and (5) in (3), output signal at ω_i becomes

$$[y(t)]_{\omega_i} = \sum_{n=1}^{\infty} \frac{1}{2^n} \sum_{(a1)}...\sum_{(an)} X_{a1}...X_{an} \cdot A(\omega_{a1}-\omega_r)...A(\omega_{an}-\omega_r)G_n(\omega_r)B(\omega_i-\omega_r) \cdot \exp\{j(\omega_{a1}+...+\omega_{an})t\} \quad (6)$$

where

$$\omega_{a1}+...+\omega_{an} = \omega_i \quad (7)$$

$$-p \le a1 \le p,...,-p \le an \le p \quad (8)$$

We define the notation of $\sum_{(a1)}...\sum_{(an)}$ as a sum of all terms which satisfy the relation shown in Eq. (7) and (8).

When a single-carrier is input to an amplifier, $y(t)$ can be given by

$$y(t) = B(\omega_i-\omega_r)W \quad (9)$$

where

$$W = G_1(\omega_r)\{X_iA(\omega_i-\omega_r)\} + \frac{3}{4}G_3(\omega_r)\{X_iA(\omega_i-\omega_r)\}^3 + \frac{5}{8}G_5(\omega_r)\{X_iA(\omega_i-\omega_r)\}^5 + ... \quad (10)$$

Then output signal amplitude and phase distortion are obtained

$$|y(t)| = |B(\omega_i-\omega_r)W| \quad (11)$$

$$\angle y(t) - \angle y_{small}(t) = \tan^{-1}\frac{\mathrm{Im}(W)}{\mathrm{Re}(W)} - \tan^{-1}\frac{\mathrm{Im}(W_{small})}{\mathrm{Re}(W_{small})} \quad (12)$$

where $\angle y_{small}(t)$ is the output phase at small-signal level, and W_{small} is the function of W at small-signal level. According to Eq. (9) to (12), we can verify that AM-AM/PM distortion of the amplifier (H) at ω_i can be given by AM-AM/PM distortion of the amplifier (G) and values of A(ω_i), B(ω_i).

CONCLUSION

This paper proposes a novel distortion analysis method for amplifiers considering frequency characteristics. In this method, a frequency-dependent nonlinear amplifier is represented with a model, which consists of a frequency-independent nonlinear amplifier and input/output filters. Time-domain analysis using Single-Carrier method is done for the frequency-independent amplifier, and frequency-domain analysis is applied to the filters. We calculate the third-order intermodulation of a GaAs MESFET amplifier with this method and HB method. The calculated results are in good agreement over a wide dynamic range, and the effectiveness of the proposed method is verified. Finally, we give the comparison of the proposed method and Volterra Series.

REFERENCES

[1] T. Sasaki and H. Hataoka, "An Analysis of Intermodulation Distortion in UHF Amplifiers", *Journal of Television Engineers of Japan*, vol.24, no.12, pp.958-964, Dec. 1970.

[2] T. Takagi, S. Ogura, Y. Ikeda and N. Suematsu, "Intermodulation and Noise Power Ratio Analysis of Multiple-Carrier Amplifiers Using Discrete Fourier Transform", *IEICE Trans. Electron*, vol. E77-C, no.6, pp.935-941, June 1994.

[3] R. J. Westcott, "Investigation of multiple f.m./f.d.m. carriers through a satellite t.w.t. operating near to saturation", *Proc. IEE*, vol.114, no.6, pp.726-740, June 1967.

[4] T. Sasaki and H. Hataoka, "An Analysis of Intermodulation Distortion in Frequency Dependent UHF Amplifiers", *Trans. IEICE*, vol.55-B, no.10, pp.539-548, Oct. 1972.

[5] T. Nojima and Y. Okamoto, "Analysis and Compensation of TWT Nonlinearities Based on Complex Power Series Representation", *Trans. IEICE*, vol.J64-B, no.12, pp.1449-1456, Dec. 1981.

[6] S. A. Maas, "Nonlinear Microwave Circuits", Artech House, 1988.

[7] S. A. Maas, "Volterra Analysis of Spectral Regrowth", *IEEE Microwave and Guided Wave Letters*, vol. 7, no.7, pp.192-193, July 1997.

[8] M. S. Nakhla and J.Vlach, "A Piecewise Harmonic Balance Technique for Determination of Periodic Response of Nonlinear Systems", *IEEE Trans. on Circuit Syst.* vol. CAS-23, pp.85-91, Feb. 1976.