A NONLINEAR ARMA MODEL FOR SIMULATING POWER AMPLIFIERS

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ABSTRACT

This paper presents an improved model for wideband simulation of nonlinear power amplifiers. The commonly used memoryless envelope model is limited to use on narrowband signals. The new model includes an *auto-regressive moving average* (ARMA) filter to improve performance predictions for wideband signals. Optimization of the model is performed using measurements of time-domain pulse envelopes. The new model is constructed for a 20 GHz helix *traveling-wave tube amplifier* (TWTA) and compared to the memoryless envelope model for predicting distortion with wideband signals.

1. INTRODUCTION

Communication system simulations often employ nonlinear block models to predict distortion created by power amplifiers. The most commonly used model, the memoryless envelope transfer model, has been implemented in commercial CAD programs [1, 2]. In this model the nonlinear device is characterized in terms of input and output complex envelopes. Two nonlinear transfer functions are required to describe the properties of the device: the nonlinear amplitude (AM-AM) and phase (AM-PM) functions. These functions are obtained with a *vector network analyzer* (VNA), using a single-tone stimulus. The nonlinearity is often represented by a series expansion in either polar or quadrature form.

Assumptions in the mathematical formulation of the memoryless envelope transfer model limit it to narrowband applications. The AM-AM and AM-PM are measured at the center of the band and assumed to be constant (memoryless) over the bandwidth of the signal. Other models have been proposed for more accurate simulation of wideband signals [3], but none seem to provide an efficient implementation with easily measured parameters to become widely accepted. Accurate, wideband measurements of the complex envelope are necessary in understanding the nonlinear operation of the device. Time-domain measurements

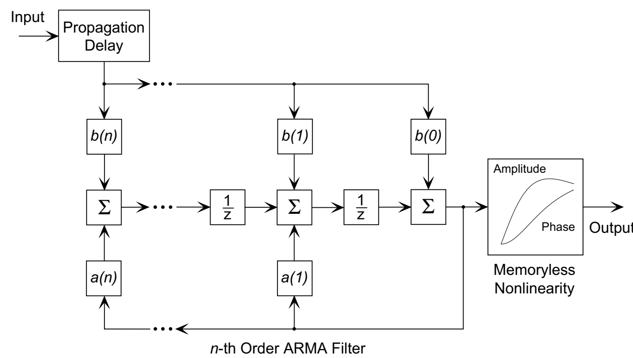

Figure 1: *Nonlinear ARMA model.*

of short duration pulses are used to construct a new model, which is capable of producing more accurate predictions for wideband signals. In this paper, we compare the performance of these models for a 20 GHz helix TWTA.

2. MODEL DEVELOPMENT

The nonlinear amplifier model developed in this paper is an extension of the memoryless envelope model to include an ARMA filter at the input. As shown in Figure 1, the nth-order ARMA model structure consists of n unit delay sections where the value of n determines the memory depth. Since the filter operates on the complex, low-pass equivalent envelope, each section consists of nonlinear feed-forward and feedback functions with complex coefficients. The incorporation of feedback allows for versatile modeling capability in a compact structure. The instantaneous nonlinearity is placed after the ARMA filter to approximate the physical operation of the TWTA, since the compression occurs near the output as the signal travels down the traveling-wave structure.

The initial values of the filter coefficients were chosen to represent the small-signal (linear) response of the TWTA. A time-domain transfer function was computed by applying FFT analysis to measured VNA frequency-

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(a)

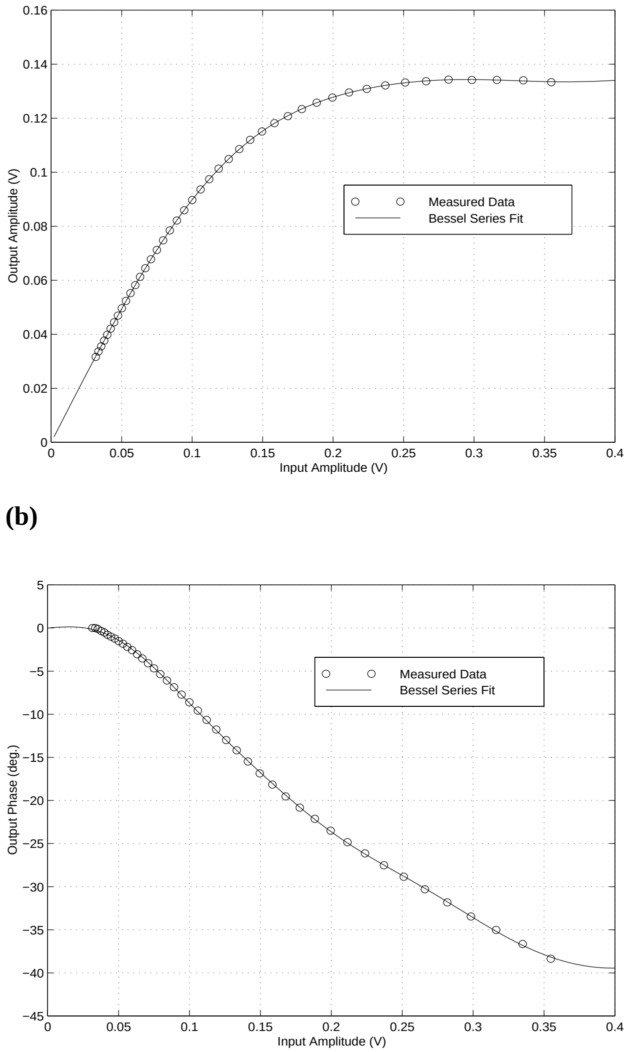


Figure 2: (a) *TWTA AM-AM characteristic.* (b) *TWTA AM-PM characteristic.*

domain data. A closed-form solution for the coefficients was obtained by minimizing the error between modeled and measured time-domain outputs. An 11th-order ARMA model was required to reproduce the filter response. The initial condition for the AM-AM and AM-PM characteristics were derived from a power sweep at the operating center frequency using the VNA. The nonlinear transfer functions are expressed in analytical form as a Bessel series expansion consisting of only odd-order terms [4]. The measured data and corresponding 7th-order Bessel series representation of the TWTA characteristics are shown in Figure 2. The model coefficients of both the filter and nonlinearity were optimized numerically, using a steepest descent (Levenberg-Marquardt) least-squares algorithm [5], to minimize the *mean-squared error* (MSE) between modeled and measured pulse waveform data.

3. WIDEBAND PULSE CHARACTERISTICS

Pulsed waveforms are ideal for characterizing amplifiers for wideband signals. Both *on/off keying* (OOK) and *bipolar phase-shift keying* (BPSK) pulses are used to fully characterize the amplitude and phase distortion. The measurement system used to obtain the low-pass equivalent waveform of these signals has been described in detail elsewhere [6]. A 0.35 ns data pulse was the shortest duration pulse available from the test equipment. After frequency conversion, the pulse is broadened to approximately 0.7 ns, which is still narrow enough to cover the operating frequency of the device. Data was taken at a sampling rate of 19.53 ps and an averaging factor of 64. The DC level of the envelope indicates the operating point (average level of the RF carrier) on which the pulse is imposed. The operating point of most interest is at or near saturation where the TWTA produces high efficiency.

The measured amplitude and phase envelopes of the OOK pulse are shown in Figure 3. The amplitude envelope covers a wide dynamic range as it approaches 0 V and returns to the DC steady-state (saturation) condition. The phase envelope is almost constant, as it deviates only $\pm 10^\circ$ maximum. The amplitude and phase envelopes of the BPSK pulse are shown in Figure 4, where the non-ideal switching between the $0^\circ/180^\circ$ phase states is apparent. An ideal BPSK signal would transition to 0 V and back to the DC saturation level in a much shorter time than the duration in the 180° phase state. The phase envelope shows that only approximately 140° of the desired 180° of phase shift is attained during the pulse duration.

4. MODEL COMPARISON

Results from the nonlinear ARMA model are compared to those from the memoryless envelope model. Figure 5 compares the model output to measured data for the OOK pulse. The nonlinear ARMA model follows the output more closely than the memoryless envelope model. The normalized MSE are 0.91% and 7.66% for the nonlinear ARMA and memoryless envelope models, respectively. Figure 6 compares the model output results to measured data for the BPSK pulse. Note the difference in scale between the OOK and BPSK pulse outputs. Figure 6(b) clearly shows the effect of the nonlinear distortion as the peak phase shift from saturation is decreased from 140° to approximately 80°. For the BPSK pulse, the normalized MSE is 1.85% and 13.18% for the nonlinear ARMA and memoryless envelope models, respectively.

(a)

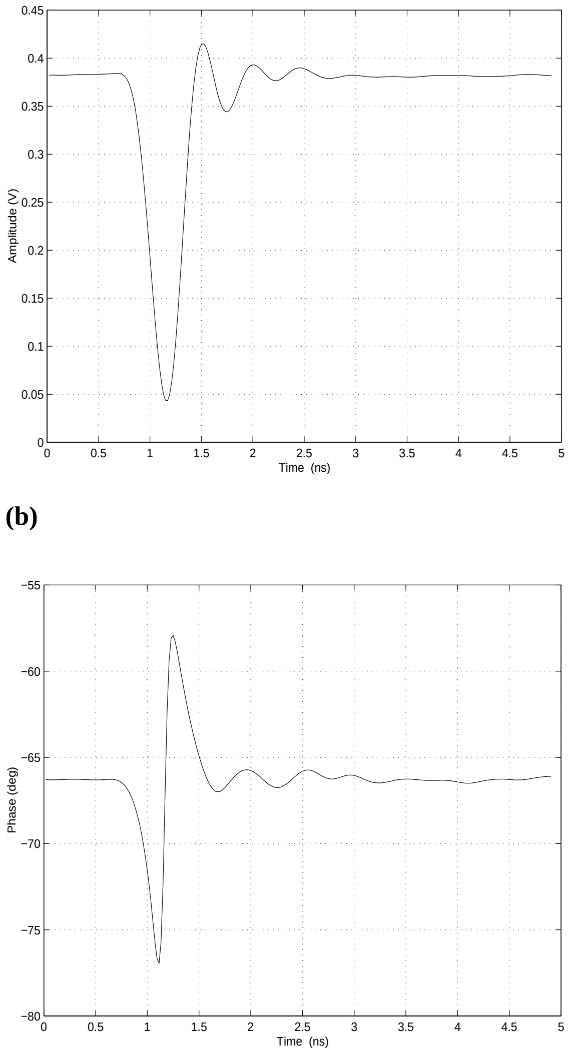


Figure 3: (a) *OOK pulse input amplitude envelope.* (b) *OOK pulse input phase envelope.*

(a)

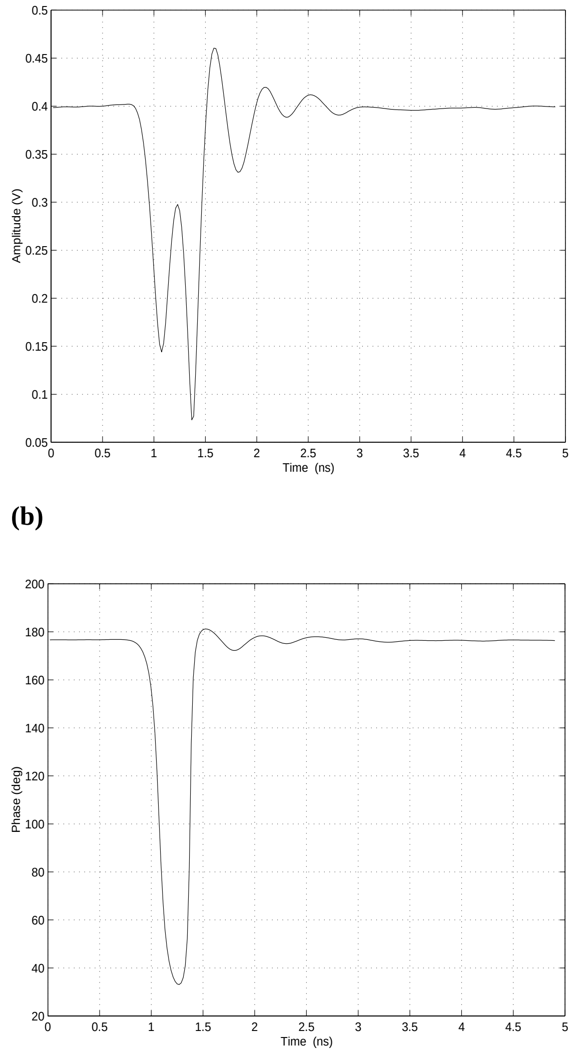


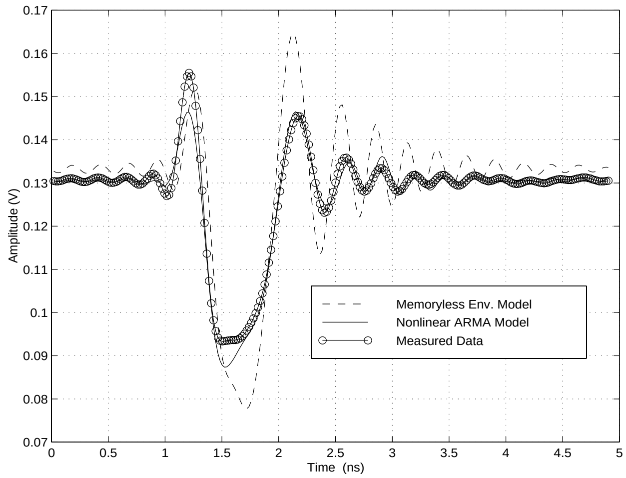
Figure 4: (a) *BPSK pulse input amplitude envelope.* (b) *BPSK pulse input phase envelope.*

The MSE normalization is based on data pulse energy. This allows the percentage error calculations to be used to estimate the model's accuracy to predict *bit-error-rate* (BER). The nonlinear ARMA model should therefore predict the BER of high data-rate signals more accurately than the memoryless envelope model.

5. CONCLUSION

A new model for communications simulation of nonlinear power amplifiers has been presented. The model is an enhancement to the commonly used memoryless envelope model that includes an input ARMA filter. Initial conditions for the model are derived from VNA measurements. The model is then optimized using time-domain complex envelope pulse data. A model was constructed for a 20 GHz TWTA and was shown to be more accurate for wideband signals than the memoryless envelope model. The model should be applicable to other amplifier types (e.g. solid state) using any type of signal modulation.

(a)



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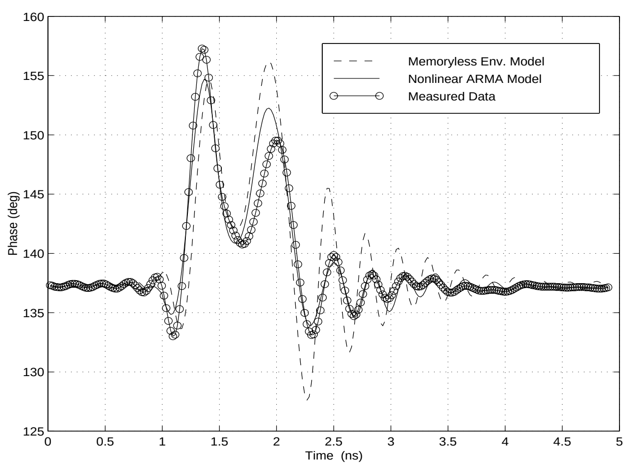
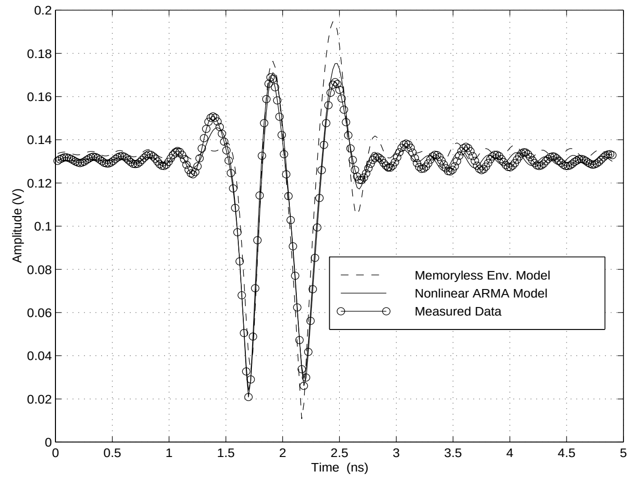


Figure 5: (a) *Model comparison of OOK pulse output amplitude envelopes.* (b) *Model comparison of OOK pulse output phase envelopes.*

(a)



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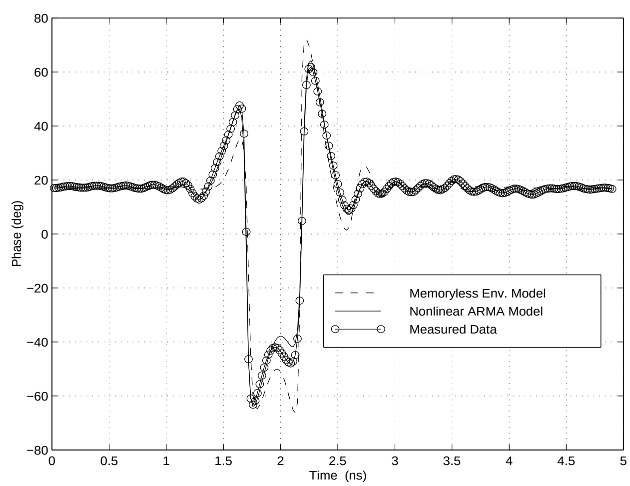

Figure 6: (a) *Model comparison of BPSK pulse output amplitude envelopes.* (b) *Model comparison of BPSK pulse output phase envelopes.*

6. REFERENCES

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