

# Broad-band Measurement and Identification of a Wiener-Hammerstein Model for an RF Amplifier\*

Philippe Crama<sup>†</sup>, Yves Rolain  
Vrije Universiteit Brussel (Dept. TW - ELEC)  
Pleinlaan 2, B-1050 Brussels  
Phone: +32 2 6292844, Fax: +32 2 6292850  
Email: Philippe.Crama@vub.ac.be

## Abstract

An RF amplifier under compression is measured using a multi-carrier signal covering the band from 500MHz to 1.5GHz, using the vectorial network analyzer for nonlinear systems (NVNA). Based on this measurement, a Wiener-Hammerstein model for this device is extracted. The model captures the wide band properties of the DUT up to 1.4% error inside the excitation band.

Keywords : estimation algorithms, identification, least-squares identification, nonlinear models, nonlinear estimation, parameter estimation.

## 1 Introduction

Nonlinear models can provide an accurate prediction of a system's behavior over a wide range of input powers. Building a general nonlinear model is very difficult, hence structural assumptions about the system class are made to reduce the search space. A popular approach that is also used here is to build up the nonlinear model structure using two basic building blocks : linear dynamic time invariant systems and static nonlinear systems. Certain combinations are widely in use and have a conventional name. The structure used in this paper is a Wiener-Hammerstein structure, as illustrated in Figure 1.

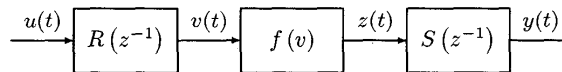


Figure 1: A Wiener-Hammerstein system.

Identification of such structures has been studied for some time. Work in this area includes [1, 2, 3] which do not concentrate on the specificities of high frequency devices or measurements. [8, 10] presented methods for the identification of RF amplifiers. This paper is the continuation of the work of [10] : there an identification procedure for the Wiener-Hammerstein model structure was proposed and demonstrated on simulations. This paper concentrates on the measurement aspects encountered when the method is applied in the real world.

---

\*This work is sponsored by the Fund for Scientific Research (FWO-Vlaanderen), the Flemish Government (GOA-IMMI) and the Belgian Program on Interuniversity Poles of Attraction initiated by the Belgian State, Prime Minister's Office, Science Policy programming (IUAP 5).

<sup>†</sup>Philippe Crama is Aspirant of the Fund for Scientific Research Flanders (FWO, Fonds voor Wetenschappelijk Onderzoek Vlaanderen)

Table 1: Characteristics of the amplifier ZHL-42 [7, pg. 136].

|        | FREQ<br>MHz |       | Gain dB |           | Maximum Power         | Input          | VSWR  |        |
|--------|-------------|-------|---------|-----------|-----------------------|----------------|-------|--------|
|        | Flatness    |       |         |           | Output                |                | Max   |        |
|        | $f_L$       | $f_U$ | Min     | max       | (1dB<br>comp.<br>min) | (no<br>damage) | Input | Output |
| ZHL-42 | 700         | 4200  | 30      | $\pm 1.0$ | +28                   | +5             | 2.5:1 | 2.5:1  |

Table 2: Characteristics of the filter SLP-1000 [7, pg. 154].

|          | Pass band, MHz<br>(loss < 1dB) |     | $f_{CO}$ , MHz, Nom<br>(loss 3dB) | VSWR      |           |
|----------|--------------------------------|-----|-----------------------------------|-----------|-----------|
|          |                                |     |                                   | Pass band | Stop band |
| SLP-1000 | DC                             | 900 | 990                               | 1.7:1     | 18:1      |

## 2 The measurements

The modeled device consists of the cascade of an amplifier and a low-pass filter. The setup is described in Figure 2. The amplifier and the filter are sold by Mini-Circuits, Brooklyn, New York. The characteristics of the ZHL-42 amplifier and of the SLP-1000 filter are shown in Table 1 and Table 2. Note that this setup does not need to be constrained in the proposed model class.

The measurements are done using a nonlinear network analyzer [4, 5, 6] which allows to sample the incoming and reflected RF waves at the input and at the output port of the device under test (DUT). The excitation signal is generated by a Sony/Tektronix AWG710 arbitrary waveform generator (AWG) with a sampling frequency of 4GHz. The complete measurement setup is drawn in Figure 3.

### 2.1 Choice of the excitation signal

A good excitation signal is supposed to help the identification process. For the proposed method [10] that will be used in this paper, the following requirements need to be met :

1. The excitation signal must cover the frequency band for which a model is desired.
2. The excitation signal must drive the DUT into the nonlinear operating region that the user wishes to model.
3. If possible, the excitation signal should help the user select the model complexity.

The available equipment limits the class of excitation signals that can be applied to the DUT, and hence determines in which cases the algorithm [10] can be applied. Ideally, the whole bandwidth of the DUT should be covered by the excitation signal. However, a 2GHz bandwidth is as high as the Sony/Tektronix AWG710 will go : the maximum sampling frequency of this AWG is 4GHz. An additional problem is the effect of the zero-order hold character of the excitation : in the frequency domain, this means that the frequencies close to 2GHz (half the sampling frequency) are only weakly excited. This situation can be corrected by calibrating the setup or predistorting the input signal since the shape of the reconstruction filter of the AWG

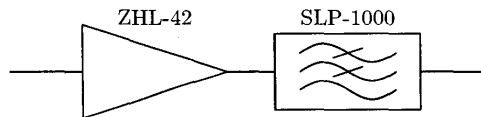


Figure 2: The setup that was measured : an amplifier (ZHL-42) followed by a filter (SLP-1000).



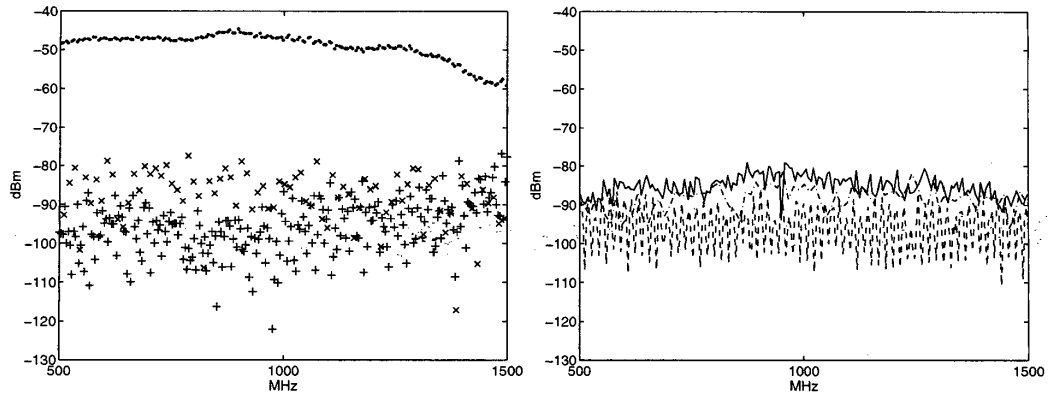


Figure 4: Spectrum of the wave going into the DUT :  $a_1$  (· : excited lines, + : even (unexcited) lines, × : odd unexcited lines, — : standard deviation of the excited lines, - - : standard deviation of the even lines, - · - : standard deviation of the unexcited odd lines).

The particular choice of which grid lines will be excited allows to gather information about the static nonlinear part of the system simply by looking at the input and the output spectra. This allows to fulfill requirement 3. When an even nonlinearity mixes two odd grid lines, the result always produces energy on an even grid line of the output spectrum. Hence, the even part of the nonlinearity does not contaminate the odd grid lines. If there is energy present at the even grid lines (500MHz, 504MHz, ..., 1496MHz, 1500MHz in our measurements) it can only come from an even nonlinearity. This is a valuable information when the terms of the static nonlinearity that will be estimated need to be selected. If no energy appears in the gaps located on odd grid lines, there are no significant odd terms to consider for the static nonlinearity.

## 2.2 Measurement results

Only the relation between  $a_1$  and  $b_2$  of the DUT will be modeled using a Wiener-Hammerstein structure. Hence, only  $a_1$  and  $b_2$  are shown in Figure 4 and Figure 5 respectively. The power in both figures appears to be very low. These amplitudes are shown as measured and hence include the losses of the coupler and the attenuator. Of course, the RF calibration would correct this.

In Figure 4, the calculated amplitudes of the excited grid lines are constant over the frequency range (see the definition of the input signal in Section 2.1). The deviation that can be observed come from the zero order hold and the reconstruction filter. Clearly, the higher frequencies have been excited about 10dB less. This will have an adverse effect on the quality of the model because the excitation will be less persistent.

Figure 5 shows that the measured device is indeed nonlinear : it can be clearly seen that grid lines that didn't carry energy in the input are significantly higher than the noise in the output. Since both the even and the odd detection lines are different from 0, it can be concluded that the nonlinearity possesses even and odd terms.

## 2.3 Imbalance in the downconversion

The first step of the identification method is to estimate the linear system to approximate  $b_2$  as a function of  $a_1$ . To obtain this model, both spectra are divided by each other. It turns out that the phase of the quotient is not suited to fitting. Figure 6 shows that the phase deviates widely from the expected "smooth" phase. This deviation cannot be explained by a pure time delay, since in such a case, the data points would be scattered evenly over the range  $[-\pi; \pi]$ .

The representation of the data points in Figure 6 was chosen specially to illustrate the following point : there is a kind of structure in the deviation from the expected phase. It looks as if 4 data sets with a

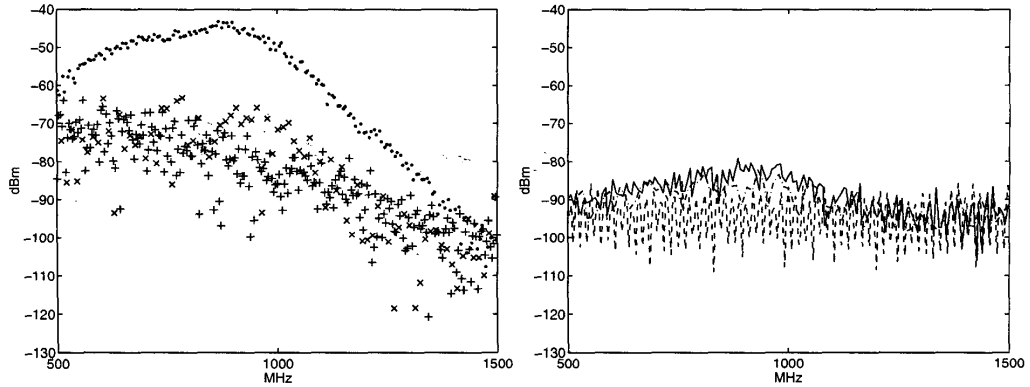


Figure 5: Spectrum of the wave coming out of the DUT :  $b_2$  (• : excited lines, + : even (unexcited) lines, × : odd unexcited lines, — : standard deviation of the excited lines, - - : standard deviation of the even lines, - · - : standard deviation of the unexcited odd lines).

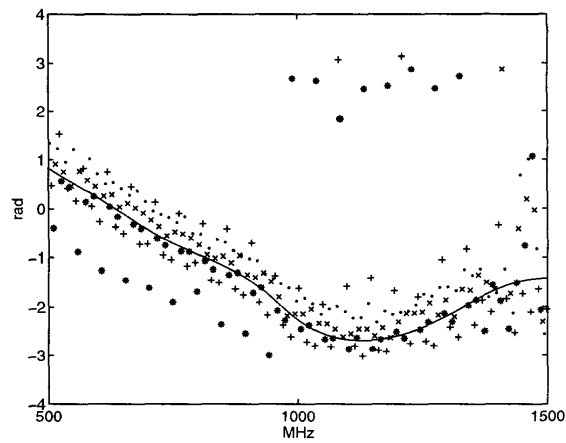


Figure 6: Phase of  $\frac{b_2}{a_1}$  without any calibration (— : phase of the model that can be fit through these data points, \*, ×, +, · : individual data points).

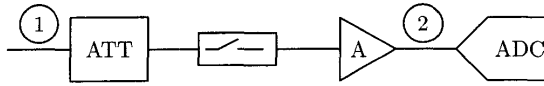


Figure 7: Downconversion of an RF wave. The circled numbers refer to Table 3.

Table 3: Shifting of some of the grid lines of the excitation signal as the signal is downconverted and sampled. The numbers in the headings of the column refer to where the signal is considered in Figure 7.

| 1     | 2       |
|-------|---------|
| [MHz] | [MHz]   |
| 502   | 5.9845  |
| 506   | -1.982  |
| 514   | 1.984   |
| 518   | 5.984   |
| 526   | -5.9815 |
| 530   | 1.9835  |
| 538   | -1.981  |
| 542   | -5.981  |

phase offset had been plotted on top of each other. This structure in the error comes from differences in the downconversion stage of  $a_1$  and  $b_2$ . Consider Figure 3 again and what happens when i. e.  $a_1$  is downconverted in Figure 7. Table 3 tracks some of the frequencies in the downconversion. This table is generated for the experimental setup that was used throughout the paper. The grid lines come from the input signal defined in Section 2.1 and the downconversion frequency was chosen to be 16.0005MHz.

Frequencies are always positive, however in Table 3, the second column contains negative frequencies. This is to differentiate which grid lines are complex conjugated in the downconversion process. Examination of the table yields that there are four groups of grid lines : those that arrive around 2MHz, those that arrive complex conjugated around 2MHz, those that arrive around 6MHz and finally those that land complex conjugated around 6MHz. Each of these frequencies sees a different phase shift defined by the IF frequency ( $\approx 2$ MHz or 6MHz and if they are complex conjugated or not). If the  $a_1$  downconversion channel has a different phase response than the  $b_2$  downconversion channel, then each of these four groups will have a phase offset that is different from the three others.

Obviously, the phase difference between both channels introduces a big error that will prevent to get a good model : the model errors are hidden by the phase error for which the model can not account. Getting rid of the biggest error source is a priority before considering other possible errors. The approach taken here is to calibrate away the effects of the imbalance between both IF channels. Therefore, an assumption was made : one channel has been supposed to be perfect.

$$H(\omega_{IF}) = \frac{b_2^F(\omega_{IF})}{a_1^F(\omega_{IF})} \quad (2)$$

The DUT was replaced by a through in the setup from Figure 3. Then, another multisine covering every grid line used in the band of interest (this means at 500MHz, 502MHz, 504MHz, ... 1.5GHz, or in other words, including the odd detection grid lines and the even grid lines also) was measured :  $a_1^F$  and  $b_2^F$ . Neglecting any RF effects (crosstalk between the waves in the directional couplers) and transfer function of the through, both measured waveforms should be equal. In (2), the correction factor to get  $a_1^F$  equal to  $b_2^F$  is computed. The frequency dependence  $\omega_{IF}$  has IF in the subscript to remind us the frequency domain where the correction is executed.

$$a_{1,IF}^c(\omega_{IF}) = H(\omega_{IF}) a_{1,IF}(\omega_{IF}) \quad (3)$$

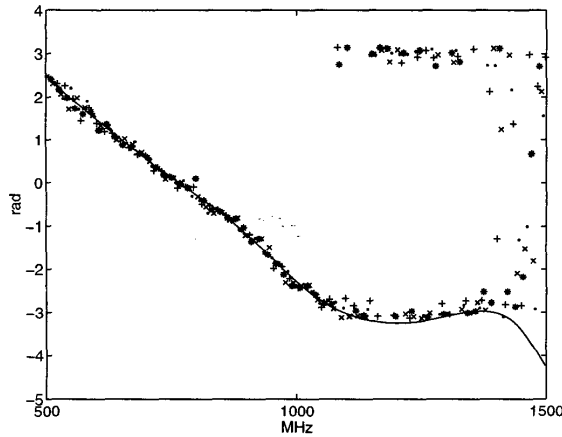


Figure 8: Phase of  $\frac{b_2}{a_1}$  after IF calibration (— : phase of the model that can be fit through these data points, \*, ×, +, · : individual data points).

$$b_{1,IF}^c(\omega_{IF}) = b_{1,IF}(\omega_{IF}) \quad (4)$$

In the calibration process ((3) and (4)), the downconverted waves are corrected in the assumption that the downconversion of  $b_2$  to  $b_{2,IF}$  introduces no distortion (4). When the calibrated waves are transformed back to the RF (this is only a reordering of the grid lines to invert the shuffling introduced by the downconversion), the phase of the transfer function can be computed with these calibrated signals. The result in Figure 8 is much better than the result in Figure 6. The result are expected to be even better after an RF calibration. Figure 9 shows the amplitude of  $\frac{b_2}{a_1}$ .

### 3 The model

The main purpose of this paper is to demonstrate the the algorithm [10] on measurements. So, only the identification results will be shown. Figure 10 show the estimation results.

This nonlinear model allows to predict the output measurements with a relative error of the power of 1.4%. The relative error is much higher when only the non-excited lines are examined : there, the relative power of the error is 46%. This can be compared to a linear model, which has a relative power error of 1.7% if all lines are considered, but of 75% when only the non-excited lines are taken into account. This shows that the excitation did not drive the amplifier to far into its nonlinear behavior and that the input was not really pure : for the ideal excitation signal, the error of the prediction of the linear model would be 100%.

### 4 Conclusion

An amplifier has been measured over a band of 1GHz. There is still work on the modeling process : the non-linear model should perform much better than the linear model, which is not really the case here.

### References

- [1] Maximum Likelihood Identification of Stochastic Wiener-Hammerstein-Type Nonlinear Systems, C. H. Chen, S. D. Fassois, Mechanical Systems and Signal Processing (1992), Vol. 6, No. 2, pp. 135–153.

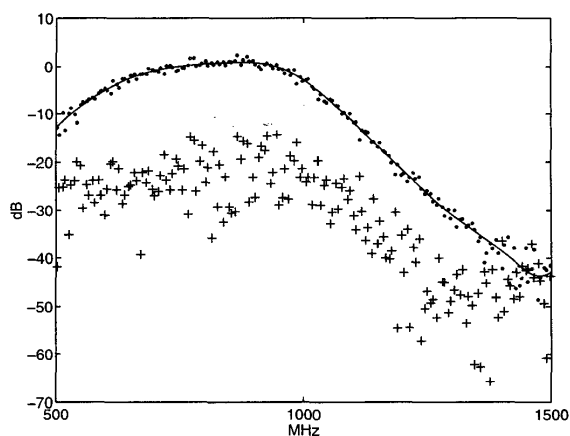


Figure 9: Amplitude of  $\frac{b_c^c}{a_c^1}$  after IF calibration (· : data points, — : model fit through this data ( $G_R$ ), + : difference between the linear model and the data).

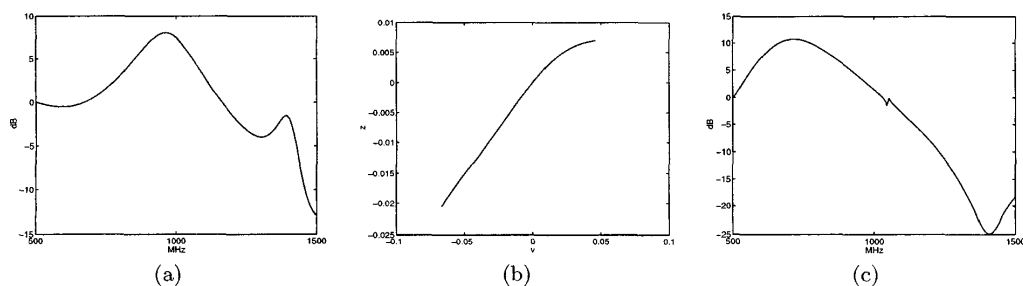


Figure 10: Best model obtained for the Wiener-Hammerstein system (Figure 1) : (a) input linear system, (b) static nonlinear characteristic, (c) output linear system.

- 
- [2] Recursive Identification Method for MISO Wiener-Hammerstein Model, M. Boutayeb, M. Darouach, IEEE Transactions on Automatic Control (1995), Vol. 40, No. 2, pp. 287–291.
  - [3] Non-parametric Estimation of the Frequency-response Functions of the Linear Blocks of a Wiener-Hammerstein Model, Gerd Vandersteen, Yves Rolain, Johan Schoukens, Automatica (1997), Vol. 33, No. 7, pp. 1351–1355.
  - [4] Complete 3-Port Measurement of Microwave Mixers Using a Nonlinear Vectorial Network Analyser, Yves Rolain, Philip Vael, Wendy Van Moer, Alain Barel, Proceedings of the IEEE MTT-S International Microwave Symposium, Baltimore, Maryland, June 7–12, 1998, Vol. 3, pp. 1491–1494.
  - [5] Calibration of a Wideband IF Nonlinear Vectorial Network Analyser, Wendy Van Moer, Yves Rolain, 53rd ARFTG Conference Digest, Anaheim, California (USA), June 18, 1999, pp. 98–103.
  - [6] An Automatic Harmonic Selection Scheme for Measurements and Calibration with the Nonlinear Vectorial Network Analyser, Wendy Van Moer, Yves Rolain, Johan Schoukens, IEEE MTT International Microwave Symposium Digest Volume III, Boston, Massachusetts, June 11–16, 2000, pp. 1855–1858.
  - [7] RF/IF Designer's Guide Y2K, Mini-Circuits, Brooklyn, New York.
  - [8] Introduction to Polyspectral Modeling and Compensation Techniques for Wideband Communications Systems, Christopher P. Silva, Andrew A. Moulthrop and Michael S. Muha, 58th ARFTG Conference Digest, Fall 2001, Nov 29th and 30th 2001, San Diego, California.
  - [9] Design of Multisine Excitations to Characterize the Nonlinear Distortions During FRF-Measurements, Kenneth Vanhoenacker, Tadeusz Dobrowiecki and Johan Schoukens, IEEE Transactions on Instrumentation and Measurement (2001), Vol. 50, No. 5, pp. 1097–1102.
  - [10] Wiener-Hammerstein System Estimator Initialisation Using a Random Multisine Excitation, Philippe Crama and Johan Schoukens, 58th ARFTG Conference Digest, Fall 2001, Nov 29th and 30th 2001, San Diego, California.