A MEASUREMENT TECHNIQUE FOR HIGHLY NONLINEAR TRANSFER FUNCTIONS

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ABSTRACT

This paper presents a new method to estimate nonlinear transfer functions of tube amplifiers or distortion effect stages. A special test signal and a sorting algorithm allow the calculation of the nonlinear transfer functions. PSPICE simulations of a tube amplifier as well as real-time measurements of a tube amplifier with a high quality 24bit/96kHz sound card will be presented.

1. INTRODUCTION

Modeling of vintage analog synthesizers and vintage analog effect processors is the subject of current research and development. Especially tube and transistor based audio effect processors are in the focus of digital simulation techniques. The interesting properties of special tube and transistor based processors are mainly due to the combination of linear filters and nonlinear transfer characteristics of the amplifying stages. The exact digital simulation of these nonlinear devices needs a detailed analysis of the nonlinear transfer functions and special measurement techniques which allow the calculation of the nonlinear transfer functions. The interaction of the nonlinear transfer functions with the linear filters of an analog effects processor form the basis for the exact digital simulation. In this paper we will concentrate on the determination of the nonlinear transfer characteristic based on PSPICE simulations and measurements of real analog systems.

2. PSPICE SIMULATION OF A TUBE AMPLIFIER

For the study of analog circuits the PSPICE simulation program is a powerful analysis tool which leads to a detailed insight into the voltage and current behavior insight an analog circuit [1,2]. DC transfer functions can be estimated when the nonlinear transfer element is DC coupled, which means without any coupling or feedback capacitors in the signal path. The simple diode limiter shown in Fig. 1 is simulated in PSPICE and analyzed by a DC-Sweep from -3 V to 3 V. Figure 2 shows the nonlinear voltage transfer function from input to output. If the nonlinear transfer element has a capacitor in the signal path, this method can not be used, and a sine wave signal must be employed.

The simplified schematic of the VOX AC30 guitar tube amplifier, shown in Fig. 3, is simulated with a transient analysis in PSPICE. The PSPICE probes are placed at the input and the output of the phase splitter stage. The result of the transient analysis in PSPICE when probe V(C1:1) is the x-axis is shown in Fig. 4. The input signal is a simple sine wave with 4.3 Vp and 400 Hz. This method for estimating the nonlinear transfer function is not usable, due to the capacitors in the signal path.

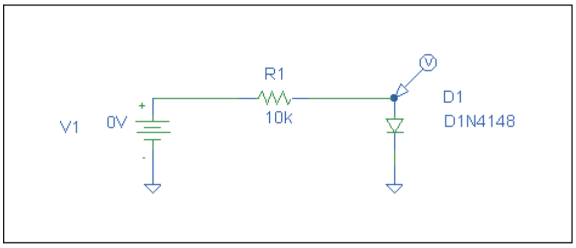


Figure 1: *PSPICE schematic of a simple diode limiter.*

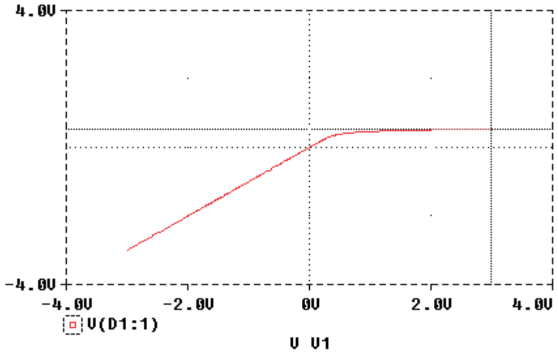


Figure 2: *PSPICE DC-transfer function of diode limiter (output voltage versus input voltage).*

3. TEST SIGNAL AND SORTING ALGORITHM

The probability density function of the test signal should have amplitudes covering the entire amplitude range. Therefore a decaying sine burst with alternating polarity can be used which is shown in Fig. 5a. The periodic sine burst signal is given by $y_{\text{pos}}(t) = U\sin(2\pi ft)/\exp(At)$ and $y_{\text{neg}}(t) = -U\sin(2\pi ft)/\exp(At)$. The parameters are the frequency $f = 400$ Hz, the amplitude $U = 3.4$ Vp and the damping factor $A = 400$. The PSPICE probes are placed at the input and the output of the phase splitter stage. The PSPICE simulation data of the circuit shown in Fig. 3 are exported to MATLAB. Figure 5 shows the input and output signals. The result of the transient analysis is shown in Fig. 6. This analysis is based on the simple plotting of all output versus input amplitudes. A simple manipulation of the input/output pairs leads to a more significant description of the input/output behavior.

For the computation of the nonlinear input/output characteristic the input and output data are sorted by the `sort.m` algorithm. Figure 7 shows the nonlinear transfer function if calculated with

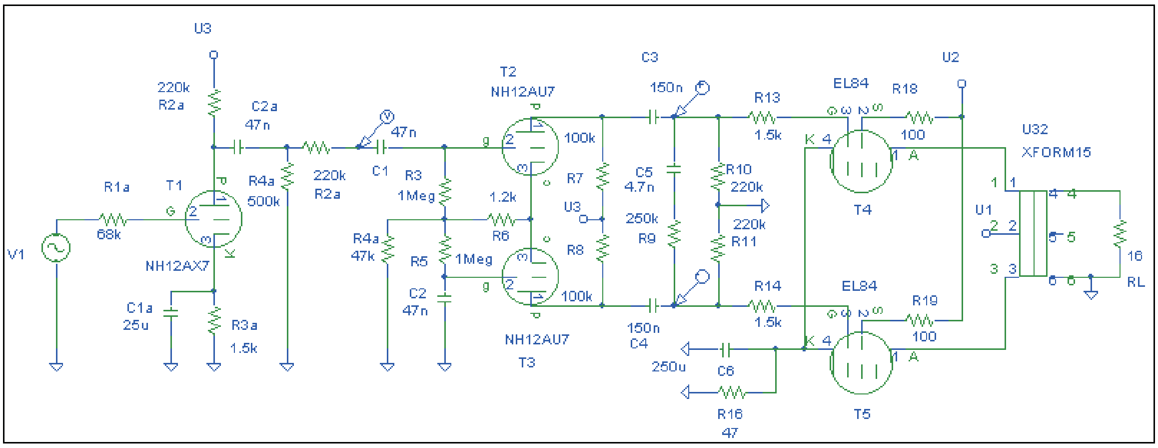


Figure 3: *Simplified schematic of Vox AC30 Tube amplifier.*

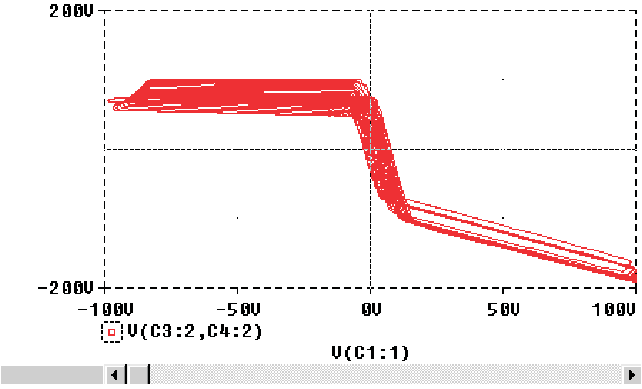


Figure 4: *Simple transfer function plot with PSPICE transient analysis, with x-axis=V(C1:1) (x-axis = input, y=axis = output).*

the `sortrows.m` algorithm and the `sort.m` algorithm in MATLAB. The `sortrows.m` algorithm sorts the x/y data pair wise whereas the `sort.m` algorithm performs sorting x and y data independently. The `sort.m` algorithm is more robust against phase shift between x/y signal data than the `sortrows.m` algorithm, but the `sort.m` algorithm is mathematically only able to show monotonic nonlinear transfer functions, whereas `sortrows.m` can do any function. Nevertheless, it is feasable to use `sort.m` for normal amplifiers and music instruments distortion elements, because their nonlinear transfer functions are monotonic. Figure 7b shows the smooth nonlinear transfer curve of the phase splitter stage, which is based on the `sort.m` algorithm and the alternating sine wave test signal.

The influence of the test signal on the resulting transfer function will be shown by using two different signals. Figure 8a shows the nonlinear transfer function obtained from a VOX AC30 measurement with an alternating sine burst test signal. The histogram of the output signal depicted in Fig. 8b shows that low levels occur with a high probability. Input and output signals are shown in Figures 8c and 8d. In comparison, a periodic noise burst test signal leads to the nonlinear transfer function shown in Fig. 9a. The histogram in Fig. 9b shows a nearly uniform distribution of amplitudes in the respective amplitude range compared to the alternating sine burst signal. This signal improves the accuracy for higher input amplitudes. A further measurement can be performed by using an alternating sine burst with adjustable frequencies.

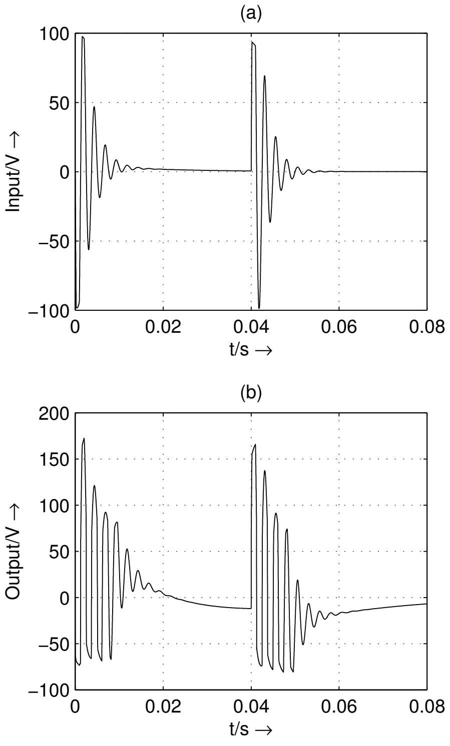


Figure 5: *Phase splitter: (a) input signal and (b) output signal.*

3.1. MEASURING NONLINEAR TRANSFER FUNCTIONS

Simulating circuits in PSPICE has its limitations due to simplified model approximations. So it is necessary to prove that the `sort.m` algorithm can be used for real measured data which are

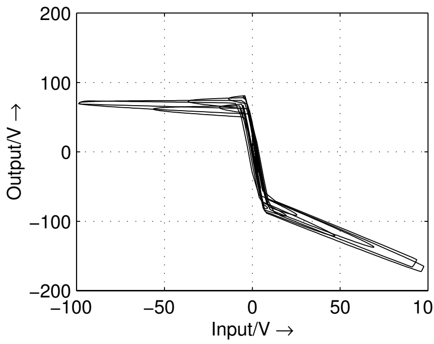
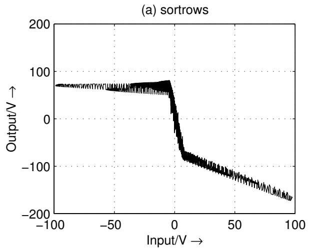


Figure 6: *Simple nonlinear transfer function plot with PSPICE Transient Analysis, with x-axis=V(C1:+).*


(a) sortrows

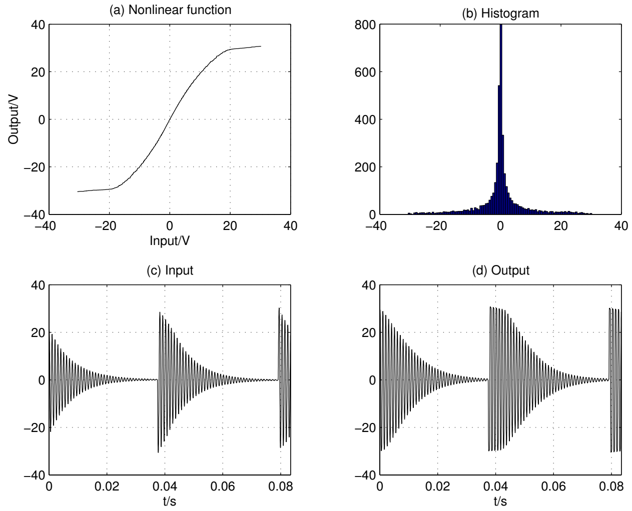
(b) sort

Figure 7: *Nonlinear transfer function calculated in MATLAB shown both with* `sort.m` *algorithm and* `sortrows.m` *algorithm.*

imported by a high quality 24bit/96kHz sound card. To make amplifier measurements, specially with tubes, some electrical preparations and precautions have to be considered. A balanced/unbalanced amplifier has to be connected to the sound card, because the output of the VOX AC30 phase splitter has to be measured with balanced probes. Also a 1:100 voltage divider with 1uF coupling caps is necessary because of the high AC and DC voltages at the tubes. The input impedance of the divider has to be high enough (> 1 MOhm) so that the device under test is not loaded with the probes. The entire measurement procedure and consists of the following steps:

1. Compute exponential sine burst signal with variable length, amplitude, frequency and damping factor
2. Compute multiple sine bursts with variable amounts of bursts
3. Play burst signal on sound card and record DUT (Device Under Test) output signal with sound card simultaneously
4. Voltage level calibration according to sound card specification
5. Detrend recorded data, to remove trends due to coupling caps
6. Trigger algorithm for define starting position of bursts
7. Average data to reduce noise
8. Remove DC offset

The following MATLAB file performs the measurement with a high-quality sound card and the subsequent calculation of the nonlinear transfer function:


(a) Nonlinear function

(b) Histogram

(c) Input

(d) Output

Figure 8: *Influence of test signal: alternating sine wave signal and resulting transfer function for the power amp/transformer stage.*

```
File1=’default’;
Anzahl=10; fs=96000; fx=5000; Lexp=2000;
Ax=11; % Exponential curve 1=long 20=short
pol=-1;
% Polarity of nonlinear element:
% y-axis inverted if pol=-1
Voldb=-30; Vol=10^(Voldb/20);
texp=0:1/fs:Lexp/fs;
A=1./exp(1.5^Ax*1e4*texp/Lexp);
% The envelope remains constant, independent
% of Lexp and f with this expression
yexpos=sin(2*pi*fx*texp).*A;
yexpos=yexpos/abs(max(yexpos));% normalize
yexneg=-sin(2*pi*fx*texp).*A;
yexneg=yexneg/abs(min(yexneg));% normalize
yexp=Vol*[yexpos,yexneg];
texp=[texp,texp+texp(length(texp))];

y=yexp;t=texp;
Lexp=length(y);

% Complete vector with multiple yexpos/yexpneg
for i=1:(Anzahl-1)
   y=[y,yexp];
   t=[t,texp+t(length(t))];
end;

Cal=3.47/0.34; % Level calibration
wavplay(y,fs);
ym=Cal*wavrecord(length(y),fs,2,’double’);
ym2=ym(:,2)’;
ym1=ym(:,1)’;ym2=ym(:,2)’;

% Sound card + measurement amplifier
% have coupling caps that charges up slowly
% if signal is clipped asymmetrical
% - > detrend  compensates this
ym1=detrend(ym1);ym2=detrend(ym2);ym1=pol*ym1;
```

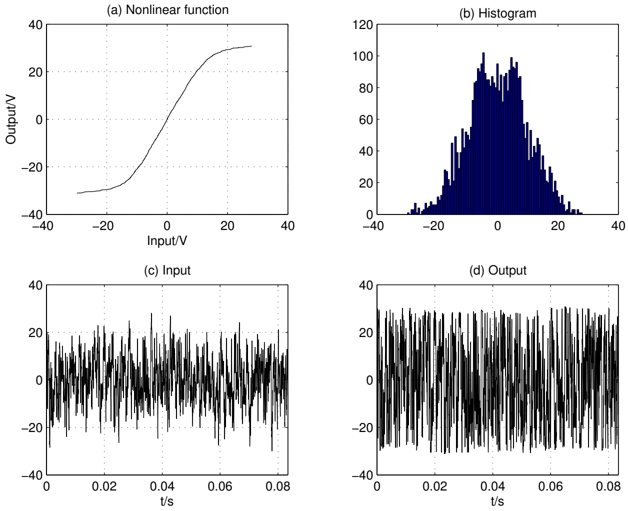


Figure 9: *Influence of test signal: periodic noise burst signal and resulting transfer function for the power amp/transformer stage.*

```
% Triggering
triglevel=0.9;
pretrig=-(Lexp-round(fs/fx/1));

% Pulse length minus 1/2 fx-Periode
if abs(max(ym2)) > abs(min(ym2));
   [a,b]=find(ym2>(triglevel)*max(ym2));
else
   [a,b]=find(ym2<(triglevel)*min(ym2));
end;
start=b(1)-pretrig;
ende=b(1)+(Lexp-1)-pretrig;

% Averaging
M=round(length(ym1)/(Lexp))-2;
y1avg=0;y2avg=0;

for j=1:M
y1avg=y1avg+....
ym1(start+((j-1)*Lexp):ende+((j-1)*Lexp));
y2avg=y2avg+...
ym2(start+((j-1)*Lexp):ende+((j-1)*Lexp));
end;
y1avg=y1avg/(M);
y2avg=y2avg/(M);

% Sorting with two methods
index=1:1:length(y1avg);
yavg=[y1avg;y2avg;index];
ysortrows=sortrows(yavg')';
ysort=sort(yavg')';
```

Figure 10 shows measurement results for a VOX AC30 amplifier. The left column plots show the nonlinear transfer characteristics and the right column plots the output signals for the input stage (Fig. 10a,b), the phase splitter (Fig. 10c,d), and the power amp/transformer (Fig. 10e,f). Harmonic distortion is mainly produced by the phase splitter and the power amp. An input signal of ±1 V is mapped by the input stage to a voltage range of ±20 V (see Fig. 10a). This voltage range represents the input range for the phase splitter (see Fig. 8a), which operates completely in the nonlinear part of the transfer function. The output range of the phase splitter is ±40 V, which is the input range of the power amp (see Fig. 9a). The power amp/transformer output range is ±30 V.

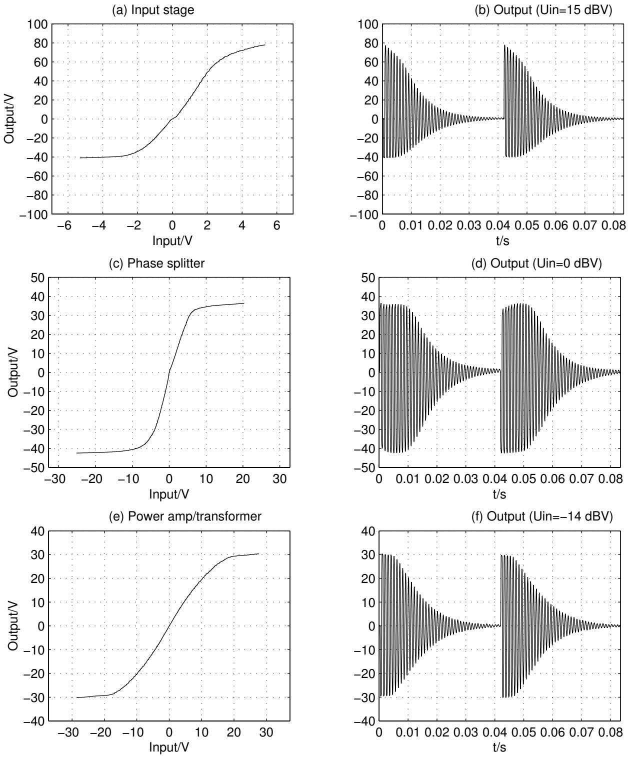


Figure 10: *VOX AC30 measurement results. Input stage (a/b): output signal is anode voltage of input tube. Phase splitter (c/d): input signal is anode output signal from input tube and output signal is difference signal between both anodes from the phase splitter tube. Power amp/transformer (e/f): input signal is difference signal after phase splitter and output signal is transformer output.*

4. CONCLUSIONS

This paper has described an efficient measurement technique based on decaying sine bursts and noise bursts as a test signal and a simple sorting algorithm for the calculation of the nonlinear transfer function. PSPICE simulations and real measurements have proven the effectiveness of the proposed measurement technique. The combination of analog PSPICE simulations and measurement techniques of highly nonlinear analog systems builds the basis of digital simulation techniques.

5. REFERENCES

[1] W. Marshall Leach, Jr., “SPICE Models for Vacuum Tube Amplifiers,” *Journal of the Audio Engineering Society*, Vol. 43, No. 3, pp. 117–126, 1995.

[2] J.-C. Maillet, “A Generalized Algebraic Technique For Modeling Triodes,” *Glass Audio*, Vol. 10, No. 2, pp. 2–9, 1998.