A CONVOLUTION-BASED BLACK-BOX APPROACH FOR INCORPORATING LINEAR CIRCUIT BLOCKS DESCRIBED BY FREQUENCY-DOMAIN DATA INTO A NON-LINEAR TRANSIENT TIME-DOMAIN SIMULATOR.

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ABSTRACT

The requirements of the microwave MMIC and high speed digital engineer have led to the need for a true transient time domain simulator capable of incorporating frequency-dependent phenomena. In this paper a new convolution-based black box approach is used to incorporate arbitrary linear circuit blocks, described by frequency-dependent s-parameters, into a general-purpose non-linear circuit analysis program (SPICE) yielding a general non-linear transient time domain simulator. The technique is validated by comparisons with measurement and with conventional SPICE simulation.

1. INTRODUCTION

It is generally accepted that direct numerical integration techniques such as used in SPICE [1] offer the most effective way of performing transient analysis of non-linear circuits. The main limitation, as seen by the MMIC or high speed digital engineer, is the inability to include frequency-dependent phenomena. Every element, both linear and non-linear has to be simulated in the time domain. The increased component density in modern MMICs leads to simulations requiring more memory and faster CPUs. The move to higher frequencies and the requirement for single-design-iteration success has forced microwave engineers towards electromagnetic solutions for the linear parts of their circuits, producing information which is naturally in a frequency domain format. At the same time, in digital systems with rise times in the region of 100ps, the simple lumped element equivalent circuits used at the package, interconnect, and board level are no longer sufficient to describe effects such as crosstalk and false triggering. Actually, such networks are complex microwave systems comprising of several different closely coupled transmission media. To compound matters, the terminating networks are invariably non-linear.

Linear microwave networks can be characterised accurately using a variety of techniques based in the frequency domain. Standard linear circuit modelling techniques offer an efficient method of analysis. If a more exotic network is being examined, then electromagnetic simulation techniques [2] may be employed. Alternatively direct characterisation via measurement is an option. Normally, this data, however it is derived, is in the form of frequency-dependent N-port scattering parameters. For steady state analysis the data may be readily imported into a Harmonic Balance based simulator, however the MMIC designer may require to simulate with pulsed RF while the digital designer normally requires the response to a step or perhaps pulse input. Thus an analysis technique is required which embodies a continuous range of frequency information in the time domain. Once this has been achieved convolution-based techniques can be employed to incorporate the time domain description into a non-linear transient analysis program, such as SPICE.

Previous techniques developed to include frequency-dependent behaviour in a time domain simulator are centred on the development of SPICE compatible models [3]. These techniques can involve complex equivalent circuits and are impractical in cases such as interconnect networks surrounding a pin grid array package. Other convolution-based techniques [4] use frequency domain data but are also limited to simple structures like a single transmission line.

In this paper we propose a convolution-based black-box approach. The frequency domain data, gathered from simulation or measurement is transformed to the time domain using a transform technique termed, *Causal Convolution* described in [5] [6]. The main aspects of the computed time domain functions is that they are finite and causal, they interpolate the frequency domain data accurately, and are genuinely discrete. In the first section we give a review of the technique used to calculate the impulse responses, while section two details the incorporation of this time domain representation into SPICE yielding a flexible time domain non-linear simulator capable of including complex frequency-dependent phenomena. Two examples are presented, the first of which demonstrates the use of measured frequency domain data for a microwave passive network in a transient simulation. The second example involves an ECL driver, connected to a passive non-linear load via an interconnect network. Causal Convolution is used to include the effects of interconnect loss. Validity is confirmed by comparison with a direct SPICE simulation, for the lossless case.

2 THE CAUSAL CONVOLUTION TRANSFORM TECHNIQUE.

The technique proposed by Brazil in [5] and [6] is fundamentally based on the fact that continuous periodic functions in the frequency domain correspond to discrete impulse functions in the time domain. In effect it allows the isolation of a segment of the continuous system function from DC to some maximum "boundary" frequency and the description of such by a real valued, discrete and causal impulse response in the time domain.

The transform is given by:

$$x(nT) = \frac{T}{2\Pi} \int_{-\omega_m/2\pi}^{+\omega_m/2\pi} X(\omega) \exp[+jn\omega T] d\omega \qquad (1)$$

$$X(\omega) = \sum_{n=0}^{\infty} x(nT) \exp[-jn\omega T] \qquad (2)$$

where $X(\omega)$ is an hermitian system frequency function, and $x(t)$ is its corresponding impulse function. Applying the transform to a non-periodic system function results in a quasi-causal impulse response. The novelty of the technique is that this quasi-causal impulse response still maintains excellent interpolation properties in the frequency domain in the sense of fitting the original system function between the sample points used for its derivation. The above is possible when two simple criteria are obeyed at the boundary frequency. That is, within the context of the periodic extension of a non periodic function about a boundary frequency, the process of periodic extension should not introduce any discontinuity into the real and imaginary parts (or their higher order derivatives) of the new periodic function formed. The purpose of this paper is to show how linear system blocks described in this way may be integrated into a non-linear time-domain transient simulator (SPICE).

3 INCORPORATING THE LINEAR NETWORK DESCRIBED BY DISCRETE IMPULSES INTO SPICE

During a transient analysis, SPICE integrates the differential equations associated with a network. Stepping along through time, SPICE requires of any device to present a discrete equivalent circuit at each iteration of each time point. Capacitors and inductors obey ordinary differential equations and so numerical techniques must be applied to these elements in order to

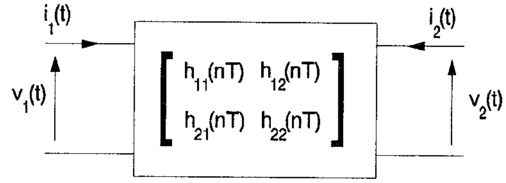

Fig. 1.0 : **A Linear two portnetwork represented by discrete impulse responses.**

produce a discrete equivalent circuit at each iteration. Associated with the application of numerical techniques is the overhead of error calculation and control. An element or block which is naturally discrete comes without these overheads and so is particularly suitable for implementation within SPICE.
Consider for illustration a linear two-port, Fig. 1, described in time by a set of discrete impulse responses as outlined in SECTION 2. Say these impulse responses represent S-parameter frequency functions. The two-port equations may be written in time as:

$$b_1(t) = h_{11}(nT) * a_1(t) + h_{12}(nT) * a_2(t) \qquad (3)$$

$$b_2(t) = h_{21}(nT) * a_1(t) + h_{22}(nT) * a_2(t) \qquad (4)$$

with $b_1(t) = \dfrac{g_0 v_1(t) - i_1(t)}{2\sqrt{g_o}}$, $a_1(t) = \dfrac{g_o v_1(t) + i_1(t)}{2\sqrt{g_o}}$,etc..

In (3) and (4) $*$ denotes convolution, but as h_{mn} are discrete these convolutions are exactly summations i.e. :

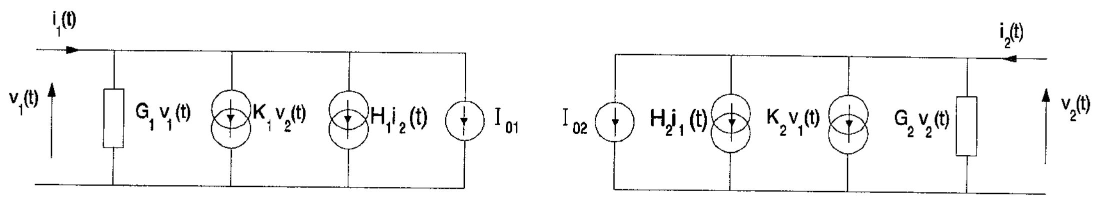

Fig. 2.0 : Equivalent circuit represented to SPICE at each iteration.

$$h_{11}(nT) * a_1(t) = \sum_{k=0}^{2N-1} a_1(t - kT) h_{11}(kT) \qquad (5)$$

(3) and (4) may be cast in the form:

$$i_1(t) = G_1 v_1(t) + K_1 v_2(t) + H_1 i_2(t) + I_{01} \qquad (6)$$

$$i_2(t) = G_2 v_2(t) + K_2 v_1(t) + H_2 i_1(t) + I_{02} \qquad (7)$$

Equations (6) & (7) are represented by the equivalent circuit shown in Fig. 2. As can be seen it contains a conductance, a VCCS, a CCCS and an independent CS attached to each port. This is the discrete circuit presented to SPICE at each iteration. In this way a 2-Port described in the frequency domain may be incorporated within a time domain simulator. Extensions to the n-port case are straightforward.

4 EXAMPLES

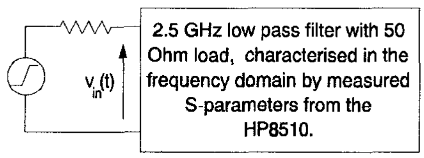

Fig. 3.0 : One port characterised with measured data embedded into a transient simulation.

The first example involves the incorporation of measured data into a linear transient simulation. A linear circuit is used for simplicity, avoiding the complicated issues associated with the modelling of non-linearities but at the same time proving the effectiveness of the technique. The measured data is derived from a HP8510 ANA. A one port measurement is made of a 2.5 GHZ Low pass filter with 50 Ohm load attached to one end. The filter is realised on a lossy PCB board. We require to incorporate this one port represented by measured S-parameters into a transient simulation and validate the results with a direct time domain measurement from a HP85120 digitising scope. Hence, the network into which we incorporate the measured data is particularly simple, as shown in Fig. 3.

In Fig. 4 we compare the simulated and measured response, proving the usefulness of the technique in this application.

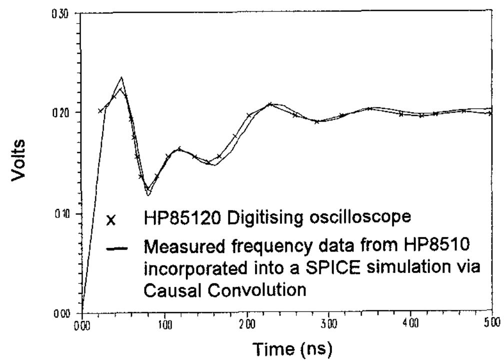

Fig. 4.0 : Measured vs Simulated response.

The second example involves the transient simulation of a non-linear circuit. This example is taken from [7] and involves a BJT driver (which includes 12 BJTs and 20 diodes) connected to a non-linear passive load via a lossy interconnect, Fig. 5. To validate the Causal Convolution technique we model the interconnect with an ideal transmission line and perform a conventional SPICE simulation. This ideal interconnect is then treated as a linear black-box described by frequency domain data and causal convolution techniques are used to incorporate it into a SPICE simulation.

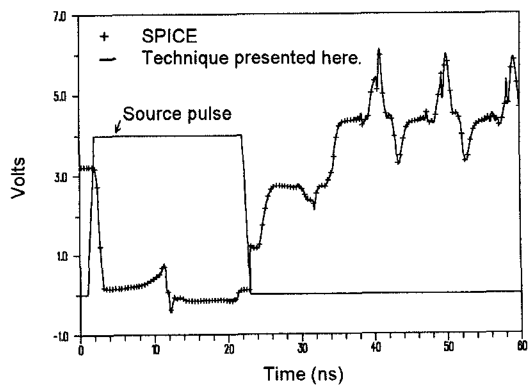

Fig. 6a : Validating Causal Convolution with direct SPICE simulation, (Driver end voltage).

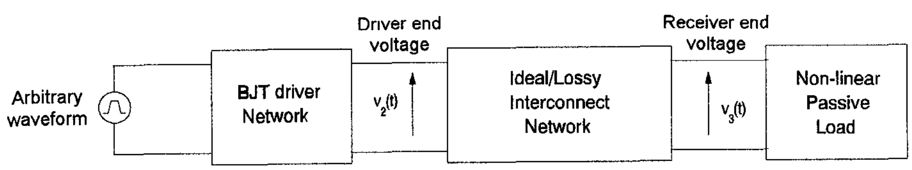

Fig. 5.0 : Non-linear network composed of a BJT driver, Interconnect network, and non-linear load.

As shown in Fig. 6a both methods yield results which are in perfect agreement. Runtimes are 15.3 sec. and 25.2 sec. respectively the latter being dependent on the precise details of the representation. Causal Convolution is then used to include the effect of interconnect loss , the results of which are shown in Fig. 6b.

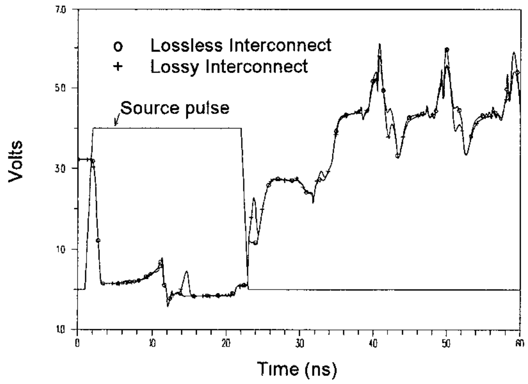

Fig. 6b : Using Causal Convolution to incorporate interconnect loss, (Driver end voltage)

Runtime was 23.2 seconds. In order to put this result into perspective, the same network was simulated using Harmonic Balance but with a square wave excitation using 32 harmonics. Convergence was not directly possible, but was achieved with source stepping. Harmonic balance analysis time was 36 minutes. All simulations were carried out on the same computer platform.

5 Conclusion

A convolution-based black-box approach is used to include linear networks represented by frequency domain information into a SPICE non-linear analysis, yielding a flexible transient time domain simulator capable of simulating the kinds of frequency-dependent phenomena so important in MMICS and modern high speed digital circuits. The main novelties are the time domain representation of the linear circuit and its implementation into a numerical integration based time domain simulator such as SPICE. Simulated examples validate the technique by comparison with SPICE, and with measurement.

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