Immunity Modeling of the LM2902 Operational Amplifier

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Abstract—Component models that predict functional failure are necessary for predicting the immunity of systems to electromagnetic interference (EMI). A method to extract these models using measurements on integrated circuits (ICs) already exists. This measurement method for ICs with single-ended connections is extended, to include ICs with differential connections. The LM2902 op-amp is measured and modeled as a first case study.

Index Terms—immunity, integrated circuit, ICIM, DPI, modeling, differential connection, operational amplifier

I. INTRODUCTION

To reduce the number of prototyping cycles in the development of electronic products, we would like to predict the immunity of a product to electromagnetic interference (EMI) in an early stage. Specifically, we would like to be able to predict functional failure of a product under test using a circuit simulator like PSPICE. In order to be able to simulate the complete product, we first need component models that adequately predict functional failure. Models of passive components, including parasitics, are readily available [1], so we focus on Integrated Circuit (IC) models.

In earlier work, an immunity model was developed, including a measurement method to extract model parameters from various Integrated Circuits (ICs) with single-ended connections [2], [3]. This model and the corresponding method are summarized in section II. Then, an extended measurement method is proposed to characterize ICs with differential connections in section III. Characterization results of the LM2902 operational amplifier are presented and a behavioral model is suggested in section IV. In section V, we use this model to predict functional failure in simulation. These immunity predictions are then compared with measurements. Finally, we draw conclusions on the suitability of the proposed method and we indicate its current shortcomings (section VI).

II. STATE OF THE ART

For components with single-ended connections, an immunity model and a corresponding measurement method to extract the model parameters were developed in earlier work [1], and are briefly summarized below.

As suggested in [3], the model consists of a PDN (Passive Distribution Network) and an IB (Immunity Behavioral) part. The goal of this model is to describe the immunity of an IC under CW (Continuous Wave) disturbance. The failure mechanisms under CW disturbance or transient disturbance are in general quite different. This leads to different model structures and therefore, we do not try to obtain one model to describe the immunity to both types of disturbance.

The first part of the model, the PDN, is a linear circuit that describes the propagation of power. Regarding the kind of disturbance considered for this model (only a few watts of forward power in a DPI (Direct Power Injection) test configuration [4]), nonlinearities on the input and transfer impedances are generally quite negligible [2]. This observation leads us to use an S-parameter description to characterize and model an integrated circuit. This approach is compliant with typical end user constraints, who need to consider an IC as a black box. The S-parameters can be measured using a Vector Network Analyzer (VNA).

The second part of the model is the IB, and [2] suggests that the immunity of an IC is directly linked to a transmitted power threshold. This threshold power can be extracted by a DPI experiment [4] consisting in injecting disturbances directly on a pin of an IC in a controlled environment. For each frequency, the injected forward power is increased until the IC fails. This failure threshold power as function of the frequency is called the DPI performance. (The essence of the DPI measurement setup is given in Figure 1.) From the forward power threshold
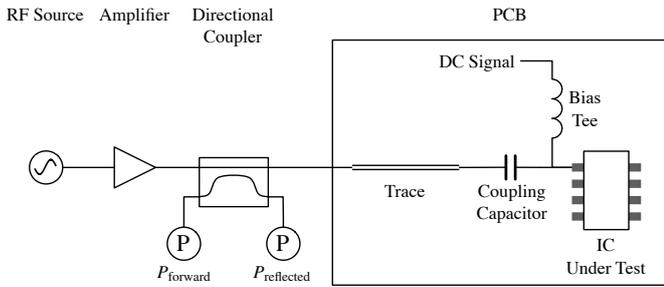
Figure 1. Typical DPI test setup as defined in IEC 62132-4 for single pin injection. [4]
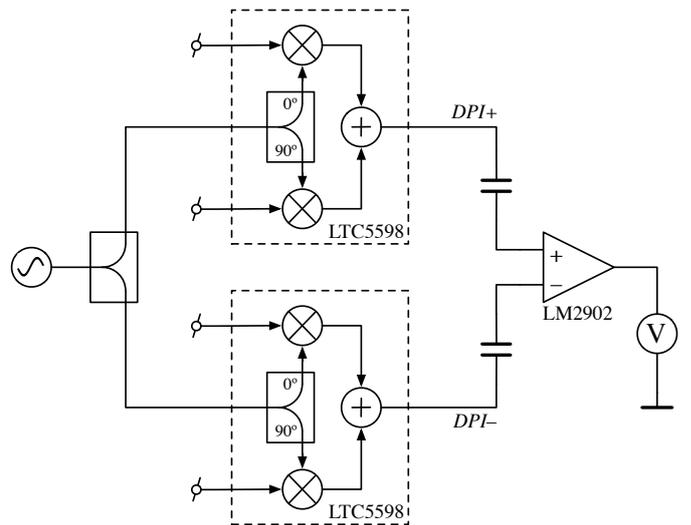

Figure 2. Principle of the differential disturbance injector, which uses two quadrature modulators. The biasing circuitry of the LM2902 is not shown.

thus found, the transmitted power threshold is extracted by means of simulation as developed in [2], [5].

With these measurements (S-parameters and DPI performance), we obtain a model that is able to predict the propagation of a disturbance until the IC inputs (reflection coefficients) and through the IC (transmission coefficients). This allows us to compute the total transmitted power to the IC in any configuration and to compare it to the threshold transmitted power available in the model.

This approach was successfully applied for the immunity prediction of various IC families, such as logic gates, LIN transceivers, MOSFETs, transistors and LDOs. It is interesting to note that the transmitted power seems to be a generally valid electrical criterion to describe the immunity of an IC.

III. MEASUREMENT SETUP

The extension of the transmitted power criterion to devices with differential connections is not obvious. For example, should the powers transmitted to the + and − inputs simply be added? Or does only the differential power matter? To find out, we develop a test setup that allows us to inject a variety of signals. Afterwards, we will evaluate whether or not we can describe the failure with a transmitted power threshold.

We choose to start with a case study on an LM2902 operational amplifier. From practical experience, we know that this op-amp converts high-frequency EMI to a DC offset voltage at its output. Depending on the application, a certain output offset voltage will cause functional failure of the product.

As will be discussed in section IV and as is pointed out in [6], the output offset of op-amps under a Continuous Wave (CW) disturbance is a function of v_{cm}, v_{dm} and ϕ_{cmdm}, being the common-mode disturbance voltage amplitude, the differential-mode disturbance voltage amplitude and the phase shift between common-mode and differential-mode disturbance, respectively. In order to properly characterize this kind of IC, we need to develop a test setup that allows us to independently control v_{cm}, v_{dm} and ϕ_{cmdm}, since the traditional DPI test method does not allow this.

To generate two Direct Power Injection (DPI) signals, one for the + input and one for the − input of the LM2902 op-amp that have a controllable ϕ_{cmdm}, the common-mode and differential-mode signals need to be coherent. Consequently,

DPI+ and DPI− should have a fixed phase relationship. Therefore, a single CW source is used to derive both DPI+ and DPI− disturbance signals from (cf. Figure 2). Two quadrature mixers derive a sine and a cosine from this single source. Using four DC-coupled control signals, the amount of sine and cosine in both DPI+ and DPI− disturbance signals can be individually controlled, to generate every combination of v_{cm}, v_{dm} and ϕ_{cmdm}. Finally, the voltage offset at the output of the LM2902 is measured.

This measurement principle was realized using two LTC5598 quadrature mixers on DC1455 demonstration boards, generously provided by Linear Technology. An IFB 2023 RF signal generator was used as CW source, followed by a custom resistive power splitter. An Agilent 34401 multimeter was used to measure the output offset voltage. For monitoring purposes, a Tektronics TDS5104B oscilloscope was connected to the DPI+ and DPI− nodes. The generic DPI PCB developed in [2] was used to mount the LM2902 on, and to provide its biasing circuitry. The resulting setup is schematically depicted in Figure 3, the realization in Figure 4.

A PC calculates the modulator control voltages from the wanted v_{cm}, v_{dm} and ϕ_{cmdm} and drives the D/A converter to apply these voltages to the modulators.

Currently, we are not able to control the modulators very accurately, so we use the oscilloscope to measure the actually applied v_{cm}, v_{dm} and ϕ_{cmdm}. There is an important disadvantage to this solution, however: the input impedance of the LM2902 pins is not, in general, 50 Ω. As a result, for high frequencies, there will be standing waves on the transmission line from the modulator to the IC. Although the oscilloscope is placed close to the IC, there will be a discrepancy between the voltage measured by the oscilloscope and the actual voltage on the LM2902 pin. The connecting cable is 1 m length, so at 100 MHz, half a wavelength fits in the cable. Somewhere around this frequency, we should start to be critical toward
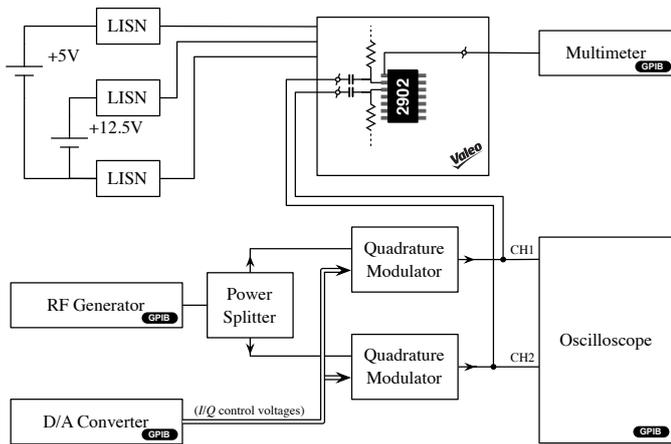
Figure 3. Schematic measurement setup, used to characterize the LM2902 op-amp. A PC (not depicted) controls the RF generator and D/A converter, and reads measurements from the multimeter and oscilloscope. LISNs (Line Impedance Stabilizer Networks) are included, to have a defined and known power supply.
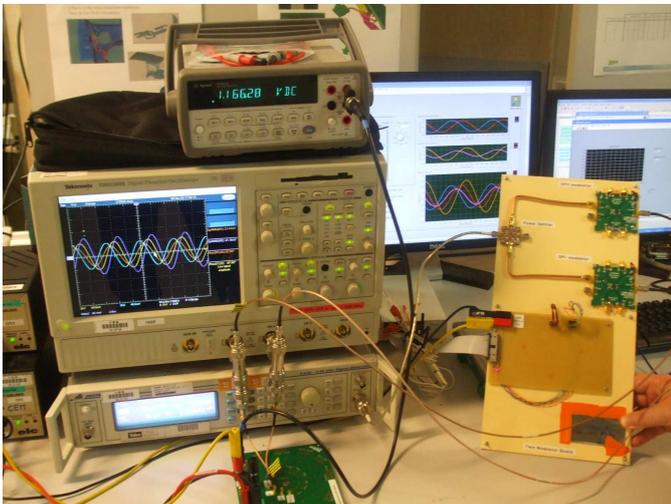

Figure 4. Realized measurement setup. The PCB at the bottom is used to mount the LM2902, the board at the right contains the power splitter and the two quadrature modulators. The PC is running the LabView control software.

the oscilloscope's readings. The modulators, however, work well up to 1.6 GHz, so if we would improve the modulator control, thereby obsolescing the oscilloscope, we could extend the frequency range up to 1.6 GHz.

For low frequencies, for yet unknown reasons, there seems to be an imbalance between the sine and cosine components generated by the modulators. We compensate for this effect in software, but this negatively affects accuracy for low frequencies. Therefore, the current setup is limited to frequencies above 5 MHz.

To sum up, we have developed an injection setup that allows us to inject a CW disturbance into a differential input. We can individually control v_{cm}, v_{dm} and ϕ_{cmdm}. The CW frequency can be set between 5 and 100 MHz.
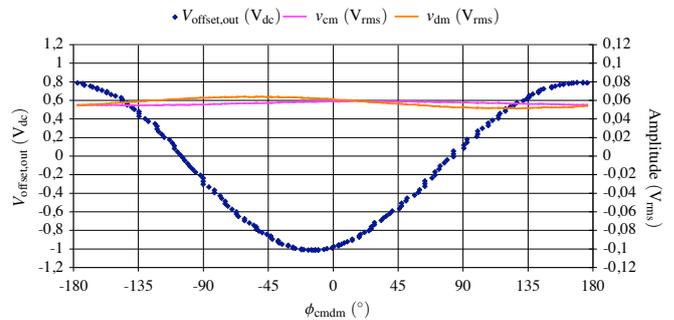

Figure 5. Measured output offset voltage, while sweeping ϕ_{cmdm} and trying to keep v_{cm} and v_{dm} constant at $f = 60$ MHz.

IV. CHARACTERIZATION RESULTS

In the first sweep that we perform, we try to keep v_{cm} and v_{dm} constant and sweep ϕ_{cmdm}, while the CW frequency is 60 MHz. The result is plotted in Figure 5.

Note that the injection setup succeeds somewhat in keeping v_{cm}, v_{dm} constant, albeit not perfect ($60\,\text{mV}_{rms} \pm 10\,\text{mV}_{rms}$). Furthermore, the main observation is that the output offset voltage is a shifted sinusoid as function of ϕ_{cmdm}. This might correspond to the analytical prediction of [6, Eq. 12 and 13]:

$$V_{\text{offset,in}} = \frac{g_p v_{cm} v_{dm} |Y(j\omega)|}{2 g_m} \cos(\phi_{cmdm} + \angle Y(j\omega)), \quad (1)$$

where g_p, g_m and $Y(j\omega)$ are transistor and technology parameters. $V_{\text{offset,in}}$ is the equivalent RF-induced input offset voltage. In closed loop op-amp configurations, this input offset appears attenuated at the output, depending on the loop gain. Given a certain loop gain (op-amp open loop gain times feedback gain), and a certain disturbance frequency, the output offset voltage should also be a sinusoid as function of ϕ_{cmdm}.

While comparing our measurements (Figure 5) with the model of (1), we notice two significant differences. First and foremost, the average output offset voltage is nonzero, while the average of a cosine is zero. Second, $\angle Y(j\omega)$ should be between $90°$ and $0°$ [6, Eq. 8]. Most probably, there is a phase reversal somewhere in our setup with respect to the analysis of [6], although we have not yet been able to find it.

Treating the op-amp with a fixed feedback network as a black box, we can state the following anonymous behavioral model:

$$V_{\text{offset,out}} = v_{cm} v_{dm} \left[F(\omega) \cos(\phi_{cmdm} + G(\omega)) - H(\omega) \right], \quad (2)$$

where F, G and H are (real) fit-parameters. Note that we added H to describe the currently unexplained nonzero average offset. We can test the hypothesis that (2) constitutes a good model, by performing a ϕ_{cmdm}-sweep with different v_{cm}/v_{dm} combinations. We fit an F, G and H to the results of each sweep, and we check that F, G and especially H stay about constant. The results of this experiment are enumerated in Table I.

For v_{cm}/v_{dm} ratios close to 1, H (as defined in (2)) seems to be a competent model. For other ratios, H starts to deviate (cf.

Table I
FIT F, G AND H FOR DIFFERENT v_{CM}/v_{DM}
COMBINATIONS IN ϕ_{CMDM} SWEEPS AT 60 MHZ.

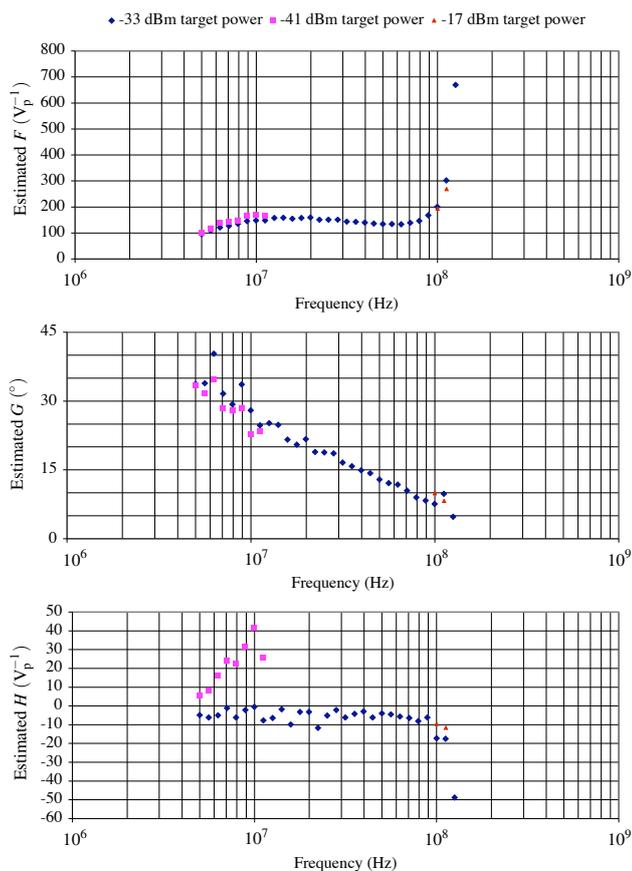|	Stimulus		Fit parameters		
	v_{cm}	v_{dm}	F	G	H
no.	(mV$_p$)	(mV$_p$)	(V$_p^{-1}$)	(°)	(V$_p^{-1}$)
1.	11.9	12.1	131.9	12.2	5.50
2.	11.9	12.2	131.3	11.5	5.46
3.	80.4	82.0	137.4	11.1	5.35
4.	80.0	55.1	142.3	10.8	5.04
5.	79.8	29.2	138.4	12.5	11.85
6.	53.3	80.8	141.5	11.6	4.66
7.	27.5	79.8	137.6	12.3	7.60

Figure 6. Fitted F, G and H to ϕ_{cmdm}-sweeps at different frequencies and different forward injection powers.

sweep 5-7). To first order approximation, however, H suffices (cf. sweep 1-4). As for F and G, the results suggest being reproducible within ± 5 V$_p^{-1}$ and $\pm 1°$, respectively.

Finally, we perform ϕ_{cmdm} sweeps among a range of frequencies, to determine $F(\omega)$, $G(\omega)$ and $H(\omega)$, see Figure 6. In these sweeps, $v_{cm} = v_{dm}$. F and G are relatively smooth as function of the frequency, but H is quite noisy and apparently, dependent on the forward injection power.
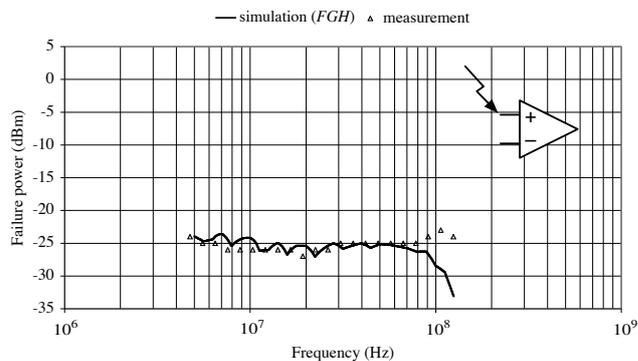

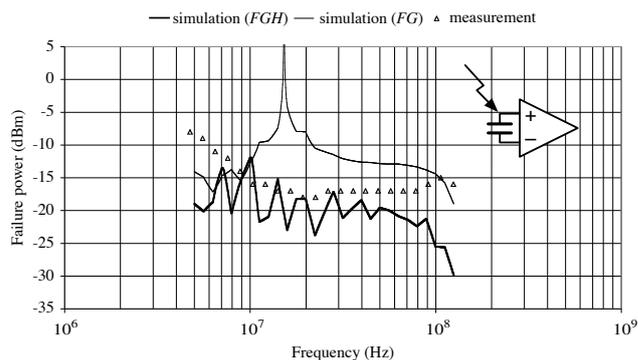Figure 7. DPI+ performance of the LM2902, simulated and measured.

Figure 8. DPI+ performance of the LM2902 with 100 pF between + and −. Simulated using (F, G, H)-parameters (thick curve) and simulated with only (F, G)-parameters (thin curve).

V. SIMULATION VS. MEASUREMENTS

Now that we have a model (2) and now that we have measured the model parameters (Figure 6), we would like actually to perform a product simulation. For example, what is the DPI performance of the LM2902, when we inject only on the + input? How does this DPI performance change (improve?) if we add a 100 pF capacitor between the + and − inputs?

As with the ICIM (Integrated Circuit Immunity Model) method described in section II, we characterize the LM2902 by measuring its S-parameters with a Vector Network Analyzer (VNA). These are transferred in PSPICE, using [7]. This allows us to predict the voltages on all IC pins, given a 0 dBm disturbance injected on one of the pins. Simultaneously, the simulator looks up the measured F, G and H as voltages for each frequency. Using Allegro AMS Simulator macros, we calculate the forward injection power that would cause the failure output voltage offset. Note that the failure output voltage offset must be chosen in the macros. This means that the same model can be used for applications requiring different maximum output offsets.

First, we simulated the DPI performance of the LM2902, for injection on the plus pin, only with the op-amp and its biasing circuitry. The result is plotted in Figure 7, together with a DPI

measurement. The failure criterion was $|V_{\text{offset,out}}| > 50\,\text{mV}$. Another pair of simulations and measurement was performed, with a 100 pF capacitor between + and – pins (Figure 8). This simulation was carried out with and without H, to assess the improvement of the model by adding H.

The simulation of the clean configuration (Figure 7) matches quite well with measurements ($\pm 2\,\text{dB}$ until 100 MHz). We suppose the deviation close to 125 MHz to be caused by the standing wave problems during parameter estimation. Furthermore, we note ripples in the simulation results that might be caused by nonsystematic errors during parameter estimation measurements.

The simulation of the LM2902 with a 100 pF capacitor inserted, has bigger deviations (cf. Figure 8). The argument of the cosine in this configuration is closer to $90°$ than in the unfiltered configuration; actually, the cosine argument crosses $90°$ at 15 MHz. In a simulation without H, this means that the LM2902 is infinitely immune at this frequency, hence the peak in the (F, G)-simulation (thin curve). Adding the H-parameter (thick curve) makes the simulation more realistic. On the other hand, the simulation becomes noisier because of uncertainties in H.

VI. Conclusions and Recommendations

We have proposed a model to predict the immunity of an LM2902 op-amp to CW injected power, using model data solely gathered using measurements on the LM2902. We have indication that this model is also applicable to other op-amps. Using this model and measurement method, we are able to predict the immunity of the clean LM2902 within $\pm 2\,\text{dB}$, and the LM2902 with a certain filter within $\pm 10\,\text{dB}$, in the 5-100 MHz frequency range.

Despite these promising results, many assumptions were made during this research project. Therefore, the question is not what assumptions should be verified, but in what order. The first priority would be to obsolete and remove the oscilloscope to avoid standing-wave problems. The next step would be to understand the sine/cosine imbalance problem, which will increase the frequency range somewhat, but mainly will increase the accuracy.

Then, using this more accurate setup, the model of (2) should be extensively verified, especially the validity of H, also for high frequencies (close to 1 GHz). Next, the model should be tried with different filters and with different op-amps.

As a future perspective, we could use this setup to investigate the immunity of various ICs with differential connections to CW disturbances. This includes digital ICs, such as CAN-bus transceivers.

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