Accelerated characterisation of Operational Amplifiers' susceptibility using multitone disturbance

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***Abstract*—This paper presents an original approach to accelerate susceptibility testing of Operational Amplifiers (op-amp), using large band multitone signals, for a Direct Power Injection (DPI) setup. The relation between Continuous Wave (CW) and multitone susceptibility results, the associated limits and the global characterisation flow are discussed.**

***Index Terms*—susceptibility, operational amplifier, multitone disturbance, accelerated characterisation, integrated circuits**

I. Introduction

Testing Integrated Circuit (IC) susceptibility to CW disturbance is essential for functional safety but can be very long and costly [1]. In today's industrial context, the need for periodic testing, to track EMC level drift e.g. caused by ageing, or to ensure system robustness after software updates as in automotive industry, arises. Thus, a fast susceptibility characterisation method is required to avoid recurrent extensive testing time.

The idea of injecting large band multitone signals to accelerate susceptibility tests appears in various publications for different experimental setups such as, radiated susceptibility or near-field scan [2][3][4][5]. In addition, multiple studies propose approaches to understand the effect of Dual-Tone and multitone disturbances [6][7][8][9]. The principle is to test the system susceptibility to multiple frequencies simultaneously. To use this method and draw conclusions from multitone measurements, having a relation between CW and multitone tests is necessary. Hence, an initial analysis is required to identify suitable test parameters, considering information quantity, where a valid link between large band and CW tests exists.

The aim of this paper is to apply the same principles to a DPI test for two general-purpose op-amps from a black box perspective. The paper is structured as follows: First, the op-amps used as a case study and the experimental setup are briefly presented. Section III presents the CW test results and the failure mechanisms that occur. Then the large band injection results and the possible links with the CW test results with the associated limits are discussed. Finally, a comparison of the two op-amp's CW and multitone results is done followed with an overview of the global characterisation flow.

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II. Case study and experimental setup

This paper focuses on two op-amps, the LMV721M5 from Texas Instruments and the AD8601ARTZ from Analog Devices. They are two general purpose, low power op-amps with a gain–bandwidth product of few MHz in the same SOT23-5 package from different manufacturers. Each op-amp is mounted in a typical non-inverting configuration on the same evaluation board to avoid layout differences.

As presented in [6], all experiments are based on the IEC62132-4 DPI standard because of its good repeatability (1 dB error). The experimental setup is described on Fig. 1.

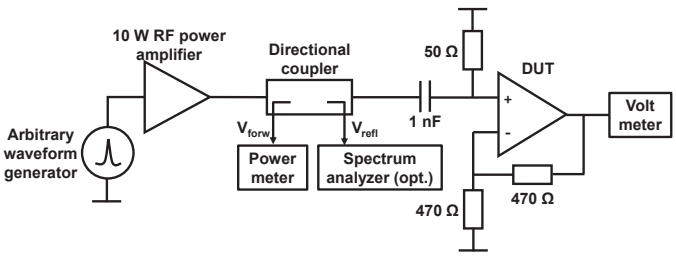


Fig. 1: Experimental setup

An arbitrary waveform generator (AWG) generates the disturbance signal amplified by an RF-amplifier. The disturbance signal is monitored by a power meter using a directional coupler. A spectrum analyser monitors the return signal to verify that no intermodulation product is detected ensuring

stability of the non-inverting input impedance. The EMI-induced DC offset on the output pin is monitored with a precision voltmeter. Main equipment are listed in Table I with their references.

TABLE I: Table Type Styles

Equipment	Reference
AWG	Tektronix AWG710B
RF power amplifier	Amplifier Research 10W1000B
Power meter	HP 437B
Spectrum analyser	ROHDE & SCHWARZ ESPI3
Volt meter	Agilent 34401A

III. CW DISTURBANCE SUSCEPTIBILITY

Op-amps present two different failure mechanisms leading to an output DC offset when perturbation on the input pin is rectified. Slew Rate (SR) asymmetry dominates at low frequency (usually up to 100 MHz), while Weak Distortion (WD) of the differential pair dominates at high frequency (usually above 100 MHz)[10].

Figs. 2 and 3 present the susceptibility threshold of both op-amps to CW disturbance for different offset values as failure criterion. The test is restricted between 10 MHz and 1 GHz.

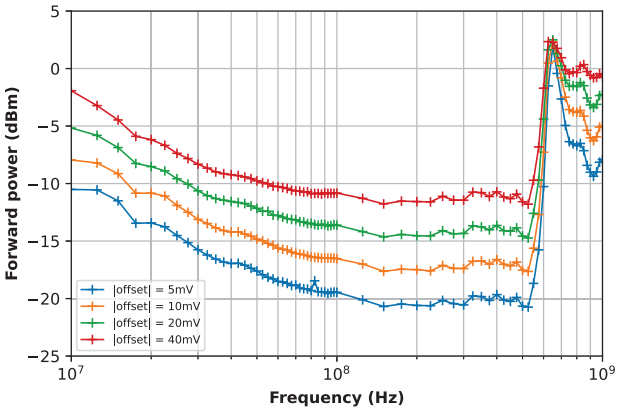


Fig. 2: AD8601ARTZ susceptibility threshold to CW disturbance for different offset values

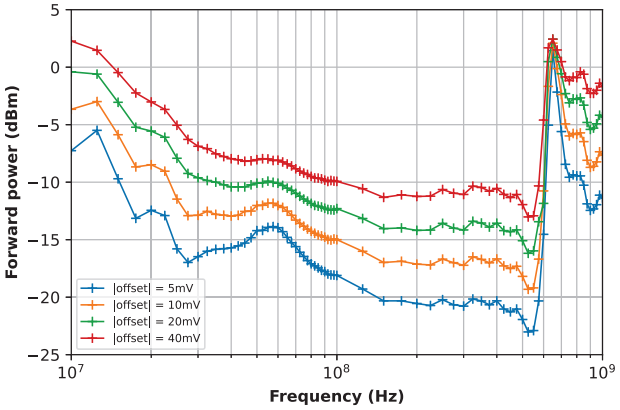


Fig. 3: LMV721M5 susceptibility threshold to CW disturbance for different offset values

Susceptibility thresholds are quite similar from one op-amp to the other, each showing a 3 dB increase of the forward power each time the failure criterion is doubled. Frequency ranges where WD and SR respectively dominate are not clearly delimited because the sign of the generated offset is the same in both cases. Transition around 600 MHz is a layout effect independent of the Device Under Test (DUT). It was verified by experimental tests made on the same IC but mounted on a different PCB. The transition around 600 MHz was not visible, proving the independence of the failure mechanism on this transition frequency.

IV. MULTITONE DISTURBANCE SUSCEPTIBILITY

A. Multitone signal definition

In this section, op-amps' susceptibility to multitone comb signal, defined by N equidistant harmonics of constant amplitude E_0 spread over a frequency range is tested. Signals are defined by (1) and (2) with f_{min} and f_{max} the frequency limits.

$$E(t) = \sum_{k=1}^{N} E_0 \cdot sin(2\pi f_k t) \tag{1}$$

$$f_k = f_{min} + (k-1)\frac{f_{max} - f_{min}}{N-1} \tag{2}$$

The average and peak powers of the signal are given by (3) and (4), where all parameters are expressed in dB, with P_{harmo} the average power per harmonic, considering equal emission power for every harmonic composing the multitone signal. In reality the power for every harmonic is not exactly constant due to AWG and RF amplifier characteristics but this can be compensated by calibration. Increasing N can result in saturation of the RF amplifier because of a high peak power even for small average power. This must be avoided as amplifier saturation leads to intermodulation product [2].

$$P_{avg} = P_{harmo} + 10log(N) \tag{3}$$

$$P_{peak} = P_{harmo} + 20log(N) + 3 \tag{4}$$

B. Relation between CW and multitone susceptibility

Previous work introduced the interference coefficient I to quantify the impact of every frequency component of a multitone disturbance [3]. When the disturbance superposition principle applies (i.e. the contribution of each frequency component of the multitone disturbance to the failure adds up independently), a failure occur when $I = 1$. Considering op-amp, [6] proposes two different formulas depending on the failure mechanism valid for small offset values. Equation (5) gives the interference coefficient when WD dominates while (6) gives the interference coefficient when SR dominates. P_{Ek} represents the power of a specific harmonic while P_{Sk} represents the CW susceptibility threshold for this specific frequency.

$$I = \sum_{k=1}^{N} \frac{P_{Ek}}{P_{Sk}} \tag{5}$$

$$I = \sqrt{\sum_{k=1}^{N} \left(\frac{P_{Ek}}{P_{Sk}}\right)^2} \tag{6}$$

For this article the frequency ranges where WD and SR respectively dominate are not well delimited. Hence (7), with a typically between 1 and 2, proposes a generalised formula to handle cases where both failure mechanisms arise.

$$I = \left(\sum_{k=1}^{N} \left(\frac{P_{Ek}}{P_{Sk}}\right)^a\right)^{\frac{1}{a}} \tag{7}$$

When the disturbance superposition principle is verified, (8) gives the relation between average power of the multitone disturbance and susceptibility threshold in CW test considering P_{Ek} as constant and equal to P_E. Hence, if the disturbance superposition principle is verified, a failure arises when average power of the multitone disturbance is equal to a generalised harmonic mean formula of the CW susceptibility threshold.

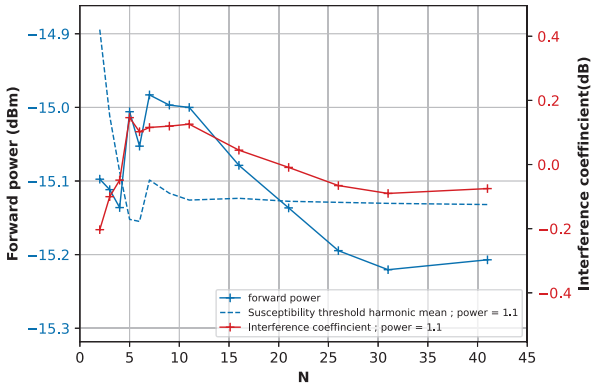
$$P_{avg} = N \cdot P_E = \frac{N}{\left(\sum_{k=1}^{N} \left(\frac{1}{P_{Sk}}\right)^a\right)^{\frac{1}{a}}} \tag{8}$$

If $a > 1$, the generalised harmonic mean does not converge to a constant value as N increases. If $N_1 \neq N_2$ with N_1 and N_2 sufficiently high to consider a good sampling of the frequency range, (9) gives the relation between both generalised harmonic mean. Hence, for all the following figures, forward power and generalised harmonic mean in multitone tests are normalised according to (10).

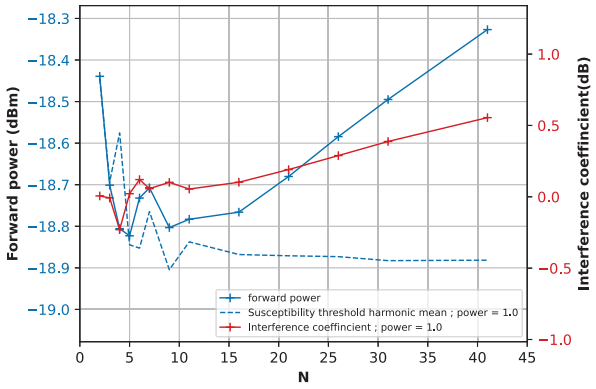
$$\frac{P_{avg1}}{N_1^{\frac{a-1}{a}}} = \frac{P_{avg2}}{N_2^{\frac{a-1}{a}}} \tag{9}$$

$$P_{norm} = \frac{P_{avg}}{N^{\frac{a-1}{a}}} \tag{10}$$

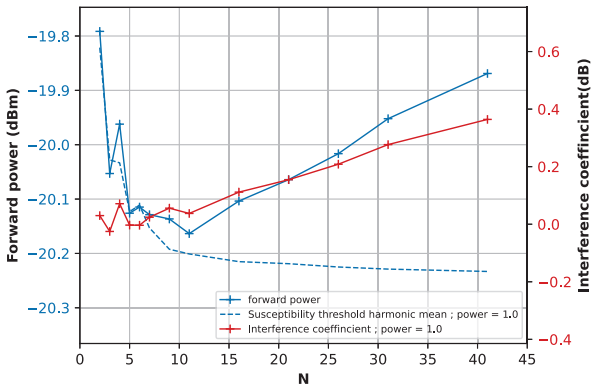
Fig. 4 presents multitone results for AD8601ARTZ with a $5mV$ offset failure criterion for different values of N. The frequency range is divided into four sub ranges. After tuning the a parameter, $I = 1$ with less than 1 dB error. This becomes less true for high N values, as peak power increases,



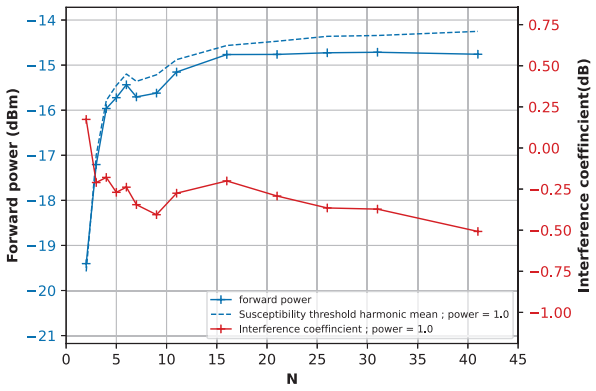
(a) Frequency range : 10 MHz - 45 MHz



(b) Frequency range : 45 MHz - 100 MHz



(c) Frequency range : 100 MHz - 450 MHz



(d) Frequency range : 450 MHz - 1 GHz

Fig. 4: AD8601ARTZ interference coefficient and susceptibility threshold to multitone disturbance vs N for 5 mV offset

inducing a strong non-linear distortion of the op-amp. Hence the parameter N is limited and a balance is necessary for frequency band selection as it must be sufficiently large to accelerate characterisation, and sufficiently narrow to avoid missing sensitive frequencies. CW susceptibility threshold variations over the frequency range induce scale differences. Results are similar for LMV721M5.

C. Disturbance superposition principle's offset dependence

Reference [6] mentioned that the disturbance superposition principle works for small offset value. Then, offset selected as failure criterion should be chosen cautiously. Fig. 5 presents multitone interference coefficient vs N for AD8601ARTZ op-amp on frequency range 450 MHz - 1 GHz. The higher is the offset value, the smaller is the N number when a strong non-linear distortion of the op-amp appears. A balance is required as a low offset is more difficult to detect or imply greater uncertainties.

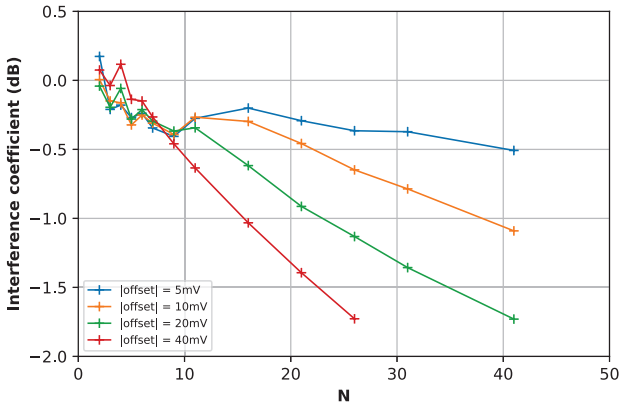
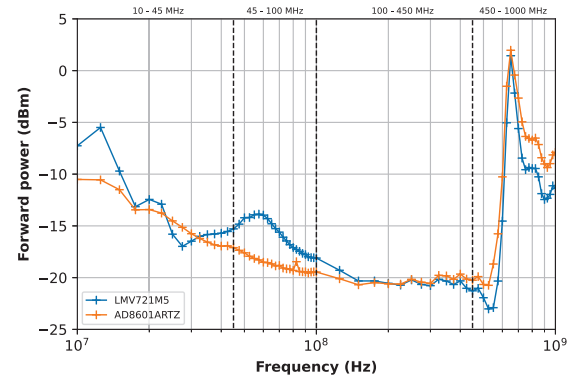


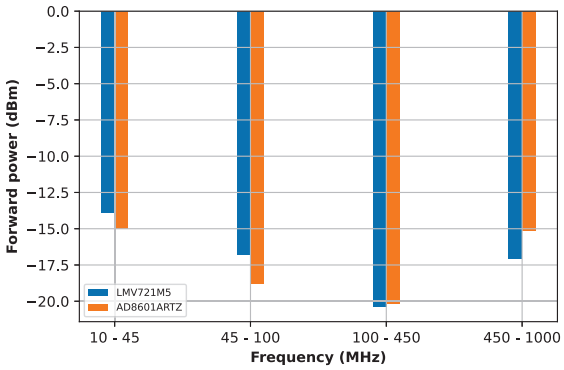
Fig. 5: AD8601ARTZ interference coefficient vs N for different offset values on frequency range 450 MHz - 1 GHz

V. Comparison of CW and multitone results

Without directly investigating EMC level drift (e.g. caused by IC ageing), the results for the two op-amps are compared to see the impact of CW measurements differences on multitone measurements. Fig. 6 presents a comparison between CW and multitone disturbance results for the two op-amps. Considering the previous analysis, a value of $N = 11$ is selected with a failure criterion of $5mV$ offset. On the four frequency ranges, CW differences induce a difference on the average multitone level which correspond to a generalised harmonic mean of the CW susceptibility threshold as $I = 1$. The susceptibility ranking is conserved as AD8601ARTZ is less robust than LMV721M5 on the two first frequency ranges, AD8601ARTZ is approximately as robust as LMV721M5 on the third frequency range and AD8601ARTZ is more robust than LMV721M5 on the last frequency range.



(a) Continuous wave results



(b) Multitone results

Fig. 6: AD8601ARTZ and LMV721M5 CW and multitone susceptibility results for 5 mV offset and $N = 11$

VI. Discussion

Multitone susceptibility testing cannot replace CW measurement because of the lack of information on sensitive frequencies. However, when a disturbance superposition principle exists, multitone disturbance tests allow to reduce characterisation time of recurrent tests, for example required to follow a drift of susceptibility level during a accelerated aging test. Fig. 7 presents the global characterisation flow presented in the article. Multitone susceptibility tests are based on a first CW test and an initial analysis to find for which parameters the disturbance superposition principle applies. A tuning step is then required to obtain a satisfactory relation between CW and multitone test. After this preliminary study, multitone injection can be used for periodic characterisation.

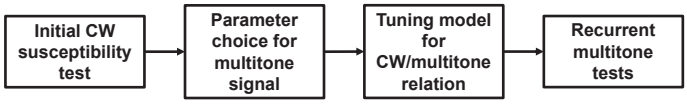


Fig. 7: Global characterisation flow

Despite the lack of a more advanced study dedicated to time saving, a first estimation can be done to compare CW and multitone injection methods. If, for example, an CW susceptibility test is performed on 30 samples (for statistical analysis), with 73 frequency points (as in this paper), with

5 incident power values for each frequency (considering an initial study as been performed, reducing the research scope for the susceptibility threshold) and with a dwell time of 2 seconds for each measurement, the total measurement time is approximately 6 hours. If the same test is performed with a multitone strategy, reducing the 73 frequency points to 4 frequency ranges, the total measurement time is reduced to approximately 20 minutes. Hence, even though additional considerations are required, this gives a first estimation of the methodology impact on work scheduling and EMC level drift detection.

VII. Conclusion

This paper has presented a large band disturbance injection approach on a DPI setup to efficiently perform susceptibility tests. This method can't replace Continuous Wave tests but, at the cost of an initial study, it can be used to reduce characterisation time of periodic tests in industrial context such as software update handling or ageing impact monitoring. It is likely to be extended to other type of analog components, digital components or entire systems. The experiments should be extended to other op-amps in future studies.

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