DIGITAL MODELLING TEST TECHNIQUE FOR MIXED MODE CIRCUITS

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Specially dedicated to

My beloved parents and sisters My Xiao Tian Xin, Yen Nee

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ABSTRACT

Recent demands in mobile communications, process control, automotive ASICs and smart sensors has accelerated the mixed-signal market and escalated the importance of mixed-signal test development. Mixed-signal circuit or mixed mode circuit is normally tested separately based on their core function. However, there is no guarantee that such testing approach would ensure that the system would function perfectly as a single entity. The main objective of this research is to investigate the application of digital modelling testing technique on mixed mode circuits. Digital modelling test technique is a method in which the test vector is simplified as a digital test vector. The investigation examined the suitable defect models as well as test procedures. The research also investigates the effectiveness of employing power supply voltage control (PSVC) testing technique together with the digital modelling. The reason of this test approach is due to independent reports of the effectiveness of these two test techniques. The circuit under test in this work includes a second order Butterworth low pass filter, an ADC and an op-amp. These circuits were chosen to represents a family of mixed – analogue and digital circuits. For comparison purpose, the ADC was tested using code density or histogram test technique. An analysis at bias point is presented to highlight why certain defects are exposed while others are not. The overall results showed that digital modelling test technique is able to model and expose unified analogue and mixed-signal faults. This is supported by the results from testing on discrete and CMOS circuitries. PSVC test coupled with digital model and pulse sampling can increase fault coverage for digital modelling test technique. The main advantages of digital model are it can reduce test time and eliminate circuit partitioning test.

ABSTRAK

Keperluan kini dalam bidang telekomunikasi mudah-alih, kawalan proses, ASICs untuk automotif dan penggesan pintar telah mempercepatkan pasaran isyarat bercampur dan merangsangkan kepentingan bidang perkembangan pengujian isyarat bercampur. Litar isyarat bercampur atau litar mod bercampur adalah diuji secara berasingan mengikut kepada fungsi dasarnya. Bagaimanapun, kaedah pengujian ini tidak dapat memastikan bahawa sistem yang diuji akan berfungsi dengan baik seperti dalam satu unit. Objektif utama dalam penyelidikan ini adalah untuk menyiasat aplikasi teknik pengujian permodelan digit bagi litar isyarat bercampur. Teknik pengujian permodelan digit adalah satu penyelesaian dimana vektor-vektor pengujian disimpifikasi kepada vektor-vektor digit. Kajian ini memeriksa kesesuaian model kecacatan dan prosedur pengujian. Penyelidikan ini juga menyiasat keberkesanan dalam penggunaan teknik pengujian pengawalan voltan bekalan kuasa (PSVC) berserta dengan teknik pengujian permodelan digit. Ini adalah berdasarkan kepada laporan berasingan tentang keberkesanan kedua-dua teknik pengujian. Litar-litar dalam pengujian untuk kerja ini adalah termasuk penapis laluan rendah Butterworth peringkat kedua, penukar analog kepada digit dan penguat operasian. Litar-litar ini dipilih untuk mewakili keluarga litar bercampur – litar-litar analog dan digit. Untuk tujuan perbandingan, penukar analog kepada digit diuji menggunakan densiti kod atau teknik pengujian histogram. Analisis kepada titik bias dipersembahkan untuk menunjukkan kenapa sesetengah kecacatan dapat dikesan dan yang lainnya tidak. Keseluruhan keputusan menunjukkan bahawa teknik pengujian permodelan digit adalah berkebolehan untuk memodel dan mengesan kecacatan kesatuan litar analog dan isyarat bercampur. Ini disokong dengan keputusan pengujian litar diskrit dan CMOS. Teknik PSVC bersama-sama dengan permodelan digit dan persampelan dedenyut dapat meninggikan liputan kecacatan teknik pengujian permodelan digit. Kebaikan utama teknik pengujian permodelan digit adalah ia dapat menggurangkan masa pengujian dan menggelakan pengujian litar secara pengagihan.

TABLE OF CONTENTS

CHAPTER

1

TITLE

PAGE

TITLE	i
DECLARATION	ii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	V
ABSTRAK	vi
CONTENTS	vii
LIST OF TABLES	xii
LIST OF FIGURES	XV
LIST OF SYMBOLS	xvii
LIST OF APPENDICES	XX
LIST OF PUBLICATIONS	xxi

INTRODUCTION11.1Background and motivation11.2Problem statement41.3Objective51.4Goal51.5Scope51.6Thesis layout6

LITERATURE REVIEW

2.1	Analogue and mixed mode IC test	8
	2.1.1 Importance of IC test	8
	2.1.2 Functional test versus parametric	9
	test	
2.2	Specification-based analogue and	10
	mixed-signal IC test	
	2.2.1 DC parametric test (analogue	11
	portion)	
	2.2.1.1 Leakage test	11
	2.2.1.2 Impedance measurement	11
	2.2.1.3 Offset measurement	12
	2.2.1.4 Gain measurement	13
	2.2.1.5 Power supply rejection	13
	ratio	
	2.2.1.6 Common-mode rejection	14
	ratio	
	2.2.2 DC parametric test (Digital	14
	portion)	
	2.2.2.1 I_{IH}/I_{IL} measurement	14
	$2.2.2.2 V_{IH}/V_{IL}$ measurement	14
	$2.2.2.3 V_{OH}/V_{OL}$ measurement	15
	$2.2.2.4 I_{OH}/I_{OL}$ measurement	15
	$2.2.2.5 I_{OSH}/I_{OSL}$ (short circuit	15
	current) measurement	
	2.2.3 AC parametric test (analogue	16
	portion)	
	2.2.3.1 Gain and level tests	16
	2.2.3.2 Phase tests	17
	2.2.3.3 Distortion tests	18
	2.2.3.4 Signal rejection test	19

8

	2.2.3.5 Crosstalk	20
	2.2.3.6 Noise tests	21
2.3	Defect-oriented testing technique	21
	2.3.1 Supply current monitoring test	22
	technique	
	2.3.1.1 Quiescent supply current	22
	test (I _{DDQ} test)	
	2.3.1.2 Dynamic/ Transient power	23
	supply current test (I _{DDT}	
	test)	
	2.3.2 Power supply voltage control test	23
	technique	
	2.3.3 Transient response testing (TRT)	24
	Technique	
	2.3.4 Digital modelling test technique	26
2.4	Conventional ADC test technique (using	26
	statistical data processing method)	
	2.4.1 Histogram/ code density test	27
	2.4.1.1 Linear ramp histogram	27
	approach	
	2.4.1.2 Sinusoidal histogram	28
	approach	
	2.4.2 Other conventional ADC testing	28
	techniques	
	2.4.2.1 Sine wave curve-fitting test	28
	2.4.2.2 ADC spectral test	29
	2.4.2.3 Output response	30
	transformation	
	2.4.3 Static ADC measurements	30
	2.4.3.1 DC gain error	30
	2.4.3.2 DC offset error	31
	2.4.3.3 Differential Nonlinearity	32
	(DNL) error	

	2.4.3.4 Integral Nonlinearity (INL)		32
	error		
2.5	Fault model		34

3	3.1	Project introduction	36
3	3.2	Project approach	37
		3.2.1 Project flow	37
		3.2.2 Fault model	39
		3.2.3 Faulty and fault free	42
		3.2.4 Test frequency	42
3	3.3	Circuit under test (CUT)	43
		3.3.1 Second-order low pass filter	43
		3.3.2 3-bit flash ADC	46
		3.3.2.1 Digital modelling test	48

RESEARCH METHODOLOGY

	3.3.2.1 Digital modelling test	48
	technique	
	3.3.2.2 Code density/ histogram	49
	test	
	3.3.2.3 Power supply voltage	50
	control test coupling with	
	digital modelling test	
	technique	
	3.2.3.4 Pulse transition sampling	50
	3.3.3 Operational Amplifier (Op-Amp)	51
3.4	Mathematical calculation and applied	52
	tools	
	3.4.1 Sallen-key low pass filter	52
	3.4.2 Histogram test technique (ramp	53
	input)	

analysis

4	RESULT AND DISCUSSION	59
	4.1 Active analogue filter	59
	4.1.1 CUT with unity gain	59
	4.1.2 CUT with non-unity gain	65
	4.2 3-bit Flash Analogue-to-digital converter	70
	4.3 Differential Op-Amp	79
5	CONCLUSION, FUTURE WORK AND	88
5	SUGGESTION	00
	5.1 Conclusion	88
	5.2 Future Work and suggestion	89
	REFERENCES	91
	APPENDIX A	96
	APPENDIX B	105
	APPENDIX C	106
	APPENDIX D	107
	APPENDIX E	108
	APPENDIX F	109
	APPENDIX G	117
	APPENDIX H	129

LIST OF TABLES

TABLE	NO.
--------------	-----

TITLE

PAGE

Characteristics comparison between functional	10
and parametric test	
Various signal to noise and distortion formula	18
The tradeoffs for different ADC functional testing	29
techniques	
Configurations of PSVC test coupling with	50
Digital modelling test technique	
Experimental result for low pass filter testing	61
Fault coverage for hard short and open faulty	62
component (experimental)	
Fault coverage for CUT with $gain = 11$	65
Fault coverage for undetected faults in 2 nd , 3 rd , 5 th	69
and 7 th cutoff harmonics	
Fault coverage for large resistive short fault in	70
resistor string module	
Fault coverage for large resistive short fault in	70
comparator module	
Fault coverage for large resistive short fault in	71
encoder module	
Fault coverage for narrow open fault in resistor	72
string module	
Fault coverage for narrow open fault in	72
comparator module	
	 and parametric test Various signal to noise and distortion formula The tradeoffs for different ADC functional testing techniques Configurations of PSVC test coupling with Digital modelling test technique Experimental result for low pass filter testing Fault coverage for hard short and open faulty component (experimental) Fault coverage for CUT with gain = 11 Fault coverage for undetected faults in 2nd, 3rd, 5th and 7th cutoff harmonics Fault coverage for large resistive short fault in resistor string module Fault coverage for large resistive short fault in encoder module Fault coverage for narrow open fault in resistor string module Fault coverage for narrow open fault in

4.10	Fault coverage for short-to- V_{GND} fault in resistor	73
	string module	
4.11	Fault coverage for short-to- V_{GND} fault in	73
	comparator module	
4.12	Fault coverage for short-to- V_{GND} fault in encoder	73
	module	
4.13	Fault coverage for short-to- V_{DD} fault in resistor	73
	string module	
4.14	Fault coverage for short-to- V_{DD} fault in	73
	comparator module	
4.15	Fault coverage for short-to- V_{DD} fault in encoder	73
	module	
4.16	Change in the operating region of faulty transistor	75
	when fault is introduced	
4.17	Fault coverage for each defect at different	78
	observing points	
4.18	The change of the CUT's operating points for	79
	exposed defects	
4.19	Result of faulty device/node (with large resistive	80
	short) and their characteristics	
4.20	Result of faulty device/node (with narrow open)	81
	and their characteristics	
4.21	Result of faulty device/node (with short-to- V_{DD})	82
	and their characteristics	
4.22	Result of faulty device/node (with short-to- V_{GND})	82
	and their characteristics	
4.23	Faults which do not change the CUT operating	83
	points at all	
4.24	Faults unable to propagate to the output	83
4.25	Result of faulty device/node (with large resistive	84
	short) and their characteristics	
4.26	Result of faulty device/node (with narrow open)	84
	and their characteristics	

4.27	Result of faulty device/node (with short-to- V_{DD})	85
	and their characteristics	
4.28	Result of faulty device/node (with short-to- V_{GND})	85
	and their characteristics	
4.29	Output level versus minimum applied load	86

LIST OF FIGURES

FIGURE NO.

TITLE

PAGE

1.1	ABM of an output pin	2
1.2	Chip structure	2
2.1	Basic PSR and PSRR setup	20
2.2	Channel to channel crosstalk	20
2.3	Comparator and its Karnaugh map	26
2.4	Gain error for a linear 3-bit ADC after offset	31
	error correction	
2.5	Offset error for a bipolar ADC	31
2.6	Transfer function for DNL error	32
2.7	Transfer function for INL error	33
2.8	Analogue and mixed mode circuit catastrophic	35
	fault model	
3.1	Project Flowchart	38
3.2	Applied fault models	39
3.3	Hard fault introduces to a discrete CUT	40
3.4	Resistive fault introduces to a CMOS CUT	41
3.5	Experiment setup for low pass filter	44
3.6	Low Pass Filter schematic for experiment	44
3.7	LPF with $A_V = 11$ and $f_{cutoff} = 10$ -kHz	46
3.8	3-bit ADC (Netlist and full schematic show in	47
	Appendix A and B)	
3.9	3-bit ADC block diagram	47
3.10	Fault free signatures for ADC with different	49

initial logic

	lilitiai logic	
3.11	Open-loop Op-Amp tests by Digital modelling	51
3.12	General Sallen-Key low pass filter	52
3.13	GUI for bias point analysis	56
3.14	Bias point analysis flow chart	57
4.1	Faulty and fault free response for Node 2 (at 1	60
	kHz test frequency)	
4.2	Transient response for faulty R2 (at 1 kHz test	63
	frequency)	
4.3	The output responses of R ₂ open circuit	65
4.4	Faulty responses (R3-hard short and R4-hard	66
	open) in transient time	
4.5	Faulty responses (R3-hard short and R4-hard	67
	open) in frequency domain for low pass filter	
	with fault free gain, $Av = 11$	
4.6	Undetected output response for low pass filter	68
	with gain, $Av = 11$	
4.7	Output signature of M ₂₇₈ for fault free and	74
	faulty transistor	
4.8	Distribution of V_{GS} and V_{DS} for Digital	77
	modelling test (with initial stimuli logic 0) for	
	faulty transistors	
4.9	Op-Amp fault free response	80
4.10	Undetected Op-Amp faulty response	87
5.1	Microcontroller based digital tester	90

LIST OF SYMBOLS

ASIC	-	Application Specified Integrated Circuit	
PGA	-	Programmable Gain Amplifier	
GUI	-	Graphic User Interface	
LPF	-	Low Pass Filter	
ADC	-	Analogue to Digital Converter	
DAC	-	Digital to Analogue Converter	
PLL	-	Phase locked Loop Circuit	
SoC	-	System on Chip	
MCM	-	Multi Chip Module	
DfT	-	Design for Test	
BisT	-	Build in self Test	
IEEE	-	Institute of Electrical and Electronics Engineer	
SPICE	-	Simulation Program with Integrated Circuit Emphasis	
VHDL	-	Verilog High Description Language	
V _{o-cm}	-	Common-mode offset	
V _{os}	-	Input offset voltage	
PSS	-	Power supply sensitivity	
ΔV_{O}	-	Rate of change output voltage	
ΔPS^+	-	Rate of change positive power supply	
ΔPS^{-}	-	Rate of change negative power supply	
PSRR	-	Power supply rejection ratio	
CMRR	-	Common-mode rejection ratio	
$G_{\scriptscriptstyle CM}$	-	Common-mode gain (DC)	
$G_{\scriptscriptstyle D}$	-	Differential gain (DC)	
V_{CM}	-	Common-mode signal	
\mathbf{I}_{IH}	-	Input leakage current, logic high	

I_{IL}	-	Input leakage current, logic low
\mathbf{V}_{IH}	-	Input high voltage
\mathbf{V}_{IL}	-	Input low voltage
V _{OH}	-	Output high voltage
V_{OL}	-	Output low voltage
I _{OH}	-	Output high current
I _{OL}	-	Output low current
I _{OSL}	-	Current flowing into the pin
I _{OSH}	-	Current flowing out of the pin
Re	-	Real part
Im	-	Imaginary part
τ (f)	-	Group delay
$G_{cm}(f)$	-	Common-mode gain (AC)
$G_{diff}(f)$	-	Differential gain (AC)
X _{rl}	-	Channel's input
X_{lr}	-	Channel's output
ICN	-	Idle channel noise
INL	-	Integral Nonlinearity
DNL	-	Differential Nonlinearity
ω _o	-	Angular applied frequency
FFT	-	Fast Fourier Transform
I _{DDQ}	-	Quiescent current
I _{DDT}	-	Dynamic/Transient power supply current
PSVC	-	Power Supply Voltage Control
TRT	-	Transient Response Test
CV	-	Coefficient Variation
PRBS	-	Pseudorandom Binary Sequence
LFSR	-	Linear Feedback Shift Register
DM	-	Digital modeling
Op-Amp	-	Operational Amplifier
H(s)	-	Transfer function
K	-	Filter gain
ω_{π}	-	Natural frequency

Q	-	Quality factor
ξ	-	Damping ratio
Y	-	Detectable
Ν	-	Not detectable
D	-	Drain open
S	-	Source open
G	-	Gate open
**	-	No repetition
D-S	-	Drain and Source terminal short
G-D	-	Gate and Drain terminal short
G-S	-	Gate and Source terminal short
^	-	Fault detected at (500.06-500.24) us
Θ	-	Fault detected at (1.00002-1.00015) ms
@#	-	Analogue modules (resistor and comparator)
&#</td><td>-</td><td>Digital module (priority encoder)</td></tr></tbody></table>		

LIST OF APPENDICES

APPENDIX

TITLE

PAGE

А	3-bit ADC Schematic Netlist	96
В	3-bit ADC Full Circuitry	105
С	Op-Amp Schematic Netlist	106
D	Op-Amp Full Circuitry	107
E	Histogram Test	108
F	MATLAB Scripts for Bias Point Analysis	109
G	Filter: short-to- V_{DD} and short-to- V_{GND}	117
Н	Filter: hard open and hard short	129

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 Leong Mun Hon and Abu Khari bin A'ain. Simple Analogue Active Filter Testing Using Digital Modelling. *Proceeding of the 2003 Third Student Conference on Research and Development (SCOReD 2003).* August 25-26, 2003. UPM, Malaysia: IEEE. 2003. ELE-5/6.
 Leong Mun Hon and Abu Khari bin A'ain. An Investigation on ADC Testing Using Digital Modelling. *Proceedings of the 2004 IEEE Region-10 Conference (TENCON 2004).* November 21-24, 2004. Ching Mai, Thailand: IEEE. 2004. 245-249.
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CHAPTER 1

INTRODUCTION

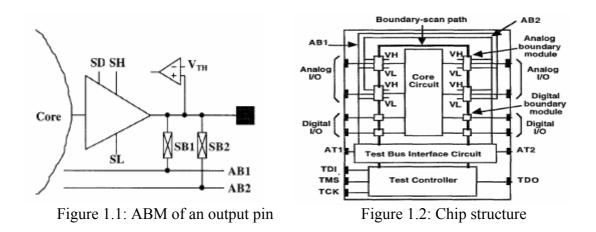
1.1 Background and Motivation

The trend towards the implementation of entire systems on chip and growing markets in mobile communications, process control, automotive ASICs and smart sensors has accelerated the mixed-signal market and escalated the importance of mixed-signal test development.

A mixed-signal circuit, or in generally mixed mode circuit, is defined as a circuit consisting of both digital and analogue elements in a single entity. Examples of basic mixed mode realm are CMOS analogue switch, programmable gain amplifier (PGA), analogue-to-digital converter (ADC), digital-to-analogue converter (DAC), phase-locked-loop (PLL), and other complex mixed mode circuits such as System-on-Chip (SoC), Application Specific Integrated Circuit (ASIC) and Multi-chip Module (MCM).

For the current IC trend - increase in the number of circuit nodes and circuit complexity, Design-for-Test (DfT) becomes the mainstream of mixed-signal test development in order to reduce test cost due to test pin limited. There are a variety of DfT and BisT techniques proposed for different mixed mode circuits. One of the current issues is to provide a consistent and structured framework for system-level and board-level test development, and for DfT approaches. Hence, IEEE 1149.4-1999 was born.

Nowadays, many high density and complex mixed mode circuits, for example SoC and MCM, come out with built-in boundary scan path as defined by IEEE 1149.4-1999 (Mixed Signal Test Bus Standard). Under this standardization, digital and analogue circuits are separately in testable modules, called Digital Boundary Module (DBM) and Analogue Boundary Module (ABM). All of these modules enclosed by internal and external test path, and external access by separate test pin. Actually, this standard is a complementary of IEEE 1149.1-1990, and gains extra features (such as ABM, the analogue test bus, an extended Test Access Port (ETAP) and controller, and various register for analogue test bus operation). Figure 1.1 shows the ABM for an analogue pin [1], and Figure 1.2 shows IEEE P1149.4 basic chip structure [2].



However, for those basic cores of mixed mode circuit, such as ADC, DAC, PLL and PGA, each realm has its own test technique differently implemented to and seldom compliance with 1149.4 cells. For example ADC, the conventional test technique used commonly at industry is Code Density test technique or simply Histogram test. Besides, there is still a lot of mixed-signal ASICs that do not facilitate with boundary scan due to trade off with area overhead.

Although analogue circuits such as filter and Op-Amp are widely used in the market and possessed with their own separated conventional functional test (specification-oriented testing), it is much more complex for test development with

the same implementation when the input and output share the same signal transmission in mixed mode environment.

In today's highly competitive semiconductor world, it is critical to reduce the actual test time on expensive automatic test equipment (ATE). Test time on highend mixed-signal tester costs about three to five cents per second [3]. Due to this, most commercial mixed mode ICs are tested by separate testers (digital tester and analogue tester). Mixed-signal tester generally comes in variety of architectures and test routines depend on vendors due to competitive advantage in the market. However, many of these testers consist of useful features that are common among each other.

Test simulation and defect-oriented testing are the two among other cost saving test methodology emerging trends for mixed-signal IC [4]. Test simulation promises the ability to simulate and debug the test program for tester and CUT developed by SPICE, VHDL or others software-modelling languages before actual silicon CUT is received. Defect-oriented testing is based on the mathematical analysis and software modelling of a circuit major failure mechanism that expose the failures in a limited set of measured parameters [4]. Both of these methods not only cut down the production test cost, but also accelerate the time to market for certain product.

Because of a lot of information can be abstracted directly from transient response of a CUT, test researchers work with transient response almost for a decade [5–10], they proposed that analogue and mixed mode CUTs could be unified test by Transient Response analysis with Pseudo Random Binary Sequence (PRBS). The output data are then analyzed and processed using mathematical calculation, such as Sample values, Rate of change, Auto-correlation and Cross-correlation and Response Digitisation. Further studies and researches on Transient Response analysis can be found in [11–22]. They proposed a DfT method - Interface Scan bus in CUT in order to increase fault coverage especially for particular fault. Besides, they categorized any detectable fault using generated Index Functionality from cross-correlation function for the CUT.

1.2 Problem Statement

The number of mixed-signal circuit blocks of an IC is getting more and more. High-density CMOS transistors and limited pin count in mixed-signal chips become a test challenge to semiconductor industry. This will either increase time-to-market or face the risk of decrease quality during early production.

DfT and BisT approach are getting popular in many testing arena. However, with the extra pin overhead and add in extra register, for example DfT approach, cost development increase and die space become limited for application. Besides, for example in BisT approach, extra bus and block partitioning is needed. Then, analogue block and digital block have to be tested separately, and this includes also block interface testing. All of these increases production cost if production volume is in medium or lower scale. According to [23] and [24], the IC designs with a 200 μ m pad-pitch, pad limited layout and no boundary scan, adding IEEE P1149.4 test bus and controller will increase the cost by 15-30%, especially for low cost mixed mode ICs (< \$2) and low pin count (< 60 pins) ICs will increase the design cost dramatically.

In semiconductor industries, cost for a mixed-signal tester in the market is very expensive compared to digital tester or analogue tester alone. Test time increases if customer tests their product using both analogue and digital testers concurrently. Normally, this ATE is in giant size and not portable. This lead to profit losing if opponent can reach to market earlier. However, most IC industries are accommodated with digital tester. A defect-oriented testing technique, which facilitate the mixed-signal test with minimum modification or make use of digital tester, will be welcomed.

Therefore, the main questions being addressed in this research work are:

- a) Is it possible to integrate analogue and digital test as a single entity?
- b) Would digitally modelled analogue test help to ease mixed mode test?

1.3 Objective

The objectives of this project are:

- a) To facilitate mixed mode circuit test using digital modelling of analogue circuits.
- b) To study the feasibility of introducing digital modelling coupled with other test techniques to ease mixed mode test.

1.4 Goal

The goals of the project are:

- a) To investigate the effectiveness of digital modelling.
- b) To detect faults in mixed mode circuit in transient domain.
- c) To unify tests of mixed mode circuit.

1.5 Scope

The scope of the project is as listed below:

- a) To study the idea of digital modelling for analogue circuit.
- b) To study the idea of Power Supply Voltage Control test technique.
- c) To study and analyse characteristics of analogue active filter in discrete level.
- d) To test a second order Butterworth low pass filter based on experimental and simulation using digital modelling coupled with Power Supply Voltage Control test technique.
- e) To test a flash ADC using digital modelling and Power Supply Voltage Control test techniques, and compare the result to Code Density or Histogram test technique.
- f) To test a CMOS Op-Amp at transient level and AC Sweep by digital modelling coupled with Power Supply Voltage Control test technique.

1.6 Thesis Layout

Basically, this thesis can be divided into five chapters as stated below

- a) Introduction
- b) Literature review
- c) Research methodology
- d) Results and discussion
- e) Conclusion, future work and suggestion

The first chapter gives a brief description of the work and thesis. It includes explanation on mixed-signal background and motivation, as well as the project objectives, goals and scopes.

In the second chapter, the importance of mixed-signal testing and digital modelling test technique is described as well as the different between functional test and parametric test. Literature review on defect oriented tests and, some conventional analogue and mixed-signal parametric tests are also discussed in this chapter. Histogram test, which special to ADC- mixed mode circuit, is also briefly described in this section.

The methodology of the overall project is explained in detail in chapter three. The project approach as well as simulation using PSpiceTM is described. Three CUTs as sample study are presented in this chapter. For discrete analogue filter test, explanation is given on how to set up the experimental work that include setting up the equipment, as well as simulation work. Simulation an Op-amp and 3-bit flash ADC are carried at CMOS transient level. Explanation on how to conduct the test in simulation is discussed.

In chapter four, result as well as discussion for the CUT are discussed and analysed. Selected transient and frequency response for discrete analogue filter will be looked in detail. For flash ADC, transient response and bias point analysis as well as Histogram test will be discussed. CMOS bias point for Op-amp as well as transient and frequency response will be collected and analyse. The bias point analysis is based as MATLABTM test program. All the results, which digital model coupled with PSVC technique, are also collected and will be analysed in this chapter.

Finally, in the last chapter, Chapter five, a conclusion will be drawn along with the suggestion for future development in this subject.

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