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SCA METHOD BASED ON QUALITATIVE SIMULATION

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ABSTRACT

It is an effective method to use qualitative reasoning theory to realize sneak circuit analysis (SCA). The method using qualitative modeling combined with functional simulation to realize sneak circuit analysis. The qualitative models of resistive element, switch, transistor, MOS pipe, digital devices, analog devices, mechanical devices and other types of components were established and the qualitative simulation process was studied. Self-developed QSCA software (qualitative simulation-based sneak circuit analysis) is applied to analyze typical cases and verify the technical correctness. The result shows that this method could provide technical support for the system to find sneak circuit problems at the early design stage and it can also be used in the field of fault modes and effects analysis.

Keywords: *Sneak Circuit Analysis (SCA), qualitative simulation, qualitative modeling*

1. INTRODUCTION

Sneak circuit refers to the phenomenon of the system generating (or inhibiting) non-desired functions (or desired functions) under certain conditions. It is difficult to detect the phenomenon with conventional detection method and reliability analysis method due to its deep concealment and latency, sneak circuit will cause great harm to the system once it is stimulated, so SCA is carried out in many critical systems.

There are two main methods available for Sneak Circuit Analysis (SCA): comprehensive sneak circuit analysis method and simplified sneak circuit analysis method [1-2]. The former uses network tree generation tool to generate network forest data after the network system division and simplification, and then apply clue sheet to conduct sneak circuit analysis (SCA). This analysis method is comprehensive and complete, but requires huge workload and high costs. The latter is a simplified method that developed on the basis of comprehensive sneak circuit technology, which is based on the analysis of sneak circuit problems of key components and modules. Simplified sneak circuit analysis does not need to generate the network tree, but employ the method of taking the key points to search critical paths instead, and then conduct Sneak Circuit Analysis (SCA) for the critical path by applying suggestive clues table about important components or combinations. Simplified SCA method employs more computer-aided analysis ingredients in data input, automatic prompt of clues and other aspects to reduce manual workload and cut down the cost of analysis. Both methods conduct analysis on the basis of clue table, but clue table can not be completed within the short-term, because it is a summary and refinement of a lot of experience and lessons of system design and testing. Hence, it is learned that Boeing Company has to spend 15 years in establishing a more comprehensive and rich clue table. On the basis of these two methods, some other analysis methods are studied now [3-6], such as analysis based on neural network, network flow simulation, topological patterns identification and so on.

Qualitative simulation is a reasoning simulation technology depending on qualitative model and system topology connection diagram [7-8]. Weighted resistor network diagram obtained from qualitative modeling could abstract and simplify network characteristics and simulate operation

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behavior of devices. Thus, this paper establish a qualitative model of the circuit and effectively combine with functional model of the system for the realization of SCA so as to provide technical support for the system finding sneak circuit problems at the early design stage by reference to the idea of qualitative simulation to.

2. QUALITATIVE MODELING

Qualitative modeling is an abstract reflection of the structure and features of the problem areas to a certain extent. According to different goals and needs, there are many modeling methods and different forms of models, mainly including qualitative modeling based on amount space, qualitative physical modeling based on acausal category, modeling based on qualitative causal relationship, qualitative modeling using state transition probabilities and et al [9]. In this paper, modeling method based on qualitative causal relations was employed to simplify and abstract physical characteristics of the components, "port", "node" and "control law" are adopted to describe the impact and interaction between variables.

For the working condition of the device, the model uses State field for characterization, with numerical range [active, inactive] respectively characterizes on / off the branch circuit.

Most simple devices and complex devices can construct qualitative resistor network with 0, L (0 <L <∞), ∞ as weight values by virtue of establishing its internal network topology and variable table. 0, L (0 <L <∞), ∞ respectively represents the short circuit, load and open state of the device, which could effectively describe physical properties of the system in Sneak Circuit Analysis (SCA). This paper described qualitative modeling methods of several different types of devices.

1) Simple switch device modeling

For most of two-pin analog devices, only one qualitative parameter value can characterize working condition of the device. Such as diodes, qualitative weight value is 0 in case of positive conduction; qualitative weight is ∞ in case of reverse-blocking. The qualitative modeling of fuses, resistors and SPST switch are similar to this condition.

2) Transistor

Semiconductor transistor is one of the most commonly used analog devices in analog circuit and also an important constituent element of many ICs. In NPN transistor, for example, NPN-type transistor equivalent weight resistor network derived from input and output switching curve of transistor is as shown in Figure 1 (a):

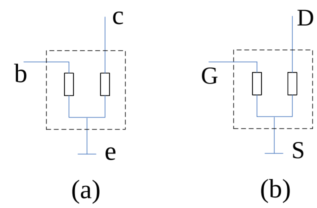

Figure 1 Weighted resistor network diagram of the model

The transistor has three different operating states, corresponding to three different combinations of device states as shown in Table 1:

Table 1 Qualitative Weight Table of Various Working States of Transistor

	Rbe	Reb	Rce
Cut-off state	∞	∞	∞
Magnifying state	L	∞	L
Saturated state	L	∞	0

3) MOS Transistor

N-channel enhancement-type MOS transistor is a semiconductor FET of the most common type. Controlled by threshold voltage between drain and source, FET may work in cutoff, amplification and fully conductive state.

Analysis by input-output characteristic curve of FET, weighted resistor network under amplification and fully conductive state could be expressed by the same qualitative resistance. Weighted resistor network is as shown in Figure 1 (b), corresponding qualitative resistance value is as shown in Table 2:

Table 2 Qualitative Weight Table of Various Working Status of N-channel Enhancement-type MOS Transistor

	Rgs	Rds
Cut-off state	L	∞
Conductive state	L	L

4) Digital Devices

Sneak circuit problem of pure digital system mainly refers to logical flow sneak circuit, requiring simulating various functions implemented by logic function of digital device. Qualitative simulation method has no outstanding advantages in dealing with such problems. However, for mixed analog-digital circuits, research on its modeling techniques has practical significance.

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Each input and output of digital device is set as "external node" of a device, expressed by NIn ×× and NOut××, these external nodes and other devices have state variables with interactive relationship, its causal relationship shall be described by “control law” which is established by the user. Causal relationships within the device shall determine the qualitative transfer function through logic function and truth table of digital devices.

Diode and gate, for example, the circuit diagram is as shown in Figure 2 [10]:

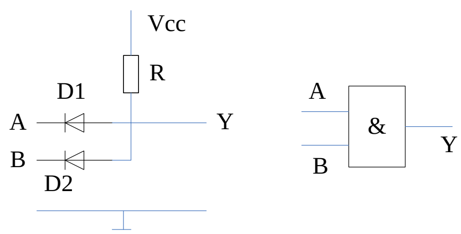

Figure 2 Diode And gate

Set three "external nodes" for this digital device, respectively NinA, NinB and NOutY. Qualitative value range of each node is [on, off], indicating different node status. Qualitative transfer function is:

NOutY =NInA·NInB

In which, "•" is qualitative “And” is equivalent to logic AND operation in logic algebra. Actual value of NinA and NInB depends on analog devices associated or external node value of other digital devices, the dependency is determined by “control law”, which is usually described in the format: If the control point status = [X], Then charged point (such as: NInA) status = [on] or [off].

5) Analog Integrated Circuits

In SCA analysis, qualitative modeling of such devices has two ways. First, based on the modeling idea of digital devices, but what is different is that qualitative value range of external node can have more options. However, interior the device, causal relationship described by performance function replaces qualitative transfer function established in compliance with logic algebra. The second is to study the function and internal structure of the device, use a qualitative abstract simple weight resistor network to simulate device behavior. When needed, internal state variables can also be established so that the description of the behavior of the device can be closer to the actual situation. The value range of external nodes is [0, L, ∞]. Normally-open relay, for example, as shown in Figure 3.

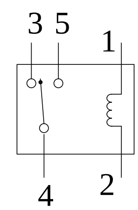

Figure 3 Qualitative Modeling Diagram of Normally Open Relay

When the coil is not energized, there is no current flowing through the coil, and the coil stays in non-operating state, qualitative weight value is ∞, the contact switch is engaged with normally-closed contact 3, qualitative weight between node 3 and node 4 is also 0, while qualitative weight between contact 5 and contact 4 is ∞; when coil winding is energized to work, qualitative weight is 0, the contact switch pull, contact 5 and contact 4 are conductive, qualitative weight becomes 0, weight between node 3 and node 4 also changed to ∞.

Another example, integrated operational amplifier. When ideal operational amplifier works in linear workspace, its input resistance is infinite, both inputs have "virtual short-circuit" and "virtual open-circuit” characteristics. Therefore, input current of the two inputs are 0, the net input voltage is 0; When it works in nonlinear state, differential-mode input resistance remains infinite, while the net input current is 0, but net input voltage is no longer 0. The output voltage is either positive maximum voltage or negative maximum voltage [11].

Qualitative model established on the basis of characteristics of integrated operational amplifier is shown as follows:

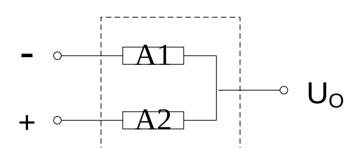

Figure 4 Qualitative Modeling Diagram of Integrated Operational Amplifier

Qualitative resistance in the figure: RA1 = ∞, RA2 = ∞.

6) Mechanical device modeling in the circuit

Modeling of such devices will first extract the main output physical characteristic quantity of mechanical devices and define as the port. Each characteristic quantity is a port, and each port may

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have multiple qualitative values depending on specific circumstances of devices. These port values as the input control quantities of electrical part which affect the behavior of circuit network through "control law".

For example, engine is used as implementation device, See Figure 5.

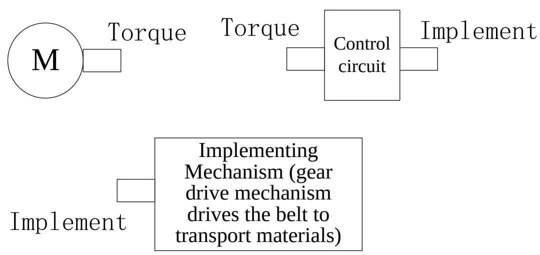

Figure 5 Mechanical Device Modeling Example

Physical characteristic quantity of engine is the forward/reverse rotation. The characteristic quantity defines the port Torque, port qualitative value range [left, right] respectively indicating forward/reverse rotation. The port value, by controlling electric network, output control signal on the port Implement in convergence with another executive mechanism. If Torque = left (forward), then Implement = on, gear transmission mechanism works, the belt began to transport materials.

7) Other devices

Due to the time delay factors for devices, it is required to add model parameters characterizing delayed time into qualitative modeling. Meanwhile, continuous time variables shall be expressed with qualitative time area. : 10ms, 5s, 1min. They are used to indicate the order of execution of various “control laws”, but do not represent the time in the true sense.

For some devices with memory functions, the next state values of them are not only dependent on the input value of the device, but also closely related to the previous state of the device. Their qualitative model need more than doubled amount of internal state variables to general model to simulate its law of behavior; this will not be elaborated here.

3. QUALITATIVE SIMULATION

On the basis of establishing qualitative model of different types of devices, qualitative simulation model of circuit may be formed by combining circuit topology. Function and behavior of the circuit system can be abstracted into a set of states of various constituent devices, and the system working state can be obtained through qualitative emulator simulating the system operation. Qualitative simulation-based SCA analysis is to report the state combination of undesired functions by applying similar behavior principles on the basis of qualitative simulation so as to help and identify sneak circuit. Qualitative simulation process is shown in Figure 6:

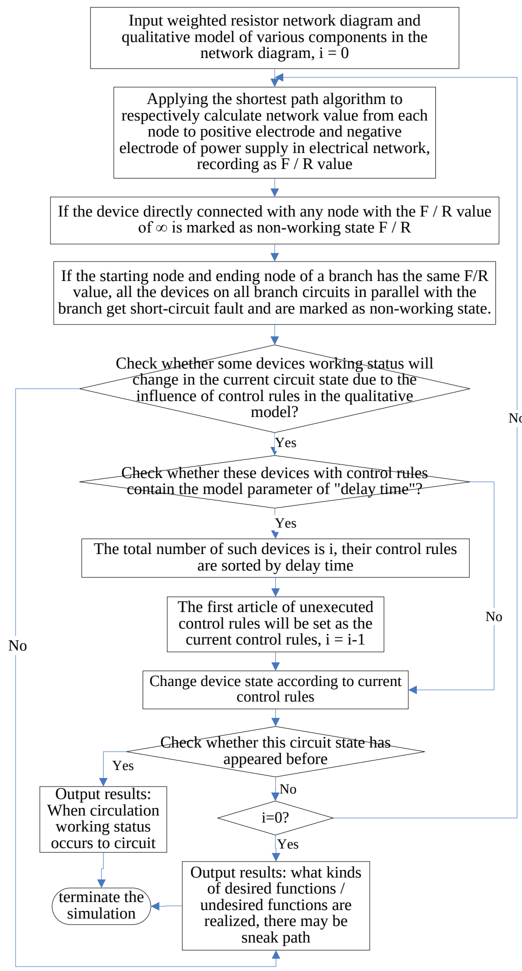

Fig. 6 Qualitative Simulation Flowchart

F/R value worked out in the second step in the process characterized the load number of the node to the power supply positive/negative pole. If a value of them is ∞, indicating that the load value of current circuit of the device to positive power or negative of power supply is infinite, the device does not work. If starting node and ending node of a branch have the same F/R value, they are equivalent to the same node on the branch, and the branch is in short-circuit status, all devices on all branches in parallel will stay in non-working state.

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4. CASE APPLICATION

Part of the circuit in automatic control system of an aircraft is as shown in Figure 7, for example, sneak analysis is as follows.

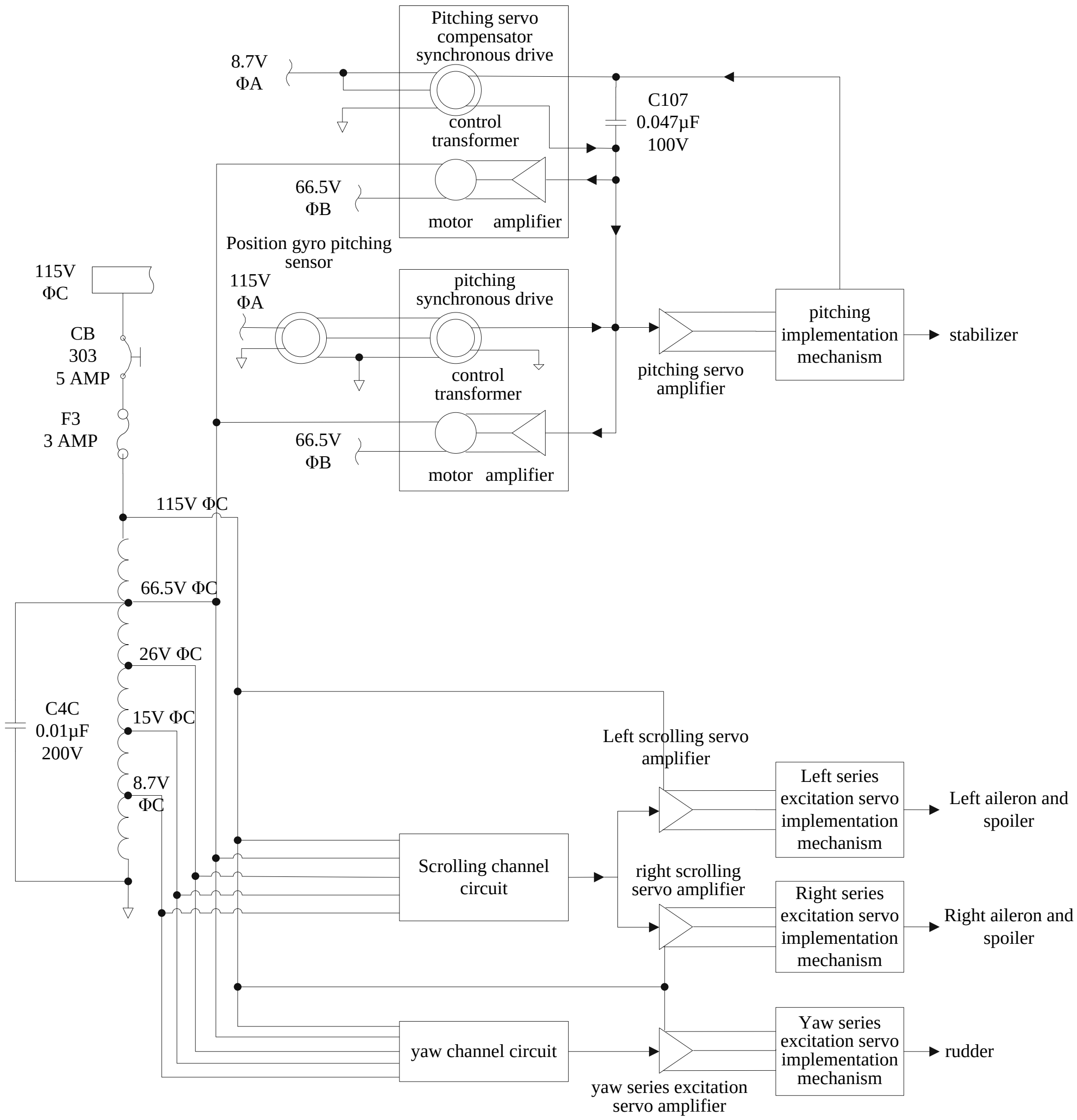

Figure 7 Part of the Circuit in Automatic Control System of an Aircraft

For the specific situation of various components, qualitative modeling for the above cases by applying the method described herein, qualitative modeling of some devices is as shown in Table 3, and the entire circuit is established with a weighted resistor network diagram after abstract and simplification, which is as shown in Figure 8.

Qualitative simulation shall first calculate f / r values of each node, shown in Table 4, marking status of each device shown in Table 5, and then change qualitative resistance of F3 to ∞ according to control law, some port value also changed according to "control law", thereby it is required to recalculate f/r value of each node and determine the working condition of the device until the work status does not change.

Above analysis shows that, C4C short-circuit fault will cause disconnection of all the power in the circuit diagram, resulting in yaw, roll and pitching channel failure in working, leading to serious consequences.

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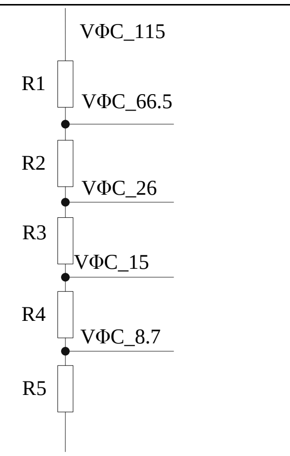
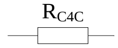
Table 3 qualitative modeling of control amplifier and capacitor

Device class	qualitative model			description
	resistor network diagram	description of resistance value	Control rules	
amplifier	…			
control amplifier	 VΦC_115, R1, VΦC_66.5, R2, VΦC_26, R3, VΦC_15, R4, VΦC_8.7, R5	R1=L R2=L R3=L R4=L R5=L	If R1 active Then VΦC_115 active; If R2 active Then VΦC_66.5 active; If R3 active Then VΦC_26 active; If R4 active Then VΦC_15 active; If R5 active Then VΦC_8.7 active;	Upper end of the device connects positive electrode of power supply, the lower end of the device earthing.
capacitor	R_{C4C} 	$R_{C4C}=0$		What is researched herein is short circuit failure that occurs to R_{c4c}

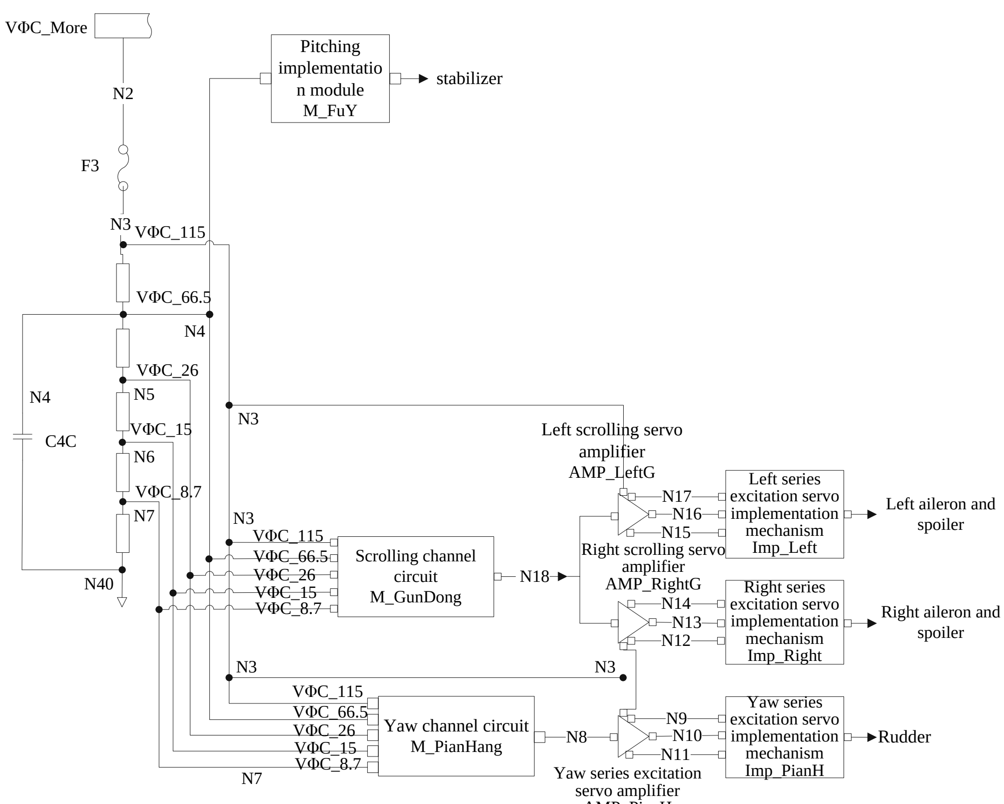


Figure 8 Weighted Resistor Network of the Circuit

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Table 4 f/r value of each node

node	N2	N3	N4	N5	N6	N7	N40
F/R value	0/L	0/L	L/0	2L/L	3L/2L	4L/L	L/0

Table 5 status of each device

SN	Device name		Device class	Work status		SN	Device name	Device class	Work status
1	F3		Fuse	Active		5	M_GunDong	Circuit module	active
2.1	AMP_Control	Rl	Qualitative Resistor	Active		6	AMP_PianH	amplifier	active
2.2		R2	Qualitative Resistor	Inactive		7	AMP_RightG	amplifier	active
2.3		R3	Qualitative Resistor	Inactive		8	AMP_LeftG	amplifier	active
2.4		R4	Qualitative Resistor	Inactive		9	Imp_PianH	Mechanical device	active
2.5		R5	Qualitative Resistor	Inactive		10	Imp_Right	Mechanical device	active
3	C4C		capacitor	active		11	Imp_Left	Mechanical device	active
4	M_PianHang		Circuit module	active		12	M_FuY	implementation module	active

5. CONCLUSION

Based on qualitative simulation, this paper establishes SCA analysis techniques method which can easily conduct SCA analysis in functional level of the system and thus has its unique advantages in the early design stage lack of detailed information. The method can not only save a lot of business costs of SCA analysis, but also solve circuit analysis problems encountered in simulation overflow of quantitative digital simulation. Meanwhile, qualitative modeling technique in the method can easily extend to qualitative automated FMEA (Failure Modes and Effects Analysis) in the field, which has a great application prospect.

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