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INTEGRATED CIRCUIT FOR MILITARY AND DEFENSE PURPOSES, SUPPORTING THE TESTING OF ANALOG CIRCUITS WITH USE OF BIST

Abstract

The increase in the number of electronic systems – just like in electronic military systems –, the increase of complexity, and the high demands of reliability and operation safety requires new error diagnostic methods. It is relatively simple testing by method of BIST (Built-In Self Test) the digital devices which are compatible to IEEE-1149.1 boundary scan standard. On the other hand, built-in self testing analogue or mixed signal circuits are difficult, or it is can't implement. In this paper I suggest to create an integrated circuit, or functional "building block", which can be controlled over IEEE-1149.1, and it is able to generate the current for measurement purposes, and to sense the produced voltage.

Az elektronikai rendszerek – és így a katonai elektronikai rendszerek – számának növekedése és összetettebbé válása, valamint a velük szemben támasztott megbízhatósági és üzembiztonsági követelmények teljesítése új hibadiagnosztikai módszerek alkalmazását teszi szükségessé. A peremfigyeléssel (IEEE-1149.1) rendelkező digitális áramkörök bevonása a beépített öntesztbe viszonylag egyszerűen megvalósítható. Ezzel szemben az analóg vagy kevert jelű áramkörök beépített öntesztbe vonása nem, vagy csak nehézkesen valósítható meg. Jelen cikkben javaslatot teszünk egy olyan integrált áramkör, illetve funkcionális egység létrehozására, amely IEEE-1149.1 peremfigyeléses buszon keresztül vezérelhető, és képes előállítani a kevert jelű áramkörök beépített önteszteléséhez a gerjesztő áramot, és mérni a válaszfeszültséget.

Keywords: *self test, mixed signal test, boundary scan, automatic testing ~ önteszt, kevert jelű teszt, peremfigyelés, automatizált tesztelés*

INTRODUCTION

The large part of the military and defense electronic devices and equipment not work at a fixed location, but they are mobile. These mobile devices the user brings to its destination, then uses (enjoying the benefits of mobility, such as hand or body-mounted operation), or may be temporarily installs them. A part of the field devices operates autonomously for some time (e.g unattended ground sensors), then after a while it becomes inoperable or will be destroyed. However, during the operation, these devices should provide highly reliable data, because they often give strong points for high-level decisions. As an example, can have an autonomous land or air robot's operation safety: case of failure they can make personal injury and/or property damage.

At field devices – in electronic aspects – there are many problems due to the extreme conditions during the operation and testing. Examples are the extreme temperature or relative humidity, impurities such as dust, solid and liquid materials (e.g. sand, rain), and mechanical stress (shock and vibration). These problems are not (or only moderately) occur at a non-field equipment.

During the manufacturing of electronic devices, the Boundary Scan technique became a very important, almost indispensable technology. Most of the modern, complex digital devices (e.g. processors, FPGAs, FLASH memories, ASICs) contain the additional circuits (overhead) for Boundary Scanning, which also used for testing the individual integrated circuit, before the installation. On a circuit board, or in an electronic system, the number of the electronic devices, which can be tested by Boundary Scan can be increased by appropriate component selection (e.g. using a boundary scanneable bus driver instead of one without it), or in complex systems by using additional or extra components such as Scan Path Linker or Addressable Scan [1]. By using the technique described in the standard IEEE-1149.1 [2], the test tasks arising during the production can be performed by the inspection of digital circuits and their surroundings (connections, clusters), and the programming and configuring of programmable devices, such as FLASH memories, FPGAs and processors.

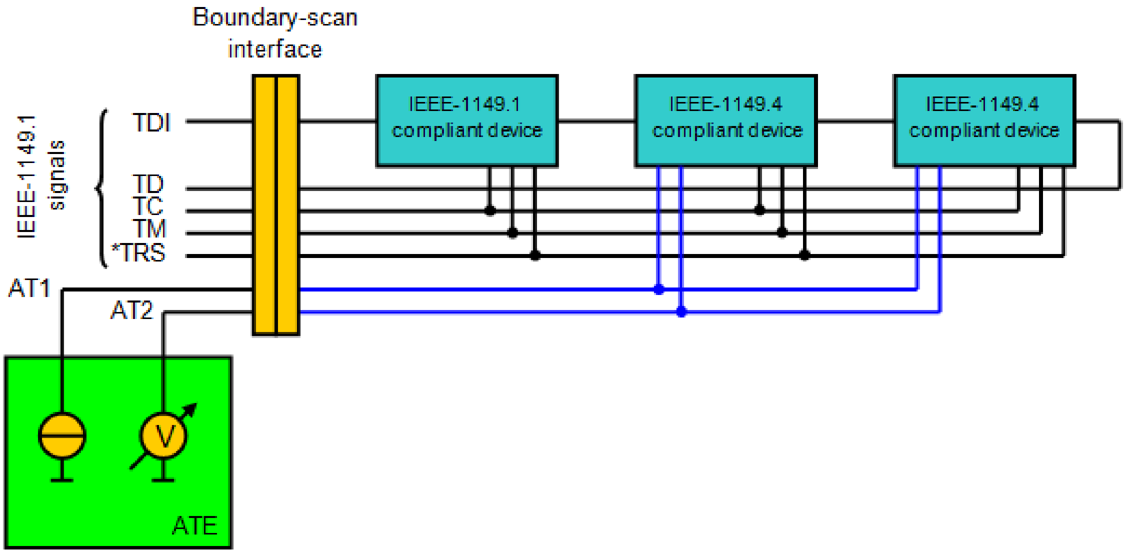
But a system – in most cases – cannot be considered pure digital, because the most of the "real world" signals are analog, so the system's interface is analog too (e.g. input and output ports of a data acquisition board). Therefore there are digitizers and "analogizers" (A/D and D/A converters), and additional functions (amplifiers, filters, etc.). To involve these analog and mixed-signal circuits into the tests is very difficult, or – in some cases – impossible. However, to increase the fault-coverage, and need to apply only one test technique, it can be beneficial, if analog circuits could be tested by boundary scan technique. The analog, or more precisely the mixed-signal boundary scan test method was standardized in 1999, known as IEEE-1149.4 [3]. In certain applications, it is very important to understand, that the circuit testing could be performed without connecting external devices. For example in a difficult to access field or remote device it is a very big advantage, if there is a built-in test controller, which can conduct the test, and can evaluate the results. In this case, the investigation can be remote-initiated, or it can be a scheduled, and can be executed by the built-in test controller. This technique is called Built-in Self-Test (BIST).

I. EXAMINIG CIRCUITS BY MIXED SIGNAL BOUNDARY SCAN TEST

For preparing a mixed-signal boundary scan test, there must be an additional infrastructure compared to digital scanning. Addition to the required digital lines, required by IEEE-1149.1 (TDI, TDO, TCK, TMS, *TRST), there is a need for two analog lines (AT1 and AT2). The line called AT1 is to carry the stimulating current, and line AT2 is for measuring the induced voltage. The target in IEEE-1149.4 standard is to measure impedances at 1% precision, in range 10 Ω…100 kΩ, and recommends the following [3]:

- the upper cutoff frequency is a minimum of 100 kHz, the allowed variation in the transmission is 0.5% between 10 Hz and 10 kHz
- the minimal range of the excitation (measuring) current is in a range of ±100 µA (this current the line AT1 must have to endure)
- the induced voltage must stay in the range of Vss-100 mV and Vdd+100 mV

According to the standard, for testing it is necessary to apply an external current source, for providing the measuring current trough the line AT1, and a voltmeter on AT2, for measuring the voltage generated by the measuring current on the tested impedance. (Of course, if one only wants to measure a voltage on a test point, the injection of the measuring current is not necessary.) In most cases, the current source and the voltmeter are provided by an Automatic Test Equipment (ATE) as seen on Fig. 1.



1. figure. The IEEE-1149.4 infrastructure, and the connection of an external AutomaticTest Equipment (edited by the author)

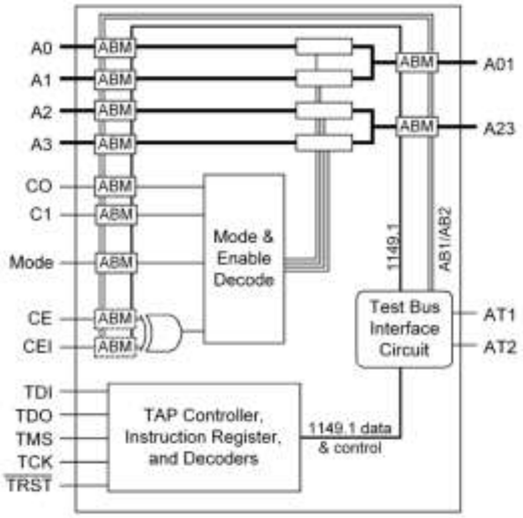
The IEEE-1149.4 standard defines 10 commands, of which are mandatory, and optional. These commands are described in details in the standard [3].

Mixed signal boundary scan solutions according to IEEE-1149.4, and non-compliant solutions

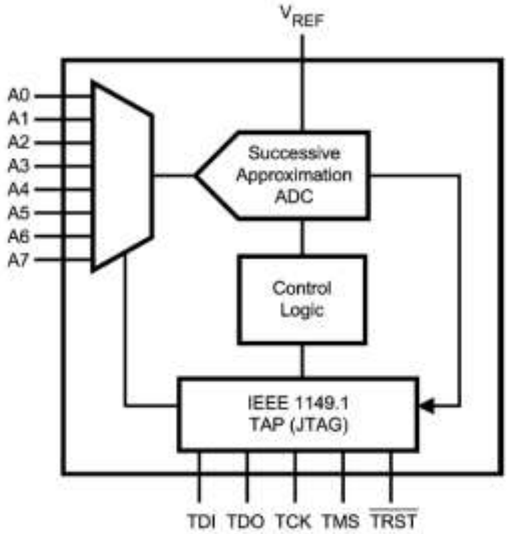
Unfortunately, nowadays testing analog circuits using mixed-signal boundary scan is not widespread, actually an untapped potential. There was only one purchasable device, which fully implemented the IEEE-1149.4 standard. This device called STA400, manufactured by National Semiconductor until 2011, when Texas Instruments acquisited National Semiconductor. In 2013, it is not known, that TI intends to manufacture this device (or an improved one) or not. The STA400 is a dual 2:1 analog multiplexer, which can be configured as a single 4:1 multiplexer [4]. On 11 pieces of analog pins there are Analog Boundary Modules (ABM), and the device can be connected to the IEEE-1149.4 test bus. It can be also interesting, that the device can be configured to "virtual probe" mode. In this mode the user can use 9 of the device pins as a voltmeter input (PROBE operating mode).

The other device, which is suitable to measure analog voltage on multiple points, designated as STA476, but this device is not IEEE-1149.4 compliant. (STA476 was also manufactured by National Semiconductor, and this component is manufactured by Texas

Instruments in 2013.) This device contains a 12 bits A/D converter, and an 8-input analog multiplexer [5]. The A/D converter has a voltage reference input, so the measuring range can be fit to the application. The multiplexer can be programmed via boundary scan bus, and the result of A/D conversion can be read by this way. The main application of STA476 are diagnostics, testing and service-supporting [5]. The internal structures of STA400 and STA476 are shown on Fig. 2 and Fig 3.



2. figure. Structure of STA400 [4]



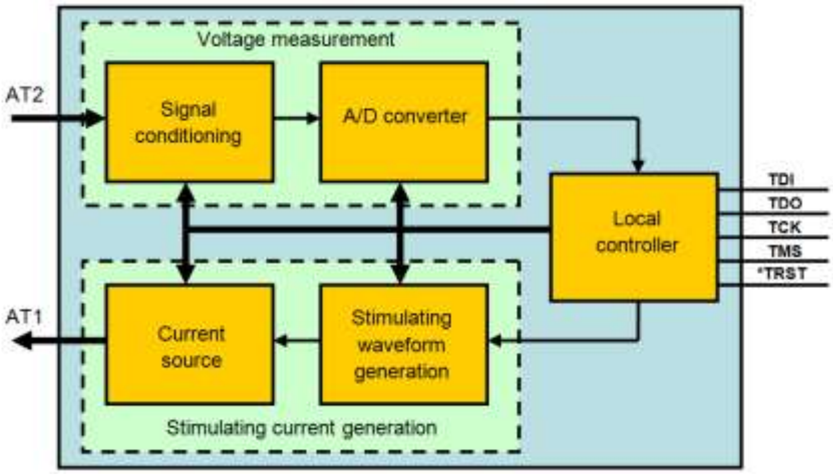
3. figure. Structure of STA476 [5]

II. REQUIREMENTS FOR AN INTEGRATED CIRCUIT SUPPORTING THE TEST OF MIXED SIGNAL COMPONENTS

If a digital circuit is tested by an embedded test controller, the test controller must generate test vectors for boundary testing. The test vector generation can be performed by an implemented algorithm, or by reading the previously computed vectors from the memory. After the evaluation of responses of the tested circuits one can decide, whether it is operating error-free or not. The stimulus and the response are both serial digital information, and it is optimal for a digital test-controller.

Testing a mixed signal circuit is a special case. Stimulating an analog circuit requires analog stimulus, and the response is analog too. In a mixed signal circuit to perform a test by an embedded test-controller, without connecting any external equipment, there is a need for an analog source (current or voltage), and an analog measuring unit. For performing these analog tests, the source and the measuring unit must operate with high precision, because the test must be accurate and reproducible. The built-in test controller can be any device, which can be empowered by "intelligence": DSP, FPGA or microcontroller. Some of these devices are not (or not fully) able to generate analog stimulus and measure analog response. The FPGAs are totally digital, and not able to handle analog signals. Most of DSPs do not contain analog peripherals such as A/D or D/A converters. Microcontrollers usually contain analog peripherals: 8…12 bits resolution, multi-channel A/D converter is common, and there are a few types, which have D/A converter. The alternate method to generate analog signals is the PWM module (which is a frequently used peripheral), but it requires a good quality external (active) analog filter, and it is not suitable for frequencies above few kHz. In overall, the quality of a microcontroller's analog peripherals is not good enough for precise tests.

Performing mixed signal self-tests by embedded test-controller in a mixed signal circuit requires an integrated circuit, which can solve the problem described above. Handling, controlling and reading the measurements of this integrated circuit, it is the obvious way to be done it through the IEEE-1149.1 test bus. The main functions of this integrated circuit are: to generate the stimulating current, and measure the response voltage (Fig. 4.) In the local controller can be implemented extra functions, such as computing various signal parameters (e.g. RMS, Fourier-spectrum, etc.). In the following, we discuss the several topics of developing this prospective integrated circuit. The aim is not to perform these built-in tests (for checking the functionality of the analog circuits) at high precision (but relative precisely), therefore yielding a 2% error for the entire measurement chain.



4. figure. Block diagram of integrated circuit supporting mixed signal boundary test (edited by the author)

The primary target is to create a model, which would be built up with existing, factory components, and able to demonstrate the usefulness of the prospective integrated circuit Secondary target is to examine how can be this circuit implemented as an integrated circuit. Researches in connection with these two topics we will review in a future article.

Requirements of generating analog stimulating signal

1. The current source must be able to generate stimulating current from DC to the maximum of the measuring frequency (to line AT1). The variation in signal amplitude must be less than 0,5%
2. The maximum frequency of stimulating signal is at least 100 kHz – in line with the values fixed in the IEEE-1149.4 standard.
3. The peak value of the stimulating current – also according to the IEEE-1149.4 standard – must be at least ±100 μA. (If we want to measure lower impedances at adequate precision, we need to provide higher peak values (at least ±1 mA). This range can be used in that case, if the infrastructure (mainly the analog test line AT1, and the integrated switches and circuits of connected circuits) is able to tolerate this current.

Requirements of measuring analog response signal

1. The measuring "instrument" must be able to measure DC and AC voltages at least between the power lines (0…5 V), up to 100 kHz (or up to the maximum frequency of the current generator).
2. The measurement error must be equal or lower than 0,5%.
3. If it is possible, must be suitable to calculate various signal parameters such as peak voltage, RMS value, Fourier-spectrum, etc.

III. OPPORTUNITIES OF IMPLEMENTATION

The next paragraph is a brief overview of the main ways to generate analog stimulating signal.

Analog function generator

At this technique the frequency of the oscillator is determined by analog components (R-C, L-C). Tuning these components is difficult, it do not fit to the digital systems. Maybe only the resistor of these components can be tuned digitally. The digital potentiometers can't be tuned continuously, there are 64…1024 fixed steps, the value of the resistor can be controlled by host processor via SPI or I2C bus. The voltage on the resistor can't exceed the power supply lines, which is usually in range 0…5 V. These potentiometers can be used up to 50…4000 kHz, the bandwidth depends on the nominal value of the resistor, higher the value, the maximal frequency will be lower. The inductor and the capacitor can't be tuned by this or similar way. Only it is possible to change fixed value capacitors or inductors by an analog multiplexer to change the frequency range. As we know, integrated, continuously tunable capacitor and inductor with suitable precision and stability, and at acceptable price can't be realized using the manufacturing technologies of today. It should be noted that the analog signal generator can generate only one waveform (sinusoidal or triangle), other waveforms can be produced only by signal shaping circuits. My opinion to produce stimulating signal by analog method is not recommended.

Generating stimulus by pulse-width modulation (PWM)

Using pulse-width modulation can be produced DC and AC signal. In digital systems due to the unipolar power supply it is suitable to use unipolar PWM signal (Fig. 5.). The signal amplitude is Vdd (Logic High level) during the pulse, and 0 V (Logic Low) when it is switched off.

If the pulse-width or duration (D) and period (T) of the PWM signal are constant, the average value of PWM signal is DC, and the value is defined by pulse duration (D). If it is desired, can generate AC signal by changing the pulse width. The average value of the PWM signal is:

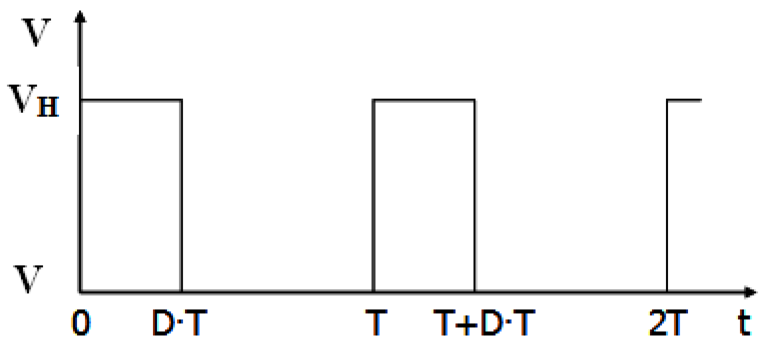
$$\overline{V} = \frac{1}{T}\cdot\int_0^T f(t)dt = \frac{1}{T}\cdot\left(\int_0^{D\cdot T} V_H dt + \int_{D\cdot T}^{T} V_L dt\right) = \frac{1}{T}\cdot(D\cdot T\cdot V_H + T\cdot(1-D)\cdot V_L) =$$

$$\underline{\underline{D\cdot V_H + (1-D)\cdot V_L}}$$

1. Equation.

And whereas $V_L = 0\,[V]$, so $\overline{V} = D\cdot V_H\,[V]$

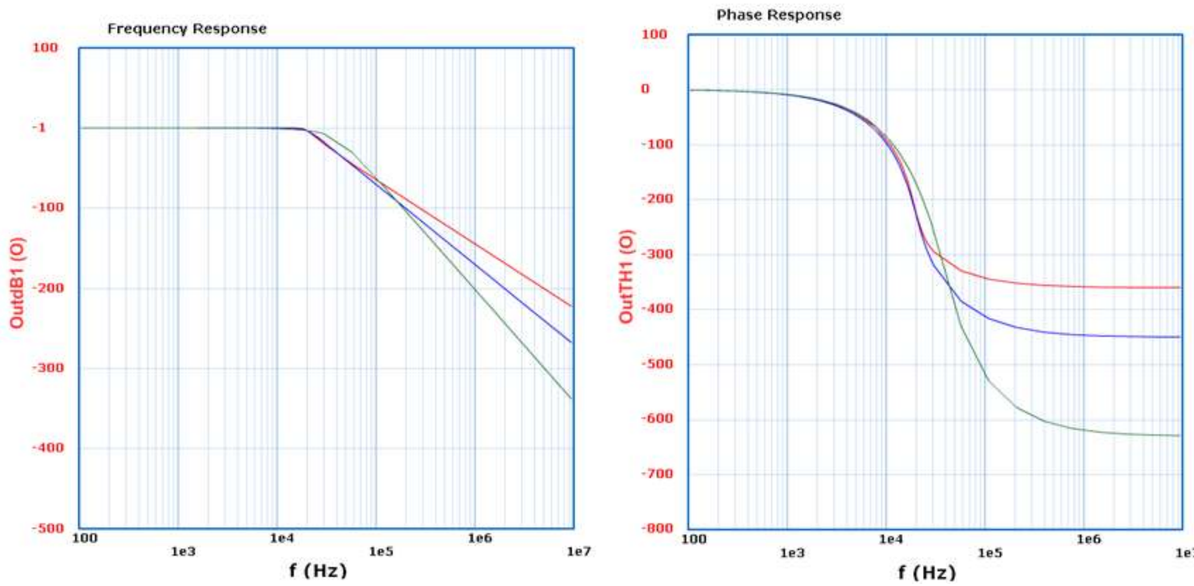
2. Equation.



5. figure. Unipolar PWM signal (edited by the author)

For generating alternating voltage, pulse width should be changed. For basic waveforms (sinus, triangle, square) to achieve an acceptable signal quality (shape fidelity, distortion…) the frequency of the PWM signal must be twice to five times higher, than the frequency of the generated signal. This ratio is affected by the parameters of the averaging circuit.

For averaging, a low-pass filter can be used, which can be realized by passive or active circuit. The closer the generated frequency to the PWM frequency, and the smaller the variation of the response, the higher order filter should be used. Suppose, that the PWM frequency is 100 kHz, and the generated signal frequency is 10 kHz, and we want the PWM frequency presence is no more than 0,1% in the generated signal. In this case at 10 kHz we must provide at least 60 dB rejection to 100 kHz signal components. For demonstrating, I used the Texas Instruments's WEBENCH® Active Filter Designer tool [6]. I simulated a filter, which has cutting frequency of 20 kHz, the stop band starts at 100 kHz, where the attenuation should be at least 60 dB. On the Fig. 6. the simulating results (frequency and phase response) can be seen. There is three different filters, with a minimum required order (Red: 4th order Chebyshev (0.1 dB ripple), blue: 5th order Butterworth, green: 7th order Bessel). The attenuation of the filters at 100 kHz: Chebyshev - 64 dB, Butterworth – 69.9 dB and Bessel – 64-6 dB.



6. figure. Frequency and phase response of the filters designed in the Active Filter Designer (cut out from the Active Filter Designer [6])

For generating alternating voltages, the duty of the PWM signal should be redefined in every signal cycle. This can be done by reading stored (pre-computed) values from a table, or can be computed in run-time. The first solution has a low resource requirement, and can be used well for standard waveforms. The second solution has higher resource requirement, but can be used at special waveforms.

The signal generation by PWM method fits well to digital systems, and can be used for generating DC or AC signals. But the PWM frequency limits the signal frequency (and the PWM frequency is limited by the microcontroller's peripherals). This method requires a high order active low-pass filter, it's parameters are critical.

Generating analog signals by D/A converter

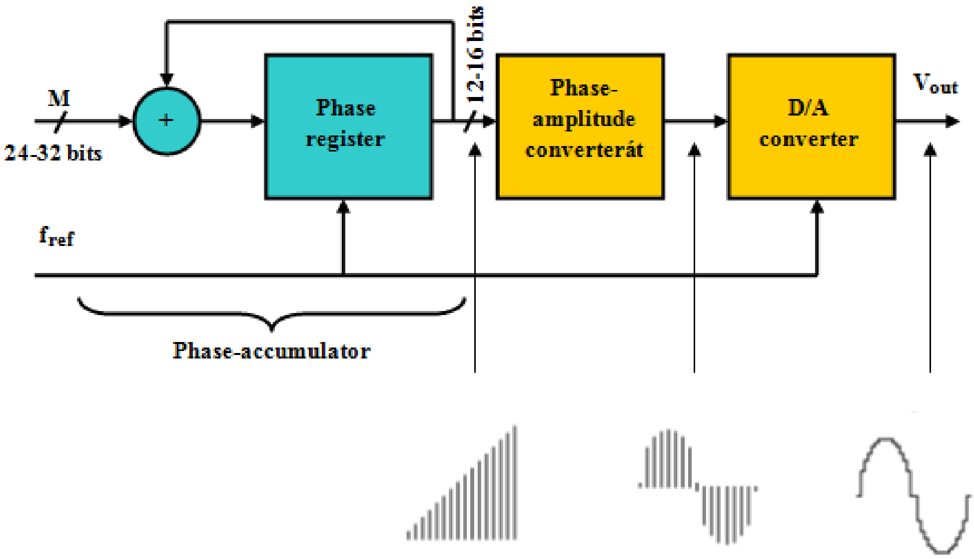
There are many types of D/A converters, they fit optimally to digital systems. They require voltage reference to operate, which determines the accuracy and stability of the converter. Quality characteristics easy to control, and high precision D/A converters can be realized inexpensively. Using D/A converters it is possible to generate AC or DC voltage or current.

To generate AC output, similar methods are possible than as we have seen at PWM, and the problems are similar too. If we want to generate DC voltage, there is no need for filter, but it is necessary for generating AC output. If we want to achieve precision of amplitude of 0,1%, we need at least 10 bits converter. As the converter has errors, we need 11 or 12 bits converter, which can be integrated cheaply and easily.

Using D/A converters is a realistic alternative for generating analog test stimulus.

Generating analog signals using method of direct digital synthesis (DDS)

Direct digital synthesis is a modern method for generating analog signals. It has high precision (high resolution), wide frequency range and excellent stability, because uses crystal oscillator as reference. Can be controlled easily by the host, only one tuning word determines the output frequency. The method is suitable to generate various periodic signals, although it is basically planned to generate sinusoidal output. The structure of the DDS generator is shown on Fig. 7.



7. figure. The structure and basic operation of the DDS signal generator (edited by the author)

The phase accumulator adds the M tuning word to the previous value of the phase register, scheduled by reference frequency (f_{ref}). The upper 12…16 bits of phase accumulator addresses a phase-amplitude converter, which is actually a memory. The memory contains the numeric amplitude values for each phase. The data read out from this memory is the input for the D/A converter, which produces the analog signal. The specialty of the phase accumulator is that, there is no phase-jump passing through the 0 phase point, the output phase is continuous.

The filtering of the analog signal on the DDS generator's output has a very high effect to the signal quality. In our case, the maximum frequency of the generated signal is 100 kHz, and the reference frequency of DDS generator is 20…100 MHz (depends on the used device), the output filter's specification is not very strict: it is enough to use 1^{st} or 2^{nd} order low pass filter. As the DDS technique requires only digitally controlled elements (memory, register, digital multiplexer), so optimally suited for digital systems. DDS technique is suitable for generating basic and special waveforms, and it is suitable for generating DC voltage, if the phase-amplitude converter contains the same value for each phase point.

The current generator

As the stimulus applied to the analog test line AT1 should be a current, so the generated signal must be converted to current, or must be amplified. In that case, if the generated signal is a voltage, there is a need for a voltage-current converter. If the generated signal is a current, it should be amplified to the desired level. The current generator must provide the proper load capacity, the stability and the accuracy. As the full signal chain error was fixed in 2% (1% due to the stimulus, and 1% for the measurement), so the error of the current generator should not exceed a few tenths of a percentage. These criteria are achievable easily with an integrated sub-circuit. This hypothesis is confirmed, if we examine the off-shelf voltage controlled current source devices' characteristics.

In the next, we provide a brief overview of the implementation opportunities of the circuits in relation of the measuring the analog signals.

Signal conditioning

The measuring amplifier, the "analog front end" is a very important chain link. If it has not an appropriate quality, despite the precision of the A/D converter, the conditioned input voltage will be affected by errors, and can't be determined the accurate value of the input voltage. The main function of the measuring amplifier to transform the relative wide input voltage range into the voltage range of the A/D converter, without offset and amplification error, and with high linearity in amplitude and frequency. There is no need for extra protection on the input of the amplifier, because the usual problems (overvoltage, ESD, etc..) will not occur on the input, due to the closed environment.

The IEEE-1149.4 standard of the mixed-signal boundary scan targets to measure impedances between 10 Ω and 100 kΩ. If the stimulating current is the maximal (100 μA), the response voltage will be in the range of 1 mV and 10 V. As can be seen, if we want to transform these voltages into the range of the A/D converter, there is a need for amplification at low voltage levels, and attenuation at high voltage levels. This will provide the optimum conversion accuracy. In the table below (Table 1.) there is a summary of the resistance ranges, stimulating current values in particular ranges (I_m), and the necessary amplification in each range (A_v).

(At the calculations it was considered, that the optimal range is used, i.e. the lower 10% of the ranges is not used.) The shaded lines overfulfill the measurement range described in the standard.

In the signal conditioner there is a possibility to analog computing of some signal parameters, such as peak value, average value or effective value. However these computations can be performed in an intelligent system controller at a higher performance, and with a lower error. If it is necessary it is a need to be implemented an anti-aliasing filter in the signal conditioner.

Range	I_m	A_v	V_{AD}
10 Ω	100 μA	2500	0…2.5 V
100 Ω	100 μA	250	0.25…2.5 V
1 k Ω	100 μA	25	0.25…2.5 V
10 k Ω	100 μA	2,5	0.25…2.5 V
100 k Ω	25 μA	1	0.25…2.5 V
1 M Ω	2.5 μA	1	0.25…2.5 V

1. table. Some parameters of the signal conditioner (impedance measurement) (edited by the author)

The A/D converter

A wide variety of A/D structures are known (e.g. flash, successive approximation, integrating (dual slope), sigma-delta). The today's technology enables to manufacture relatively cheap A/D converters with resolution of 8…20 bits, above this resolution increases the cost of production. The speed of digitizing is one of the important characteristics. If we want to process a signal with a frequency of 100 kHz, it should be sampled at more than 200 kHz, according to the Nyquist rule. So there is a need for an A/D converter, which has at least 200 kS/s sampling rate. The higher the sampling frequency, the lower the requirements of the anti-aliasing filter (e.g. it is enough lower slope, i.e. lower order). In resolution, it is required that at the 10% of the measurement range the measurement error should be less than 0.5%. According to Table 1. the minimum voltage to measure is 0.25 V, so the resolution is lower or equal than 1.25 mV (Eq. 3.)

$$r = 0.25\,V \cdot 0.5\% = 1.25\,mV \qquad \text{(Equation 3.)}$$

If the full scale is 2.5 V, Eq. 3. determines the minimal resolution of the converter:

$$N = \log_2(2.5\,V / 1{,}25\,mV) = 10.97 \qquad \text{(Equation 1.)}$$

so there is a need for an ideal 11 bits A/D converter. If the converter has the error of 1 LSB, we can use a 12 bits A/D converter. In speed, resolution and price one of the options to choose an successive approximation A/D converter. This type of ADCs is widely used in microcontrollers, e.g. in Microchip's PIC30F1010 there is an 12 bits, 2 MS/s successive approximation A/D converter [7].

The reference needed for A/D converter can be integrated well, easily can be found of the manufactured devices, which has the error less than 0.1%, and stability is better than 50…100 ppm.

Controller

The main function of the controller is to communicate through the JTAG interface, and to coordinate the units in the planned integrated circuit. The built-in test controller instructs the measurement controller to perform tests (e.g. to measure an impedance, or voltage), then reads the results from it. The measurement controller sets the stimulating signal's frequency, waveform and amplitude, sets the current source (if necessary), sets the signal conditioner's parameters, then starts the measurement, and collects the results.

Further functions can be implemented in the measurement controller, as mentioned above. If there is a need to compute some signal parameters, the controller must store many digitized values in an interval, then it can compute the required parameters. In this case the controller should have a relatively high intelligence. If we use a DSP, it is able to control the inner units, and to compute signal parameters, so it can be a good choice for measurement controller.

By this time, we use a DSP in the planned integrated circuit, it is only the imagination is the limit to what kind of capabilities will have the device. Also requires additional considerations, where to draw the limits: which functions will be in the measurement controller, and which functions will be in the built-in test controller.

SUMMARY

In year 2013 there is no device which has these features described above. The planned integrated circuit can help to spread the mixed-signal boundary scan, and outlines new built-in self-test applications. If we extend the boundary scan self-test the more circuit element, the fault coverage will be higher, and can be decided more reliably if the circuit or device is functioning well, or not. In many applications it is very important that the occurring faults can be detected before the malfunction can produce incorrect information.

Testing of military and defense field devices is very important due to the increased risk of failure and to achieve the continuous reliability. However, the circumstances of testing are very special. So at designing a field equipment efforts should be made to avoid the need of external devices for testing, and the tests to be carried out by the user or the equipment itself. This aim would be achievable more easily by using this proposed integrated circuit.

In the next, there are a number of questions remain to be examined. It is very important to create a model of this circuit built up with off-shelf parts, and this model will help to decide if the planned structure is functional or not. The basis of experiences can be designed the integrated circuit. The measurement functions to be implemented can be supplemented by special ones, in addition to the standard functions. E.g. in some cases it is useful to perform tests with stochastic stimulus, however, these methods are require very different approach, and a very different measuring methods, as usual.

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