XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

A MEASURING SYSTEM FOR FAULT DETECTION VIA OSCILLATION

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Abstract: A method and the test and measuring system for fault detection (FD) in electronic analog circuits, based on the modified oscillation-test approach, are presented. For FD purpose the circuit under test (CUT) is forced to oscillation, which parameters are monitored. Existing faults cause deviations of measured parameters, or result in the loss of oscillation. The novelty of presented approach are technique of converting higher-order circuits to oscillators by feedback structure assignment and the solution of test and measuring system with the automatic digital amplitude control. Microprocessor based system enables not only measurements of the oscillation frequency but also examination of variations in the amplitude step response parameters: rise time and steady-state error, that indicate faulty behaviour of the CUT. The increased quantity of diagnostic information results in the improved fault coverage in comparison with the method exploiting only frequency measurements.

Keywords: diagnosis of analog circuits, oscillation-test method, measuring system

1 INTRODUCTION

The widespread mass production of analog and mixed signal electronic circuits and necessity to maintain yields and quality standards, raises the problem of testing to be of the utmost importance. It is possible to distinguish between a good and a faulty circuit by performing specification tests but many circuits, for example higher-order stagger-tuned filters, have specifications which require expensive testing procedures. It is hence desirable to substitute specification tests by simpler tests, with compressed diagnostic signal. One of such approach, investigated recently, is oscillation-test method [1, 2]. For fault detection purpose, the circuit under test (CUT) is forced to oscillation which frequency is monitored. Existing faults cause deviation of the frequency, or result in the loss of oscillation.

According to the conventional oscillation-test approach, a higher-order circuits ought to be partitioned, by a designer, into stages with the aid of incorporated isolating switches. During the test mode, each stage is rearranged one by one as an oscillator producing a frequency whose value depends on the stage's parameters. The method is in some measure intrusive, because switches placed in the signal path have some impact on the performance of CUT during normal operation.

The first aim of the paper is to remove this drawback by establishing oscillation in CUT without in-circuit switches. We propose using only input/output terminals and makes to oscillate whole higher-order circuit on a few different frequencies successively. The proposed technique of converting complex circuit into the oscillator consist of adding feedback loop to it, and then assign the feedback structure to establish oscillation at a predetermined frequency by shifting only selected pair of poles to the imaginary axis on the s-plane.

The second aim of the paper is to improve fault coverage by increasing the quantity of information about the CUT. Knowledge of the value of oscillation frequency is not enough in many cases for full parametric fault coverage. In order to improve fault coverage, additional parameters of diagnostic signal, for example amplitude level, should be measured. Unfortunately, amplitude of sinusoidal oscillators constructed from a linear circuit is usually unstable. Nonlinear bounding of the amplitude, as by amplifier saturation or by added nonlinear element, contributes to harmonic distortion in the output waveform. From the diagnostic point of view, amplitude of the distorted signal is of little value, owing to the small diagnostic sensitivity with respect to the parametric faults of the linear elements. The proposed solution to this problem is using the Automatic Amplitude Control (AAC) in order to keep the amplitude level in a linear region of CUT characteristic with greatly limited distortion, and without loss of diagnostic information contained in the signal.

In such arranged testing circuit, instead of the amplitude level measurements, we propose examination of amplitude step response parameters: steady-state error and rise time.

2 FEEDBACK STRUCTURE ASSIGNMENT

Proposed methodology of the testing oscillatory circuit synthesis by feedback structure assignment will be considered on the example of sixth-order bandpass filter realized as a cascade of second-order Friend [3] stages (Fig.1).

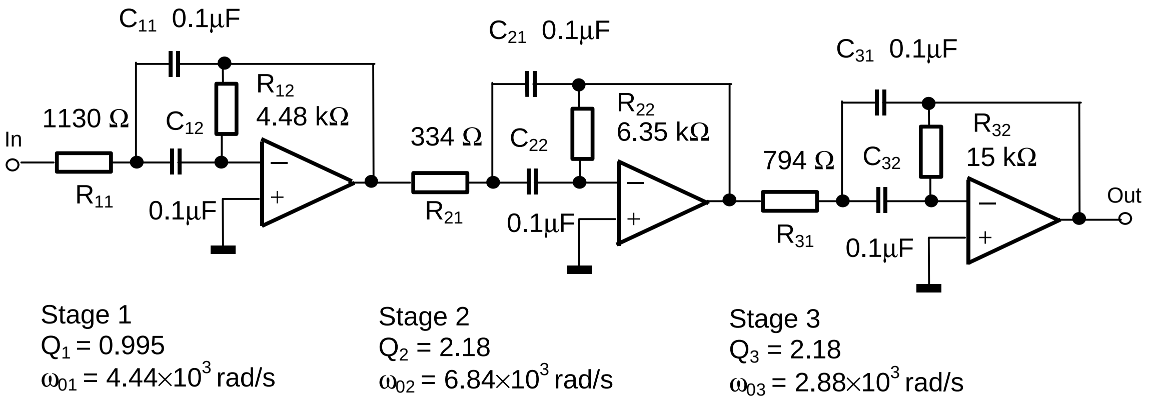


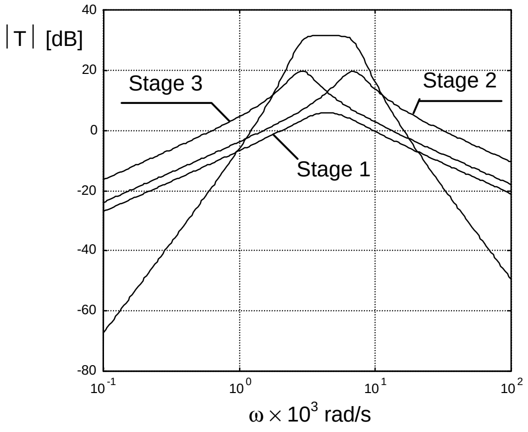
Figure 1. The circuit under test: 6-th order stagger-tuned active bandpass filter.

The specification for each stage is given in terms of the quality factor Q_i and the frequency ω_i to which that stage must be tuned. Because each stage is tuned to a different value of frequency, the combined circuit is said to be stagger tuned. For each of the three stages we have transfer function

$$T_i(s) = \frac{-2Q_i\omega_{0_i}s}{s^2 + \frac{\omega_{0_i}}{Q_i}s + \omega_{0_i}^2}, \qquad i = 1, 2, 3 \tag{1}$$

where i is the number of the stage being considered.

The plot of the magnitude response for each of the three stages is presented in Fig. 2 along with the composite magnitude response found by summing the responses of each of the three stages, which is the Butterworth type also known as maximally flat.



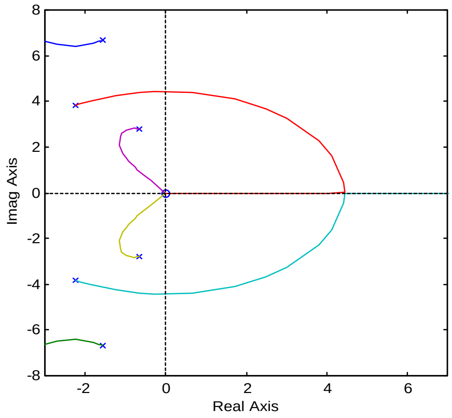


Figure 2. Magnitude response of CUT.

Figure 3. Root locus plots for positive feedback.

The combined circuit behaves as a filter-amplifier with a maximum value of gain 31.5 dB at the centre frequency. We reduce the gain at the input to the circuit to obtain pure filter behaviour without amplification. The overall transfer function with the gain reduced to one is

$$T = \frac{-88.5s^3}{s^6 + 8.9s^5 + 99s^4 + 440.8s^3 + 1953.5s^2 + 3475.8s + 7688.4} \tag{2}$$

To form the oscillator we incorporate the CUT in a feedback loop of an amplifier with the amplification factor K. The closed-loop system has a new transfer function

$$T_f = \frac{K}{1 \pm KT} \tag{3}$$

where sign in the denominator depends on the type of feedback.

Design of oscillator should be carried out making use of the conventional root locus method, based on the system’s characteristic equation

$$1 \pm KT = 0 \tag{4}$$

The method will give the closed-loop pole positions for all possible changes in the loop gain K. The closed-loop system exhibit sinusoidal oscillations in steady state if the pair of roots of the characteristic equation (4) is placed on the imaginary axis. When there are unrepeated poles having a real part of zero and no poles with positive real parts, then the closed-loop system is marginally stable. The intersections of root loci with the imaginary axis correspond with the value of open-loop gain K that will give the oscillation. These values of K can be found from Routh stability criterion [4]. To determine gain K using Routh’s array, the closed-loop characteristic equation (4) must be transformed into the form

$$D(s) = \sum_{i=0}^{n} a_i s^{n-i} = 0 \tag{5}$$

For analyzed system we have obtained closed-loop characteristic equation

$$D(s) = s^6 + 8.9s^5 + 99s^4 + (440.8 \pm 88.5K)s^3 + 1953.5s^2 + 3475.8s + 7688.4 = 0 \tag{6}$$

For this polynomial, the Routh array is shown below

$$\begin{array}{cc|cccc}
\text{Row} & & & & & \\
\hline
1 & s^6 & a_0 & a_2 & a_4 & a_6 \\
2 & s^5 & a_1 & a_3 & a_5 & \\
3 & s^4 & b_1 & b_2 & b_3 & \\
4 & s^3 & c_1 & c_2 & & \\
5 & s^2 & d_1 & d_2 & & \\
6 & s^1 & e_1 & & &
\end{array} \tag{7}$$

The first two rows are made up from the characteristic equation coefficient in the obvious manner. The elements in the third row onwards are obtained from elements in the previous two rows in the following way:

$$b_1 = a_2 - \frac{a_0 a_3}{a_1},\quad b_2 = a_4 - \frac{a_0 a_5}{a_1},\quad b_3 = a_6,\quad c_1 = a_3 - \frac{a_1 b_2}{b_1},\quad c_2 = a_5 - \frac{a_1 b_3}{b_1},\ldots \tag{8}$$

It is well known that the case when all the coefficients of a row in the Routh array become zero indicates the presence of roots symmetrically located about the origin of the s-plane [4]. If additionally there are no roots with positive real parts, appearance an all-zero row must indicate the presence of at least one pair of the pure imaginaries conjugate poles.

The feedback can be inverting, or noninverting types. With the negative sign of feedback, the first and only element of row 6 in the Routh array (7) become zero for gain K=1. The overall feedback is positive and one pair of poles is moved within the s-plane to the imaginary axis. The system’s root locus plot (Fig. 3) indicates all possible closed-loop pole positions for all values of amplifier gain K. Every stage is represented by a pair of complex conjugate poles and a zero at the origin. The axis crossing points correspond to K=1. For such gain, closed-loop system produces sinusoidal waveform, which frequency is equivalent to the natural frequency of Stage 1. With the positive sign of feedback, all elements of row 4 in the Routh array become zero for gain K=2.99. The overall feedback is negative and in this case two pairs of poles are placed on the imaginary axis simultaneously (Fig. 4) resulting in the severely distorted output signal (Fig. 5). In order to prevent distortion and obtain nearly–sinusoidal oscillations we use feedback structure assignment idea. With the aid of the additional feedback loop (Fig. 6.b) we remove one pair of poles from the imaginary axis, leaving the another pair unchanged.

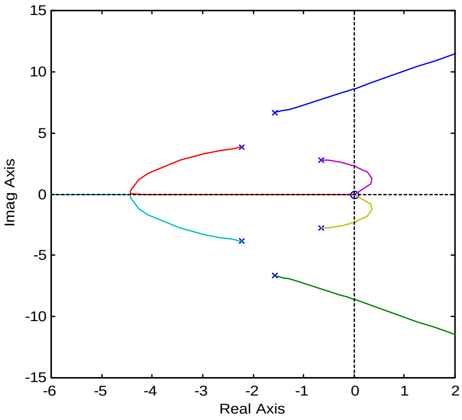


Figure 4. Root locus plots for negative feedback.

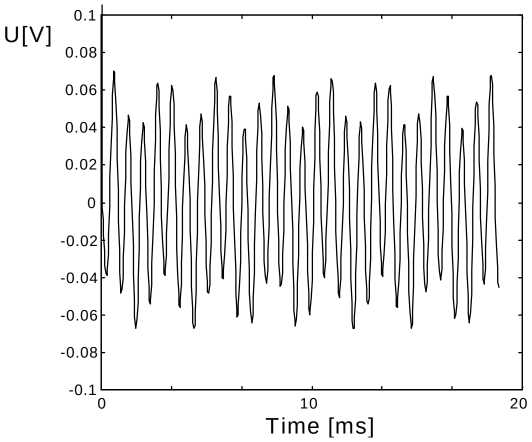


Figure 5. Output waveform of the oscillator.

In additional feedback path second-order bandstop (notch) circuit is used with transfer function in the form

$$H = \frac{s^2 + \omega_i^2}{s^2 + \frac{\omega_i}{Q}s + \omega_i^2} \tag{9}$$

where ω_i is the point of intersection of root loci (that ought to be unchanged) with the imaginary axis. As a result we obtain oscillatory circuit with sinusoidal output signal. The oscillatory circuit is synthesized individually for each of the three stages (Fig. 6).

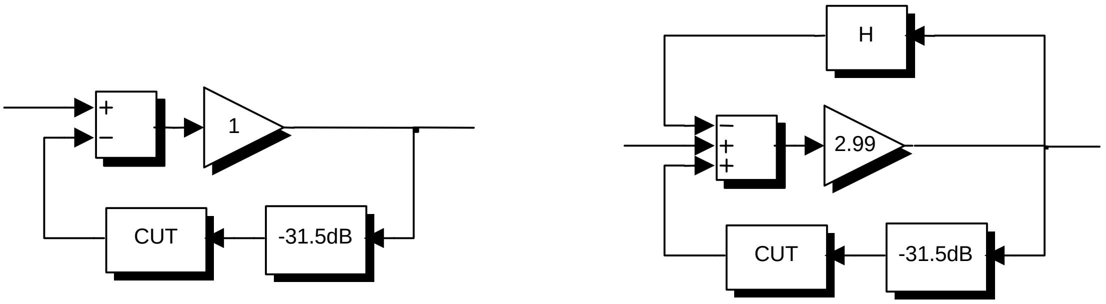


Figure 6. Architecture of the testing oscillatory circuits: a) for Stage 1, b) for Stages 2 and 3.

3 THE TEST AND MEASURING SYSTEM

The slightest disturbance, for example the effect of temperature on component values, would cause the poles of the oscillatory transfer function to move from the imaginary axis of the s-plane slightly to the left, or slightly to the right. In such cases the oscillations would eventually die away or they would gradually grow. The basic idea of the test and measuring system is to stabilize the amplitude level in the way that doesn't annihilate the diagnostic information contained in the signal.

In an earlier paper [5] the concept of test and measuring system has been verified throughout extensive simulations. In this contribution it is implemented in the experimental microprocessor-based system. The role of measuring system is twofold:

- performs the digital automatic amplitude control (DAAC),
- measures frequency of generated signal, and parameters of amplitude step response.

The goal of extended measurements is to extract more diagnostically relevant information from generated signal than it is obtainable with the method exploiting only frequency measurements. For this purpose two parameters of amplitude step response are examined (Fig. 8a): the steady-state error, which is the difference between the demand input and the steady-state output and rise time taken as the time from 10% of the final value of the response, to when it achieves 90 % of its final value.

The experimental measuring system is a hybrid of continuous-time and discrete-time elements. A block diagram of system is presented in Fig.7. It consist of the testing oscillatory circuit designed in the previous section and additional elements forming feedback loop of DAAC. The amplitude detector (DET) converts amplitude of oscillations instantaneously into a dc voltage which is next converted to the digital signal in A/D. A four-quadrant multiplying digital to analog converter (D/A) arranged as a programmable amplifier provides a small amount of feedback of either sign as a means of controlling amplitude of oscillations. The magnitude and sign of feedback are determined by the digital control input to the multiplying D/A converter. This digital control signal is derived by microprocessor (µP) from the difference between the detector output and a demand value.

User of system can view measurement data: frequency, rise time, amplitude error, and perform control operation from the graphical interface installed on personal computer (PC). System makes possible programming the gain in the DAAC loop and the magnitude of step function excitation.

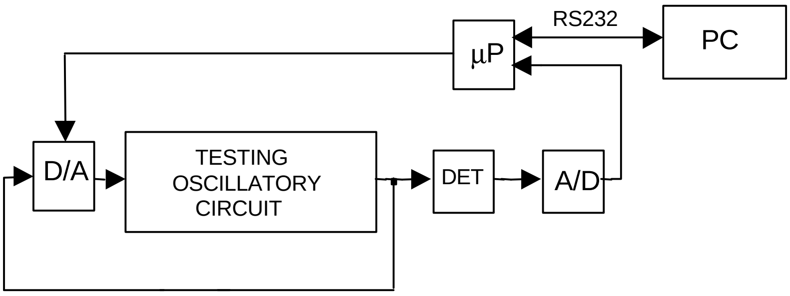


Figure 7. Block diagram of the test and measuring system.

4 RESULTS

The proposed approach and measuring system have been verified by testing the second-order bandstop filter and 6-th order stagger-tuned bandpass filter from Fig.1 with injected parametric faults.

Results of experiments presented in Fig.8a show, that in order to maintain the diagnostic information contained in the steady-state error and rise time, gain of the DAAC loop ought to be deliberately limited to the value A = 1 - 5.

During experiments with bandpass filter, 20% of deviations from the nominal value in both directions + (R↑) and – (R↓) have been introduced for all resistors successively. For each fault bandpass filter has been forced to oscillations three times. The injected parametric faults cause steady-state amplitude error ε and deviation of the oscillation frequency $\Delta\omega$. Fig.8b presents envelopes of the amplitude step response of CUT for faults injected in R11.

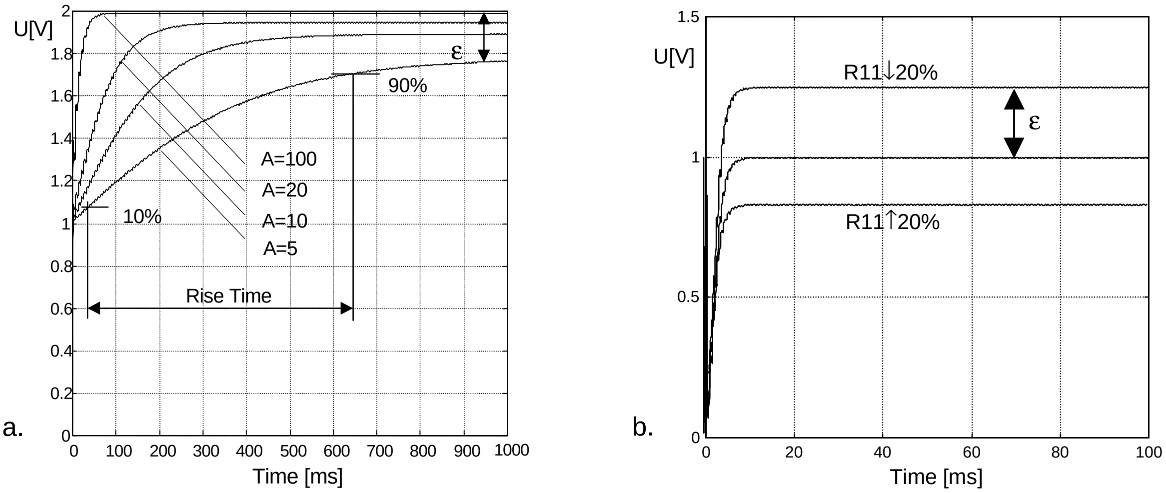


Figure 8. Envelopes of the amplitude step responses: (a) bandstop circuit [5], (b) bandpass circuit (Fig.1) with injected parametric faults.

Test results are summarised in Table 1. One can observe generally high diagnostic sensitivity of steady-state error and relatively low diagnostic sensitivity of produced oscillation frequency. For increasing diagnostic sensitivity of frequency, CUT ought to be partitioned into three separate stages during the test mode. The highest values of steady-state error (marked in Table 1) refer to those elements which form the composite magnitude response of CUT in surrounding of the oscillation frequency. For example, we can see by comparing Table 1 with Figures 1 and 2, that in the case of oscillation frequency $\omega_1 = 4.44\times10^3$ rad/s the highest values of steady-state error refer to resistors R11, R12, R22, R31. Resistors R11 and R12 form the shape of centrally tuned Stage 1, resistor R22 forms the left slope of Stage 2 and resistor R31 forms the right slope of Stage 3.

Table 1. Summary of test results for injected parametric faults in the active bandpass filter from Fig.1.

Measurand	R11↑	R11↓	R12↑	R12↓	R21↑	R21↓	R22↑	R22↓	R31↑	R31↓	R32↑	R32↓
Poles of Stage 1 shifted to the imaginary axis ($\omega_1 = 4.44\times10^3$ rad/s)												
ε [%]	-17	+25	+20	-20	+6	-9	+34	-29	-25	+44	-7.1	+7.6
$\Delta\omega_1$ [%]	-4	+6	-5	+6	-3	+4	-1.7	+1.4	-1	+2	-3	+4
Poles of Stage 2 shifted to the imaginary axis ($\omega_2 = 8.6\times10^3$ rad/s)												
ε [%]	-14	+20	+4	-8	-18	+20	0	-10	-14	+18	-1.2	-0.8
$\Delta\omega_2$ [%]	0	+0.5	-1	+1.5	-1	+3	-2	+3	0	0	0	0
Poles of Stage 3 shifted to the imaginary axis ($\omega_3 = 2.29\times10^3$ rad/s)												
ε [%]	-6.6	+4	+14.6	-16	-1	-1	+14	-15.3	-10	0	+17	-20
$\Delta\omega_3$ [%]	-1	+1	0	0	0	0	0	0	-2	+2	-2	+1

5 CONCLUSIONS

In the paper, two new measurands have been introduced to the oscillation-test methodology. The presented results and cited paper [5], prepared by the author, have shown that both of them: steady-state amplitude error and rise time of amplitude step response are diagnostically relevant. Their applicability depends on the kind of CUT. Particularly steady-state error has remarkably high diagnostic sensitivity with respect to faults injected into bandpass Friend circuit, even in the circumstances when conventional oscillation-test method has failed. Experiments with measuring system have shown that it is practically possible to test analog electronic circuits by proposed modified oscillation-test method. The technique of converting higher-order circuits to oscillators by feedback structure assignment could be applied for testing many another circuits with accessibility limited to input/output terminals.

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