Studying the impact of intermittent variations using sensitivity analysis

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Fault diagnostics focuses on the detection, identification and isolation of failures. However, this becomes challenging when investigating fault alarms that cannot be verified, diagnosed or even duplicated under standard manual inspection regimes. To improve system effectiveness, it is essential to investigate these instances, along with the effects of design parameters on system dynamic characteristics. Recent research has identified intermittent fault behaviour within components as one of the primary focuses for false alarms, and hence a direct consequence to the phenomenon of 'no fault found'. This paper examines the performance characteristics of an electronic system under intermittent component variations. Understanding occurrences in parameter deviations (and their impact) can help with understanding the requirements for improving system fault tolerance. It is shown that, in many cases of practical importance, components do not have the same sensitivity to intermittent variations and hence can be better suited for monitoring. The analysis provides extra information and guidance for the maintenance decision-making process in organisations on resource requirements.

Keywords: sensitivity analysis, no fault found, Fourier series, mathematical modelling, model-based fault detection.

1. Introduction

With the increasing reliability requirements of complex systems, test technology and capability has become one of the significant areas for recent research[1,2]. This also reflects the drive towards reaching optimal designs in electronics products whilst guaranteeing performance at minimal manufacturing costs[3,4]. Although, from a practical point of view, it may not be sufficient for a design specification to be satisfied for a set of nominal parameter values under intermittent conditions, it has been advocated that system reliability could be assessed by the system fault rate, *ie* the number of faults that occur during operation[5]. However, such an indicator can be misleading, as system failures also often result from faults that are intermittent in nature and do not necessarily affect the reliability. An intermittent fault can often be described as a momentary deviation from the nominal value, which occurs occasionally due to factors such as degradation, external influences or uninitialised software variables[6,7]. Therefore, it is important to study the reliability of systems subjected to intermittent and permanent faults. Due to the random and non-reproducible nature of the incidents, intermittent faults can be a frustrating, elusive and expensive issue to detect and locate in a system.

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Khan *et al* suggest that intermittent faults are one of the main culprits for false alarms and, as a consequence, directly result in 'no fault found' (NFF) events during manual inspections[8], even though there may be various reasons contributing to this overall process, *ie* the operator (or maintainer) lacks the appropriate knowledge, incorrect procedures in manuals, lack of testability equipment, etc. The aerospace industry has reported a majority of such instances, probably due to the system complexity or tighter tolerance levels on their trigger mechanisms[7]. None the less, the alarm itself may not always provide any other direct diagnostic information that can help to narrow down the focus of the investigation. Decisions made after an organisation has been unable to reduplicate the fault (or isolate it) with the standard test equipment and procedures are of paramount importance to ensure safety standards and regulations are satisfied.

Model-based fault detection and diagnosis has gained a lot of attention in the literature[9,10,11]. By utilising a mathematical model of a system, idealistic data signals can be compared to the raw system measurements to present a health status. Residual generation methods (such as system identification or parameter estimation) can be used to obtain residuals to detect and diagnose faults. Although, before a fault can be diagnosed, it is important to understand the system dynamics, the environmental factors and the technology being used by the application. It should be noted that such approaches are only effective if a correct and accurate model is available and may not be suitable for complex systems. This paper makes use of the sensitivities of specific parameters under intermittent conditions that can impact the operational performance of the overall system. It also reports the results of using a structured approach to understand the requirements of particular components that affect the results of a system, depending upon their sensitivity to the output.

The paper is structured as follows: Section 2 discusses the problem of false alarms and how component sensitivity analysis could be a useful tool for design engineers. In Section 3, the authors then describe the modelling approach undertaken to study the impact of intermittent variations on electronic components. Discussions are presented on the simulation results, followed by conclusions from the preceding analysis.

2. False alarms in NFF events

It is well established that degradation increases over time until a point where the component will completely fail; it stands to reason that the nature of intermittent faults will also change with this degradation. It is accepted that degradation changes over time as a result of electronic ageing and environmental exposure. What is not so recognised is how electronic ageing affects the degradation characteristics over time. What actually occurs is randomly occurring intermittent discontinuities that start out as a mere nuisance and eventually result in a 'hard fault'. However, monitoring the impact of intermittent faults by studying the sensitivity of certain electronic components in turn could be helpful in predictive maintenance strategies[13].

Most complex engineering designs undergo environmental testing in order to prove reliability and robustness as part of the respective certification process. However, systems often behave differently during unpredictable operating conditions that may not have been considered during the design testing process[7]. This results in fault symptoms manifesting themselves only under those specific conditions, for example when the temperature changes or in vibration conditions, which are not normally present during acceptance (or maintenance) testing. It has been argued that three major environmental conditions must be controlled for obtaining good diagnostics data: humidity, vibration and temperature[12]. However, existing testing standards do not require these environmental factors to be controlled together. Each of these typically depends on factors such as temperature and humidity fluctuations with varying conditions, *ie* altitude, time of year, weather patterns, etc. When a monitoring system is commissioned, it is often put through robust in-house test procedures to ensure its functionality[1]. However, during real-time operation, some alarms might be triggered that result in 'no fault found' events and require manual inspection to assess the exact causes. Such inspections are necessary and highlight the importance of establishing adequate environmental data and information management to speculate the root causes of the issue[13].

A typical scenario is illustrated in Figure 1, where the monitoring system triggers an alarm. This initiates the operator (or maintainer) to troubleshoot and investigate the reasons for the trigger according to a maintenance manual (as the current standard in troubleshooting guidance is the fault isolation manual[7,14]). Here, the investigator must make a decision on how to categorise the fault:

- If it is listed in the manual, then it can be dealt with according to the outlined procedure;
- If is it not listed, the investigators will rely on their experience depending on the symptoms of the faults, for example the fault could be due to the environmental conditions;
- Classify this incident as a false alarm and report a NFF event[1].

Some fault conditions may not have been anticipated by the design engineers and therefore the traditional diagnostic systems may not be able to rectify them. In those cases, human ingenuity

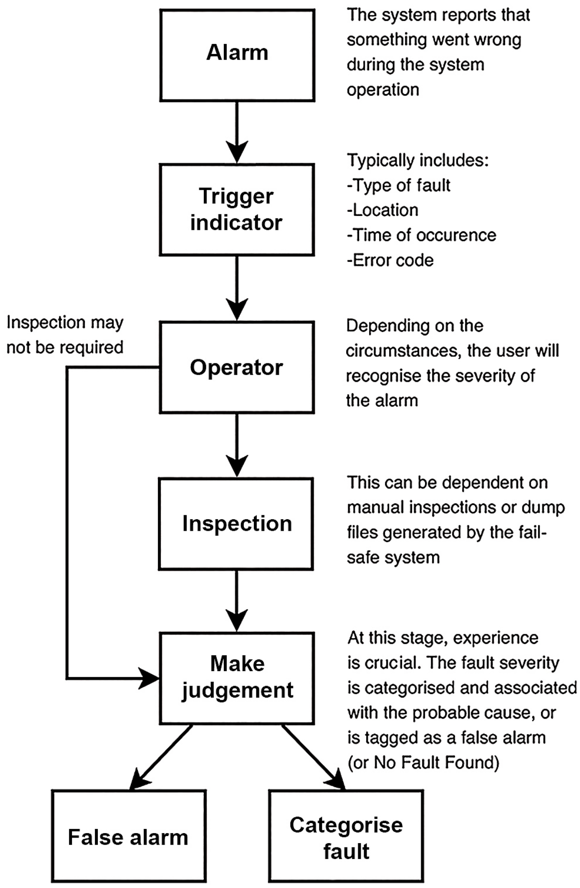

Figure 1. Typical alarm indicator scenario

is often the best option to resolve the problem; however, it is important to establish procedures to enable a pathway for some of this troubleshooting knowledge to make its way back into any manual updates[15]. In addition, this information must be fed back into engineering to modify the system design for better diagnostic and reduced false alarm instances. Therefore, from a practical point-of-view, there are many reasons why it may be important to consider parameter variations when making condition monitoring design decisions[16]:

- Parameter values of physical components may not always be known prior to implementation. There are always discrepancies between the parameter values in a system model;
- During the system's life, some parameters are subjected to change through the ageing process by environmental influences, for example the capacitance in components increases during high humidity. A sensitivity analysis will therefore be required to determine the critical parameters;
- The manufacturing process causes deviations within parameter values and establishing individual component tolerances may not be sufficient enough to guarantee the overall system performance.

3. Modelling approach

It is important to understand the impact of physical events during implementation. Consider a typical RLC network circuit under normal conditions, as shown in Figure 2. Using Kirchoff's Voltage Law:

[1]It should be noted that not all NFF events can be classified as false alarms. An in-depth analysis on the topic can be found in[7]

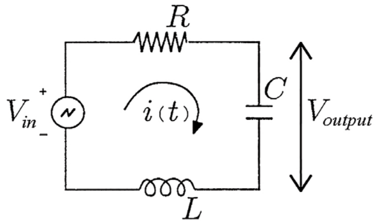

Figure 2. A series RLC circuit

$$V_{in} = Ri(t) + L\frac{di(t)}{dt} + \frac{1}{C}\int i(t)\,dt \quad (1)$$

where V_{in} is the voltage of the power source, $i(t)$ is the current in the circuit, R is the resistance of the resistor, L is the inductance of the inductor and C is the capacitance of the capacitor.

To develop a mathematical representation of the relationship between the input and output, a Laplace function can be defined:

$$H(s) = \frac{n_0 + n_1 s + \ldots + n_i s^j}{1 + m_1 s + \ldots + m_i s^j} \quad (2)$$

where n_j are the numerator coefficients, m_j are the denominator coefficients and j is the order of the function.

Equation (1) can used to define the set of interconnected components:

$$H(s) = \frac{i(t)}{V_{in}} = \frac{1}{R + sL + \frac{1}{sC}} = \frac{sC}{s^2LC + sRC + 1} \quad (3)$$

The output voltage (capacitor voltage) V_{output} is:

$$H(s) = \frac{V_{output}}{V_{in}} = \frac{\frac{1}{sC}}{R + sL + \frac{1}{sC}} = \frac{1}{s^2LC + sRC + 1} \quad (4)$$

3.1 *Sensitivity analysis*

In the design of any system (or function), it is important to know the effect on the system performance due to the variations of some system parameters. This will allow designers to intelligently specify the type and precision of electronic components to be selected. A measure of this effect can readily be expressed in terms of its relative sensitivity function, or simply the sensitivity of a circuit, with respect to a particular parameter x, can be defined as:

$$S_x^{H(s)} = \frac{\partial H(s)}{\partial x} \cdot \frac{x}{H(s)} \quad (5)$$

The system's transfer function is of considerable importance, and having the availability of its given parameter values can effectively be used in relating the sensitivity of the function to a percentage change. If this calculation is large, then a small change in a component's value will give a large change in the transfer function output. Therefore, it is essential to understand the requirements for selecting particular components in order to ensure its robust performance under various intermittent conditions. With respect to the RLC circuit from Equation (4), the sensitivity equations will take the form:

$$\frac{\partial H(s)}{\partial L} \cdot \frac{L}{H(s)} = \frac{-s^2LC}{s^2LC + sRC + 1} \quad (6)$$

$$\frac{\partial H(s)}{\partial C} \cdot \frac{C}{H(s)} = \frac{-s^2LC - sRC}{s^2LC + sRC + 1} \quad (7)$$

$$\frac{\partial H(s)}{\partial R} \cdot \frac{R}{H(s)} = \frac{-sRC}{s^2LC + sRC + 1} \quad (8)$$

The sensitivity Equations (6) to (8) are functions of frequency and can be presented as a vector of the independent components by substituting $s = jw$. With $R = 1\omega$, $L = 0.1H$ and $C = 0.01F$, Figure 3 illustrates that any variations in L and C will have the most impact on the output response, whereas the circuit is less responsive at the deviation of R in the vicinity of the cut-off frequency. This hypothesis can be verified by making use of the Fourier transform and studying the impact of parameter variations[17].

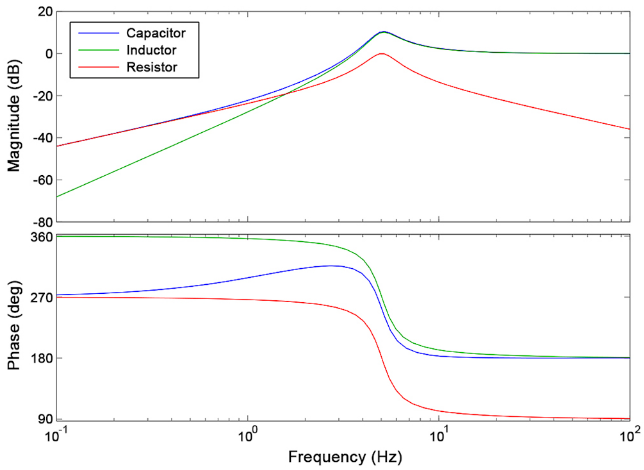

Figure 3. Frequency response of the coefficient sensitivities: $R = 1\omega$, $L = 0.1H$ and $C = 0.01F$

3.2 *Fourier coefficients evolution under intermittent conditions*

A technique that can help study the process is by performing the 'evolution of the Fourier coefficients', which performs frequency calculations in the time domain. It is a combination of frequency domain and time domain analysis based on the Fourier series. Consider a periodic signal $f(t)$, which is expressed by a Fourier series:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_0(t)\cos(nw_1 t) + b_0(t)\sin(nw_1 t) \quad (9)$$

where $\frac{a_0}{2}$ is the DC component of the signal and n represents the rank of the harmonics ($n = 1$ corresponds to the fundamental component). The remaining variables can be described as:

$$a_n(t) = \frac{2}{T_F}\int_{T_F}^{t} f(t)\cos(nw_1 t)\,dt \quad (10)$$

$$b_n(t) = \frac{2}{T_F}\int_{T_F}^{t} f(t)\sin(nw_1 t)\,dt \quad (11)$$

$$T_1 = \frac{1}{f_1} = \frac{2\pi}{w_1} \quad (12)$$

$$T_F = kT_1,\ k > 0 \quad (13)$$

where f_1 is the fundamental frequency and T_F is the integration time being averaged via a moving window over k periods of the fundamental for the Fourier analysis. The definition of the Fourier coefficients, a_n and b_n, presented in Equation (9), are considered to be functions of time and therefore can be used to describe the behaviour of the signal frequency characteristics in the time domain. The magnitude and phase of the observation signal $f(t)$, or the selected harmonic component, can be calculated by the following equations:

$$|H_n| = \sqrt{a_0^2(t) + b_0^2(t)} \quad \text{.............................(14)}$$

$$\angle H_n = \arctan\left(\frac{a_n(t)}{b_n(t)}\right) \quad \text{.............................(15)}$$

After performing the Fourier analysis of the function output and input signals, the frequency response of the transfer function is computed by:

$$Gain = \frac{H_{output}}{H_{input}} \quad \text{....................................(16)}$$

$$Phase(\phi) = \angle H_{output} - \angle H_{input} \quad \text{.....................(17)}$$

The frequency response parameters for $f = 0.1$, 0.5, 1, 2, 3, 4 and 5 Hz is illustrated in Figure 4. Here, the Fourier result reaches a steady-state value after an initial transient stage; however, this preliminary stage dies out once the Fourier coefficients reach a steady state[2].

3.3 *Results*

As discussed earlier, the scope of the Fourier analysis technique can be extended to study the changes in the response to specific intermittent variations in electronic component values. This will provide a much more accurate answer to the frequency response characteristics on how the variation affects the system. Making use of the RLC network from Equation (4), with $R = 1\omega$, $L = 0.1H$ and $C = 0.01F$, individual components are varied by 25% at $t = 3$ s and $t = 6$ s. The intermittent variation lasts for only 0.02 s in both instances and the effects are observed. The exercise is later repeated with component variations at 50%. The simulations carried out are listed as follows: Figures 5 and 6 illustrate the effect of intermittency in R, Figures 7 and 8 illustrate the effect of intermittency in L and Figures 9 and 10 illustrate the effect of intermittency in C.

3.3.1 *Discussion*

The Fourier transform is accepted to be the ultimate tool for evaluating the system response and to provide an acceptable solution for the frequency response characteristics. However, it can also be crucial when considering testability requirements for implementing condition monitoring techniques; this includes the identification of key analogue operational parameters to be monitored for uncharacteristic deviations. Such a technique would move away from a reactive maintenance concept into more proactive practices, providing vital information on root causes unavailable from traditional built-in-tests (BITs), and also aid in overall maintenance decision making. It should be noted that such a technique alone will not fully mitigate intermittent problems, but rather be used to narrow the focus down to only specific subsystem sensitive parameters that could be monitored by BITs. In either case, NFF events can be reduced if the monitoring methodology is more specific to highly sensitive components and localises the failures.

It has been established, analytically, that intermittent variations are proportional to the amount of change in the component value and that a sensitivity analysis can be used to provide an indication of which components are prone to a greater effect. Also, the closer the system frequency moves towards its cut-off region, the impact of intermittency becomes much more apparent (as compared to lower frequencies with the same variation amplitude). This effect is visible for higher frequencies in Figures 7 to 10.

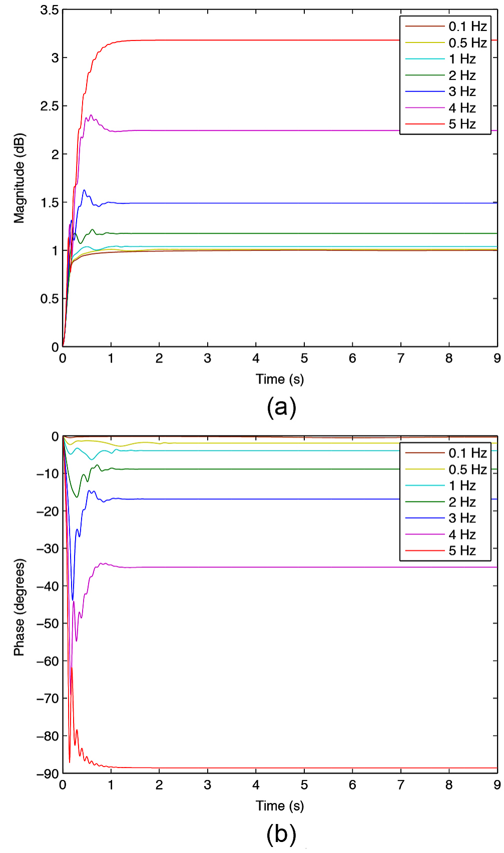

Figure 4. Calculating the magnitude and phase of Equation (4) at particular frequencies in the time domain

4. Conclusion

Transfer functions can provide useful expressions for the characteristics of a particular system. These expressions remain valid even when their parameter values change, whilst accurately simulating the system behaviour. This paper presented an analytic and simulative technique to identify the most sensitive parameters that affect the behaviour of a system. When exposed to intermittent deviations, some component values can be regarded as better indicators of fault occurrence. One of the disadvantages of the method is that a large number of electronic parameters could complicate the analysis. However, as discussed in this paper, providing better insights into the effect of parameter variations can be of interest in some specific industrial applications. This

[2]This effect is not visible when computing the frequency response using a Bode plot, which plots only the final value of the Fourier coefficients

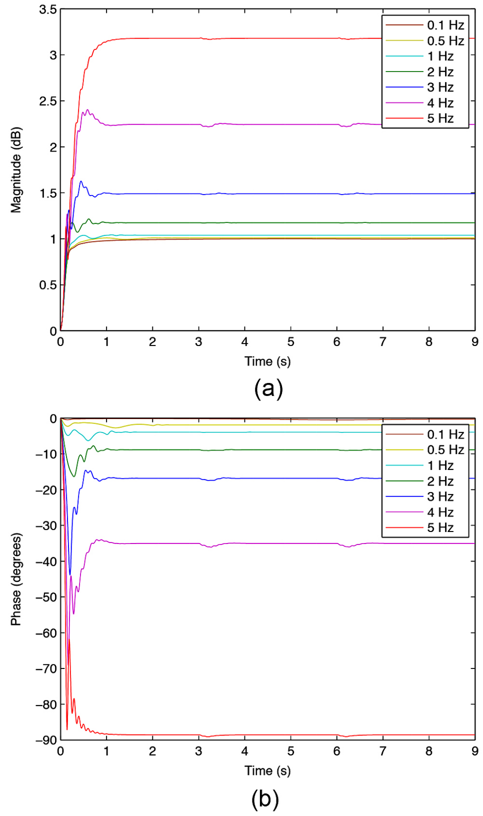

Figure 5. R is varied by 25% at $t = 3$ s and $t = 6$ s

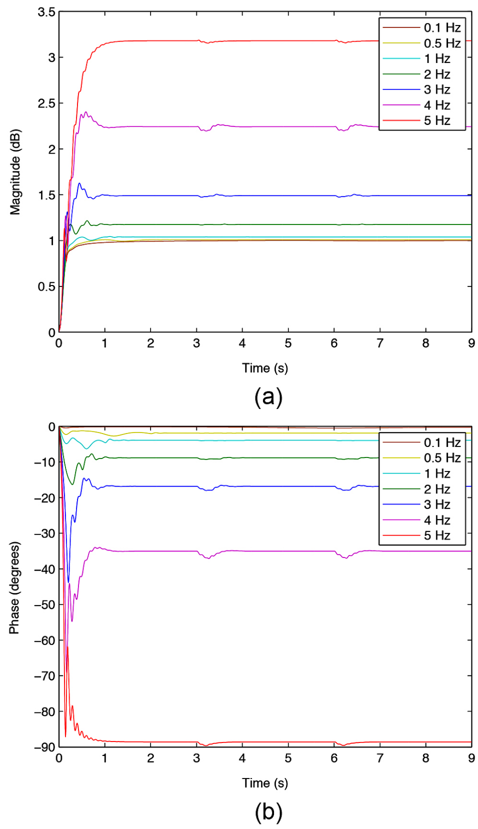

Figure 6. R is varied by 50% at $t = 3$ s and $t = 6$ s

may include defining tolerance bounds or the particular types of component that are more robust or less prone to abrupt variations.

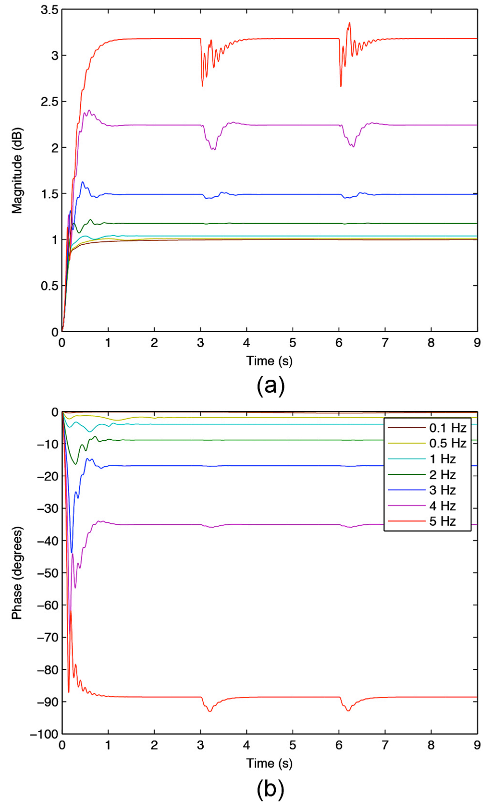

Figure 7. L is varied by 25% at $t = 3$ s and $t = 6$ s

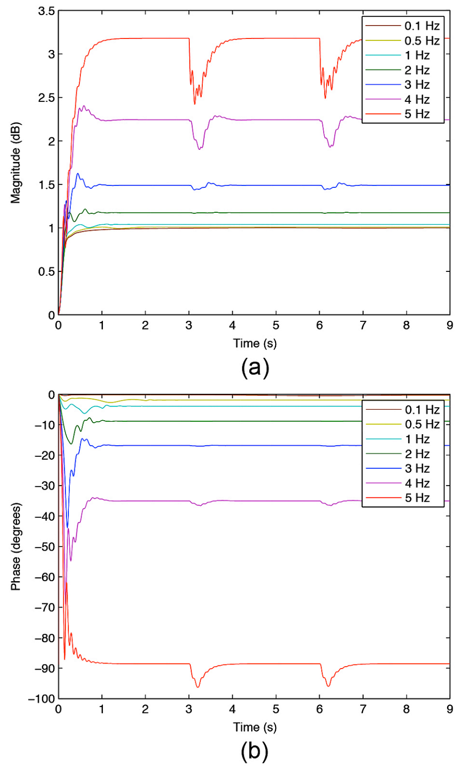

Figure 8. L is varied by 50% at $t = 3$ s and $t = 6$ s

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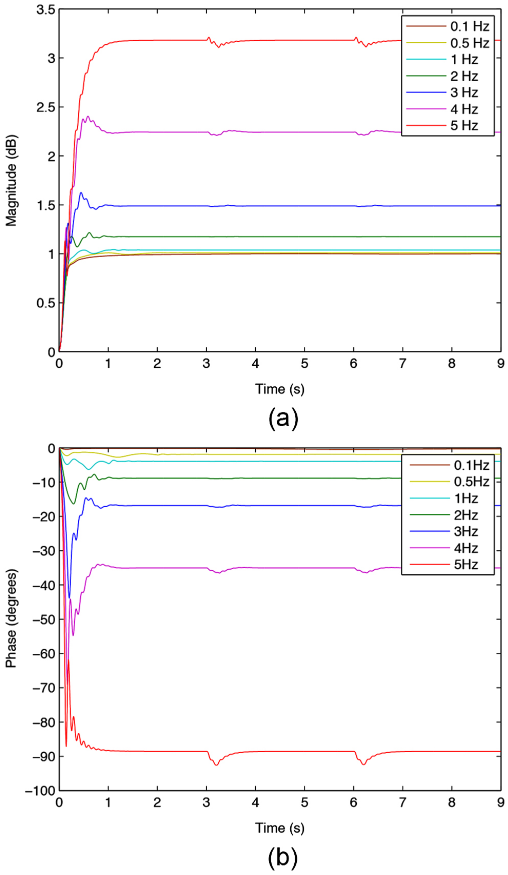

Figure 9. *C* is varied by 25% at *t* = 3 s and *t* = 6 s

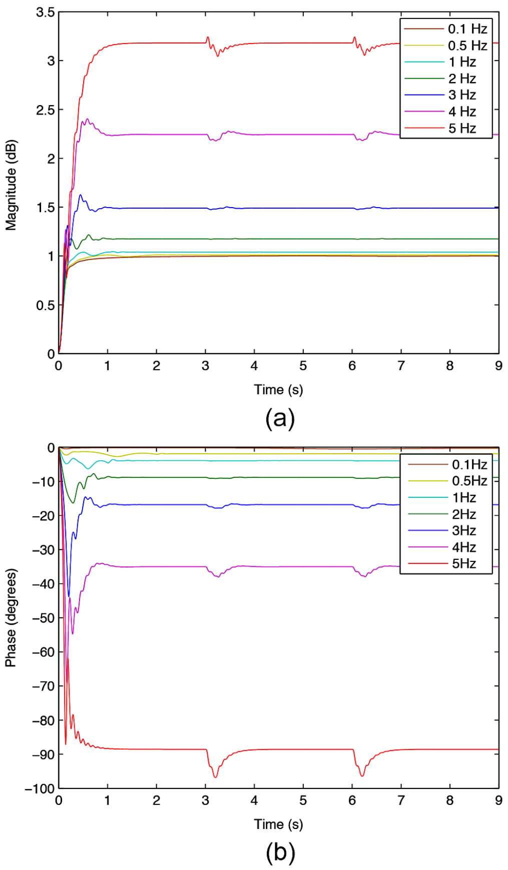

Figure 10. *C* is varied by 50% at *t* = 3 s and *t* = 6 s

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