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Non-Contacting Sensor for Small Displacement and Vibration Monitoring Based on Reflection Coefficient Measurement

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Abstract—In some cases, such as at a boiler tank and other large-size mechanical systems, it is more realistic to employ a non-contacting sensor to detect small displacement or vibration. In this paper, a non-contacting sensor for monitoring small displacement or vibration based on measurement of antenna reflection coefficient is proposed. A theoretical and numerical study is performed to investigate the proposed method and to determine the post processing method associated with the antenna reflection coefficient data. To avoid the ambiguity in the measured data, the detection of both the magnitude and phase components of the antenna reflection coefficient is required to compute the small displacement of the target. The distance between antenna and target has to be determined in order to minimize the ambiguity range in the data. The frequency domain observation is more appropriate for determining the amplitude and frequency of the target vibration. Magnitude detection, phase detection and Fourier analysis are used as main tools in the post-processing part of the proposed method.

1. INTRODUCTION

In several cases, measuring a physiological and mechanical vibration or small displacement cannot be performed using contacting sensors or measurement device. Some examples are detection of victims buried under the debris of the collapsed building, estimation of small displacement in civil structures, and detection of vibration of boilers or other large-size mechanical systems. Non-contacting sensors are generally required in the aforementioned cases. The use of electromagnetic wave propagation principles for developing non-contacting sensors has been proposed in previous researches. Doppler radar was studied and proposed for detecting vital sign, for examples respiratory and heartbeat [1–5]. In order to monitor the condition of civil structures, the use of radar systems as tools for measuring the structure displacement and monitoring the vibration characteristic was evaluated [6–9]. The application of radar systems as non-contacting sensors is considered to be more appropriate for monitoring a large area due to the cost consideration. On the other hand, for monitoring a specific system, such as a boiler or a large machinery, a simple and low-cost system is generally more practical. Motivated by the fact that mechanical vibrations play an important role in favoring correct operation of electromechanical system, detail mechanical vibrations were investigated for the control of nonlinear large-scale electromechanical system [10]. Non-contacting sensor that is proposed in this paper can be used in the aforementioned control system as a tool to capture the mechanical vibration that occurred.

From the theory of conventional radar system, a high-range resolution radar is required for detecting small displacement or vibration. This high range resolution leads to a large required bandwidth [11–13]. In order to mitigate this issue, some previous works proposed the use of phase data processing as a basic detection principle to avoid the need of large bandwidth for high range resolution [1–4].

With respect to antenna devices, the matching impedance at antenna terminals is also influenced by electromagnetic interaction between the antenna and objects surrounding the antenna, especially the

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ones that are located within the near field region [14, 15]. Note that, if the antenna is located nearby a vibrating object, the reflection coefficient at its terminal will vary according to the small displacement that leads to vibration.

By exploiting this fact, the vibration or small displacement information can potentially be extracted from antenna reflection coefficient data. In this paper, a theoretical study on how to extract the information about small displacement or vibration of an object using antenna reflection coefficient model is introduced and discussed.

Theoretical analysis is formulated based on a simple measurement model which consists of a half wavelength dipole antenna placed near the conductor plane that plays a role as the measurement target. Phase data processing is introduced in the proposed method for detecting the displacement or vibration of conductor plane. A directional coupler is introduced to separate the reflection wave from the incident wave at antenna terminal. The simulation study of the formulated theoretical analysis indicates that an antenna device can be potentially implemented as a non-contacting sensor that measures the small displacement or vibration of a localized or individual target.

This manuscript is organized as follows: Section 1 introduces the motivation for the theoretical study of the proposed method. Section 2 describes the proposed method and its theoretical analysis containing the derivation of reflection coefficient model and the extraction model of displacement data. Section 3 provides discussion on the resulting analysis, which covers the advantages and the limitations of the proposed method as well as the system implementation. Section 4 provides the conclusion of the entire analysis in the preceding sections.

2. PROPOSED METHOD

The proposed vibration detection method is motivated by the existence of electromagnetic interaction between the antenna and the nearby objects. The objects that are located within antenna near field region will influence the antenna characteristics, including the reflection coefficient. Altering the position of an object near the antenna will modify the value of the antenna reflection coefficient. The interest is then to find a method to extract the displacement information of the object from the antenna reflection coefficient data. This will provide an opportunity to develop alternative methods using non-contacting sensors to detect vibrations or to estimate the value of the small displacement. The proposed method generally shares some similarities with Time Domain Reflectometry (TDR). In TDR, the behavior of electromagnetic wave is used to detect a phenomenon at the end or at a particular point of the transmission line. The object or parameter which is to be detected is modeled as a load at the end of the transmission line or at a particular point at the transmission line. This load will influence the value

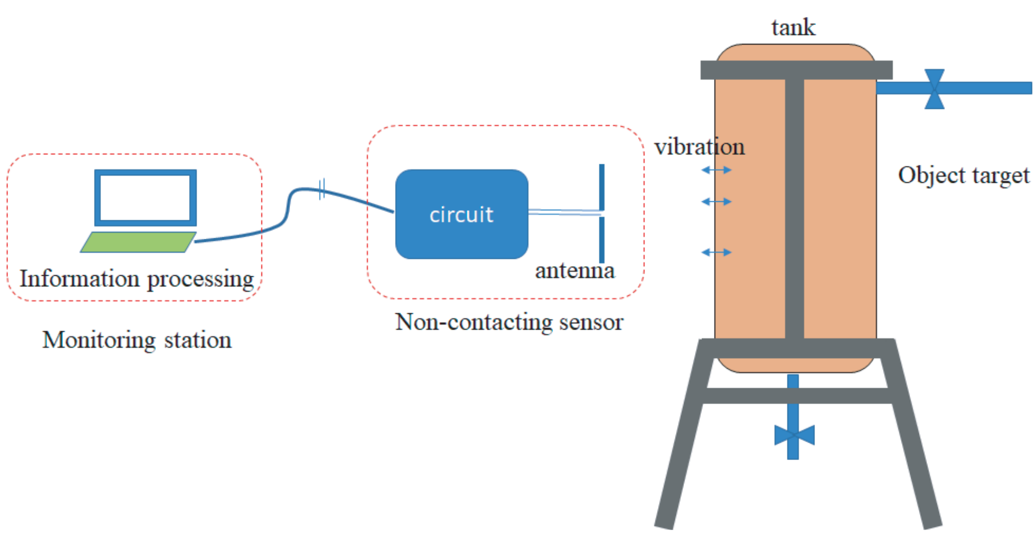

Figure 1. Illustration of non-contacting sensor based on antenna reflection coefficients.

of the reflection coefficient at the origin of the transmission line. Several applications of TDR, which has been reported, include the detection of landslide [16], the measurement of the water content of the soil [17], and a fault detection method for a transmission line or fiber optic [18].

Figure 1 illustrates an application of the antenna as a non-contacting sensor used to detect vibration of a water tank. The vibration on the surface of the tank will influence the value of the antenna reflection coefficient. The important information related to the vibration can possibly be extracted from the antenna reflection coefficient. The research introduced in this paper starts by deriving the reflection coefficient of the antenna that is placed near a target. Next, the equation describing the relationship between the reflection coefficient and the vibrating target is derived. Here, the vibration is modeled using sinusoidal function as a time-varying small displacement. Based on the reflection equation coefficient, a numerical study is performed by applying the derived equation on several scenarios in order to investigate how the proposed method can be used to detect vibrations and estimate small displacements. The obtained results can then be used as a reference for determining the required post-processing method.

Theoretical analysis of the proposed method is performed by considering the sensing model illustrated in Figure 2. A simple half-wavelength dipole antenna is employed as a sensoring part in which the electromagnetic interaction with the target occurs. The antenna is placed near the target that is represented by a conductor plane. When the antenna is connected to a signal source, the antenna radiation will be reflected by the conductor plane, and part of the radiation will be returned to the antenna. As a result, the reflection coefficient at the antenna terminal can be expressed as follows:

$$\Gamma(\omega, t) = \frac{b(\omega) + B(\omega, t)}{a(\omega)} \tag{1}$$

where $a(\omega)$ is the incident wave, $b(\omega)$ the reflected component at the terminal when the target does not exist or when the target is located far away from the antenna, and $B(\omega, t)$ the component reflected by the target back to the antenna terminal. If $\Gamma_A(\omega)$ represents the reflection coefficient of the antenna when the target does not exist, then Eq. (1) can be rewritten as:

$$\Gamma(\omega, t) = \Gamma_A(\omega) + \frac{(1 - \Gamma_A(\omega))(B(\omega, t))}{a(\omega)} \tag{2}$$

Let us now consider the electromagnetic interaction between antenna and conductor plane. The analysis model in Figure 2 shows that $d(t)$ is the distance between the antenna and conductor plane and next will represent the displacement or vibration. It is important to underline that the dependence

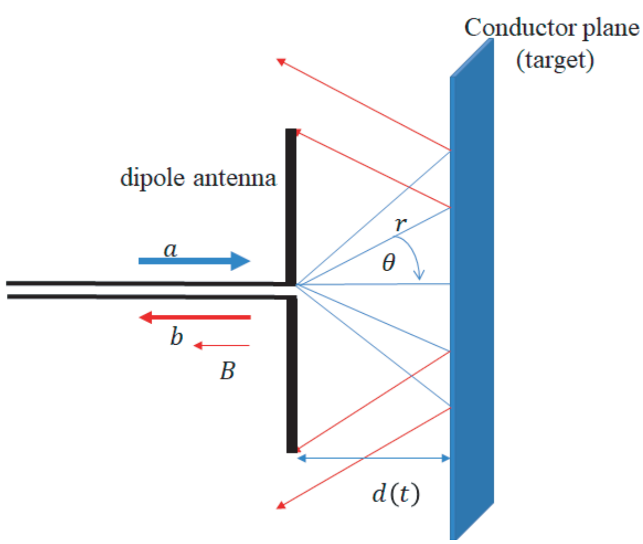

Figure 2. Reflection coefficient of dipole antenna as non-contacting sensor in the detection of target vibration.

of B on $d(t)$ is related to the total received electromagnetic wave at the antenna from conductor plane reflection. If $\Gamma_W(\omega)$ is the reflection coefficient of conductor plane, then the electric field that is reflected to the antenna can be expressed as follows:

$$E = \Gamma_W(\omega)(1 + \Gamma_A(\omega))a(\omega)\frac{\cos(0.5\pi \cdot \cos(\theta))e^{-j\beta 2r}}{\sin(\theta)} \tag{3}$$

Then the electric potential associated with the above electric field can be derived from line integral along the dipole aperture as written as Eq. (4). With respect to θ, r can be substituted by $d(t)/\sin(\theta)$, and Eq. (4) is written as Eq. (5). The component $e^{-jd(t)}$ in Eq. (5) is a constant on the integral operation so that Eq. (5) can be simplified into Eq. (6).

$$V(\omega, t) = 2\Gamma_w(\omega)(1 + \Gamma_A(\omega))a \int_{\theta_{d(t)}}^{0.5\pi} \frac{\cos(0.5\pi \cdot \cos(\theta))e^{-j\beta 2r}}{\sin(\theta)} d\theta \tag{4}$$

$$V(\omega, t) = 2\Gamma_w(\omega)(1 + \Gamma_A(\omega))a \int_{\theta_{d(t)}}^{0.5\pi} \frac{\cos(0.5\pi \cdot \cos(\theta))e^{-j\beta 2\frac{d(t)}{\sin(\theta)}}}{\sin(\theta)} d\theta \tag{5}$$

$$V(\omega, t) = 2\Gamma_w(\omega)(1 + \Gamma_A(\omega))ae^{-jd(t)} \int_{\theta_{d(t)}}^{0.5\pi} \frac{\cos(0.5\pi \cdot \cos(\theta))e^{-j\frac{\beta 2}{\sin(\theta)}}}{\sin(\theta)} d\theta \tag{6}$$

The integral calculation can be approximated by the numerical expression in Eq. (7) by taking N uniform samples of the associated function in the integral operation in the interval between the lower and upper limits of the definite integral in Eq. (6). Δ is the interval between samples. Then the expression of Eq. (7) can be simplified to Eq. (8). Substituting Eq. (8) into Eq. (7), we obtain Eq. (9). After conducting several mathematical manipulations from Eq. (10) to Eq. (11), the final expression of antenna reflection coefficient is written as Eq. (12). From the reflection coefficient expression in Eq. (12), it can be seen that the reflection coefficient varies with the change of the distance $d(t)$. Next, the information about $d(t)$ needs to be extracted from the antenna reflection coefficient. Note that $d(t)$ gives influence on both the reflection coefficient amplitude and phase. From Eq. (12), we can conclude that a small displacement of the target can possibly be detected by using magnitude or phase of antenna reflection coefficient and theoretically, and we can select one of them. In the next section, a much deeper analysis will be presented based on the investigation on the numerical result of the antenna reflection coefficient in several cases.

$$\begin{aligned} K &= \int_{\theta_{d(t)}}^{0.5\pi} \frac{\cos(0.5\pi \cdot \cos(\theta))e^{-j\frac{\beta 2}{\sin(\theta)}}}{\sin(\theta)} d\theta \\ &\approx \sum_{n=1}^{N} \frac{\cos(0.5\pi \cdot \cos(\theta_{d(t)} + (n-1)\Delta))e^{-j\frac{\beta 2}{\sin(\theta_{d(t)}+(n-1)\Delta)}}}{\sin(\theta_{d(t)} + (n-1)\Delta)} \Delta \end{aligned} \tag{7}$$

$$\Delta = \frac{(0.5\pi - \theta_{d(t)})}{N} \tag{8}$$

$$V(\omega, t) = 2\Gamma_w(\omega)(1 + \Gamma_A(\omega))ae^{-jd(t)}K \tag{9}$$

$$\Gamma(\omega, t) = \Gamma_A(\omega) + \frac{(1 + \Gamma_A(\omega))V(\omega, t)}{a} \tag{10}$$

$$\Gamma(\omega, t) = \Gamma_A(\omega) + \frac{(1 + \Gamma_A(\omega))2\Gamma_w(\omega)(1 + \Gamma_A(\omega))ae^{-jd(t)}K}{a} \tag{11}$$

$$\Gamma(\omega, t) = \Gamma_A(\omega) + \left[(1 + \Gamma_A(\omega))^2 2e^{-jd(t)}K\right] \tag{12}$$

Vibration can be modelled as a time-varying small displacement that occurs at the target surface. In many articles vibration is expressed as a sinusoidal function [12–14]. By substituting sinusoidal function of $d(t)$ into Eq. (12), the antenna reflection coefficient can then be written as Eq. (13). D is the vibration amplitude, and ω is the angular frequency of the vibration. The antenna reflection coefficient expression in Eq. (13) is similar to the narrowband frequency modulation equation which can be derived into Bessel function, and thus, the antenna reflection coefficient can be modified as Eq. (14).

$$\Gamma(\omega,t) = \Gamma_A(\omega) + \left[(1+\Gamma_A(\omega))^2 2e^{-jD\sin(\omega t))} K\right] \tag{13}$$

$$\begin{aligned}\Gamma(\omega,t) = {} & \Gamma_A(\omega) + \Big[2K(1+\Gamma_A(\omega))^2 (J_0(D)) + \ldots \\ & 2\sum_1^{\sim} J_K(D)\cos(2K\omega t) 2\sum_1^{\sim} J_{k+1}(D)\cos((2K+1)\omega t)\Big]\end{aligned} \tag{14}$$

From Eq. (14), it is clear that, as a result of the sinusoidal vibration, the spectrum of the antenna reflection coefficient consists of the fundamental frequency and its harmonic frequency components associated with the vibration function. The zero order Bessel function is related to the vibration frequency, and other higher order Bessel functions are related to the harmonic frequency of the vibration. The significance of the harmonic components depends on the amplitude of the vibrations. From the point of view of the narrow band frequency modulation model, the vibration amplitude will determine the modulation index which is associated with the significant Bessel function that appears. Furthermore, the observation of the amplitude and frequency of the vibration from the target can be performed better in the frequency domain than in the time domain.

3. RESULT AND ANALYSIS

By referring to the reflection coefficient equation that has been derived in the previous section, several numerical calculations are conducted to investigate the influence of the target displacement to the antenna reflection coefficient. If the antenna is placed at a distance of d_0 from the target (conductor plane) and Δ is the small displacement of the target by referring to the initial distance d_0, then $d = d_0+\Delta$ may vary with the change of Δ. Considering Eq. (12), the change in Δ will give influence on the antenna reflection coefficient. In this study, half wavelength antenna is used as a sensor that is assumed to have perfect impedance matching with its transmission line. The conductor plane target is assumed as a perfect conductor that reflects all incident electromagnetic wave. Figure 3 shows the magnitude and phase of reflection coefficient of the antenna as a function of distance d/λ. Increasing d/λ will cause the magnitude and phase of antenna reflection coefficient converge to certain values, and it indicates that the existence of target does not give significant influence on antenna reflection coefficient if the target location is far from the antenna. The result also shows that the target gives significant influence on antenna coefficient reflection if d/λ is small. It means that by exploiting near-field antenna, the proposed method has potential for measuring a small displacement, such as vibration. Figure 4 shows a significant effect of the small displacement occurring on the target with respect to the magnitude and phase of

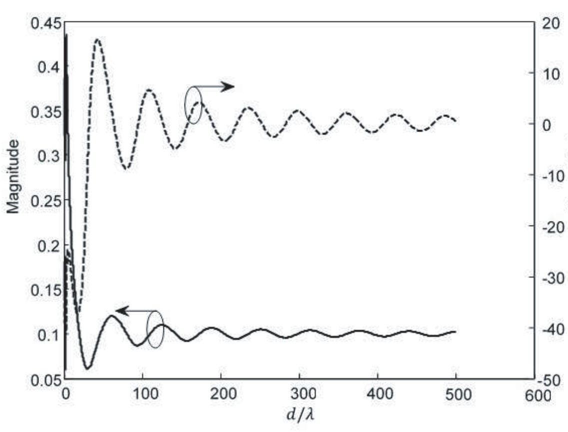

Figure 3. Antenna reflection coefficient as a function of d/λ.

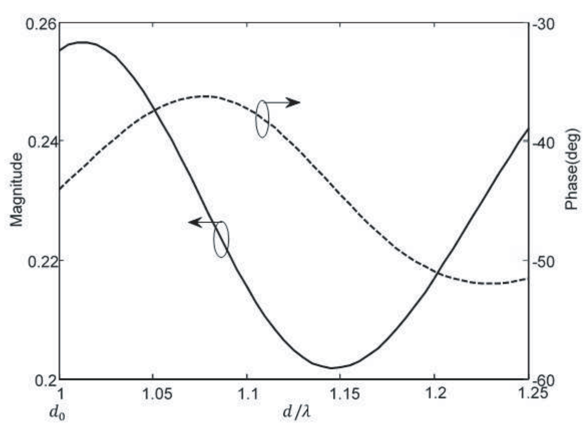

Figure 4. Antenna reflection coefficient as a function of d/λ at $d_0 = \lambda$.

the antenna reflection coefficient when the antenna is placed at a distance of one wavelength from the target. It means that the proposed method is capable of detecting small displacements. Variations of the small displacement of the targets from range zero to quarter lambda can be identified either from the magnitude or phase data of the antenna reflection coefficient although the ambiguity found on the reflection coefficient data still needs to be overcome.

The resolution of the proposed method in measuring small displacement depends on the antenna frequency operation. For single frequency operation, propagation distance is $2d/\lambda$. The reflection coefficient data will be repeated with period 0.5λ, and to avoid ambiguity the range of detection is reduced to 0.25λ. If the resolution in centimeter is required, the antenna should have frequency operation of 7.5 GHz.

Figure 5 shows the ambiguity range of magnitude and phase data of antenna reflection coefficient in measuring the small displacement. S-2 is the ambiguity range for magnitude data, and S-3 is the ambiguity range for phase data. Figures 5, 6 and 7 are antennas' reflection coefficients at three different d_0. The value of d_0 affects the ambiguity range of magnitude and phase data of the antenna reflection coefficient. The optimum value of d_0 is required to minimize the ambiguity range of the magnitude and phase data. For example, the antenna reflection coefficient depicted in Figure 7 is the result when the antenna is located at $d_0 = 1.2\lambda$ from target. In the S-1 range, there is ambiguity in the phase data and there is no ambiguity in the magnitude data in that range. In S-2 range there is ambiguity in the magnitude data and no ambiguity in the phase data. Based on the result in Figure 7, it can be determined that in S-1 range, small displacement information is suitably extracted from magnitude data, and in S-2 range, the small displacement information is suitable extracted from the phase data. Determining the antenna distance from the target (d_0) then becomes important consideration in implementing the proposed method. In measuring small displacement by using antenna reflection coefficient method, magnitude and phase detector is needed to give a wider range of detection. IQ demodulator can be implemented to achieve magnitude and phase data of antenna reflection coefficient. The IQ demodulator can be used to decompose the antenna reflection confident data into real and imaginary components, and then from these two components, magnitude and phase can be calculated.

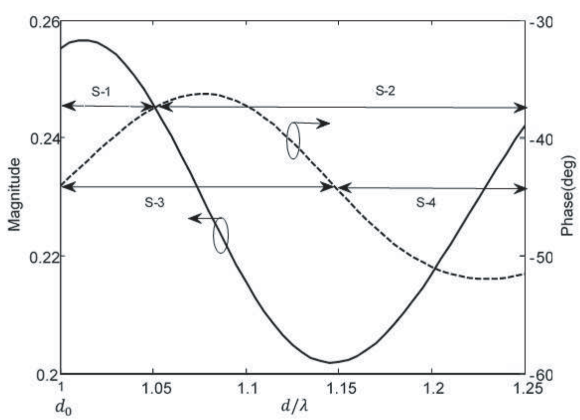

Figure 5. Ambiguity range of magnitude and phase data of antenna reflection coefficient as a function of d/λ at $d_0 = \lambda$.

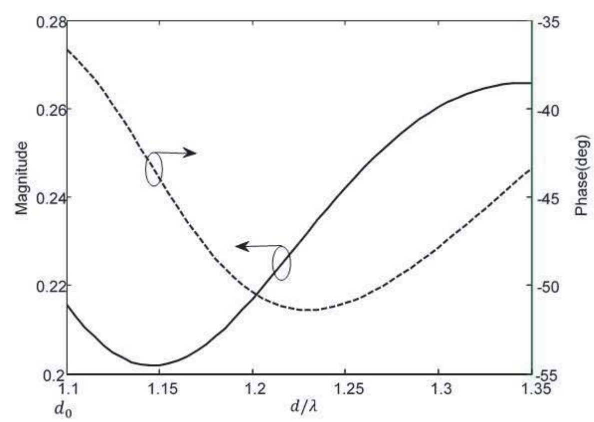

Figure 6. Antenna reflection coefficient as a function of d/λ at $d_0 = 1.1\lambda$.

In further analysis, small displacement in terms of vibration is also investigated, and as theoretically studied in previous section, frequency domain representation is more suitable than time domain. Figure 8 shows a Fourier transform of the antenna reflection coefficient when being used to observe a small vibration at the target surface. Two vibrations with different amplitudes and frequencies, first with amplitude of 0.01λ and frequency of 30 Hz and then with 0.05λ and frequency of 20 Hz. The two vibrations in Figure 8 can be distinguished based on the frequency domain data of the antenna reflection coefficient. It means that the vibration at the target can be identified by using the antenna reflection coefficient method. The amplitude of vibration information can be extracted from the peak magnitude of frequency spectrum, and the frequency of the vibration is associated with the frequency of peak magnitude of the spectrum. The lower vibration amplitude has a lower peak magnitude of its spectrum and vise versa. Considering the theoretical discussion in previous section that reflection coefficient equation according to vibration is similar to narrow band frequency modulation signal model, we can see that at higher amplitude vibration, the harmonic frequency will appear. For example, the second harmonic on 60 Hz appears at vibration with amplitude of 0.01 lambda and frequency of 30 Hz in Figure 8.

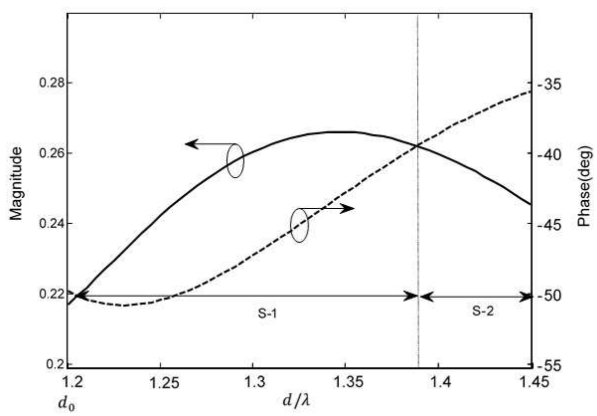

Figure 7. Antenna reflection coefficient as a function of d/λ at $d_0 = 1.2\lambda$.

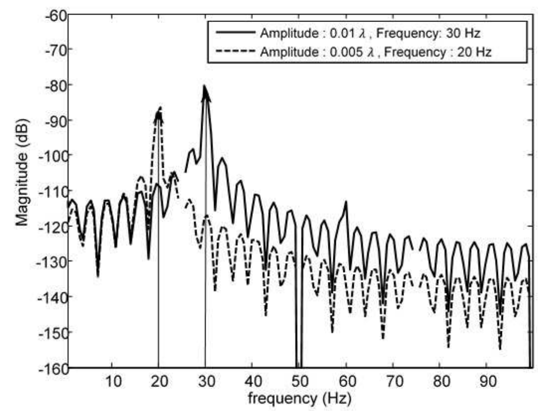

Figure 8. Frequency domain of antenna reflection coefficient for two different vibrations.

4. CONCLUSION

A non-contacting sensor for small displacement and vibration detection based on the antenna reflection coefficient measurement has been proposed. A theoretical and numerical study on the antenna reflection coefficient measurement for detecting small displacement and vibration is performed. The results show that small displacement and vibration information can be extracted from the antenna reflection coefficient data when the antenna is located near the target. Both magnitude and phase of antenna reflection coefficient are important data in determining the small displacement or vibration detection. There is an ambiguity in certain range in both magnitude and phase data in estimating the small displacement. To avoid the ambiguity in the measured data, the detection of both the magnitude and phase components of the antenna reflection coefficient is required to estimate the small displacement of the target. The distance between antenna and target has to be determined in order to minimize the ambiguity range in the data by increasing the linear range of the magnitude and phase data. The frequency domain observation is more appropriate for determining the amplitude and frequency of the target vibration. Magnitude detection, phase detection and Fourier analysis are used as main tools in the post-processing part of the proposed method. IQ demodulator can be implemented as a magnitude and phase detector.

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