Mm-wave Radar Based Micro-Deformation Monitoring for Highway and Freight Railway Bridges

Yingsong Li [1,2], Zelong Shao [1,3], Xiangkun Zhang [1,3,*], and Jingshan Jiang [1]

[1] Key Laboratory of National Microwave Remote Sensing
National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China
*zhangxiangkun@mirslab.cn

[2] College of Information and Communication Engineering
Harbin Engineering University, Harbin, 150001, China
liyingsong@ieee.org

[3] School of Electronic, Electrical and Communication Engineering
University of Chinese Academy of Sciences, Beijing, 100490, China

Abstract ─ In this paper, a mm-wave radar is devised to monitor the micro-deformation of bridges and its performance is verified via monitoring a highway and a freight railway bridges. The radar interferometry technology is utilized to develop the compact and portable mm-wave radar. Experiments are set up to monitor a highway bridge around Beijing-Tianjin expressway which is near the sixth ring roads of Beijing and a Daqin freight railway bridge in Yanqing, Beijing. The experimental results demonstrate that the devised radar can detect the micro-deformation of the bridge vibration with a super-resolution and high precision, making the mm-wave radar promising for bridge monitoring, dam monitoring, debris flow monitoring applications.

Index Terms ─ Micro-deformation monitoring, millimeter (mm) wave radar, super-resolution and high precision.

I. INTRODUCTION

The status of the bridges is very important, which can help to check and repair the bridge damages [1]. In particular, the bridges are increased rapidly for constructing the modern highway, high-speed railway and roads [2-3]. Thus, it is useful to monitor the status of these bridges to understand the bridge healthy status [4-5]. Moreover, these bridges should be monitored in real-time and repaired on time.

Recently, several methods or devices have been presented to monitor the status of the bridges, such as gauges, accelerometers, total stations, digital levers, global position system [4-5]. Although these devices or methods, including the sensors, can well detect the status of the bridges, the installations of these devices are difficult since they should contact with the bridges, which are dangerous, time-consuming, and they are sensitive to the weather and the environments [6-8]. In addition, the installation of these devices might give unnecessary to the transportation and the economy. It is a best way to find out a solution to monitor the status of the bridges using non-contacting method, which can also provide a real-time and online monitoring. To overcome the drawbacks of these devices and meet the practical requirements, radar interferometry technique has been studied for providing an all-weather and non-contract method for monitoring the status of the bridges [9-12]. In comparison with the above mentioned techniques, the radar can overcome the disadvantages, and it has been used for detecting the civil structures. An IBIS radar is designed by Italy and it has been used for monitoring the simple bridges [13]. However, there is no comparison with the different bridges. Moreover, there is no radar-based micro-deformation monitoring for highway and freight railway bridges.

In this paper, a mm-wave radar is devised for monitoring the micro-deformation of the bridges. The radar is designed in our laboratory and its performance is verified for monitoring a highway and a freight railway bridges. In the designed mm-wave radar, interferometry technique is considered for improving the precision of the measurement. The measurement results are presented to prove that the devised radar can well monitor the micro-deformation of the bridge vibration with a super-resolution and high precision. The proposed mm-wave micro-deformation monitoring method can detect the displacement with a distance from the targets and it also is easy to install in the practical engineering. In our paper, we mainly discuss the micro-deformation monitoring based on our design mm-wave radar to detect the bridges vibrations of highway and freight railway.

Submitted On: June 20, 2018
Accepted On: September 8, 2018

II. THEORY AND STRUCTURE OF THE MM-WAVE RADAR

In the mm-wave radar design, frequency-modulated continuous wave (FMCW) mode is considered to make the radar compact and simple [14-15]. Additionally, it also has many advantages in comparison with traditional radars, such as high resolution and low transmitting power [14]. Thus, the radar can be used to monitor the bridges since the vibrations from the bridges are very small, which is always smaller than 5mm. As for the FMCW radar, the range resolution is described as [14-16]:

$$\Delta r = \frac{c}{2B}, \tag{1}$$

where B denotes the bandwidth of the radar while c represents the speed of light. The interferometric technique is used for improving the micro-deformation detection ability by taking echo phase difference into consideration [17]. The micro-deformation and the echo phase difference has a relationship which is given by:

$$\Delta R = \frac{\lambda}{4\pi}\Delta\varphi, \tag{2}$$

where ΔR is the change of the bridge, $\Delta\varphi$ is the echo phase shift, λ is the wavelength of the center frequency. Since the radar is designed at mm-wave, its wavelength is very small, and hence, the minimum deformation of the bridge vibration can be detected. In addition, phase unwrapping and phase calibrated methods are also utilized to guarantee the phase accuracy which can accurately measure the micro-deformation of the bridges [17]. The monitoring installation is illustrated in Fig. 1 to get the micro-deformation of the bridges [19-25].

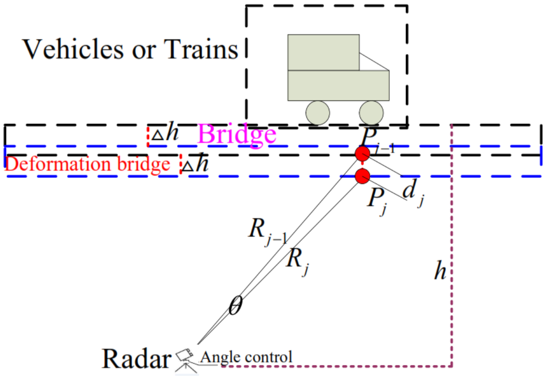

Fig. 1. Correction scheme of radar bridge monitoring.

In Fig. 1, the radar is always under the bridge to get the accurate deformation. If the mm-wave is installed with an angle to the bridge. The micro-deformation measurement results should be corrected by using the correction scheme listed in Fig. 1 and the computations are given in [20]. In Fig. 1, the deformation on the direction of sight is [20]:

$$d_j = R_{j-1} - R_j \quad (j = 1, 2, 3 \cdots), \tag{3}$$

and we have

$$\Delta h^2 = d_j{}^2 + (R_{j-1}\theta)^2 - 2R_{j-1}\theta \cdot d_j \cdot \cos(\frac{\pi-\theta}{2}), \tag{4}$$

when θ is very small. Herein,

$$(R_{j-1}\theta) - 2 \cdot d_j \cdot \sin(\frac{\theta}{2}) \approx (R_{j-1} - d_j)\theta. \tag{5}$$

Thus, we can get the micro-deformation:

$$\Delta h = \sqrt{d_j{}^2 + (R_{j-1}\theta)^2 (R_{j-1} - d_j)}. \tag{6}$$

In fact, the micro-deformation is very small obtained from the vibration of the bridges in comparison with the distance between the radar and the bridges. And the micro-deformation is gotten from the measurement, which will be affected by position of the radar and the monitoring angle. To well get the measurement accuracy of the bridge vibrations, many experiments have been done and compared with the ANSYS simulations [20]. As we know, the highway bridge and the freight railway bridges are so wide that we should consider the monitoring position and the angle of the radar installation [19].

On the basis of the bridge micro-deformation monitoring applications, an mm-wave radar is designed, which is comprised of slot antennas, transmitter, receiver, data processing module, and power supplies. In this design, the two slot antenna arrays with high isolation of 60dB are used for transmitting antenna and receiving antenna, which are connected via the cable-to-waveguide transformer to the transmitter and receiver. Herein, the antenna array has a beam width of 4º×10º. In the antenna design, we use the simple slot antenna to form an array, which is based on the experience in our lab. In the data processing, control and signal sampling units are utilized and integrated into the radar system to provide a data sequence control. Additionally, a battery and a voltage regulator are used for providing a stable voltage in the out bridge monitor testing. For the transceiver, the radio frequency signals are generated at the same time. Mixing the received signal with a local replica of the transmitting signal maintains coherence and makes the system compact. In the transmitter, a linear frequency-modulated chirp signal is generated by a direct digital synthesizer, which has a bandwidth of 300MHz, and then it is modulated to intermediate frequency (IF) of 3750MHz ±150MHz. The IF chirp signal conveys to the transmitter and is up-converted to a signal with a center frequency of 36.05 GHz. Thus, the signal with a center frequency of 36.05 GHz and bandwidth of 300MHz is transmitted to the air. Then, the signal is received by the receiving antenna for processing by the receiver. The receiver is comprised of low noise amplifier (LNA), a mixer and an IF amplifier, where the LNA is used for amplifying the received echo signal. After that, the amplified signal is down-converted to IF. Then, the IF amplifier further boosts the IF signal and conveys it to a 16-bit ADC with 10MHz sampling rate. A high-speed Compact Flash (CF) card is used to store the data. The FPGA is used as the controller of the designed radar system. All the radar is designed by us, including the software and the hardware.

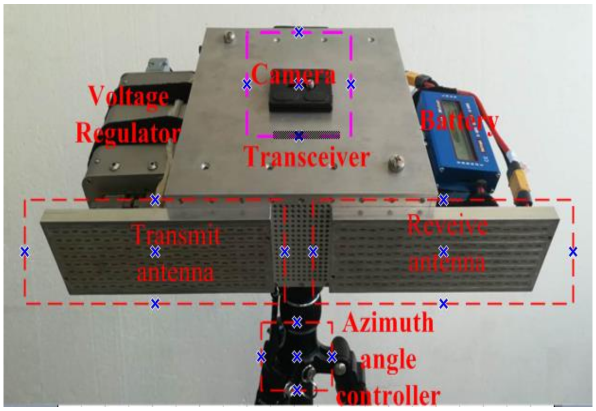

Fig. 2. Photograph of the designed mm-wave radar.

For the outside testing, the data is copied from the CF card and processed by using a laptop. In addition, a camera is installed on the top of the mm-wave radar to give a comparison between the monitoring and the practical scenarios. The designed mm-wave radar is shown in Fig. 2.

III. EXPERIMENT

To verify the effectiveness and the stability of the devised mm-wave radar system, two experiments have been constructed to monitor the micro-deformation of highway and the freight railway bridges. Based on the previous studies for monitoring the micro-deformations of the corner reflectors and the city railway bridges in Beijing, a highway bridge around Beijing-Tianjin expressway which is near the sixth ring roads of Beijing is monitored by using our developed mm-wave radar. The setup of the experiment is given in Fig. 3, where the radar is setup under the bridge. This is to say that the antenna array of the radar is pointed to the bridges directly. If the antenna array is installed and pointed to the bridge with an angle, the correction method should be adopted to ensure the accuracy of the monitoring. As we know, the health condition of the bridge is related the magnitude of the vibration. In the monitoring, the micro-deformation is given in continuous magnitude, which is to illustrate the displacement of the vibration. The monitored micro-deformation can give a reference to the health condition detection of the bridges.

The monitoring scenario is described in Fig. 4, where there is a truck passing though the monitored bridge. The monitored result is illustrated in Fig. 5. It is found that there is no vibration when this is no vehicles passing across the bridge. The status of the bridge changes quickly when there are vehicles running though the bridge.

Fig. 3. Setup of the bridge vibration monitoring.

Fig. 4. Scenario of highway bridge monitoring.

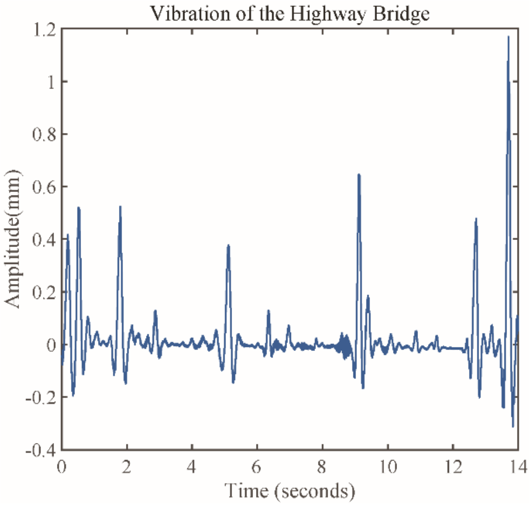

Fig. 5. Experiment result on vertical vibration of the highway bridge

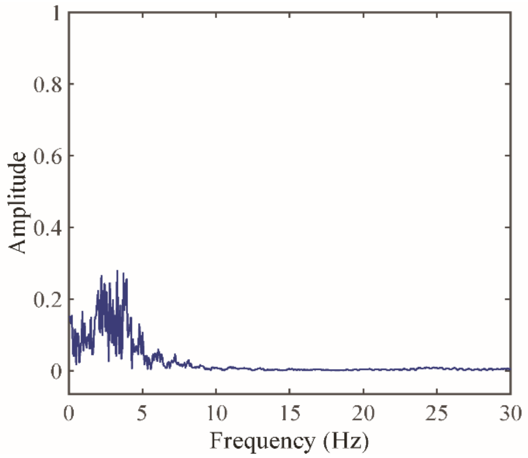

Fig. 6. Spectrum of the vertical vibration of the highway bridge w/o filter (Normalized amplitude in millimeter).

From the bridge monitoring experiments and the monitoring results of the highway bridge vibration monitoring, we found that the calculation method for loading vibration of highway bridge is similar with calculation method for loading vibration of light-railway bridge in [20]. At the same time, there are several trucks and cars running on the bridges. These vehicles hit the bridge to produce the strong vibrations during the different time at 0.5s, 0.8s, 2s, 5s, 9s, 12.3s and 13.8s. When the vehicles leave the bridge, the vibrations disappear quickly. There is some residual in the monitoring period, which might be caused by the radar installation position which is set under the bridge. Since the highway bridge is wide, the vibration is different at each side, which also depends on types of the vehicles. From the results, we can see that truck gives a strong hit to the bridge, and hence, an obvious vibration is appeared around 13.8s. Also, the vibrating frequency is considered to provide a reference for avoiding the self-resonance of the bridges.

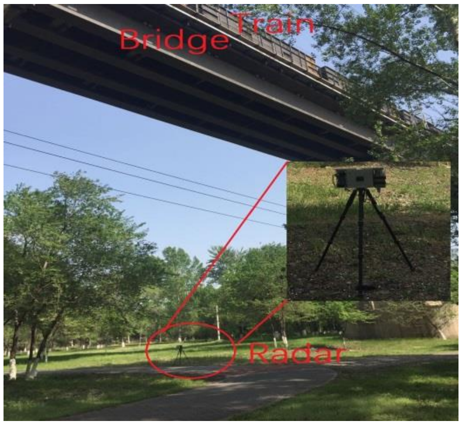

Fig. 7. Setup and scenario of freight railway bridge monitoring.

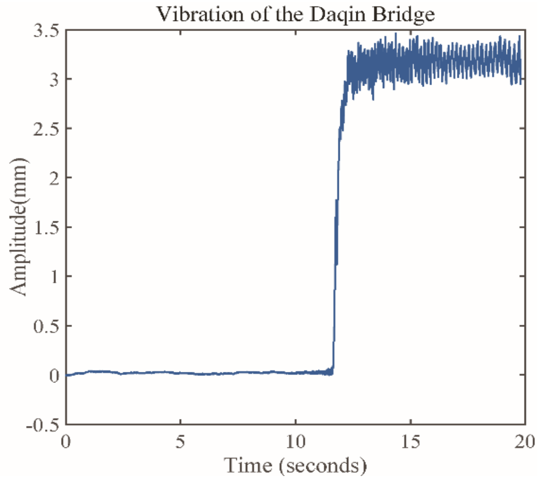

Fig. 8. Experiment result on vertical vibration of the freight railway bridge.

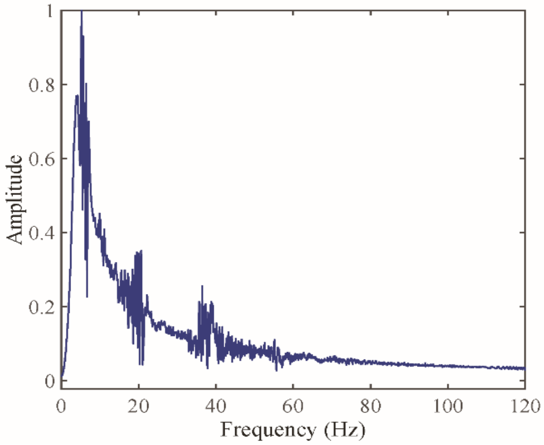

Fig. 9. Spectrum of the vertical vibration of the freight railway bridge with filter (Normalized amplitude in millimeter).

The spectrum of the highway bridge vibration can be gotten, which is illustrated in Fig. 6. From Fig. 6, it is clearly seen that the bridge vibration during the monitoring period is comprised of serval different vibration frequencies which are focus on 0-5Hz. Base on the analysis and comparison with the optical picture, we found that the loading vibration frequency of the bridge is caused by the truck at 13.8s, while the vibration appeared at 12.8s is caused by the smaller truck. The bridge is a prestressed continuous concrete bridge made of several spans, which is supported by box girders [26]. The loading frequencies of the box girder caused by different vehicles are approximately 3Hz, which have relationship to the length of these vehicles. Herein, the relationship is given by [20]:

$$f = \frac{v}{L}, \tag{7}$$

In this experiment, the velocity of the truck is 110km/h. The length of the truck and the car is around 15m. Thus, the vibration frequency happened at 2-3Hz, and the complex vibration frequencies may be caused by the other vehicles passing though the bridge.

The vibration of the bridge will be affected by the material and the structure of the blocks and the boxes [22], which can be calculated by the following equation [20, 27]:

$$f_s = \frac{1}{2\pi}\sqrt{\frac{\frac{1}{2}EI_b\left(\frac{\pi}{L_b}\right)^4 L_b}{\frac{1}{2}m_b L_b}}, \quad (8)$$

where EI_b denotes the stiffness of the vertical bending of the bridge, L_b represents the length of bridge span, and m_b is the weight of the bridge per unit length. Thus, if we can get the accurate parameters of the bridges, we can also get the natural frequency of the bridge vibration.

The natural frequency of the bridge vibration is about 2-3Hz, which is approximately equal to the vibration frequency of the bridge obtained at 13.8s. Moreover, the vibration of the highway bridge is complex since there are many vehicles running on the bridge, and the structure, material and geographical positions are complex, making it difficult to select a good position to install the designed mm-wave radar. However, our designed mm-wave radar can get the accurate vibration of the bridge.

As for freight railway bridge monitoring, a freight railway bridge on the Daqin freight railway around Yanqing is monitored. The setup of the railway bridge monitoring and monitoring scenario for freight railway bridge vibration are presented in Fig. 7, where the radar is still installed under the bridge and a train has more than 100 boxes which are full with mines, is passing though the bridge. The monitored result is presented in Fig. 8. We can see that the bridge is static when there are no trains. When a train reaches the bridge, there is a strong vibration whose magnitude is large. Then, the vibration magnitude is invariable when the train is passing though the bridge in about 3 minutes. Thus, we found that the vibration of the freight railway bridge is different with the highway bridge and high-speed railway bridge. The spectrum of the freight railway bridge vibration is analyzed and is given in Fig. 9. It can be seen that the bridge has a strong vibration as the train arrive the bridge, and the vibration frequency is about 6Hz. There is a resonance at 20Hz and 40Hz which might be caused by the head of the train lying at the middle of the train and the leaving of the train from the bridge. Also, the free vibration of the monitoring freight railway bridge is complex since it is near a highway and crosses on a river. From the above monitoring results, we found that the vibrations from the freight railway bridge and highway bridge are mainly determined by the changes of the bridge structure. The dominant vibrations of such bridges are symmetry with vertical bending of the main girder when the interferometry radar is fixed. From the experiments and discussions, it is worth noting that the vibrations of the bridges can be well monitored. To get the fast and accurate monitoring, the antenna array should be pointed to the bridge directing.

VI. CONCLUSION

A mm-wave radar has been designed and used for bridge micro-deformation monitoring. Two experiments have been setup to monitor a highway and freight railway bridges. The monitoring results showed that the proposed mm-wave can well monitor the vibrations of the highway and freight railway bridges with a high resolution and a good precision. In addition, the proposed mm-wave radar can also well detect the coming of the train in the freight railway bridge, which makes the radar very useful for bridge micro-deformation and the rail vibrations. In the future, we will develop reconfigurable and MIMO antennas based on defected ground plane to make the designed radar light [28-31].

ACKNOWLEDGMENT

This paper is supported by the National Key Research and Development Program of China (2016YFE0111100), Key Research and Development Program of Heilongjiang (GX17A016), the Science and Technology innovative Talents Foundation of Harbin (2016RAXXJ044), the Natural Science Foundation of Beijing (4182077), China Postdoctoral Science Foundation (2017M620918), the Fundamental Research Funds for the Central Universities (HEUCFM180806).

REFERENCES

[1] Z. Li, T. Chan, and J. Ko "Evaluation of typhoon induced fatigue damage for Tsing Ma Bridge," *Engineering Structures*, vol. 24, no. 8, pp. 1035-1047, 2002.

[2] X. He, W. Teng, Z. Yu, et al., "Recent developments of high-speed railway bridges in China," *Struct. Infrastruct. Eng.*, vol. 13, no. 12, pp. 1584-1595, 2017.

[3] X. He, Z. Yu, and S. Hu, "Main achievements and technical challenges of high-speed railway bridges in China," in *Proc. IABSE Conf.*, 2016.

[4] M. R. Chowdhury, et al., "Accelerometers for bridge load testing," *NDT E Int.*, vol. 36, no. 4, pp. 237-244, 2003.

[5] Z. Zhang and Q. Liu, "Research of bridge health monitoring data acquisition system," *Boletín Técnico*., vol. 55, no. 10, pp. 411-418, 2017.

[6] C. Gentile, "Application of microwave remote sensing to dynamic testing of stay-cables," *Remote Sens.*, vol. 2, no. 1, pp. 36-51, 2010.

[7] G. Luzi, M. Crosetto, and E. Fernández, "Radar interferometry for monitoring the vibration characteristics of buildings and civil structures: recent case studies in Spain," *Sensors*, vol. 17, no. 4, 2017.

[8] C. Li, W. Chen, G. Liu, et al., "A noncontact FMCW radar sensor for displacement measurement in structural health monitoring," *Sensors*, vol. 15, no. 4, pp. 7412-7433, 2015.

[9] M. Pieraccini, F. Parrini, M. Fratini, et al., "Static and dynamic testing of bridges through microwave interferometry," *NDT E Int*., vol. 40, no. 3, pp. 208-214, 2007.

[10] C. Gentile and G. Luzi, "Radar-based dynamic testing of the cable-suspended bridge crossing the Ebro River at Amposta, Spain," in *Proc. 11th Int. VMLC*, 2014.

[11] M. Pieraccini, M. Fratini, F. Parrini, et al., "High-speed CW step-frequency coherent radar for dynamic monitoring of civil engineering structures," *Electron. Lett*., vol. 40, no. 14, pp. 907-908, 2004.

[12] S. Hensley, D. Moller, S. Oveisgharan, et al., "Ka-band mapping and measurements of interferometric penetration of the greenland ice sheets by the GLISTIN radar," *IEEE J. Sel. Topics Appl. Earth Observ*., vol. 9, no. 6, pp. 2436-2450, 2016.

[13] L. Mayer, B. S. Yanev, L. D. Olson, and A. W. Smyth, "Monitoring of Manhattan bridge for vertical and torsional performance with GPS and interferometric radar systems," *Transportation Research Board 89th Annual Meeting*, Washington DC, 2010.

[14] H. Ko1, K. Cheng, H. Su, et al., "Range resolution improvement for FMCW radars," in *Proc. 5th Euro. Radar Conf*., 2008.

[15] H. Wang, M. Jiang, and S. Zheng, "Airborne Ka FMCW MiSAR system and real data processing," in *Proc.17th Int. Radar Symp*., 2016.

[16] C. Wang, H. Zhang, and Z. Liu, *Spaceborne Synthetic Aperture Radar Interferometry Measurement*, Science Press, Beijing, 2002.

[17] K. Hsu, C. Cheng, and C. Chiang, "Long-term monitoring of two highway bridges using microwave interferometer-case studies," in *Proc. 16th Int. Conf. GPR*, 2016.

[18] X. Liu, X. Tong, K. Ding, et al., "Measurement of long-term periodic and dynamic deflection of the long-span railway bridge using microwave interferometry," *IEEE J. Sel. Topics Appl. Earth Observ*., vol. 8, no. 9, pp. 4531-4538, 2015.

[19] Z. Shao, X. Zhang, and Y. Li, "Analysis and validation of super-resolution micro-deformation monitoring radar," *Progress In Electromagnetics Research (PIER) M*, vol. 62, no. 12, pp. 41-50, 2017.

[20] Z. Shao, X. Zhang, Y. Li, and J. Jiang, "A comparative study on radar interferometry for vibrations monitoring on different types of bridges," *IEEE Access*, vol. 6, pp. 29677-29684, 2018.

[21] Z. Shao, X. Zhang, J. Ren, and Y. Li, "High-speed railway bridge vibration measurement and analysis with radar interferometry," *2018 International Geoscience and Remote Sensing Symposium*, Valencia, Spain, 23-27 July, 2018.

[22] Z. Shao, X. Zhang, J. Ren, and Y. Li, "Short range SAR imaging for 2-D micro-deformation detection," *2018 IEEE International Symposium on Antennas and Propagation*, Boston, MA, USA 14-21 July 2018.

[23] X. Zhang, J. Ren, Z. Shao, J. Jiang, and Y. Li, "Vehicles detection experiments with Ka band FMCW ISAR," *The 39th Progress In Electromagnetics Research Symposium*, Singapore, 19-22 Nov. 2017.

[24] X. Zhang, Z. Shao, J. Ren, J. Jiang, and Y. Li, "Performance verification and testing for micro deformation detection radar," *The 39th Progress In Electromagnetics Research Symposium*, Singapore, 19-22 Nov. 2017.

[25] Y. Li, Z. Shao, X. Zhang, and J. Jiang, "Vibrations monitoring for highway bridge using mm-wave radar," *IEEE 7th Asia-Pacific Conference on Antennas and Propagation*, Auckland, New Zealand, 5-8 Aug. 2018.

[26] J. Li and M. Su, "The resonant vibration for a simply supported girder bridge under high speed trains," *J. Sound Vib*., vol. 224, no. 5, pp. 897-915, 1999.

[27] W. Wang, Y. Yang, P. Liu, et al., "Analysis of influence of MTMD on the vertical vibration character of high-speed railway 32m prestressed concrete simply supported box beam," *Environ. Eng*., vol. 30, no. 4, pp. 153-155, 2016.

[28] Y. Li, S. Luo, and W. Yu, "A triple stop-band filter based on defected microstrip line structures," *Applied Computational Electromagnetics Society Journal*, vol. 33, no. 7, pp. 752-757, 2018.

[29] K. Yu, Y. Li, and X. Liu, "Mutual coupling reduction of a MIMO antenna array using 3-D novel meta-material structures," *Applied Computational Electromagnetics Society Journal*, vol. 33, no. 7, pp. 758-763, 2018.

[30] T. Jiang, T. Jiao, Y. Li, and W. Yu, "A low mutual coupling MIMO antenna using periodic multi-layered electromagnetic band gap structures," *Applied Computational Electromagnetics Society Journal*, vol. 33, no. 3, pp. 305-311, 2018.

[31] L. Zhao, F. Liu, X. Shen, G. Jing, Y. Cai, and Y. Li, "A high-pass antenna interference cancellation chip for mutual coupling reduction of antennas in contiguous frequency bands," *IEEE Access*, vol. 6, pp. 38097-38105, 2018.