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Review of Bridge Structural Health Monitoring Based on GNSS: From Displacement Monitoring to Dynamic Characteristic Identification

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ABSTRACT Deformation monitoring and dynamic characteristic analysis of bridge structures are the vital and basic requirements for the safe operation of bridges. In recent years, Global Navigation Satellite System (GNSS) has become increasingly widely used in bridge structural health monitoring with the development of the GNSS technology, especially the continuous improvement and development of China's Beidou navigation satellite system (BDS). This article summarises the application process of GNSS dynamic deformation monitoring and the development of GNSS deformation measurement technology of bridge structural health monitoring, the dynamic characteristic identification method and its application in bridge GNSS monitoring. The positioning solution methods for GNSS monitoring, the high sampling rate GNSS receiver for monitoring, multi-frequency and multi-system GNSS monitoring and the weakening of multipath effect of GNSS monitoring are summarised in detail. Then, the conclusions and prospects are posed for future research and related application.

INDEX TERMS Bridge Structural Health Monitoring; GNSS Measurement; Displacement Monitoring; Dynamic Characteristic Identification; Natural frequency

I. INTRODUCTION

The bridge structure inevitably produces damage accumulation and resistance attenuation due to the influence of various factors, such as vehicles, pedestrian traffic, material corrosion, environmental excitation, earthquakes, ship collisions, resulting in a decline in its bearing capacity and reliability, regardless of the bridge types [1-3]. Similar to other civil engineering, the bridge structural modal parameters, including natural frequency, modal shape and modal damping, are functions of the physical characteristics of the structure (mass, damping and stiffness), whose changes in the latter will cause changes in the former [4-6]. Specifically, the bridge under the action of load and environmental factors may cause the dynamic response of bridge morphology [7]. Hence, bridge safety must be ensured to strengthen the monitoring of structural responses, such as bridge morphology and structural dynamics. The morphology of bridge includes linear and nonlinear deformation or displacement of the pylon and the main beam, and the dynamic characteristics of the structure focus on its modal parameters, which are important indicators of bridge safety control.

The structural deformation monitoring of the bridge belongs to the category of structural health monitoring, which mainly focuses on the dynamic evaluation and management of the dynamic parameters of the bridge structure. The linear and non-linear characteristics form on the basis of the real-time and dynamic monitoring. When an

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abnormal phenomenon occurs in some aspects if the various characteristic parameters of the bridge structure are compared with those of the normal structure, the abnormality needs to be judged whether damage has occurred. Subsequently, and then the degree and location of the damage needs to determined. Then, the current state of the structure and the trend of structural damage and even the remaining service life of the structure were evaluated [8]. Rytter divided the damage identification of structural monitoring into the following four progressive levels in his doctoral dissertation [9]: ① determine if the structure suffered damaged; ② determine the geometric location of the damage on the basis of ①; ③, quantify the damage severity on the basis of ②; and ④ predict the remaining service life of structural engineering on the basis of ③.

These tasks require the general structural condition monitoring system to closely monitor the structural load, deformation, static and dynamic response of the structure, vibration frequency and other information in long-term, continuous, real-time or post-time form [10]. Deformation monitoring mainly focuses on the static and dynamic position, displacement, settlement and, linear and even nonlinear deformation of each bridge structure, and the natural frequency (or vibration frequency) of the bridge structure is the most accessible modal parameter [11].

The commonly used vibration frequency monitoring tools, such as accelerometers, lack a trend item that is generated during the integration and cannot measure long-period quasi-static displacement [12]. Accordingly, researchers and engineers have developed and employed a large number of monitoring tools, such as Robotic Total Station [13-17], ground photogrammetric equipment [18-20], 3D laser scanners [20-22], GNSS [23-30] and Ground-based Synthetic Aperture Radar (GB-SAR) [31-36], to monitor the structural deformation. Then, these monitoring data remedy the accelerometer’s limitation or serve as one of its combined monitoring devices to identify static, dynamic and permanent deformation or displacement of the bridge in real time. However, the accuracy of photogrammetry and laser scanning methods greatly declines due to the increase of in line-of-sight distance. The synthetic aperture radar (SAR) can observe high accuracy only in the line-of-sight direction, and the accuracy of observation perpendicular to the line-of-sight direction is far inferior to conventional surveys, such as total station measurement. These approaches all have some shortcomings. The GNSS measurement technology, an important means of bridge structural monitoring, can monitor the deformation of the external structure of the bridge all-weather and all-time. However, researchers, engineers and monitoring workers prefer GNSS because of its high measurement accuracy, high sampling rate, high automation, capabilities for providing continuous 3D coordinate measurement, and qualified in climatic conditions. According to incomplete statistics, more than one-third of large bridges in mainland China have installed GNSS receivers as important monitoring sensors to provide long-term continuous deformation information for important health monitoring systems [37]. GNSS has shown unique advantages in the monitoring of bridge structures with the continuous development of software and hardware, especially the emergence of high-sampling-rate GNSS receivers and the successful global networking of BDS in July, 2020, providing a scientific basis for the healthy operation of engineering structures. The x, y, and H (denoted as 3D) coordinate time series signals in the bridge axis coordinate system that varies with time are obtained via GNSS monitoring of the dynamic deformation of structure. These signals can not only provide high-precision deformation information, also the vibration characteristics of the bridge structure. Such data can serve as early warning information for the safe operation of the bridge. For example, the collapse of Minjiang Bridge in Sichuan, China, on July 27th, 2018 caused no death and property loss. Casualty and damage were prevented because that the bridge monitoring system showed large displacement and abnormal vibration and the bridge manager timely closed the bridge [38]. Several similar examples show that the bridge health monitoring system has important guiding significance for ensuring the safe operation of bridges, and avoiding casualties and property safety.

With the development of bridges, the GNSS monitoring data during construction and operation constitute a massive 3D coordinate time series. The safety structural condition must be evaluated through abnormal displacement and deformation, but it is far from enough. The massive GNSS monitoring data acquired must be processed to accurately obtain the vibration frequency of the bridge structure and evaluate its safety status [39, 40]. The bridge GNSS monitoring data often contain rich bridge structural modal information.

However, such data often exhibit nonlinear and non-stationary characteristics and contain a substantial amount of observation noise due to the influence of environmental factors. In recent years, an increasing number of time-frequency analytical methods, such as fast Fourier transform (FFT) [41], short-term FT (STFT) [42], wavelet transform (WT) [43, 44] and Hilbert-Huang translation (HHT) [45, 46], have been employed to extract and analyse the modal parameters of bridge structures. However, these methods have certain shortcomings. In practice, an accurate identification of the dynamic deformation and modal information of the bridge structure is conducive to timely grasp its operating conditions, detect bridge damage, or further analyse and predict its remaining service life. In scientific research, accurately exploring the dynamic characteristics of bridge structures, especially the changing mechanism of natural frequencies under excitation conditions, will provide practical verification for the theoretical design of bridge structures and also a strong scientific basis to improve and optimise bridge design.

In this case, the review consists of the following contents: introduction (Section 1), application progress of GNSS monitoring dynamic deformation of bridge structures (Section 2), summary of GNSS deformation measurement technology for bridge health monitoring (Section 3), summary of the dynamic characteristic identification methods and their application in bridge monitoring (Section 4) and, conclusion and prospect (Section 5).

II. APPLICATION PROGRESS OF GNSS MONITORING DYNAMIC DEFORMATION OF BRIDGE STRUCTURES

In the 1990s, GNSS monitoring began to be applied to the dynamic deformation of bridge structures. Early in 1993, Canadian scholar Loves et al. [47] applied GNSS measurement to the 160 m-high Calgary Tower vibration measurement under strong wind. The vibration frequency in the east-west and north-south directions was at 0.3 Hz, and the maximum amplitude was 16 mm. After confirming that the GNSS technology can be used as a helpful method for structural vibration measurement, in 1995, Leroy of France pioneered the application of GNSS sensors to the dynamic monitoring of the longest suspension bridge, Normandy Bridge in France, and successfully obtained the cm-level bridge dynamic displacement [48]. This success inspired the majority of scientific researchers and engineers to continuously apply this technology to the structural condition monitoring of bridges. Then, the GNSS technology has been used in the fields of structural monitoring of huge projects, such as high-rise buildings, towers and bridges [49-53]. Ashkenazi et al. [54, 55] applied the GNSS technology to the monitoring of the Humber River Suspension Bridge with a main span of 1 410 m in 1997, and pioneered the verification of the real-time dynamic difference method for bridge 3D vibration displacement monitoring with an accuracy of up to mm level. His collaborators, Roberts et al. [56, 57] monitored the bridge again in 1999, and obtained a consistent finite element calculation result with a vertical vibration frequency of 0.117 Hz. Nakamura [58] used the GNSS technology to monitor the dynamic deformation of a suspension bridge with a main span of 720 m in 1998. The study concluded that the vibration displacement and main frequency of the main girder under wind load were consistent with the results of the wind tunnel experiments and finite element calculations.

In the 21st century, the application of GNSS in dynamic monitoring of bridge structures has been further developed. Kashima et al. [59] conducted GNSS monitoring on the Akashi Kaikyo Bridge with a main span of 1 991 m and a total length of 3 910 m in 2001. They compared the results with other sensors and verified that the GNSS technology is a reliable method for bridge health monitoring. Guo's team [60-62] from Tsinghua University began to establish monitoring systems on TsingMa Bridge in Hong Kong and Humen Bridge in Guangzhou in 2000. The team was the first time to conduct real-time online monitoring of long-span suspension bridges in China via the GNSS technology and obtain real-time bridge displacements. Then, the natural mode of the bridge was analysed, and some conclusions were achieved. Robers and Meng, from the University of Nottingham, UK have been working on the GNSS study for bridge health monitoring for a long time since 2000 [63]. Their results were applied to the Wilford Suspension Bridge in Nottingham [64-66], the Forth Road Bridge in Scotland [67, 68] and the Millennium Bridge on the Thames in London [69]. The results were encouraging. Wong and others of the Highways Department of Hong Kong, China [70] established a wind and structural health monitoring system, including GNSS receivers on Tsing Ma Suspension Bridge, Kap Shui Mun Cable-stayed Bridge and Ting Kau Cable-stayed Bridge. The accuracy of the plane and elevation direction obtained reached 10 and 20 mm, respectively. Miao and Li, et al. [71, 72] and Li and Yi, et al. [73, 74] established structural monitoring systems, including GNSS, on Runyang Yangtze River Bridge and Shandong Binzhou Yellow River Bridge, respectively, in 2004. In the same year, Larocca et al. [75, 76] applied the GNSS technology to the dynamic monitoring of the Hawkshaw cable-stayed bridge in Brazil, and found that the main frequencies of the vertical and lateral vibration are 0.57 and 0.60 Hz, respectively; the maximum vertical displacement of its vibration varies with the load. Lekidis et al. [77] used a GNSS receiver to dynamically monitor the Evripos suspension bridge in Greece in 2005, and the identified fourth-order modal frequencies were consistent with the finite element calculation results, verifying the feasibility of its use in earthquake-induced bridge vibration monitoring. In the same year, Erdogan et al. [78] applied the GNSS receiver to the vibration monitoring of the Bosporus Bridge passing by during the Eurasian Marathon. They obtained the high-frequency and low-frequency bridge vibration frequencies under different loads, which were calculated with accelerometers and finite element methods; the results are consistent. Raziq et al. [79] used a GNSS receiver to monitor the West Gate Bridge in Melbourne, Australia in 2006, and obtained the vertical displacement of the bridge deck and the vibration frequency of the bridge tower. Watson et al. [80] applied the GNSS technology to the structural dynamic monitoring of the Tamar River Bridge in Australia in 2007. The measured maximum dynamic displacements of the mid-span point of the main span and the top of the main tower reached 54 and 17 mm, respectively. Yao et al. [81, 82] applied the GNSS technology to the dynamic monitoring of Nanpu Bridge in China, in 2008, and obtained results consistent with the prediction of the finite element model. Huang et al. [25, 83] applied the GNSS technology to the deformation monitoring during the construction and operation of the Sutong Bridge in Jiangsu, China, and obtained modal frequencies of 0.166 and 0.500 Hz. Kaloop et al. [39, 84] began to apply the GNSS technology to the pylon deformation monitoring of Tianjin Yonghe Bridge in 2009. Although they failed to identify high-frequency vibration characteristics due to certain items such as the influence of noise, they successfully identified the low-frequency vibration characteristics. Such GNSS dynamic monitoring provides a scientific basis for fine dynamic monitoring and frequency extraction, and its reliability is superior.

Since 2010, GNSS bridge monitoring applications have been integrated with other technological means and further improved. Yi et al. [85] applied a 20 Hz sampling rate GNSS receiver to the structural monitoring of Dalian North Bridge in 2010. The obtained structural vibration frequency is in good agreement with that of the finite element and the accelerometer method. Meng et al. [86] began to use GNSS as the main observation method in 2013, combined with an accelerometer, an interferometry synthetic aperture radar (InSAR), a fibre grating sensor (FBG) and other sensors to establish a special bridge monitoring system (Integrated GNSS positioning and Earth Observation techniques for Structure Health Monitoring, GeoSHM); then, they carried out monitoring research on the British Forth Road Bridge and Wuhan Erqi Yangtze River Bridge. Chen and Meng [87] used this system to analyse the vertical law of deformation of the Forth Road Bridge. Moshas et al. [88] applied different sensors, such as GNSS, to the dynamic monitoring of a 40 m main span pedestrian bridge in 2011. They obtained a structural vibration displacement of 6 mm and a vibration frequency of 4.28 Hz by supposing different load conditions, verifying the potential of a rigid bridge response monitored by GNSS. In 2014, Ogundipe et al. [89] used five GNSS receivers for the dynamic monitoring of a steel box girder viaduct with a main span of 174 m in the UK, and obtained a maximum vertical vibration amplitude of 10 mm and a vibration frequency of 0.526 Hz. Ogundipe and Kaloop et al. [90-91] applied the GNSS technology to the dynamic monitoring of the Mansoura Bridge in Mansoura City, Egypt and Talkha Expressway Steel Bridge, and obtained the corresponding main frequency of the bridge vibration. Yu et al. [92] employed eight GNSS receivers and other sensors on the Aizhai Suspension Bridge with a main span of 1 176 m in Jishou City, Hunan Province. Two receivers were installed on the top of the towers in Jishou and Chadong to monitor the displacement of the tower in the longitudinal direction. The other receivers were arranged at the upstream and downstream of the quarter-span, mid-span, and three-quarter span of the bridge to monitor the lateral and longitudinal displacements of the reinforced steel beams. These approaches provide a scientific basis for ensuring the healthy operation of the ‘internet sensation bridge’ with a height difference of 355 m from the bridge deck to the valley bottom.

In this section, the development of GNSS in the ten-year phase and its overall application in bridge monitoring are introduced.

III. SUMMARY OF DEFORMATION MEASUREMENT TECHNOLOGY FOR BRIDGE STRUCTURAL HEALTH MONITORING

GNSS dynamic monitoring often employs relative positioning methods. The position of the moving carrier relative to the reference point is determined by fully using the synchronous observation data of the GNSS receiver placed on the reference point and the moving carrier; this method is called relative positioning [93, 94]. This main goals are to collect, summarise, calculate and broadcast the satellite ephemeris correction values, satellite clock offset correction values, ionospheric correction values, tropospheric correction values and other information to the receiver on the moving carrier to obtain accurate relative location [93, 94]. The time-space reference, signal structure, system configuration, positioning principle, error source, data processing method and operation application of GNSS measurement can be found in the textbook [94], which will not be provided here. When the GNSS technology is adopted for dynamic monitoring, it is generally used to obtain continuous absolute deformation of bridges and other major engineering structures. However, the level and accuracy requirements of deformation measurement in the literature are difficult to achieve [74, 95, 96] due to the influence of GNSS receivers, satellites, signal propagation paths, data processing strategies and other factors. This mechanism also limits the widespread application of GNSS in structural deformation monitoring to a certain extent. Given this issue, an increasing number of scientific researchers and engineers have focused on GNSS positioning solution methods for monitoring, high sampling rate GNSS receiver for monitoring, multi-frequency and multi-system GNSS monitoring, weakening of multipath effect of GNSS monitoring, analysis of noise characteristics of GNSS monitoring and its signal denoising to obtain continuous, real-time, high-sampling micro-deformation information of major engineering structures. These methods are constantly improving. Thus, this section contains five subsections, which are reviews on the above mentioned aspects.

A. REVIEW ON GNSS POSITIONING SOLUTION METHODS FOR MONITORING

In terms of positioning solution strategy, Lovse et al. [47] first applied the post-processing kinematic (PPK) technology to the dynamic monitoring of the Calgary Tower, and obtained monitoring accuracies of ±5 and ±10 mm. The PPK is a dynamic relative positioning technology that uses carrier phase observations for post-processing. Meng [63] reported that, the measured noise level is reduced to mm- level after the carrier phase dynamic difference and filtering via the experimental analysis of GNSS zero baseline and short baseline.

Since 1996, Ashkenaziz et al. [54] studied the application of ambiguity resolution on the fly (AROF or OTF) method. Then, real-time kinematic (RTK) was applied to the deformation monitoring of the Humber Bridge, and the structural vibration displacement of the bridge was 1-2 cm [55]. Here, the RTK is a technology that uses the carrier phase observation value to perform real-time dynamic positioning between the rover and the reference station within a certain distance (such as 15 km). Since 2000, Janssen et al. [97] changed the traditional relative positioning method of considering the single-frequency observations of the GNSS receiver only to improve the accuracy of the error correction of the baseline observation, and added the consideration of the dual-frequency observations of the GNSS receiver. Then, the influence of ionospheric error is weakened, and the deformation monitoring accuracy of the horizontal direction achieved ±1 cm, and those of elevation are ±1.5 cm to ±3.0 cm. Roberts and Meng [98, 99] applied the RTK technology to a suspension bridge on the Trent River in Nottingham, England-Wilford Bridge. Guo et al. [62] used the GPS RTK technology on the Humen Bridge in Guangdong to obtain a deformation monitoring accuracy of ±1.0 cm. Nordin et al. [100] applied the GPS RTK technology to the dynamic monitoring of a bridge in the Malaysian Polytechnic University, and provided a conclusion of the state safety assessment.

On the basis of RTK technology, Wang et al. [101] employed extended Kalman filter with a third-order difference and non-ionospheric model to eliminate the effects of ionosphere and white noise, and applied this to Donghai Bridge, which connects Pudong, Shanghai and Zhoushan, Zhejiang Province. The dynamic monitoring results were good. Wang et al. [82] used the GPS RTK technology in the dynamic monitoring of Nanpu Bridge in 2008, and Elnabwy et al. [28] did so in the dynamic monitoring of Talkha expressway steel bridge in 2010. Yu et al. [30] abandoned the conventional reference station rover model, but innovatively adopted a remote continuously operating reference station (CORS) as a reference station. They also established a network-based RTK system to monitor bridge dynamic responses. Kim et al. [102] applied the combinatorial computing method of the GNSS technology and accelerometer measurement to the dynamic displacement monitoring of the Humber Bridge in the United Kingdom, and obtained high positioning accuracy. Xiong et al. [103,104] applied the GPS RTK technology to the dynamic monitoring of super high-rise buildings in Tianjin Radio and Television Tower and Tianjin Gaoyin Finance 117 Building. They also processed the monitoring data with Chebyshev Type I high-pass filtering, and the dynamic displacement amplitude reached ±3.0 and ±5 cm. The technical method was applied to the dynamic monitoring of Tianjin Fumin Bridge [105], and a standard deviation of ±2.0 cm was obtained. Xi et al. [106] applied the RTK technology based on the BDS and GPS RTK technology to the dynamic monitoring of the Baishazhou Bridge in Wuhan. They also found that the BDS RTK has equivalent or even better ability to recognise dynamic deformation whilst acquiring dynamic characteristics.

In contrast with the aforementioned PPK, RTK, network RTK and other baseline difference resolution techniques, in the GNSS Precise Point Positioning (PPP) technology developed in recent years, users might do not need to set up a reference station and only utilise the carrier phase and code measurement pseudorange observations of only one GNSS receiver. This method fully uses high-precision satellite orbit and clock error products, and adopts model correction and parameter estimation to carefully consider the error impact related to the satellite end, signal propagation path, and receiver end on positioning to achieve high-precision positioning results [107]. Zumberge et al. [108] employed a large-scale continuously operating GPS receiver and other hardware systems to conduct PPP research as early as 1997. However, the application in geosciences was limited due to low accuracy.

With outstanding contributions to the positioning model and parameter estimation, precision satellite clock error estimation, cycle slip fixation and repair, non-difference ambiguity resolution, regional CORS network enhancement PPP ambiguity fast fixation, PPP ambiguity fixation and regional enhancement taking into account atmospheric constraints, PPP extends its areas from wide-area precision positioning, seismic monitoring, water vapor inversion, ionospheric monitoring, large-scale movement measurement, satellite orbit determination, to that of higher precision, such as deformation monitoring. Kuang et al. [109] applied the GNSS PPP technology to the dynamic displacement monitoring of high-rise buildings in 2013, and obtained high consistency compared with the results of traditional relative positioning RTK solution and accelerometer measurement. Mart ń et al. [110] showed that the accuracy of the N, E, and U directions of the relative fixed rover reached within ±7.0, ±8.0 and ±10.0 cm through real-time PPP experiments. The horizontal and vertical direction accuracies of the moving trolley could reach ±15 and ±25 cm, respectively. Although this mechanism is not as accurate as traditional reference station-rover RTK model, it provides a new direction for dynamic deformation.

Yigit et al. [111] applied the GNSS PPP technology to monitor the simulated vibration of a narrow steel plate with a micromovement of 0.1 mm on the roof of Department of Civil Engineering, Stable University of Technology in 2014. The result showed that the measurement accuracy is consistent with that of traditional relative positioning RTK solution. Yigit et al. [112] also evaluated and verified the ability of the GNSS PPP technology to monitor the vertical vibration of the structure through experiments. They believed that this technology is reliable for monitoring the vertical dynamic characteristics of long, medium and short span suspension bridges. Kaloop et al. [113] dynamically monitored the excited vertical vibration of cantilever steel bars of different lengths, employed the GNSS PPP mode and relative positioning RTK mode to solve the positioning results, and extracted the dynamic characteristics of the obtained results. The result showed that the characteristics were consistent with those calculated by the finite element method. Paziewski et al. [114] conducted microdeformation monitoring experiments on different baseline lengths, and adopted different calculation strategies of GNSS RTK, PPP and Direct Signal Processing for dynamic displacement detection GNSS Method (SPM). The accuracy of SPM with short baseline can reach that of RTK with long baseline. Tang et al. [115] established a portable manipulator driven by a motor to rotate at a certain speed on the roof of a building at University of Nottingham Ningbo China. The sampling interval of the monitoring data is set to 1 s. When calculated under strict satellite clock offset, non-difference ambiguity parameters, total zenith delay and dynamic displacement, the result is consistent with the traditional relative positioning method (double difference calculation of the base and reference stations). This GNSS PPP method was applied to the dynamic monitoring of the long-span bridge in the United Kingdom-Severn Bridge. Thus, the PPP method is a scientific and reliable alternative for bridge dynamic monitoring in the case of difficult double-difference solutions.

In this part, the development of GNSS precision positioning technology and method for the purpose of bridge structural monitoring is introduced.

B. REVIEW ON HIGH SAMPLING RATE GNSS RECEIVER FOR MONITORING

According to the relationship between the sampling rate and the measured signal frequency described by the Nyquist theorem:

$$f_s > 2f_N$$

The sampling rate f_s must be twice greater than the highest frequency component of interest in the measured signal. The frequency f_N is often referred to as the Nyquist frequency. This notion means that the bridge dynamic monitoring frequency must be $2f_0$ or higher if the highest frequency actually contained in the bridge vibration comes up to f_0.

Therefore, not only the highest requirements of accuracy and reliability must be met for the GNSS dynamic monitoring of bridge structures but also the requirements of high sampling rate of the monitoring point positioning solution. The main vibration frequency range of very large bridges is generally in the range of 0–2 Hz, so the sampling rate of the GNSS receiver must surpass 4 Hz or even higher.

Since Lovse, researchers begun to use GNSS receivers with sampling rates of 10 Hz and below for dynamic monitoring of GNSS structures [47, 60, 62, 64, 116, 117]. In recent years, GNSS receivers with a sampling rate of 10–100 Hz have emerged and been employed for more accurate structural dynamic monitoring [84, 90, 110, 116, 118-121]. In 2011, Moschas et al. [118, 122] used a receiver with a sampling rate of 10 Hz to synchronously study the dynamic characteristics of vibration excited by jump of a group of people on a 10 m short span bridge. Roberts, Meng and Wang et al. [123,124] adopted a receiver with a 10 Hz sampling rate to monitor the Forth Road Highway Bridge in the United Kingdom for 46 h in 2012, indicating that GNSS monitoring can provide the amplitude and dynamic frequency of the quasi-static deflection of the structure.

The higher the vibration frequency of the bridge comes up to, the higher sampling rate the GNSS receiver requires. To monitor the dynamic characteristics of higher frequency structures, researchers studied GNSS receivers with higher sampling rates. Kaloop et al. [39] and Yu et al. [121] used GNSS receivers with a sampling rate of 20 Hz to monitor short-, medium-, and long- span bridges. They believed that the deformation monitoring accuracy of such bridge vibration monitoring can reach a sub-millimeter level. Kaloop et al. [91,125] employed a GNSS receiver with a 1 Hz sampling rate to monitor the Mansoura Railway Bridge and the Pearl River Huangpu Bridge in Egypt. Another, GNSS receiver with 20 Hz sampling rate is used to monitor the health and damage of the Yonghe Bridge. They concluded that the high and low sampling rate GNSS measurements can extract the dynamic deformation components of the bridge, and the high sampling rate GNSS measurement is more suitable for detecting the frequency components of bridge vibration. Yi et al. [126] employed GNSS receivers with 50 and 100 Hz sampling rates to monitor the static and dynamic changes, and concluded that such high-frequency receivers can evaluate the performance of rigid and flexible structures. Moschas et al. [127] used a GNSS receiver with a sampling rate of 100 Hz to monitor the static and dynamic vibration characteristics of short-span pedestrian bridges, and obtained millimeter-level monitoring accuracy and a vibration frequency of 7 Hz.

In this part, the development of GNSS high-sampling rate receivers for bridge structural monitoring is introduced. Therefore, various rapid-developed, high-frequency GNSS receivers can meet the frequency requirements for monitoring bridge dynamic deformation.

C. REVIEW ON MULTI-FREQUENCY AND MULTI-SYSTEM GNSS MONITIORING

With the development of the GNSS technology in various countries or regions at present, satellite navigation systems that have reached a certain scale include GPS of the United States, GLObal NAvigation Satellite System (GLONASS) of Russia, Galileo of the European Union, and BDS of China. And many regional satellite navigation systems are also emerging, such as the Indian Regional Navigation Satellite System (IRNSS/NavIC), the Japanese Quasi-Zenith Satellite System (QZSS), and the Regional South Korean Positioning System (KPS). Currently, more than 130 satellites are in orbit providing for navigation and positioning related services. When a commonly used single GPS system is adopted for bridge dynamic monitoring, it may be affected by certain factors, such as a single GNSS system satellite signal occlusion and poor geometric structure, resulting in low monitoring accuracy, reliability and stability [128]. The current situation of GNSS multi-frequency and multi-system coexistence will help improve this situation.

GNSS receivers are generally divided into single-frequency, dual-frequency and triplefrequency receivers. Single-frequency receives only L1 carrier signals transmitted by GNSS satellites, dual-frequency simultaneously receives L1 and L2 carrier signals, and triple-frequency concurrently receives L1, L2 and L5 (BDS provides B1, B2 and B3 carrier signals) [129]. The single-frequency receiver takes a longer time (1 min and 30 min) to solve the fixed solution compared with the dual-frequency receiver. Accordingly, Cosser et al. [130] applied this concept to the deflection monitoring of the Wilford suspension bridge experiment with the above two receivers. The (among them, the dual-frequency receiver uses the "go and stop" method to solve the problem). The results indicated that the dual-frequency one can obtain a more accurate ionospheric model and reach better monitoring accuracy. By contrast, and the single-frequency receiver obtains poor quality of monitoring results in a short time. Thus, So Yi et al. [131] suggested that engineers should weigh the accuracy of monitoring and the price of testing equipment, and choose a compromise scheme.

People choose dual-frequency or triple-frequency receivers for structural health monitoring to ensure accuracy. Zou et al. [132] applied the Satellite-specific Epoch-differenced Ionospheric Delay model to single-frequency and dual-frequency receiver observations to obtain high crustal deformation accuracy and encrypt the GNSS control network. A plane accuracy of ±2.0 mm and an elevation accuracy of ±5.0 mm were obtained via comprehensive processing of the values obtained. Feng et al. [133] proposed the Three Carrier Ambiguity Resolution method and used it as the theoretical basis for regional relative localisation RTK. Xi et al. [134] used BDS/GPS-based triple-frequency observations to study fast initialisation in real-time bridge dynamic monitoring, and applied this to the monitoring data of Wuhan Baishazhou Yangtze River Bridge. The authors concluded that multi-frequency can help in determining the ambiguity.

Dual-frequency and triple-frequency receivers are more expensive. Some researchers and colleagues are considering “the one hand”, which is to study the feasibility of single-frequency GNSS receivers to the monitor dynamic deformation of bridges to reduce monitoring costs. Crosser monitors suspension bridges with different spans using single-frequency receivers [135]. In his doctoral dissertation, he believes that single-frequency receivers can obtain the dynamic and quasi-static displacements of long-span suspension bridges. However, only the fundamental frequency and dynamic displacement components can be monitored for small and medium-span bridges, not for the quasi-static displacement components affected by noise. Hedgecock et al. [136,137] proposed a new algorithm to improve the accuracy of the single-frequency receiver for monitoring dynamic displacement. Azar et al. [138] conducted a test with a single-frequency GNSS receiver on the Wavasan Bridge in Putrajaya Temple, Malaysia. They believed that the single-frequency receiver is only suitable for dynamic deformation of bridges over 2 cm, and amplitudes smaller than 2 cm cannot be monitored and identified. The new algorithm proposed by Larocca et al. [75] fully utilises the principle of interferometry, which focuses on collecting at least two navigation satellite L1 carrier signals to calculate the vertical vibration displacement of the structure. This scheme identified the vibration displacement and frequency of the bridge on the Hawkshaw Bridge in Canada. Single-frequency receivers have difficulty in identifying small deformation displacements due to random noise, short-term instability of the receiver clock and multipath effects. Schaal et al. [139] proved that the phase difference of a single satellite by using the L1 carrier signal only can monitor the centimeter level through experimental analysis, and the phase difference of two satellites can monitor the millimeter level deformation oscillation. Carcanague [140] determined the number of the whole cycles from the floating point solution by the integer solution estimation method based on Doppler frequency shift measurement, and applied the real-time cycle slip detection algorithm on the basis of the geometric distance observations to deformation monitoring by RTK and PPP of single frequency receivers. Jo et al. [141] replaced a certain number of dual-frequency receivers by increasing the layout density of single-frequency receivers, and obtained a deformation monitoring accuracy of 20–30 cm. Zheng et al. [142] employed combinatorial methods of satellite epoch differential ionospheric delay model, dynamic PPP and sliding window static PPP to process the dynamic observations of single-frequency GNSS receivers. The deformation monitoring can reach a plane of ±1.8 cm. The accuracy and elevation accuracy are ±2.2 cm. Huang et al. [143] used any two adjacent stations as baselines to weaken the influence of ionospheric errors and also obtained better deformation monitoring accuracy.

Bakker et al. [144] introduced multiple systems into the PPP calculation of a single-frequency GNSS receiver and obtained better deformation monitoring accuracy than single-frequency GNSS. Studies have shown that fusion processing on multi-system GNSS data increases the number of visible satellites, enhances the geometric structure of satellite observations, and improves the efficiency of ambiguity determination [145]. In the dynamic monitoring of large bridges, multi-system GNSS can enhance the availability and reliability of the monitoring system when satellite signals are blocked by certain facilities, such as bridge towers and passing vehicles, thereby improving the positioning accuracy [145]. Tu et al. [146] proposed a real-time dynamic monitoring method combined with GPS, GLONASS, BDS and strong motion recorders, and verified its reliability in high-rise buildings, dams, bridges and other projects. Paziewski et al. [114] comparatively analysed the influence of the combined GPS and BDS data fusion processing on the accuracy of deformation monitoring. Xi et al. not only combined GPS and GLONASS to eliminate GNSS signal distortion in bridge deformation monitoring [147], also proposed a combination strategy of dual-frequency carrier phase GPS and BDS to process deformation monitoring data, which can improve the reliability of bridges dynamic monitoring by GNSS [148]. Yu et al. [121] considered three different GNSS data processing modes: RTK, network RTK and PPK when identifying the dynamic displacement and modal frequency of the Wilford suspension bridge.

In addition, the new state of-the-art GNSS positioning technique, PPP-RTK, which generally characterize of PPP positioning model, real-time positioning, state-space representation (SSR) corrections and fast fixation of ambiguity, has the potential for detecting the dynamic response of vibrating structures in real time. However, it is difficult to further expand its scope of application until it solves the following 2 items: how to balance the relationship between data transmission volume, sampling rate and bandwidth; how to build a high-precision atmospheric model and determine its broadcast method.

Therefore, various rapid-developed, Multi-frequency and Multi-system GNSS receivers can meet the requirements on stability, reliability and high precision for monitoring bridge dynamic deformation.

D. REVIEW ON WEAKENING OF MULTIPATH EFFECT OF GNSS MONITORING

As previously mentioned above, the relative positioning method is used in bridge dynamic monitoring to obtain the deformation information of the monitoring point. Accordingly, the main system errors, such as the clock difference between the receiver clock and the satellite clock, can be basically eliminated. The error caused by ionospheric and tropospheric delays can be basically ignored because the distance between the monitoring points is relatively short. However, the multi-path error has so complicated relationship with the geometric association formed by the observation station, surrounding bridges, water surface and other environments; and the satellite position distribution wherein the multi-path error cannot be effectively weakened by the aforementioned data solution strategy becomes an important source of error in GNSS high-precision relative positioning measurement, especially bridge dynamic monitoring [149,150].

The impact caused by the multipath effect can be partially weakened through the appropriate selection of the station location, improving the polarisation characteristics of the antenna [151], adding a choke antenna to the receiver [152], removing the reflector near the antenna, using absorbing materials and absorbing devices at the bottom of the antenna [153,154] and other aspects. However, the multipath error has not been completely eliminated [155]. Therefore, many studies worldwide are devoted to data post-processing methods to weaken or eliminate the influence of multipath effects.

First, the multipath effect can be weakened or detected through pseudorange measurement, carrier phase measurement observations, or different combinations thereof. Ogaja et al. [156] wrote a special program to identify multipath errors in high-frequency GNSS surveys based on additional information, such as Translation, Editing and Quality Checking (TEQC) record files in L1 pseudorange surveys. The results indicated that the method was simple, effective and helpful in explaining the source of multi-path error on the GNSS stations, which is convenient for its location selection. Moradi et al. [157] proposed a new carrier phase multipath error observation method, which can isolate the carrier phase multipath error between the linear combination of observations, such as Wide-Lane (WL), and the results of applying it to RTK positioning measurement show that it makes sense. Wang et al. [158] analysed the multipath effect of BDS"s Geostationary Earth Orbit (GEO) satellite pseudo-code measurement. Ye et al. [159] analysed the multipath effect of the BDS carrier phase measurement. Strode et al. [160] proposed a method for detecting the influence of GNSS multipath by comparing the signal-noise ratio (SNR) of three frequencies. Dai et al. [161] studied the characteristics of the multipath effects of BDS’s GEO satellites, inclined geosynchronous orbit (IGSO) satellites, and Medium Earth Orbit (MEO) satellites, and established a correction model for application in deformation. The practical results in the monitoring show that the accuracy has been greatly improved. Gao et al. [162] used actual observations of GPS and BDS tri-frequency observations to analyse the phase multipath effects of three typical carrier, namely, the ultrawide lane (Extra-WL, EWL) combination, the ionospheric estimation of EWL/WL with ambiguity correction, and the combination of the narrow lane (NL) Ambiguity (AR) non-geometric, ionosphere-free (geometry-free and ionosphere-free, GIF). Thus, the established model that based on this concept to measure positioning has also achieved good results.

Second, the SNR observations, as a part of the GNSS observations, are indicators of the quality of the observed signal with S1/S2 in RINEX. The observation signal is reflected and diffracted by the surrounding environment of the observation station, showing low-frequency or high-frequency characteristics in the SNR observations [163]. Bilich et al. [164, 165] established the multipath environmental power spectral time series of the GNSS station environment to distinguish satellites and frequency bands in which SNR has an important influence on multipath errors. Luo et al. [166] proposed an improved weighted observation model based on the SNR power measurement method, and the multipath effect was considerably weakened. Benton et al. [167] designed a filter that separates the effects of multipath from the SNR data of GNSS, and the effect is considerable. Xi [145] established a refined random model on the basis of the SNR observations based on the characteristics of GPS and GLONASS SNR sequences varying with satellite altitude angles and the relationship between the accuracy of observations and satellite altitude angles. A good bridge monitoring effect can be observed in the new model compared with others.

Third, during deformation monitoring, the observation environment around the station remains unchanged. However, the satellite orbits periodically reappear with sidereal days. Researchers may consider establishing a multipath effect model based on the extraction of the residuals of the previous stellar days, which may correct the multipath effect of subsequent sidereal days [145]. Choi et al. [168] studied the repetition period of GPS satellites. They found that the repetition period of different satellites is different, and significantly varies from the commonly assumed sidereal day period. When the 1 Hz GPS measurement positioning estimate is filtered by the calculated satellite repetition period, the error of low-frequency observation may greatly fall. Agnew et al. [169] were committed to finding out the satellite repetition period by the repetition period of the orbit and the repetition time of the satellite passing over the station. They found that the repetition period changed to different degrees. This concept provides a corresponding basis for the weakening of the multipath effect during GNSS observation. Larson et al. [170] proposed an Aspect Repeat Time Adjustment (ARTA) method fitting for the data with the same direction, which can reduce the impact of multipath effects on the basis of the repeatability of GNSS, thereby greatly improving the monitoring accuracy in the horizontal direction. Given that the multipath error is likely to exceed the error tolerance when the satellite’s cut-off altitude angle is low, the GNSS data must be collected in the best state for the satellite's cut-off altitude angle. Ragheb et al. [171] compared the stability of the error repetition delay caused by the correlation processing on the basis of the coordinate sequence of consecutive days and the residual sequence of the carrier phase observation, and pointed out its advantages and disadvantages in weakening the multipath error. Zhong et al. [172] proposed a method of sidereal day filtering based on single-frequency difference, which was used to reduce the influence of multipath in the calculation of short-baseline GNSS observations and achieved good results. Atkins et al. [173] used the sidereal day filtering algorithm in the time domain to reduce the multipath error of the GNSS carrier phase measurement without ionospheric difference. Wang et al. [174] determined the contributions of different observation environment parts to the multipath effect via the time series power spectral density of the residual error from the single-difference solution of the phase.

Fourth, some researchers also determined the spatial position relationship between the surrounding environment of the GNSS station (reflections and diffractors) and the phase center of the receiver by other technical means. Then, the observations that might be reflected or diffracted will be picked out and excluded. Lau et al. [175] established a Ray-Tracking model of the station environment on the basis of the study of the geometric relationship between the satellite-reflector-antenna and the characteristics of the reflective material and the antenna, which is used to reduce the multipath effect. Yi et al. [176] studied the multipath effect of the GNSS signals in the background of different building materials, and applied this pattern to improve the accuracy of measurement and positioning. Groves et al. [177] used urban 3D maps and Non-Line-Of-Sight (NLOS) signal propagation models to weaken the impact of multipath effects. Zimmermann et al. used ground laser scanning [178] and Fresnel zone [179] to establish station environmental models to determine and exclude indirect signal observations, thereby reducing multipath errors.

Last but not least, given that the GNSS long-term observation contains the aforementioned periodic repetition characteristics, the time series of GNSS observation data contains periodic repetitive signals of a certain frequency. Many time series analytical filtering or signal denoising technologies, such as adaptive filtering (AF), Fourier transform (FT), wavelet, Vondrak and Empirical Mode Decomposition (EMD) were employed to extract (or reduce) multipath effects. Roberts et al. [180,181] eliminated the ionospheric delay, cycle jumps and background noise basically in the GNSS observations by Adaptive Filtering (AF) method. He also believes that the combination of GPS and accelerometer plus AF could reach millimeter-level vertical accuracy of monitoring displacement [182]. Satirapod and Rizos [183] weakened the multipath error caused by the phase in the original GNSS observations via the wavelet decomposition method. Zhong et al. [184] proposed a new method that combines the cross-authentication method with the Vandrak digital filter, which fully uses the periodic repetition characteristics of the GNSS multipath effect to effectively weaken the multipath effect. Huang et al. [185,186] employed wavelet decomposition and difference correction methods to process the observation data for multiple consecutive days, which effectively weakened the influence of the multipath effect. The 3D position accuracy of GPS dynamic monitoring reached mm level. Dai et al. [187] applied EMD to the extraction of an accurate GNSS multipath effect error repeatability model for the first time, and made corrections that effectively improved the positioning accuracy. Kijewski-Correa and Kochly [188] analysed the measurement results of the GNSS receiver and accelerometer on the vibration table, and verified the existence of the multipath effect. This mechanism can be weakened by FT and Wavelet Spectra (WS). Aram et al. [189] proposed a GNSS data processing method that selects the best satellite geometry on the basis of wavelet analysis, which can approximate the value of the multipath error, filter the residual error in the data and correct the multipath effect. Wang et al. [190] and Cui et al. [191] applied Ensemble Empirical Mode Decomposition (EEMD), improved EMD to the reduction of multipath errors and achieved significant results. Dai et al. [192] applied EMD, Independent Component Analysis (ICA), Principal Component Analysis (PCA) and other methods to solve the problem of stellar day filtering, weakening the multipath effect with subsequent observations when the repetitive feature is not obvious with the observation interval increasing on the first day. Lu et al. [193] concluded that Singular Spectrum Analysis (SSA) can achieve the same multipath effect weakening effect as that of wavelet and EMD through experiments and analysis.

It can be seen that with the continuous emergence of multipath error reduction methods in GNSS measurement, GNSS measurement can fully meet the requirements of bridge structure displacement monitoring in terms of monitoring accuracy and reliability.

E. REVIEW ON THE NOISE CHARACTERISTIC ANALYSIS OF GNSS MONITORING AND ITS SIGNAL DENOISING

Although a large number of researchers have made disdainful efforts in the aforementioned reduction of multipath effects, the time series obtained by GNSS monitoring still has more or less noise, which greatly hinders the process of accurately obtaining dynamic structural deformation information based on GNSS. To this end, many scholars have devoted themselves to analysing the noise characteristics of GNSS monitoring and studying signal denoising methods. Chan et al. [194] briefly analysed the accuracy and error of dynamic monitoring in three directions through simulation experiments and GNSS monitoring on high-rise buildings and long-span bridges. Genrich and Bock [195] performed geodetic instantaneous positioning measurement by a 10–50 Hz GNSS receiver and analysed the error characteristics of the time series. They concluded that the measurement noise is coloured noise, and the logarithmic spectrum is less than 0.5 Hz for dynamic monitoring with the 1 Hz sampling rate in the range of 10 km. Meanwhile, the measurement noise is high frequency, and its accuracy is 0.5 mm in the horizontal direction and 3-4 mm in the vertical direction for compared with that with in the 2-20 Hz sampling rate in the range of 40 km. Hristopoulos et al. [196] performed low-frequency de-noising and spectral analysis on the corresponding time series of wind loads on high-rise buildings monitored by GNSS. Moschas et al. [197] performed spectral analysis on short-term GNSS monitoring time series of GNSS receiver equipment with the same configuration and high frequency (greater than 1 Hz). They believe that the part below 0.2 Hz is mainly coloured low-frequency noise, and that above 2.5 Hz only contains white noise. In addition, the long-term and short-term GNSS detection records of high-frequency components hardly contain coloured noise. Moschas et al. [198] also analysed the noise characteristics of different phase locked loop (PLL) bandwidths in GNSS deformation monitoring. They found that the high and low frequency noise increases with the increase in the bandwidth from 25, 50 Hz to 100 Hz. Zhang et al. [199] analysed the characteristics of the observation noise of different navigation and positioning systems and different constellations via the zero baseline data observed by GNSS. Zhang et al. [199] analysed the characteristics of the observation noise of different navigation and positioning systems and constellations via the zero baseline data observed by GNSS. Geng et al. [200] analysed the noise characteristics of high-frequency multi-system GNSS for half-day crustal deformation monitoring. Langbein et al. [201] studied the long-term coordinate sequence observed by 740 GPS stations in the western United States and concluded that the background noise is time-dependent and can be modelled as the combination of white noise, flicker noise, random walk noise and band-pass filtering noise. He et al. [202] studied the low-frequency noise characteristics of long-term GNSS time series and believed that the background noise model is mainly power exponential noise or flicker noise with white noise.

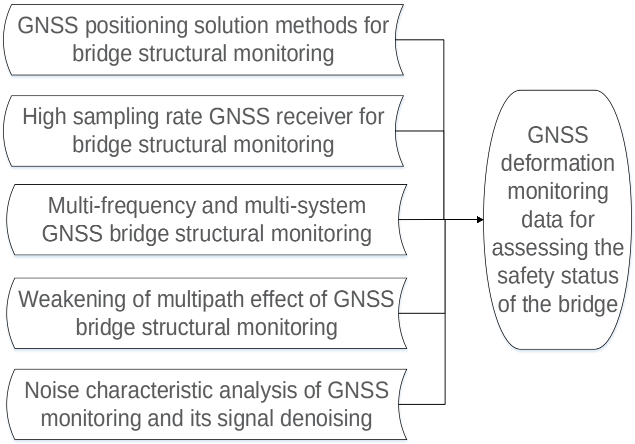

FIGURE 1. Deformation measurement technology based on GNSS for bridge structural health monitoring.

Many studies have focused on signal denoising of GNSS observation time series to obtain accurate and reliable bridge deformation information. Huang et al. [203] studied the error elimination of time series observation data by the wavelet analytical theory. Zhang et al. [204] proposed a multi-threshold criterion wavelet packet denoising method based on frequency order and segmented according to the information type. This method can eliminate the noise in each frequency and retain useful information with high frequency in the denoising signal when the sampling rate is low. Gao et al. [205] proposed an improved threshold denoising method based on the analysis of traditional hard threshold denoising, soft threshold denoising and forced denoising methods. This method is applied to process GNSS deformation monitoring data, whilst retaining data details and sudden changes, and it effectively eliminates high-frequency noise. Kaloop et al. [206] analysed the coordinate time series obtained by the specially designed GNSS short-term monitoring system on the Mansoura Railway Bridge in Egypt on the basis of wavelet analysis, integrated principal component analysis, wavelet compression, and denoising methods. The method could

TABLE I
BRIDGES IN MAINLAND OF CHINA THAT EMPLOYED GNSS RECEIVERS AS PART OF MONITORING SENSORS

No.	Bridge name	Structure type	Span length（m）	Number of receivers
1	Anqing Yangtze River Highway Bridge	Cable-stayed bridge	0+215+510+215+50	4
2	Anshun Baling River Bridge	Suspension bridge	Main span: 1088	9
3	Binzhou Yellow River Bridge	Cable-stayed bridge	Main span: 300	3
4	Shenyang Hunhe Boguan Bridge	Arch bridge	35+84+120+88+68+35	2
5	Dalian North Bridge	Suspension bridge	Main span: 132	6
6	East Sea Bridge	Cable-stayed bridge	Main span: 420	3
7	Chongqing Dongshuimen Yangtze River Bridge	Cable-stayed bridge	Main span: 520	3
8	Dongting Lake Bridge	Suspension bridge	310	5
9	Ordos Ulan Mulun River No. 4 Bridge	Cable-stayed bridge	Main span: 450	2
10	Wuhan Erqi Yangtze River Bridge	Cable-stayed bridge	Main span: 616	6
11	Ganyue Expressway Poyang Lake Bridge	Cable-stayed bridge	Main hole: 180+318+130	4
12	Hangzhou Bay Bridge	Cable-stayed bridge	116+246+116	8
13	Guangzhou Hedong Bridge	Cable-stayed bridge	Main span: 360	4
14	Guangzhou Humen Bridge	Suspension bridge	888	7
15	Guangzhou Pearl River Huangpu Bridge	Suspension bridge, Cable-stayed bridge	South branch: 290+1108+350, North branch: 383+197+63+62	14
16	Jinan Yellow River Bridge	Suspension bridge	40+94+220+94+40	1
17	Zhanjiang Bay Bridge	Suspension bridge	840	3
18	Jiangyin Yangtze River Highway Bridge	Suspension bridge	Main span: 1092	8
19	Hubei Jingyue Yangtze River Bridge	Cable-stayed bridge	(100+298)+816+(80+2×100)	5
20	Wuhan Junshan Yangtze River Bridge	Cable-stayed bridge	40+204+460+204+48	3
21	Maanshan Yangtze River Highway Bridge	Suspension bridge, Cable-stayed bridge	Left branch (Suspension bridge) 2×1080, Right branch (Cable-stayed bridge) 2×260	9
22	Ningbo Mingzhou Bridge	Arch bridge	450	3
23	Jiajiang Bridge, Nanjing Crossing River Tunnel	Suspension bridge	Main span: 248	11
24	Nanjing Second Yangtze River Bridge	Cable-stayed bridge	Main span: 628	4
25	Nanjing Fourth Yangtze River Bridge	Suspension bridge	(160+410.2)+1418+(363.4+118.4)	21
26	Chongqing Qingcaobei Yangtze River Bridge	Suspension bridge	18.867+245+788+245+17.831	2
27	Qingdao Bay Bridge	Suspension bridge	1300	3
28	Ningbo Qinglin Bay Bridge	Cable-stayed bridge	380	2
29	Ningbo Qingshuipu Bridge	Cable-stayed bridge	468	1
30	Runyang Yangtze River Bridge	Cable-stayed bridge	1490+406	16
31	Shanghai Yangtze River Bridge	Cable-stayed bridge	350+730+350	12
32	Shaoxing Binhai Bridge	Cable-stayed bridge	77.8+188+77.8	19
33	Shenzhen Bay Bridge	Suspension bridge	180	4
34	Sutong Yangtze River Bridge	Suspension bridge	1088	14
35	Taizhou Yangtze River Bridge	Cable-stayed bridge	2 x1080	10
36	Taohuayu Yellow River Bridge	Suspension bridge	Main span: 406	6
37	Tianjin Seaside Express Haihe Bridge	Suspension bridge	310+190	3
38	Tianjin Nancang Marshalling Station Bridge	Cable-stayed bridge	150+150	1
39	Xiangshan Port Bridge	Suspension bridge	688	1
40	Pearl River Xinguang Bridge	Arch bridge	177+428+177	16
41	Guizhou Yachi River Bridge	Cable-stayed bridge	Main span: 800	5
42	Wuhan Yangluo Bridge	Suspension bridge	125+1280+440	5

43	Qingyuan Yingde River Bay Bridge	Arch bridge	3x45+8x70+4x45	4
44	Nanning Yonghe Bridge	Cable-stayed bridge	25.15+99.85+260+99.85+25.15	10

effectively weaken the noise and appropriately extract the characteristic information of bridge vibration. Lu [207] proposed the EMD-WP method that integrates EMD and wavelet packet to denoise the GNSS structure monitoring data, and it can also weaken the multipath effect. Li et al. [208] proposed an adaptive filtering method, EEMD-Wavelet-SSA, which combined EEMD, wavelet threshold and SSA. This can significantly reduce the root mean square error under the condition of low SNR of GNSS monitoring data.

Due to the continuous development of GNSS measurement time series denoising methods, the obtained "pure" monitoring information can accurately describe the dynamic characteristics of the bridge and provide a scientific basis for the operation of the bridge.

In view of the advantages of GNSS and the aforementioned developments (as FIGURE 1), more and more bridges in Mainland China adopt GNSS measurement as an important and commonly used monitoring method for structural deformation monitoring (TABLE I) [37]. Nevertheless, two-thirds of bridges have not yet adopted the GNSS monitoring technology according to [37]. The reason is that sometimes the accuracy of GNSS measurement is not as high as expected, the complexity of its solution is high, the sampling rate is not as high as that of other equipment such as accelerometers, so the main vibration frequency of the bridge structure cannot be extracted well from the GNSS monitoring data. It is also related to characteristics of GNSS monitoring data which is non-stationary nonlinearity, and contain certain amount of noise. Obviously, it is urgent to develop suitable dynamic characteristics identification methods to process the bridge monitoring data.

IV. SUMMARY OF CHARACTERISTIC RECOGNITION METHODS AND THEIR APPLICATION IN GNSS BRIDGE DYNAMIC MONITORING DATA

Signal processing of the vibration dynamic response obtained by bridge monitoring, detection, positioning, quantification and evaluation of the degree of structural damage to the vibration signal are the key issues in bridge structural monitoring. Exploring the signal processing technology that can extract subtle changes (if there are) in vibration response is crucial for detecting, locating and quantifying the degree of damage to the bridge structure. With the development of various forms of structural condition monitoring after several bridge projects emerged, many dynamic feature analytical methods, especially frequency identification (or extraction) methods, are used in a large number of structural condition monitoring practices. The dynamic displacement and frequency changes of bridges are affected by various environmental incentives. The large deformation or frequency change will certainly draw monitoring engineers' special attention. Timely maintenance or reinforcement measures are observed to ensure the safe operation of the bridge.

However, the deformation and natural frequency of the bridge may gradually change with the accumulated load of the bridge and the silent material aging. It might be so long a period before failure or accident occurs that some deformation or frequency changes (if there are) is as weak as submerged in the noise of measurement equipment. Dynamic feature analysis on ceaseless monitoring data is the top priority of the bridge structure vibration analysis under environmental excitation.

This mechanism mainly focuses on extracting dynamic features from the monitored time series analytical data to determine the existence of structural damage and determine the damage location and its degree [209,210]. Over the years, the analysis of dynamic characteristics of bridge monitoring has gone through the stages of bridge natural frequency monitoring, bridge dynamic deformation monitoring, and fusion monitoring analysis of the two. Therefore, progress in these three areas will be introduced in this section.

A. BRIDGE NATURAL FREQUENCY MONITORING

Since Adams et al. proposed the concept of detecting structural damage through changes in the natural frequency of the structure [211] and conducted experimental verification with their collaborators [212], the vibration frequency of the structure has been an important modal parameter in the structural health monitoring of bridges. This aspect has made considerable progress.

Cawley and Adams [8] calculated the natural vibration frequency of the structure by using the finite element method to detect damage, determine the location of the damage, and quantify the damage. Rytter [9] divided the damage identification of structural health monitoring into the aforementioned four progressive levels in his doctoral thesis. The first level is particularly critical and is the basis for all subsequent work, and carrying out the subsequent three levels of work for the structure without damage detection is meaningless.

Such work will also bring great safety risks to the normal operation of the engineering structure if the structure actually has damage, and the structural health monitoring system fails to detect damage due to the lack of equipment, monitoring methods, and data analytical methods. The internal modifications in engineering structures will cause changes in the vibration frequency of the structure. This view has prompted scientists and engineers to insistently explore methods for structural damage identification and health monitoring.

Gardner-Morse and Huston estimated the cable tension by the natural frequency change of cable-stayed bridge cables, and verified the bridge cable tension loss when the actual frequency is less than the design value [213]. Salawu comprehensively reviewed the means and analytical methods of damage monitoring by using frequency changes, and believed that the detection of engineering structural damage requires comprehensive consideration of changes in natural frequency, modal shape and damping ratio [214]. The damage identification method based on the change of natural frequency is widely used because it is easy to obtain in the structural mode, and the identification accuracy is high [215].

Accelerometers and fiber bragg grating (FBG) sensors are often used to measure natural frequencies. Li et al. [216] established a bridge monitoring system via these techniques on the Yellow River Highway Bridge in Binzhou, Shandong, and analysed the frequency response of the traffic load to the bridge. Magalhaes et al. [217] established a dynamic monitoring system by using accelerometers on a concrete arch bridge in Bordeaux, Portugal. They studied the impact of environmental variables and operating variables on the modal parameters by the time series of the natural frequency evolution of the bridge within two years. Historical data are used as a reference to provide high reference accuracy for health monitoring. Then enough data are collected before an abnormal event occurs, and the health monitoring system can have sensitive abnormality detection capabilities [217].

Scholars have their own opinions on whether the vibration frequency change of the bridge under traffic load truly reflects the dynamic characteristics of the bridge structure under damage. Apaydin et al. [218] conducted dynamic monitoring on the Fatih Sultan Mehmet Bridge with a main span of 1090 m in Turkey. They believed that the amplitude of the bridge vibration response caused by traffic congestion on the bridge deck was significantly more severe than that under no traffic conditions. The frequency obtained by the accelerometer is similar. However, Magalhaes [217] pointed out that the measured frequency has a 0.2% change compared with the simulated data after removing the environmental and traffic factors when bridge damage occurs. Such different viewpoints make the subsequent researchers wonder about the scientific accuracy of bridge health monitoring based on the frequency changes. The frequency response is the overall dynamic characteristic of the structure, and the local damage of the structure is difficult to reflect [219]. However, this situation is also related to the accelerometer's shortcomings, such as insensitivity to low-frequency vibration [219, 220] and difficulty in removing integral errors of the accumulation [221, 222]. Therefore, the development and application of the dynamic displacement monitoring methods and technologies such as GNSS and the extraction or identification of dynamic characteristics from them is beneficial. First, the method can make up for the shortcomings of accelerometers. Second, the method can verify the scientific reliability of its dynamic characteristic recognition, thereby eliminating the aforementioned doubts.

The structural frequency changes caused by damage are not sensitive, which means that engineers will either leave it alone and wait until the damage is severe enough, especially to the extent that it can be identified with existing technology, and then immediately take measures; or they will try to find more accurate and sensitive methods to detect damage in the early stage of damage or failure, and take reinforcement measures in advance. The latter is a more sensible choice for property and life safety considerations. Similar to the quality control in machinery manufacturing, bridge health monitoring needs to adopt more appropriate strategies and methods to monitor frequency changes to detect the existence of damage in a controlled environment, which is just the meaning of the first level of structural health monitoring [9].

B. SUMMARY OF CHARACTERISTIC RECOGNITION METHOD

From the foregoing, the dynamics of bridge monitoring by GNSS has achieved certain results in geometric deformation monitoring in view of the unremitting efforts of researchers and engineers from GNSS positioning solution strategy, high sampling rate, multi-frequency multi-system GNSS, multipath impact reduction, noise characteristic analysis and signal denoising. In addition, the GNSS dynamic monitoring time series of bridges often show nonlinear and unstable characteristics, and contain imperfect noise that is weakened to a certain extent due to various environmental stimulus factors, such as load, ship impact, temperature and wind. Therefore, the research progress of dynamic characteristic identification methods must be introduced in this section.

The probability density of stationary random signals does not change with time and frequency shift, whilst the distribution parameters or distribution laws of nonlinear non-stationary signals will change with time.

To identify the vibration modal parameters in the nonlinear and stationary data series, scholars have successively developed Kalman filtering [223], SSA [224], Natural Excitation Technique (NExT) [225], autoregressive moving average (ARMA) [226], Stochastic Subspace Identification (SSI) [227,228], ICA [229] and other time domain identification methods. In the frequency domain, people often use fast Fourier Transform (FFT) [230] for vibration frequency identification. These methods are basically effective for the identification of modal parameters with low sampling rate that can be regarded as linear or steady, and each method has its own advantages and disadvantages. However, these methods cannot effectively identify the modal parameters of unsteady and nonlinear systems, especially vibration, for example, inevitable leakage and aliasing phenomena occur in the FT spectrum.

To identify the dynamic characteristics of non-stationary signals, researchers and engineers have made long-term unremitting efforts. The methods applied and developed include Short Time Fourier Transform (STFT) [231], Wigner-Ville Distribution (WVD) [232], wavelet analysis

[233-237] and empirical mode decomposition (EMD) [238] and its related improvements [239-242].

When analysing non-stationary signals based on FT, the STFT method needs to select an appropriate window function: a narrow window is often used for high frequency signals, whilst a wide window is required for low frequency signals. However, this phenomenon is a big puzzle for the analysis of non-stationary signals with unknown frequency states. After a series of development [234-237], wavelet transform developed into a decomposition method with different window lengths that can reflect the multi-scale detailed changes of the signal [242]. The selection of different wavelet bases is suitable for different example applications. An appropriate wavelet base is difficult to determine for specific applications, which had become a limitation for expanding its applications. Therefore, Huang et al. [238] proposed HHT with EMD and Hilbert Translation (HT) as the core, which can adaptively process non-linear and non-stationary signals. However, this method also has problems, such as end effect an, modal aliasing. When this method is applied in signal processing, it sometimes obtains results without specific physical meanings. For this reason, Wu and Huang [239] proposed an EEMD method based on adding white noise to the signal for multiple times and decomposing and averaging it. This method effectively improves the modal aliasing, but it also leads to large residual noise in signal reconstruction. Yeh et al. [240] proposed a complete empirical mode decomposition (CEEMD) method by adding positive and negative pairs of auxiliary white noise to the signal for multiple times and decomposing and averaging it. This method can efficiently weaken the residual auxiliary noise in the reconstructed signal.

Torres et al. [241] considered that the amplitude of the positive and negative paired white noise added for multiple times was related to the original signal in a certain way, and the amplitude gradually reduced. They also proposed CEEMD with Adaptive Noise (CEEMDAN). This method provides accurate reconstruction of the original signal. Zheng et al. [242] detected the abnormal components of CEEMD decomposition based on the permutation entropy of the signal randomness detection and discarded them. Then, they performed the EMD process, and proposed partial EEMD (PEEMD) method, which has better decomposition effect and, has a certain inhibitory effect on modal aliasing.

The stochastic resonance (SR) proposed by Benzi et al. to explain the palaeometeoro-logical problem of the glacier period [243] is different from the aforementioned frequency extraction method to separate noisy signals. This approach is a new method of using non-linear system to realise transferring noise energy to signal energy. The Adaptive SR (ASR) method proposed by Mitaim et al. [244] can seek the best amongst the signal, noise and driving force and generate stochastic resonance effects, which can also effectively detect or highlight useful frequencies and eliminate noise in low signal-to-noise ratio situations. In recent years, the application and research of stochastic resonance in mechanical vibration fault detection and signal noise processing have rapidly developed [245-251], and the achievements are encouraging. However, the research of applying this approach to the coordinate time series analysis of GNSS monitoring bridge dynamic deformation is rarely seen in the newspaper, except for the research and application in dynamic characteristic identification of bridge GNSS monitoring data [252].

Dragomiretskiy and Zosso [253] proposed a new adaptive signal decomposition method – variational mode decomposition (VMD) – in 2014. In contrast with the recursive mode decomposition method of EMD, VMD can simultaneously decompose the signal into a set of band-limited intrinsic mode functions, estimate its centre frequency online in the function and extract all modes. They verified through experiments that VMD is superior to EMD in terms of tone detection, tone separation and noise robustness [253]. Wang and Markert [254,255] further proved the superior performance of VMD. The VMD-based vibration signal analytical method has been widely applied in the field of mechanical fault diagnosis [256-260]. However, the VMD parameters used in these applications, such as the number of modal layers K and the modal frequency band control parameter (or penalty coefficient), are determined on the basis of experience or convenience. The large number of non-linear and non-stationary signals in practice (such as bridge GNSS monitoring data) are susceptible to various factors, and the changes in the signal frequency band are complicated.

This part introduces a variety of different characteristics identification methods and their development, which are not only applied to the identification of bridge vibration characteristics.

C. APPLICATION OF CHARACTERISTIC RECOGNITION METHOD IN THE GNSS BRIDGE DYNAMIC MONITORING DATA

In the massive coordinate time series obtained by the GNSS monitoring system, selection of appropriate data processing methods to extract valuable bridge vibration frequency information and its characteristics that slightly change with environmental excitation factors, identification of the bridge structural mode, and analysation of the safety state of the bridge structure are the major goals that many researchers and engineers in the field of structural health monitoring constantly strive to pursue.

The analysis of natural frequencies of bridge structures based on non-GNSS monitoring time series has been running through the development of bridge health monitoring to date. Owen et al. [261] employed autoregressive time series modelling to analyse the non-linear and non-stationary vibration signals of bridge monitoring. Ruzzene et al. [262] conducted wavelet analysis on the vibration information of the Queensboro Bridge in Vancouver, Canada under environmental excitation, and the frequencies obtained were consistent with previous research results. Huang et al. [263] applied this mechanism to the data analysis of bridge health monitoring soon after proposing the HHT method. Guo et al. [264] and Zhu et al. [265] reviewed the advantages of wavelet analysis in signal denoising, signal detection, feature extraction, and data compression in health monitoring systems. Wald et al. [266] and Chen et al. [267] reviewed the application of FT and HHT respectively in structural monitoring, including bridge engineering. Amezquita-Sanchez et al. [268] reviewed a variety of signal processing methods used in structural monitoring. Goyal et al. [2] reviewed the instruments and dynamic feature analysis analytical methods used in the monitoring of engineering structures, including bridges.

The research on the dynamic characteristic identification method of GNSS measurement that can obtain the dynamic deformation information of the bridge structure has also been continuously developed since the high sampling rate GNSS receiver was applied to the bridge monitoring. These recognition methods have also achieved considerable success. In terms of frequency extraction by using FT, Nakamura et al. [58] performed FT analysis on the monitoring coordinate time series of a Japanese suspension bridge structure acquired by a GNSS receiver with a sampling interval of 1 s as early as 2000, and obtained a vibration frequency of 0. 98 Hz. Xu and Guo et al. [23, 62] used FFT to identify the dynamic characteristics of the GNSS monitoring vertical coordinate time series of Humen Bridge, and obtained the main vibration frequencies of 0.134 and 0.170 Hz. Huang et al. [24, 25] analysed the time series obtained by the GNSS monitoring of Wuhan Second Yangtze River Bridge and Sutong Bridge by using the FT spectral analytical method. The former obtained the vibration frequency of 0.2698 Hz, and the latter achieved 0.166 and 0.500 Hz. Many researchers and engineers have continuously performed FT analysis on the time series obtained by GNSS monitoring of bridge vibration to identify the dynamic characteristics [25, 39, 66, 68, 75-78, 80-84, 86-89, 103, 104, 106, 109, 113, 115, 118-120, 126, 138, 140, 146, 147, 173, 181, 269-272]. The details have not been repeated here due to space limitations.

Recently, Kaloop et al. [125] used neural network adaptive filtering methods to denoise the time series of GNSS monitoring of the Huangpu Bridge over the Pearl River, and then identified the dynamic characteristics of the bridge by using FT. Park et al. [273] compared the frequency processed by FT on the time series of GNSS monitoring of a steel suspension bridge in Incheon, South Korea with the that calculated by the finite element method and verified the effectiveness of GNSS monitoring. Xin et al. [274] comprehensively applied Kalman Filtering (KF), AutoRegressive Integrated Moving Average (ARIMA) and Generalised AutoRegressive Condition Heteroskedasticity (GARCH) models to the monitoring data on Jialing River Bridge, Caijia by GNSS. The time series information was analysed, and better bridge vibration information was obtained by using FT.

Given that wavelet analysis is superior to FFT in frequency identification, Huang et al. [53], Ogaja et al. [275, 276], Huang et al. [116], and Li et al. [277] applied WT to the deformation analysis of high-rise buildings and other engineering structures. Later, Meo et al. [65] extracted the natural frequency of the bridge structure by using wavelet analysis, and verified that it is basically consistent with the frequency obtained by the existing method. Xu et al. [278] used wavelet multi-scale analysis to denoise the GNSS-RTK time series signals obtained by GNSS monitoring on a cable-stayed bridge's high tower and obtained the main frequency via FFT analysis. The results are consistent with those from finite element analysis. Kaloop et al. [279] verified the sensitivity of GNSS monitoring signals to bridge damage monitoring on the basis of the time series of GNSS monitoring of Yonghe Bridge, Tianjin by using STFT and wavelet analysis. Cao et al. [280] applied SSA on the time series of the pylons of Sutong Bridge monitored by GNSS and effectively extracted the vibration frequency of the pylons via wavelet analysis. Elbeltagi et al. [281] filtered GNSS monitoring data via moving average filtering and wavelet transform and extracted low-frequency bridge vibration information by using FT. Han et al. [282] conducted wavelet and FFT analysis on the data sequence obtained by the GNSS-based monitoring equipment on the Wuhan Yangtze River Second Bridge under typhoon load. The obtained main frequency of vibration of the bridge was 0.172 Hz. Kaloop et al. [90] analysed the GNSS dynamic monitoring time series obtained on the Mansoura Bridge in El-Mansoura, Egypt by combining wavelet transform and PCA methods, and obtained reliable vibration frequencies. Hussan et al. [283] analysed the GNSS monitoring information of a suspension bridge in Incheon by wavelet transform and other methods and obtained useful conclusions. Kaloop et al. [284] processed bridge monitoring data by GNSS by using wavelet spectrum and ARMA methods to detect significant changes in the bridge frequency and bridge stiffness performance. In view of the advantages of wavelet analysis, scholars often broadened it to structural deformation monitoring and its related applications, such as reducing of multipath errors [183, 189] and signal noise reduction [203-207, 285].

With the continuous development of EMD, which is superior to wavelet analysis in terms of nonlinear data decomposition, it has gradually been applied to the extraction of wind vibration monitoring features of tall buildings monitored by GNSS [286-290], the weakening of GNSS multipath effects [185, 186, 208], the attenuation of signal noise [207] and some other aspects. Xu et al. [291] analysed the GNSS monitoring time series obtained on the Wuhan Baishazhou Yangtze River Bridge by combining EEMD with random decrement technique (RDT) and obtained a clean bridge vibration mode. Liu et al. [292] processed the experimental results of the vibration monitoring of the Nanjing Third Yangtze River Bridge by using the single-frequency GNSS dynamic three-difference method, and, accurately extracted the natural frequency of

0.25 Hz at the first vertical bend of the bridge on the basis of the time series combined with FT and EMD. Yu et al. [121] also used the EEMD method when processing multi-mode GNSS monitoring data for mid-span suspension bridges.

Given that wavelet analysis, EMD and its derivative calculations still have certain shortcomings, researchers have begun to integrate different methods to process GNSS monitoring data of bridges. Xiong et al. [293] proposed a filtering algorithm combining EMD and Chebyshev hybrid filtering based on autocorrelation function, and applied it to the real displacement of bridge structural vibration, which further effectively identified bridge modal parameters. Niu et al. [105] analysed the time series of GNSS monitoring on Tianjin Fumin Bridge by combining EEMD and wavelet packet technology. The obtained frequency was in good agreement with the calculation result from the finite element. Rao et al. [294] proposed a data decomposition method that combines EMD, WT and FFT, which can effectively reduce the impact of ultra-low frequency components and noise when processing GNSS monitoring time series and extract clearer bridge vibration frequencies. Xiong et al. [295] proposed a new method by combining CEEMDAN and wavelet package (WP), which effectively weakened the high and low frequency noises of the time series monitored by GNSS-RTK on the Rainbow Bridge in Tianjin, and obtained clear bridge vibration frequency.

The Huang's team has long been committed to the GNSS dynamic monitoring and safety warning processing of large structures, such as bridges and dam. They have not only established structural dynamic monitoring systems for some buildings and structures, but also carried out a series of innovations and applications of data processing methods. A series of results has been obtained. Huang and Wang et al. [296] proposed a data decomposition method that combines EMD, permutation entropy (PE) and spectral substitution, which can effectively weaken the noise and retain the original signal when processing noisy bridge GNSS monitoring data sequences. With this method, they obtained clearer dynamic characteristics of the Wuhan Baishazhou Yangtze River Bridge. Wang et al. [297] proposed a time-frequency analysis method based on the combination of wavelet threshold denoising and HHT. The Hilbert spectrum analysis of the denoised data clearly reflected the spectral value of the bridge structure, and the numerical results agreed well with the theoretical calculations [297]. Wang et al. [252] also proposed an adaptive stochastic resonance method on the basis of quantum genetic algorithm, which can also detect clear and reliable dynamic characteristic bridge monitoring information by GNSS that has a great impact on noise.

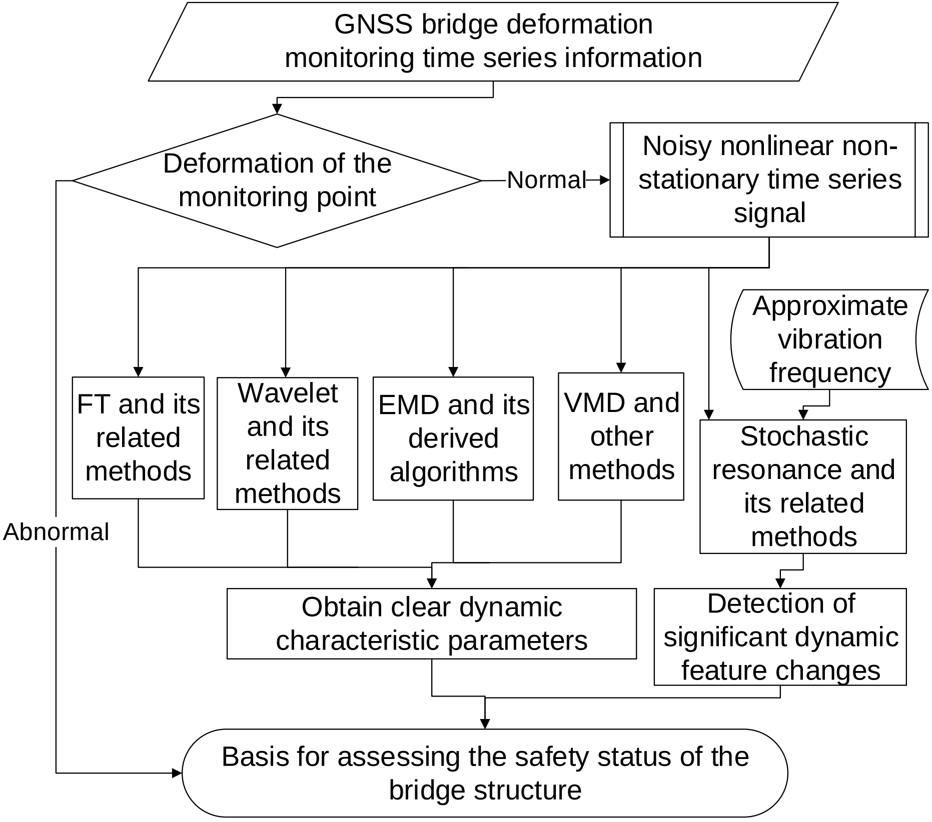

FIGURE 2. Application of characteristic recognition methods on GNSS bridge deformation monitoring data

On the basis of the unity of the sampling rate, time system, and coordinate system between GNSS and the speedometer, the displacement, including low-frequency displacement and high-frequency vibration information of bridges, was obtained with high precision by Zhang et al. [298]. By a time series analysis and spectrum analysis on the decomposed signal, it is found that the VMD algorithm can extract the low-frequency trend term in the GNSS time series with high precision. Yu et al [299] summarized different innovative data processing techniques for processing GNSS data in structural health monitoring.

This section reviews the application of characteristic recognition method in the GNSS bridge dynamic monitoring data.

With more and more characteristic recognition methods available (FIGURE 2), the use of GNSS receivers is not limited only to the dynamic displacement monitoring of bridges structure, but also to their dynamic characteristic identification such as main frequencies.

V. CONCLUSION

In summary, with the continuous development and progress of GNSS technology, monitoring the deformation of the bridge structure by using GNSS can not only obtain high-precision and high-sampling rate bridge dynamic deformation characteristic information, but also obtain scientific and reliable natural frequencies (and its changes, if any) and dynamic characteristics. Although the GNSS monitoring is subject to various environmental factors and its own limitations and contains certain noise, the vibration frequency and changes of the bridge structure in a specific environment can still be obtained by adopting or developing an effective dynamic characteristic analytical method for the non-linear and non-stationary state time series data of the monitoring.

This study summarizes application progress of GNSS monitoring dynamic deformation of bridge structures, GNSS deformation measurement technology for bridge structural health monitoring and characteristic recognition methods and their application in GNSS bridge dynamic monitoring data. It is critical to obtain continuous, real-time, high-sampling microdeformation information of major engineering structure by developing or improving GNSS positioning solution methods for monitoring, high sampling rate GNSS receiver for monitoring, multi-frequency and multi-system GNSS monitoring, weakening of multipath effect of GNSS monitoring, analysis of noise characteristics of GNSS monitoring and its signal denoising. Meanwhile, developing and improving the appropriate dynamic characteristic identification method for structural health status analysis and early warning of bridge monitoring data, is the goal of researchers to pursue.

To date, the structural health monitoring of bridges by GNSS has evolved from continuous displacement monitoring to dynamic feature identification and monitoring or both. Such research and review have great application value for early detecting and warning bridge failures as early as possible.

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