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学　位　論　文　内　容　の　要　旨

博士の専攻分野の名称　　博士（工学）　　氏名　孫 亮明

学　位　論　文　題　名

Study on environmental vibration and mitigation countermeasures caused by running high-speed train on railway viaduct
(高速列車走行による鉄道高架橋の環境振動と軽減対策に関する研究)

With the rapid economic and urban development, the high-speed railway system connecting major cities serves as a vital role in the national transportation network. Due to its high speed, punctuality, safety, comfort, high transportation capacity and less land use, it has become a new trend of railway development in the world especially in Asian and European countries. We have derived the benefits of high-speed railways since Tokaido Shinkansen as first high-speed railway was began operations in Japan in 1964. The main railway lines usually pass directly over densely populated urban areas or high-tech industrial areas, where the railway structure mainly comprises elevated bridges. Considering the extremely high speed, the bridge vibration caused by running high-speed trains (HSTs) is concerned. This long-term vibration may cause deterioration of the bridge structures, such as the cracking or exfoliation of concrete. On the other hand, the HST-induced bridge vibration propagates to the ambient ground via footing and pile structures, thereby causing long-term environmental problems. Those vibrations often bring annoyances to the residents alongside railway lines and malfunction to the vibration-sensitive equipment housed in the nearby buildings. Furthermore, they can induce the secondary vibration of the buildings, which seriously affect the structural safety of ancient buildings near the railway lines. Along with further urbanization and more rapid transport facilities, there is rising public concern about the environmental problems in modern Japan. Therefore, it is quite necessary to clarify the development and propagation mechanism of ground vibration caused by running HSTs on the rigid-frame viaducts (RFVs) in order to find out more effective countermeasures against the HST-induced vibration problems.

In this study, the vibration issues related to the train-bridge-ground interaction system: the HST-induced bridge vibration problem, the environmental vibration problem caused by running HSTs and the vibration reduction method, have been investigated by means of the 3D numerical analysis approach.

For the HST-induced bridge vibration problem, it is very important to perform effective prediction and diagnosis on the HST-induced vibration of either existing bridges or those in the planning stage and obtain some instructive information for the ground vibration analysis as well as the vibration mitigation analysis. An analytical procedure to simulate the train-bridge coupled vibration problem with considering the train-bridge interaction (TBI) as well as the effect of ground properties is established. The vibration responses of RFVs caused by running HSTs are analyzed in consideration of the wheel-track interaction including the rail surface roughness. The RFVs including the track structure are modeled as the 3D beam elements and simultaneous vibration differential equations of the bridge are derived by using modal analysis. The elastic effect of ground springs at the pier bottoms and the connection effect of the sleepers and ballast between the track and the deck slab are modeled with double nodes connected by springs. A 3D HST model modeled as multi-DOFs vibration system that can appropriately express the lateral, vertical and rotational motions of the car body and bogies is developed for the analyses. Newmark's β method for direct numerical integration is applied to solve the vibration differential equations. For the validation of the developed 3D HST model and the analytical approach, the vibration response analysis of the TBI system is carried out and the analytical results are compared with experimental ones. Based on the simulation of TBI, the vibration characteristics of the RFVs in both vertical and lateral directions including the fact where predominant vibration occurs are clarified. Frequency characteristics are clarified by Fourier spectral analysis and 1/3 octave band spectral analysis. Furthermore, the parametric study of bridge vibration caused by running HSTs is performed to examine the vibration influences of different factors including train speeds, train types, track irregularities, rail types and damping based on their analytical results.

For the environmental vibration problem caused by running HSTs, based on the developed analytical procedure for the TBI, an approach to simulate ground vibration around the RFVs of the high-speed railway is established with considering the vibration interactions between the train and the bridge as well as the foundation and the ground. The TBI models established preciously are conveniently used in this analysis. The entire train-bridge-ground interaction system is divided into two subsystems: the train-bridge interaction and the soil-structure interaction (SSI). In the stage of the TBI problem, the vibration responses of RFVs are simulated to obtain the vibration reaction forces at the pier bottoms of RFVs. Then, applying those vibration reaction forces as input excitation forces in the SSI problem, the ground vibration around the RFVs in both vertical and lateral directions is simulated and evaluated by means of using a general-purpose program named SASSI2000. Based on the simulation of TBI and SSI, the characteristics of ground vibration around the RFVs in both vertical and lateral directions including the fact where predominant vibration occurs are clarified. The ground vibration is rapidly attenuated along with the increase of propagation distance in the near field and their vibration influence in the vertical direction is much more serious than that in the lateral direction. The predominant frequency components are basically same for the different observation points and they are determined by those of bridge vibration. Frequency characteristics are also clarified by the Fourier spectral analysis and 1/3 octave band spectral analysis. It is verified that the primary vibration frequency component is dependent on the speed of HST in relation to the length of car and the higher frequency components are integer multiples of the primary one. The lower frequency band mainly exists in the vicinity of bridge piers and reduces quickly along with the increase of propagation distance. The lateral vibration is mainly affected by the higher frequency components. Furthermore, the parametric study of ground vibration caused by running HSTs is also carried out to examine the vibration influences of different factors including train speeds, train types, track irregularities, rail types and damping based on their numerical results.

Based on the vibration characteristics related to the above-mentioned vibration issues, two kinds of vibration reduction countermeasure are proposed to reduce the HST-induced vibration to meet the requirement of environmental vibration. One kind is to reinforce the hanging parts of the RFVs to firstly reduce the HST-induced bridge vibration. The other one is to install a new barrier called reinforced concrete vibration isolation unit (RCVIU) to directly isolate the HST-induced ground vibration. Then, according to 3D numerical analysis approach of the entire train-bridge-ground interaction system, the mitigation analyses are carried out to comparatively investigate the HST-induced vibration responses for three reinforcement methods and a double-layer RCVIU. Their vibration screening efficiencies are evaluated by the reduction of vibration acceleration level (VAL) based on 1/3 octave band spectral analysis and the reduction factor on the maximum acceleration from three aspects such as vibration frequency, train speed and propagation distance. Furthermore, the combined vibration reduction method with strut and RCVIU is proposed to involve the source motion control and the wave propagation obstruction. It is an effective vibration reduction method to reduce the HST-induced ground vibration around the RFVs in both vertical and lateral directions. The reduction of overall VAL is 9.67dB and 2.78dB at 25m in the vertical and lateral direction, respectively. In particular, about vibration frequency, it is more effective to mitigate the ground vibration at 25m in the lower frequency band and the high frequency band such as 1-2.5Hz and 6-25Hz. The largest reduction of VAL is 11.35dB at 8Hz and 13.68dB at 12.5Hz in the vertical and lateral direction, respectively. But it is small around the primary frequency component 3.15Hz.

According to the ground vibration response, the environmental vibration evaluation is performed by means of the uniform evaluation index such the VAL from two aspects such vibration frequency and train speed. Taking advantage of the frequency-dependent base curves of the perceptible vibration from ISO 2631-2:1989 and the threshold 70dB of the environmental vibration for the Shinkansen railway in Japan, the environmental vibration is comparatively investigated through 1/3 octave band spectral analysis. The parametric effects including train speeds, train types, track irregularities, rail types and damping are also investigated for the environmental vibration caused by running HSTs. Furthermore, the assessment for vibration reduction methods is carried out to clarify the effectiveness of improvement of environmental vibration. The results show: the VALs in the lateral direction are below the base curves and far less than those in the vertical direction; the VALs in the vertical direction easily exceed the smallest base curves in the range of 8Hz to 25Hz and the threshold 70dB at the border for the Shinkansen railway. The various impact factors can cause the change of the HST-induced vibration but the change for the rail type is very small. In particular, the train speed can easily cause the variation of predominant frequency components; the train type and damping ratio can easily cause the variation of magnitudes; the track irregularity can cause the variation of both predominant frequency components and magnitudes. Finally, the application of vibration reduction countermeasures is useful to reduce the HST-induced vibration to satisfy the requirement of improvement environmental vibration in the vibration-sensitive areas.