TGV-K의 제동함수를 고려한 고속철도 교량의 동적거동

Dynamic Behavior of Bridges for High-Speed Train Considering Braking Function of TGV-K

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국문요약

열차와 교량의 3차원 모델링을 사용한 고속철도 교량의 동적해석이 수행되었다. 철도교의 모델링은 판요소와 3차원 뼈대요소로 모델링되었다. 상판과 주형 사이의 offset은 기하학적인 구속조건을 사용하여 고려하였다. 본 연구에서 사용된 고속철도는 2량의 동력차와 2량의 모터차와 16량의 객차로 구성되어있다. 관절형 대차로 연결되는 전체 열차계의 운동방정식은 Lagrange방정식을 이용하여 유도되었으며, 차체와 대차 그리고 차축의 3차원적인 운동을 고려하였다. 이동 열차에 의한 교량의 응답은 predictor-corrector반복법에 의한 Newmark-β 법에 의해서 그 해가 구해진다. 매개변수해석에 의해서 열차의 이상화방법, 열차의 제동, 철도교량의 주행면 조도에 의한 영향이 고찰되었다.

주요어 : 교량-열차 상호작용해석, 고속철도, 이동하중, 제동하중

ABSTRACT

Dynamic analysis of railway bridges due to the high-speed train is performed using 3-dimensional full modelling of high-speed train and bridges. A railway bridge is idealized with plate and space frame elements. The offset between the slab and the main girder is connected using a geometric constraint equation. The high-speed train system investigated in the present study has 2 power cars, 2 motorized trailers and 16 passenger cars. The equations of motion of the whole train characterized by its articulated bogie system are derived from a Lagrangian equation, which considers motions of car-bodies, bogies and wheels in 3-dimensions. Dynamic responses of bridges subjected to moving trains are solved by Newmark-β method with a predictor-corrector iteration scheme. From parametric studies, the effects of the method of train idealization, the braking action of the train, and surface irregularities of railway bridges are discussed in detail.

Key words : *bridge-train interaction, high-speed train, moving loads, braking action*

1. Introduction

Among various kinds of loads applied on bridges, the load induced by moving vehicles has been recognized importantly as the vehicles are getting heavier and faster. Following earlier theoretical studies that analyzed the dynamic behavior of bridges due to moving loads, various researches of applying newly developed and revised train and bridge models have been accomplished. The researches on the impact of concrete railway bridges by freight trains have been carried out by Chu et al.[(1)] Wakui et al.[(2)] remarked on resonance suppression effects according to effective beating interval of the moving load. Yang et al.[(3)] evaluated impact formulas of bridges by analytical and numerical approaches using speed parameter and studied on resonance and resonance cancellation. The

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본 논문에 대한 토의를 2001년 2월 28일까지 학회로 보내 주시면 그 결과를 게재하겠습니다.

high-speed train that will be running in South Korea adopts the train system that has noticeable features of articulated bogie system. The vibrations of bridges caused by this high-speed train with considering bouncing and pitching motions in 2-dimension are analyzed by Chang et al.[4] In the present study, the approach based on the finite element analysis using 3-dimensional models for both train and bridge is conducted for investigating the dynamic behavior of bridges. The braking action of the train is also included.

2. Bridge system

The railway bridge considered in the present study is a steel-concrete composite bridge system which has two main I-girders and uniformly distributed cross beams. The concrete slab is idealized with Mindlin plate element with four 5 d.o.f nodes. The steel main girders and cross beams are modeled by the space frame element with two 6 d.o.f nodes, and shear deformation is considered as shown Fig. 1. Assuming full composite connection, the slab and girder can be connected using geometric constraint equation known as the rigid link element. Following general procedures of FEM, the equation of motion of the bridge system can be obtained as[6]

$$[M]_B\{\ddot{u}\}_B+[C]_B\{\dot{u}\}_B+[K]_B\{u\}_B=\{F_t\} \quad (1)$$

where, $[M]_B$, $[C]_B$, $[K]_B$ and $\{F_t\}$ denote mass matrix, damping matrix, stiffness matrix and interacting force vector of the bridge system, respectively.

It is known that riding surface conditions are important sources for inducing additional vibrations of bridge/vehicle systems. The surface irregularities of railway bridges are quite different from those of roadway bridges. In the present study, rail corrugation, and random and continuous irregularities of FRA (federal railway administration) standards[1] are considered for analyzing the effects of surface irregularities of railway bridges.

3. Train system

The high-speed train that will be running in South-Korea (so called KHST) differs from general train system. In general, train system is a series of cars that consist of one body and two bogies(or trucks) independently, but as shown in Fig. 2, the KHST adopts articulated bogie system, in which a bogie and longitudinal dampers exist between each car-body. Therefore, for scrutinizing the behavior, full modeling of the whole train system is required. The high-speed train investigated in the present study

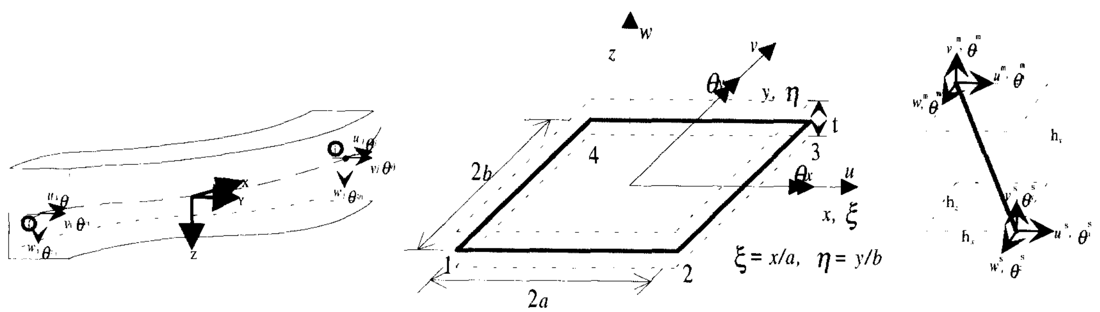
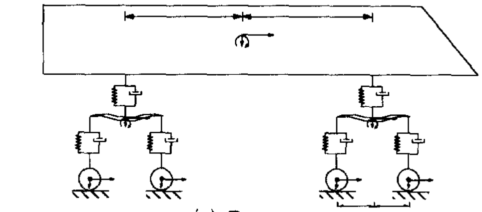
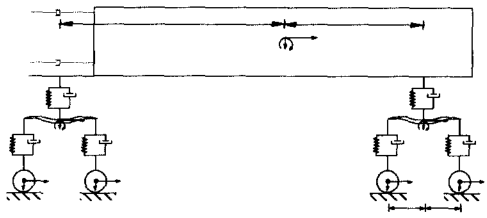


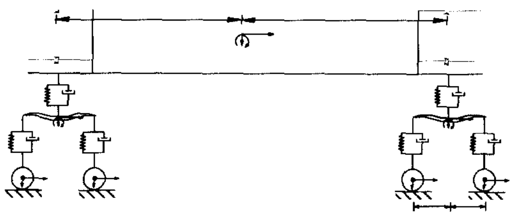
Fig. 1 Finite elements used for idealization of bridge



(a) Power car



(b) Motorized Trailer



(c) Passenger car

Fig. 2 The geometry of high-speed train

consists of 2 power cars, 2 motorized trailers and 16 passenger cars. A power car is composed of 2 bogies like general power cars, but a motorized trailer has one independent bogie and shares one articulated bogie with a passenger car, and an articulated bogie exists between passenger cars. Each bogie has 2 axles. Consequently, a KHST with total length of 380.15m has a total number of 20 car-bodies, 23 bogies and 46 axles. The assumption that the primary and secondary suspension system of the bogie is idealized by combination of linear spring and damper is applied for modeling, and the wheels of the train are assumed to remain in contact with the track.

To define the relationship between the articulated bogie and its forward and backward car-bodies, the relative displacements are assumed.

The equations of motion are derived by Lagrangian equation from Hamilton's principle. The overall equations of motion are skipped because of space limitation. The formulation in detail and used dynamic properties of high-speed train is recorded in reference.[7] Finally, the equations of motion of the high-speed train are constructed in matrix form as

$$[M]_V\{\ddot{u}\}_V+[C]_V\{\dot{u}\}_V+[K]_V\{u\}_V = \{P_t\} \tag{2}$$

where, $[M]_V$, $[C]_V$, $[K]_V$ and $\{P_t\}$ denote mass matrix, damping matrix, stiffness matrix and interacting force vector of the train system, respectively.

Although researches on vehicles running at uniform speed have been carried out considerable depth, researches on non-uniform speed of vehicles have appeared recently. In case of the KHST adopted in the present study, a combination of the two braking systems will be in use - the regenerative braking force of electric braking for the power car bogie and the disk braking of mechanical braking for the passenger car bogie.[7] Fig. 3 shows braking force per bogie versus its velocity for the regenerative and disk braking forces used in the present study.

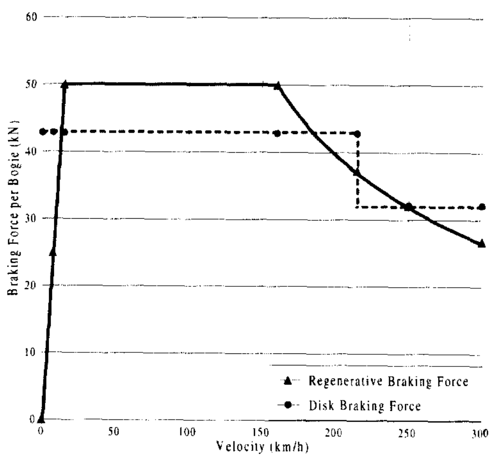


Fig. 3 Braking forces of high-speed train

4. Numerical examples

4.1 Scope

Two types of composite bridges, which are a simply-supported and a 2-span continuous bridge, are analysed.(Table 1) Damping ratio is assumed as 2%. The critical speed that is originated from the concept of resonance under the passage of uniformly distributed load is defined as

$$V_{cr} = \omega_1 \cdot S_{eff} \qquad (3)$$

where V_{cr} represents the critical speed of the train, ω_1 is a fundamental frequency of the bridge and S_{eff} represents the effective beating interval of the train that is equal to 18.7m for present type of train.

The verification of bridge model used in the present study by performing static and free vibration analysis can be found in reference.[6]

4.2 The effects of train modeling method

The effects of idealization method of the train is investigated using the simulation of different modeling methods of the train - moving constant forces(CF), 2-dimensional model(KHST2D) which considers only bouncing and pitching motions of all train components and 3-dimensional full model(KHST3D).

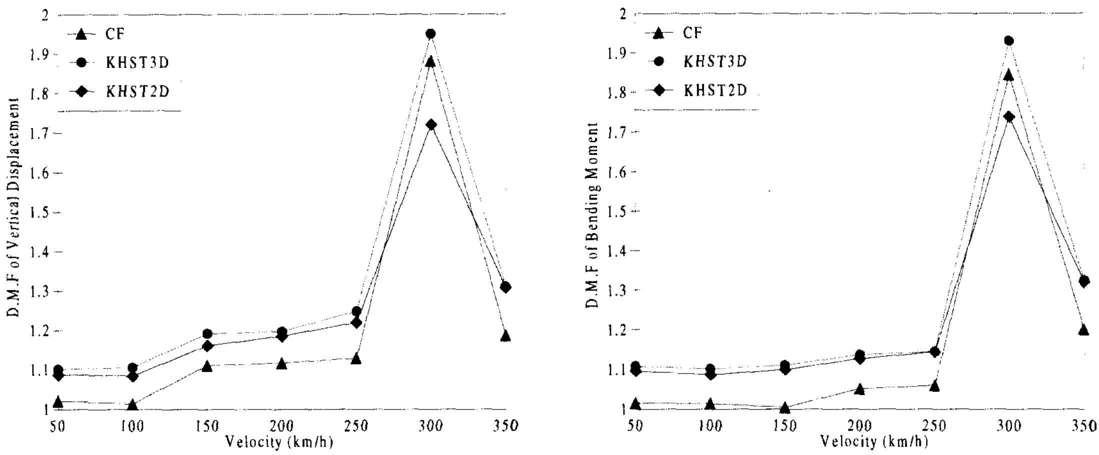
It is noted that dynamic responses of bridge with the KHST3D model are relatively higher than those with other train models at most speed ranges.(Fig. 4) This result is caused by additional interaction by pitching, rolling, yawing etc. of the train. In case of simply-supported bridge, simulation by the KHST3D model yields a maximum increase of 12.3% than simulation by CF model does. It is also found that in case of the KHST3D is simulating, the initial equilibrium status of train before entry of the bridge has considerable effects on the bridge response.

4.3 The effects of braking action of the train

The braking forces of the high-speed train from Fig. 3 is applied with initial speed of the train sets to 250 km/h and 350 km/h. It is assumed that all wheels of the train are braked at the same time. Fig. 5 shows the variation in DMF of vertical displacement in the middle of the first span girder of a conti-

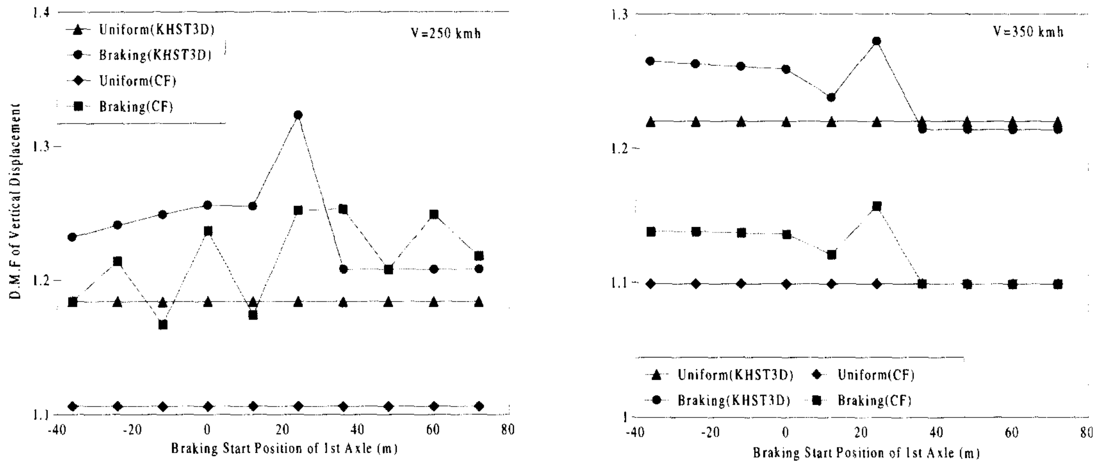
Table 1 Used properties of bridge, natural frequencies and the critical velocity

		Simply-supported bridge (40m)	2-span continuous bridge (40+40 m)
Main girder	Height (m)	3.7	3.5
	Width of flange (cm)	80	80
	Thickness of flange (cm)	5.5	7.5
Cross beam	Number	7	7/span
Slab	Width (m)	4.0	14.0
	Thickness (cm)	40	40
Natural frequency (Hz)	Plate+frame model	4.35(Bending)	4.24(Bending)
	Frame only model		4.04(Torsion), 4.45(Bending)
Critical velocity (km/h)	Plate+frame model	292.8(Bending)	285.4(Bending)
	Frame only model		272.0(Torsion), 299.6(Bending)



(a) (b)

Fig. 4 The variations of DMF of vertical displacement according to modeling method of train



(a) (b)

Fig. 5 The effects of braking force on DMF of vertical displacement

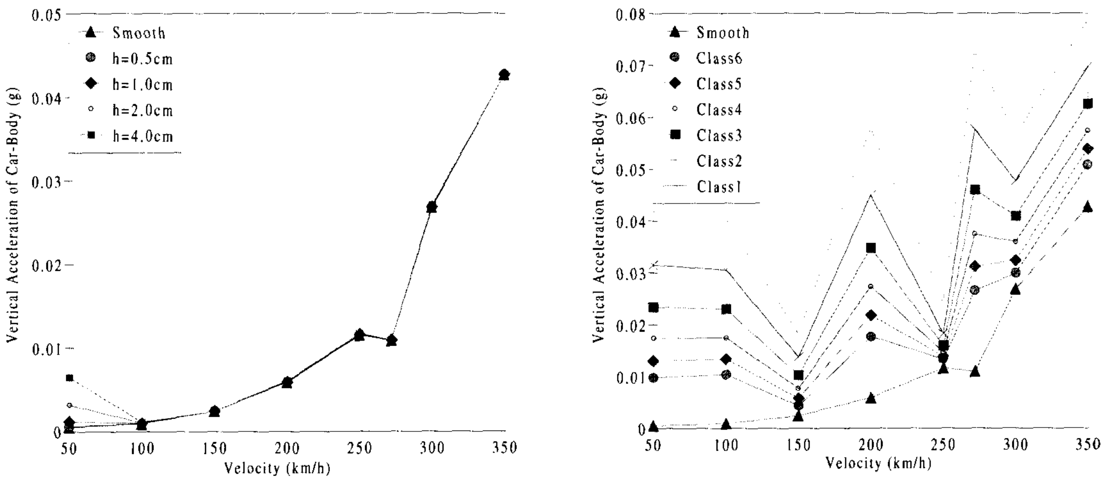
nuous bridge. As shown, increases occurred in DMF of vertical displacement up to 13.3% for the bridge appreciably due to braking force that causes additional bending moments.

4.4 The effects of irregularities of railway

Rail corrugation and random irregularities of FRA Standards are generated for verifying the effects of surface irregularities of railway on bridge-train interaction. Rail corrugation is generated using following mathematical expression.

$$f_{irr}(x) = \frac{h}{2}\sin\left(\frac{2\pi x_d}{l_{irr}}\right) \tag{3}$$

occurred at every 1m, lirr=10cm, h=0.5,1,2 and 4cm. As shown in the Fig. 6, the effects of discontinuous irregularities(rail corrugation) are small. However, as shown in Fig. 6(b), the effects of random and continuous irregularities are notice- able and these results show that vertical accelerations of a car-body can be over 0.05g in some surface conditions. Therefore, irregularities of surface would cause serious



(a) Rail corrugation (b) FRA class

Fig. 6 Effects of irregularities on riding comforts of passengers

discomfort of passengers.

5. Conclusion

A 3-dimensional model for high-speed train system that will be used in South-Korea is developed for investigation of interaction problem with 3-dimensional bridge models. From parametric studies, following conclusions are drawn.

(1) Dynamic responses of bridges by the 3-dimensional train model are larger than by the simple train model in most of speed ranges.
(2) As the braking forces of the train are applied in order to compare the motions in uniform speed, the DMF of vertical displacement can be increased.
(3) The type of braking function, the location of starting position of braking action, and the speed of the train at the instant of braking are major factors that affect the dynamic response caused by braking force.
(4) Irregularities of railway surface influence the bridge-train interaction and can increase responses of the bridge and can cause serious discomfort of passengers

Acknowledgement

The work reported on here has been sponsored by G7 project under leading by Ministry of Construction and Transportation, Ministry of Commerce, Industry and Energy, and Ministry of Science and Technology, Korea. The authors are grateful for their financial support

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