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Dynamic Problems on MAGLEV Guideway Structures

Problèmes dynamiques sur les structures de guidage à lévitation magnétique

Dynamische Probleme bei Magnetschwebebahn-Fahrwegen

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SUMMARY

This paper presents an introduction of the study for the design and technical development of a newly proposed guideway structure for the superconductive magnetically levitated railway system (MAGLEV). The design concept of the new guideway which combined twin precast prestressed concrete beams and infrastructures, and the dynamic design of structures for ultra-high-speed vehicles are described.

RESUME

Cette communication présente une introduction de l'étude sur la conception et la mise au point technique d'une structure de guidage récemment proposée pour le réseau ferroviaire à lévitation magnétique supraconductrice. Les auteurs exposent les caractéristiques essentielles du projet de ce système de guidage qui prévoit une double poutre préfabriquée en béton précontraint avec l'infrastructure correspondante. Ils fournissent une méthode de calcul dynamique des structures à prévoir pour les véhicules ultra-rapides.

ZUSAMMENFASSUNG

Der Aufsatz ist eine Einführung in die Entwurfstudien und die technische Entwicklung eines neuen Führungstragwerks für supraleitende Magnetschwebebahnen. Beschrieben werden das Konzept eines vorgespannten Zwillings-Fertigteilbalkens mit zugehöriger Ausrüstung und die Bemessung für dynamische Einwirkung aus dem Hochgeschwindigkeitsbetrieb.

1. INTRODUCTION

Extensive studies and developments are now being proceeded on the superconductive magnetically levitated railway system (MAGLEV) taking a new "side-wall levitation" as the fundamental system. All the ground coils including those for levitation, which was placed on the horizontal floor surface in the conventional system, are installed on the same vertical side-wall surface of the guideway. Although the section shape of the guideway remains the U-shape because the vehicles have to be supported by the floor slab at the time of wheel-traveling at low velocity, the new system has a lot of compositional advantages because the maintenance for the alignment of coils which require high accuracy can be conducted only by the side surface where the support, guidance and propulsion coils for the ultrahigh speed levitated-running are installed.
The authors proposed and have been developed a "Twin-Beam Guideway (TBG)" system in order to make the most of new system's advantage. The structural composition of the new guideway, and its dynamic behavior are reported in this paper.

2. STRUCTURE OF TWIN-BEAM GUIDEWAY SYSTEM

2.1 Composition of Twin-Beam Guideway

A schematic of TBG is shown in Fig.1. Its basic concept is as follows:
(1)The side surface finished to high accuracy is made of a precast concrete beam and set as a maintenance-free module with accurately aligned coils.
(2)The twin-beam (TB) can be placed on arbitrary infrastructures as both-ends supported beams. The structure of bearing is made finely adjustable in order to facilitate the correction of long-wavelength track irregularity.
(3)Separating the coil-installed module clearly from infrastructures, the coordination of inter-industrial works between structure, track and electricity is made easier and enabling a labor-saving, mechanized and rapid construction.

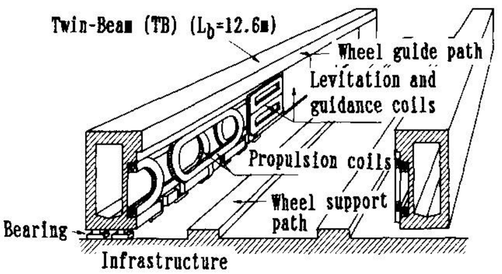


Fig.1 Twin-Beam Guideway

2.2 Structure of Twin-Beam

The sectional dimension of TB is shown in Fig.2. The determining factors for the dimension are as follows:
(1)Height is determined by the dimension of ground coils. Width is determined by the lateral rigidity and stability requirements for an independent beam. Length is set at 12.6 m to limit the deflection due to live load within 2 mm and considering the relation to the multiple of propulsion coil length (1.8 m).
(2)Box-beam is adopted except both-ends in order to obtain higher natural frequency.
(3)The pretensioning prestressed concrete structure is adopted to minimize the steel quantity in guideway and it is designed to keep full prestressing condition under service loads to sustain rigidity.

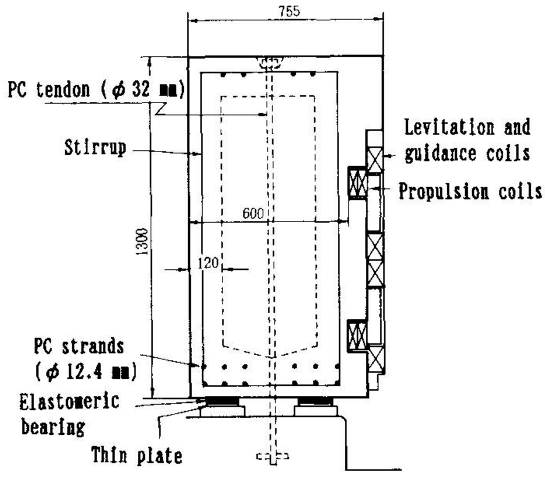


Fig.2 Cross section

2.3 Structure of bearing

The structure of bearing is shown in Fig.3 and the technical key points are as follows:
(1)Elastomeric bearings with lead cylinder at center are adopted for economic efficiency and requirements to provide enough horizontal spring constant. They allow free expansion and contraction of beam under the slow-strain loading due to temperature change.
(2)PC tendons are placed in order not to produce negative reaction at supports due to the eccentric loading of vehicle and large horizontal loading at emergency.

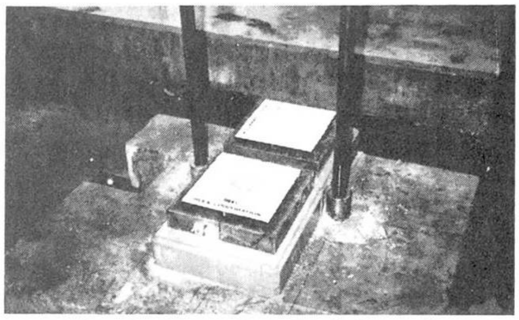


Fig.3 Structure of bearing

3. DYNAMIC RESPONSE OF GUIDEWAY FOR ULTRA-HIGH VELOCITY

The study of dynamic response of guideway is very important from the point of view not only of the structural design but also of the riding comfort because the dynamic load due to vehicle may determine the design condition and its deflection may work as a track irregularity.
As JR's MAGLEV is adopting a system of concentratedly-arranged superconductive magnets to minimize the magnetic field in the cabin, the train load becomes a series of distributed loads with a constant interval as shown in Fig.4 so that it resonates the guideway at a certain velocity. An analytical assessment of dynamic response of the TB and bridges which support them is made in this chapter.

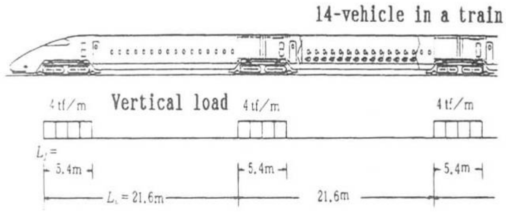


Fig.4 MAGLEV train load

3.1 Theory and Analysis of Dynamic Response

3.1.1 Equation of motion.
The equation of motion of a simply supported beam may be resolved into independent one degree of freedom systems with respect to the modes of vibration in the fundamental equation of motion of Bernoulli-Euler for the forced vibration of viscous-damped system approximating the deflection to the summation of principal mode functions as shown in Eq.(1).
Focusing on the first mode of vibration which has a dominant influence on the dynamic response of beam, the non-dimensional equation of motion as shown in Eq.(2) may be derived for a series of unit forces acting with a constant velocity and at a regular interval.[1,2]
The dynamic response of beam is governed by two dominant factors α and L_b/L_v, but the response value is obtained taking into account the additional factors ζ and N.

$$y = \sum_{i=1}^{n_b} \phi_i \cdot \sin(i\pi x/L_b) \quad (i=1,2,3,\ldots,n_b) \quad \ldots(1)$$

where, y:the deflection of beam, x:the distance from an end of beam, L_b:the span length, n_b:the mode number of beam.

$$\ddot{\phi} + \frac{2\zeta}{\alpha}\dot{\phi} + \frac{1}{\alpha^2}\phi = \frac{1}{\alpha^2}\sum_{j=1}^{N}\varepsilon_j \cdot \sin(\tau - \tau_j) \quad \ldots(2)$$

Where, $\tau_j = (j-1)\cdot\pi\cdot(L_b/L_v)^{-1}$

$$\varepsilon_j = \begin{cases} 1 : 0 \leq \tau - \tau_j \leq \pi \\ 0 : \tau - \tau_j < 0 \text{ and } \tau - \tau_j > \pi \end{cases}$$

where, τ :the non-dimensional time (the duration which a load passes through the beam is defined as π),
α :speed parameter,
$\alpha = v / (2 f_1 \cdot L_b)$ ... (3)
where, v:the velocity of vehicle (m/s), f_1:the fundamental natural frequency of beam (Hz).
L_b/L_v:the non-dimensional span length of beam (L_v:interval of loads),
N:the number of loads, ζ :the damping ratio of beam.

3.1.2 Dynamic response of simply supported beam

Substituting the MAGLEV train load (see Fig.4) into the term of excitation in right hand side of Eq.(2), the dynamic load factors, λ, (DLF=the ratio of the maximum dynamic deflection to the maximum static deflection at the center of span by the application of loads) with respect to non-dimensional span length of the beam are obtained. The influence of distributed load is taken into account in the computation.
When the load excites the beam with constant period, the beam is resonated at a certain velocity and generates peaks of DLF. The relations between λ and L_b/L_v are shown in Figs.5 and 6.

3.1.3 General law of resonance

The following laws may be derived on the resonance.[3]
(1)The velocity at the primary resonance where the DLF becomes the maximum is given by Eq.(4) using the speed parameter. Peaks of DLF also appear at one-half, one-third and so on of the primary resonant velocity.

$$\alpha = L_v \sqrt{1-\zeta^2} / (2L_b) \quad \dots (4)$$

(2)The value of DLF as shown in Figs.5 and 6 is governed by Lb/Lv, and influenced by ζ, L_f/L_v and N. (L_f:length of distributed load)

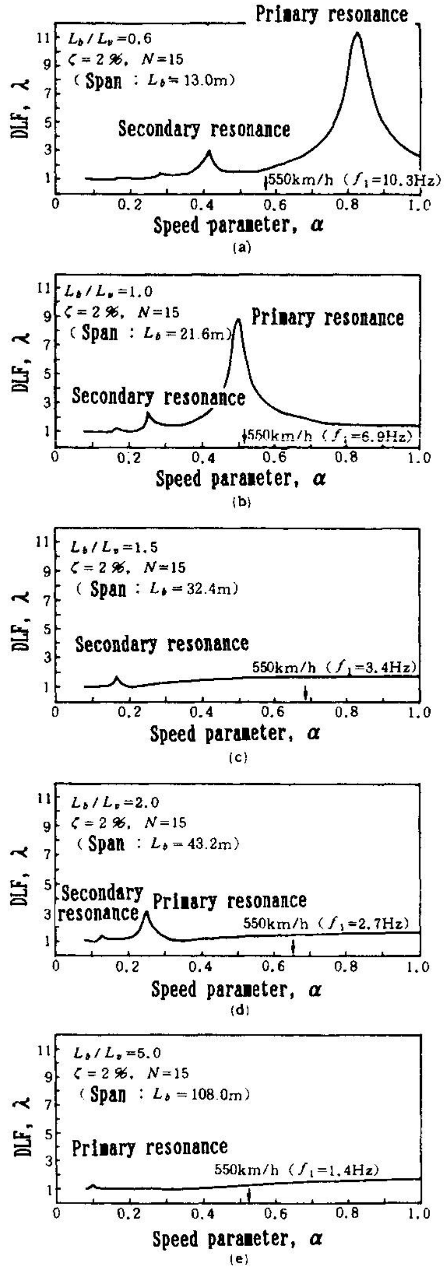


Fig.5 Dynamic response of simply supported beam

(3)When the speed parameter which is determined by Eq.(4) coincides with that of Eq.(5), the resonance does not occur. This is a singularity where no residual vibration is produced in undamped vibration system. The effect of repetition due to sequential loading disappears.

$$\alpha = 1 / (2k+1) \quad (k=1,2,3,\dots) \quad \dots(5) \qquad L_b/L_v = k+0.5 \quad (k=1,2,3,\dots) \quad \dots(6)$$

When the damping ratio is sufficiently small ($\zeta \fallingdotseq 0$), the singularity of disappearing resonance is expressed by the relation between the span and vehicle lengths as Eq.(6). As mentioned above, the dynamic response and resonance of simply supported beam by the sequential distributed load with intervals are clarified. However, the damping ratio has to be studied further to compute the appropriate DLF for the design of structure.

3.2 Dynamic Response of Bridges and Determining Factor in Design

Although the span lengths of bridges which support the TB widely range from approximately 10 to more than 100 meters, the dynamic response and the determining factor for structural design[4] may be classified by the dominant parameter L_b/L_v based on the analysis and the law of resonance as follows. (As for the values of f_1, which are necessary to convert α into the practical velocity, the standard values for bridges on the Shinkansen-line are used as appropriate ones.)

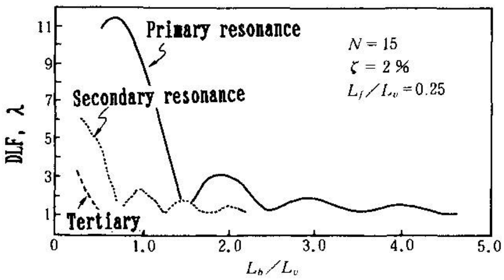


Fig.6 DLF at resonance

(1)When L_b/L_v is 0.6 (see Fig.5), the design impact factor for the assessment of ultimate limit state may be determined by the DLF of secondary resonance which appears at approximately 400 km/h.
(2)When L_b/L_v is 1.0, the primary resonance appears just around 550 km/h. If the fundamental natural frequency of bridge can be shifted higher, the maximum DLF may be avoidable. On the other hand, it can be designed to cover the primary resonance, but, careful assessments of ultimate, serviceability and fatigue limit states are essential in this case.
(3)When L_b/L_v is 1.5, α of the primary resonance coincides with one-third. It is the singularity of disappearing resonance. Only a small peak of secondary resonance is observed. Bridges can be designed by the smallest live load.
(4)When L_b/L_v is 2.0, the velocity at the primary resonance appears much lower than 550 km/h. The design impact factor for the assessment of ultimate limit state has to be determined by the DLF of the primary resonance, but those for the serviceability and fatigue limit states may be determined by the DLF at the service velocity of the train.
(5)When L_b/L_v is 5.0, the influence of the resonance is very small. The DLF becomes almost equal to that of the speed-effect of a single load. The allowable limit of deflection for the train load may become the determining factor in the design.

3.3 Dynamic Response of Twin-Beam

More detailed study on the dynamic response of TB is necessary for the following reasons:
(1)Torsional moment with vertical load acts due to the eccentric loading of vehicle.
(2)As the TB is supported by elastomeric bearings, the dynamic response may change depending on the elasticity of the bearings.

The dynamic response of the beam to the passage of MAGLEV train load (5 vehicles) is computed using a simulation program which can model the structure by 3D-FEM. Only vertical loads are used as the train load in this case.

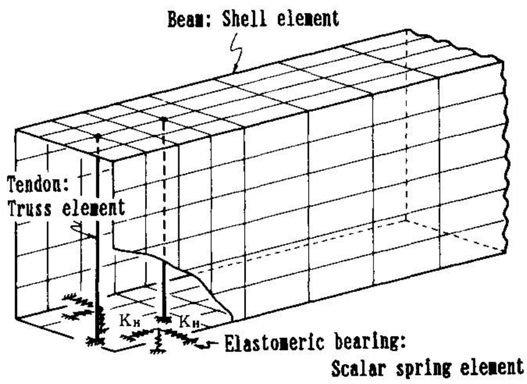
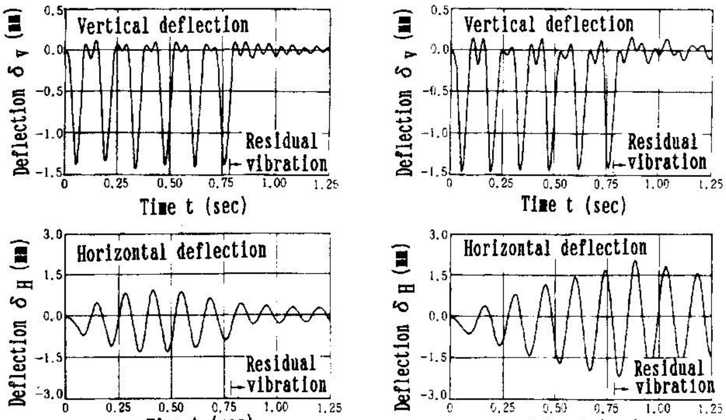


Fig.7 Analytical model of TB

A schematic of analytical model of the TB is shown in Fig.7. The beam is modeled by approximately 600 shell elements. Two cases are treated in the analysis using different spring constants for the elastomeric bearing with and without lead cylinder (K_H=9500tf/m, 2000tf/m, respectively). The response waves of vertical and horizontal deflection of the TB at 550 km/h at the center of span, and the relation between velocity and maximum response values are shown in Figs.8 and 9, respectively.
In the vertical direction, the fundamental natural frequency is approximately 17 Hz. The TB can be assumed to behave as a simply supported beam on rigid foundation judging from the magnitude of deflection. As α at 550 km/h is as small as 0.37, little incremental tendency in DLF is observed.



(a)Elastomeric bearing with lead cylinder

(b)Elastomeric bearing without lead cylinder

Fig.8 Response wave of TB (at center of span: 550 km/h)

In the horizontal direction, quite different responses are observed for the cases with and without the lead cylinder in elastomeric bearing. In the case with lead cylinder, the maximum response at 550 km/h stays approximately at 1.4 mm and convergency of response with respect to the number of vehicles seems stable. The DLF, however, has a slight increasing tendency. In the case without lead cylinder, the response seems to diverge at 550 km/h.

The relation between fundamental natural frequency and spring constant of horizontal direction is shown in Fig.10. K_H needs to be more than 7000 tf/m. When K_H is small and f_1 is less than 8 Hz, a divergency seems to appear.

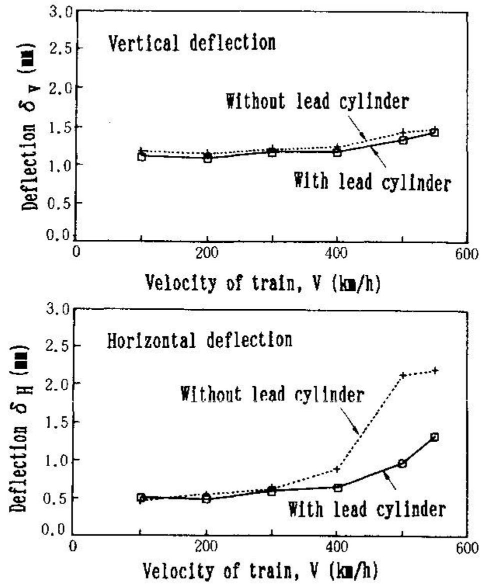


Fig.9 Relation between velocity of vehicle and maximum response

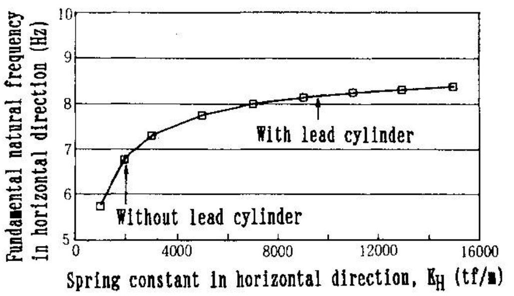


Fig.10 Fundamental natural freq. of TB in the horizontal direction

4. CONCLUSIONS

The knowledge obtained through this study is summarized below.

(1)The Twin-Beam can be manufactured very accurately and utilized as a maintenance-free module-structure with ground coils.

(2)The dynamic response with respect to the velocity of train load and the determining factors for the structural design are clarified for the concrete bridges which support the Twin-Beam.

(3)The analytical study using 3D-FEM reveals that the Twin-Beam has sufficient rigidity in the vertical and horizontal directions and shows stable dynamic response with respect to velocity of train. The premise, however, is that the horizontal spring constant of bearing be made large enough by using the elastomeric bearing with lead cylinder.

5. REFERENCES

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