

6.4. 高速鉄道の走行シミュレーション

神奈川工科大学

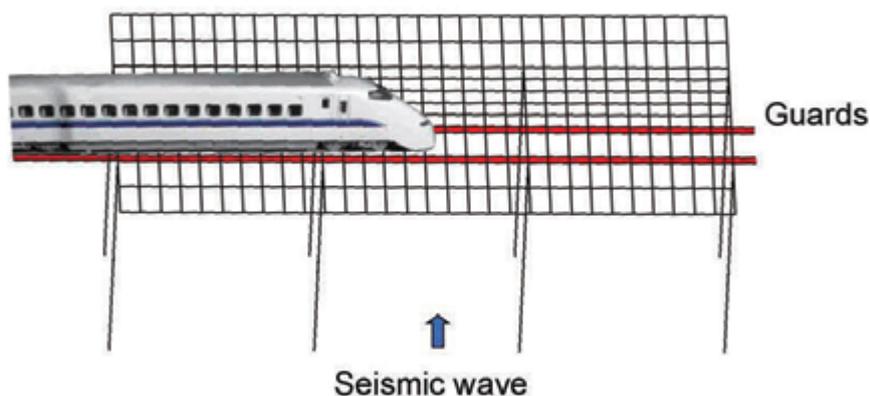
田辺 誠 氏

高速鉄道の走行シミュレーション Simulation of High-speed Railways

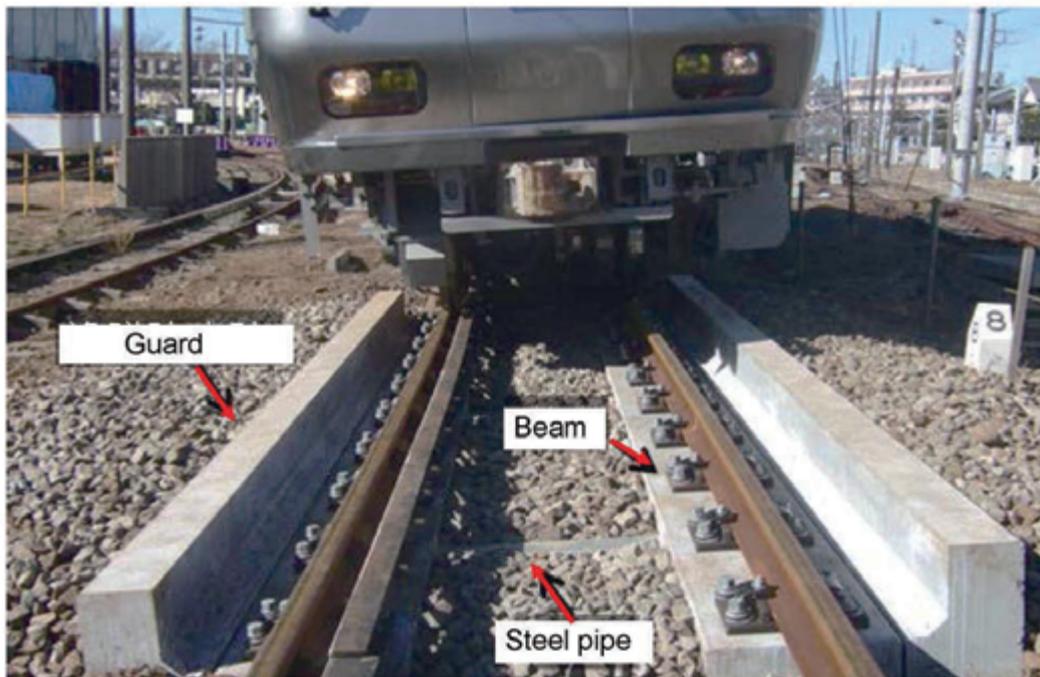
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Dynamic interaction of a high-speed train and railway structure



- The huge impact of wheel on the rail may lead to lifting of wheel, derailment and post-derailment behavior during an earthquake
- Some guards are necessary to prevent the train deviating from the track after derailment for an earthquake-safe railway



Ladder track with guards attached

Multiscale phenomenon of frequency

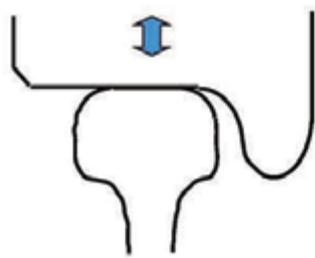
- The high-frequency response (higher than several hundred Hz) due to the impact between wheel and track structure mixed with low-frequency response (less than 20 Hz) of railway structure
- It is very important to solve the dynamic interaction including derailment and post-derailment behavior to design an earthquake-safe high speed railway.

Mechanical model for the train and railway structure

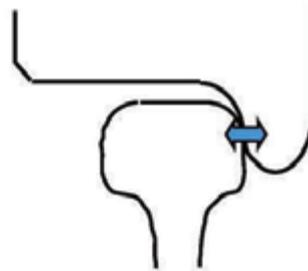
Interaction between wheel and rail before derailment

Contact and impact behavior in the normal direction

- Yawing and rolling of wheel-set are assumed to be relatively small
- Two modes of contact between wheel and rail

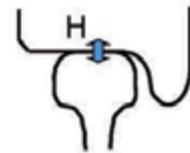


Vertical direction



Transverse direction

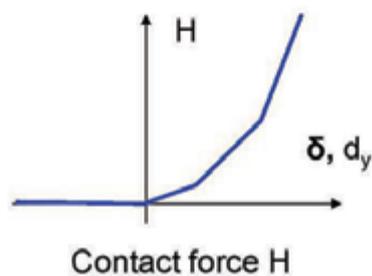
Contact mode in the vertical direction



- Contact force between wheel and rail in the normal direction H

$$H = H(\delta, d_y)$$

- δ = Contact displacement in the normal direction
- d_y = relative displacement between wheel and rail in the transverse direction

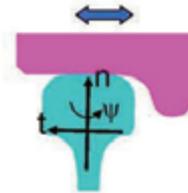


Slipping behavior in the transverse direction

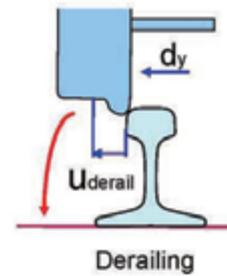
- Constitutive equation between creep force and slipping rates

$$Q_c = Q_c(S_x, S_t, S_\psi)$$

- Q_c = Creep force in the transverse direction
- S_x = Slipping rate in the longitudinal (x) direction
- S_t = Slipping rate in the transverse (t) direction
- S_ψ = Spin rate around the normal vector



- Relative displacement between wheel and rail d_y exceeds the limit U_{derail} the derailing is initiated.



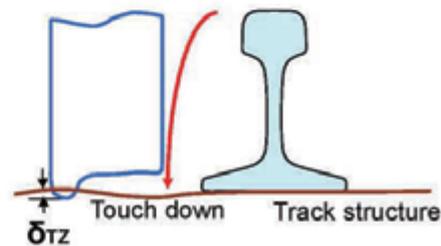
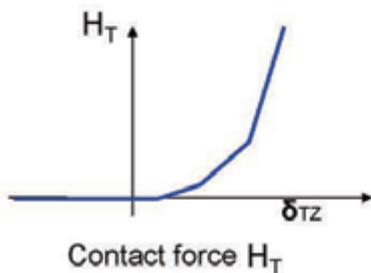
Interaction between wheel and track structure after derailment

Contact-impact behavior between wheel and track in the vertical direction

- Contact force between wheel and track structure H_T

$$H_T = H_T(\delta_{TZ})$$

δ_{TZ} = Contact displacement between wheel and track structure in the vertical direction

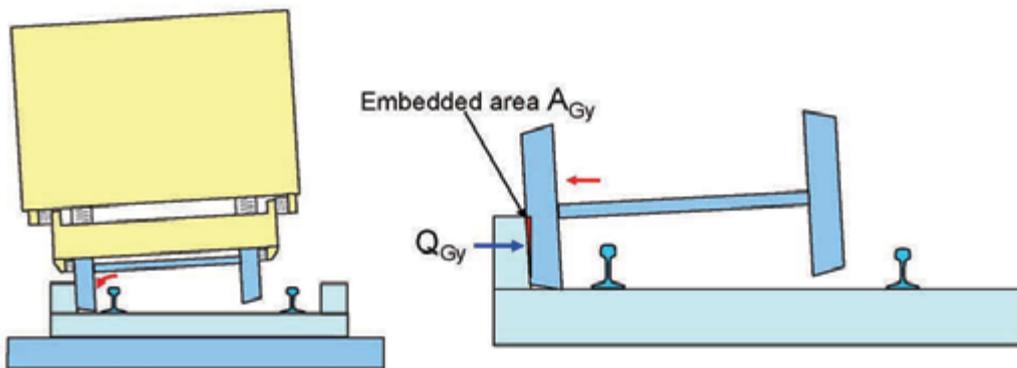


Contact-impact behavior between wheel and guard in the transverse direction

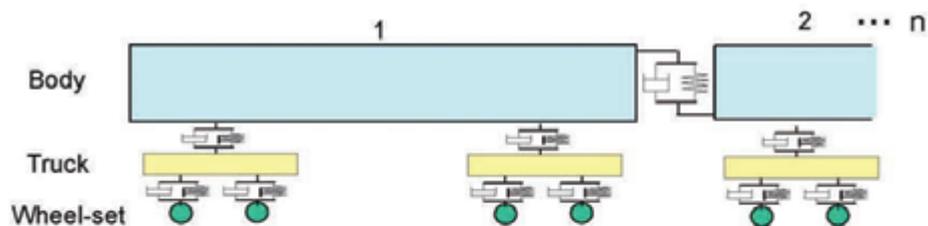
- Impact force Q_{Gy} of wheel on the guard in the transverse direction

$$Q_{Gy} = Q_{Gy} (A_{Gy})$$

A_{Gy} = Embedded area between wheel and guard in the transverse direction



Mechanical model of a Shinkansen train



- Multibody dynamics (MD)
- Each component of the train is assumed to move as a rigid body.
- Components of the train are modeled to be connected by nonlinear springs and dampers.
- The motion of the train is expressed by the DOF's at the center of the components.
- A Shinkansen train with n cars has $31n$ DOF's.

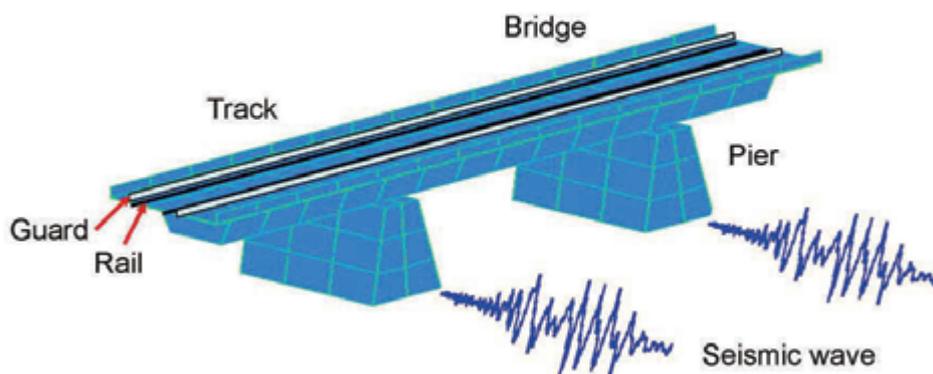
Equation of motion of a Shinkansen train

$$M^v \ddot{X}^v + D^v \dot{X}^v + K^v X^v = F^v$$

- M^v Mass matrix of the train
- D^v Damping matrix of the train
- K^v Stiffness matrix of the train
- X^v Displacement vector of 31n DOF's
- F^v Load vector

Mechanical model of the railway structure

- Modeled with finite elements such as beam, shell, solid and nonlinear spring, and also rail and track elements by MD and FEM



Equation of motion of the railway structure

$$M^b \ddot{X}^b + D^b \dot{X}^b + K^b X^b = F^b$$

Numerical method

- Modal reduction to the equations of motions is applied.
- The equations of motions in the modal coordinates are solved by the Newmark time difference scheme or the exact time integration developed for a very small time increment needed.
- Iterative calculations are made until the norm of unbalanced forces become small enough.
- Adaptive time increments are employed.

DIASTARS

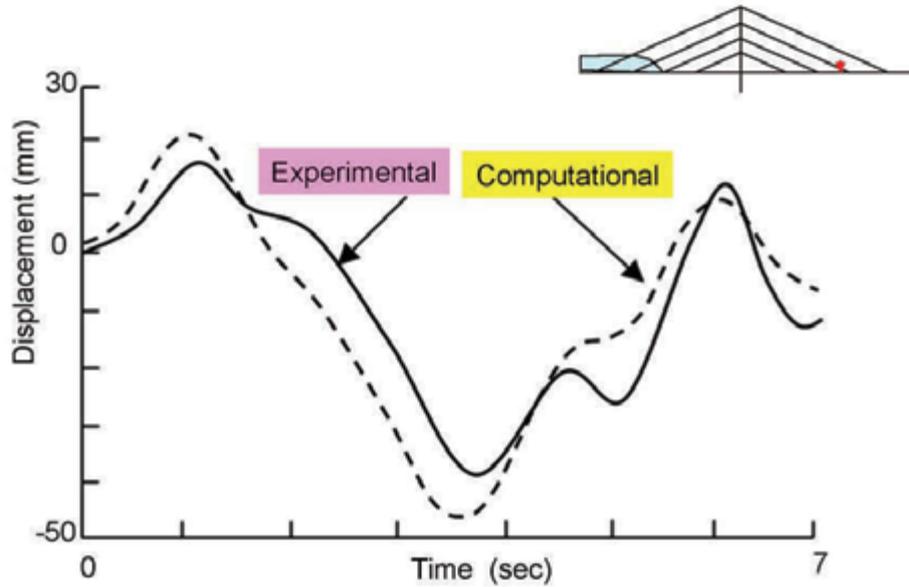
- A computer program DIASTARS for the simulation (numerical experiment) of a high-speed train running on the railway structure during an earthquake has been developed.

Numerical examples



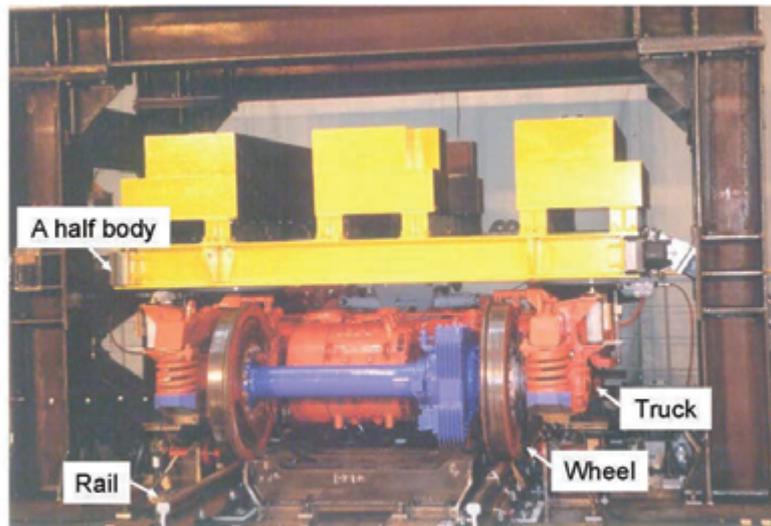
Cable-stayed long-spanned concrete bridge (Length 270m, Height 96m)
Cikuma river, Hokuriku Shinkansen

Comparison between numerical and experimental results



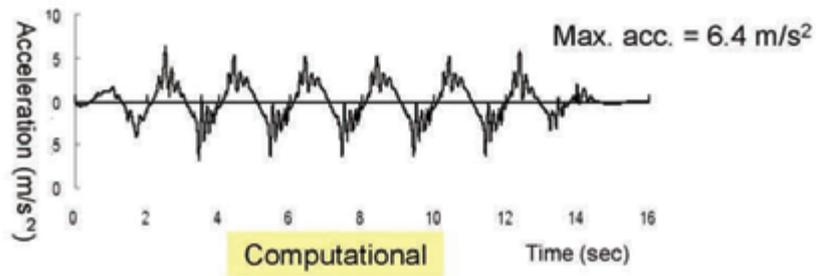
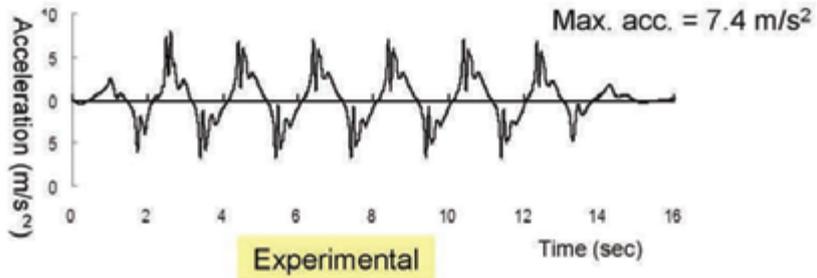
Vertical displacement at 3/5 point of the second span, V=252km/h

Comparison with experiments of a Shinkansen car on the shaking table

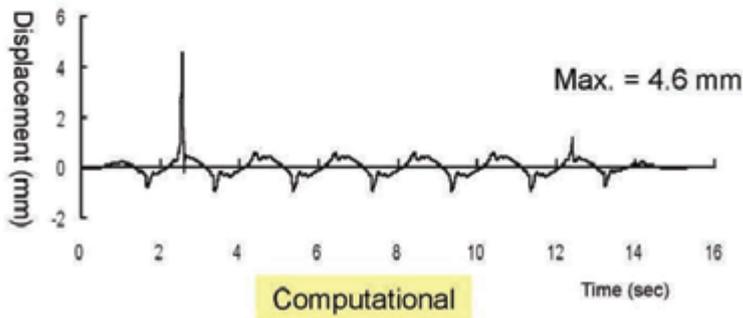
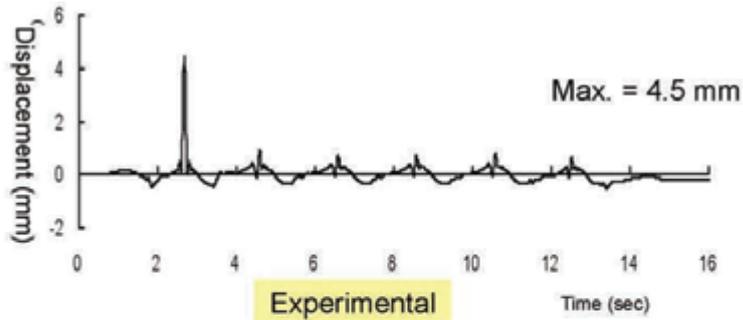


- Experiment using a half Shinkansen car on a large-scale shaking table (50 tonf)
- A sinusoidal acceleration in the transverse direction
frequency = 0.5Hz, amplitude = 2.3 m/s²

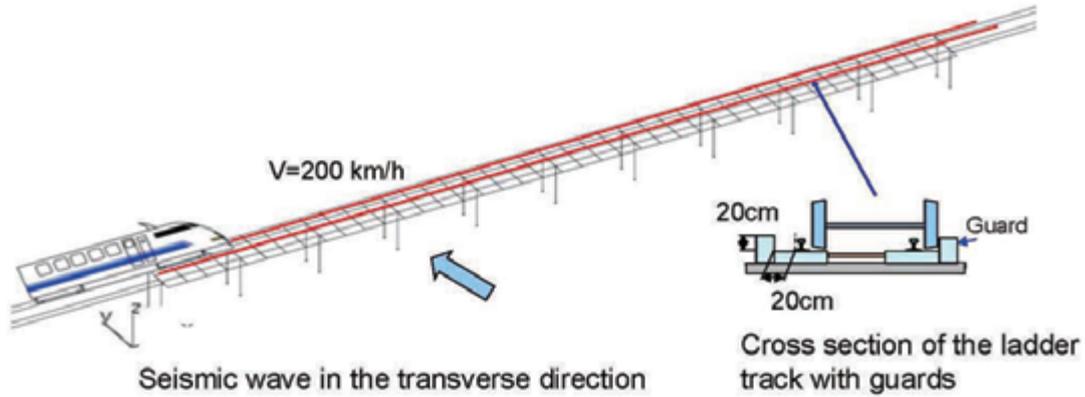
Transverse acceleration of car body



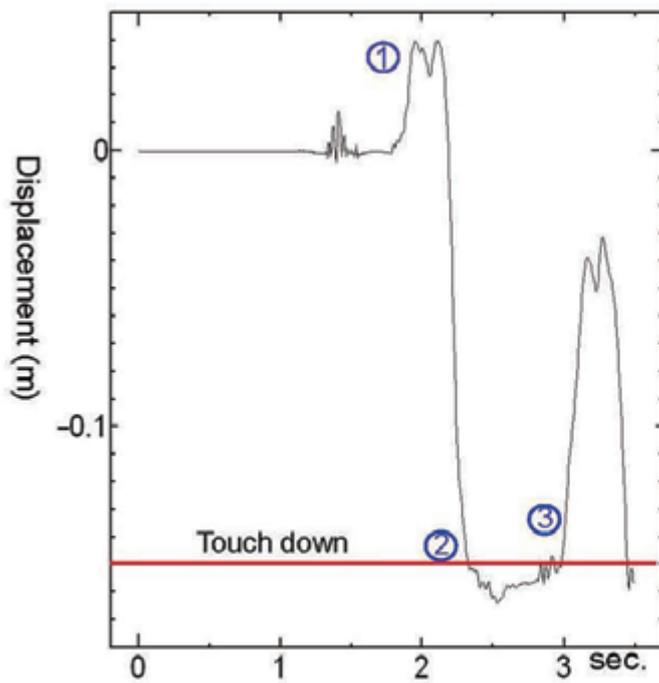
Vertical displacement of right wheel



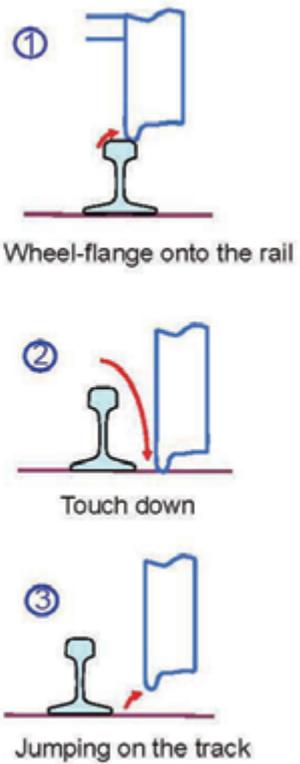
Simulation of a Shinkansen car on the ladder track with guards attached on a 10 spanned viaduct under a sinusoidal seismic wave

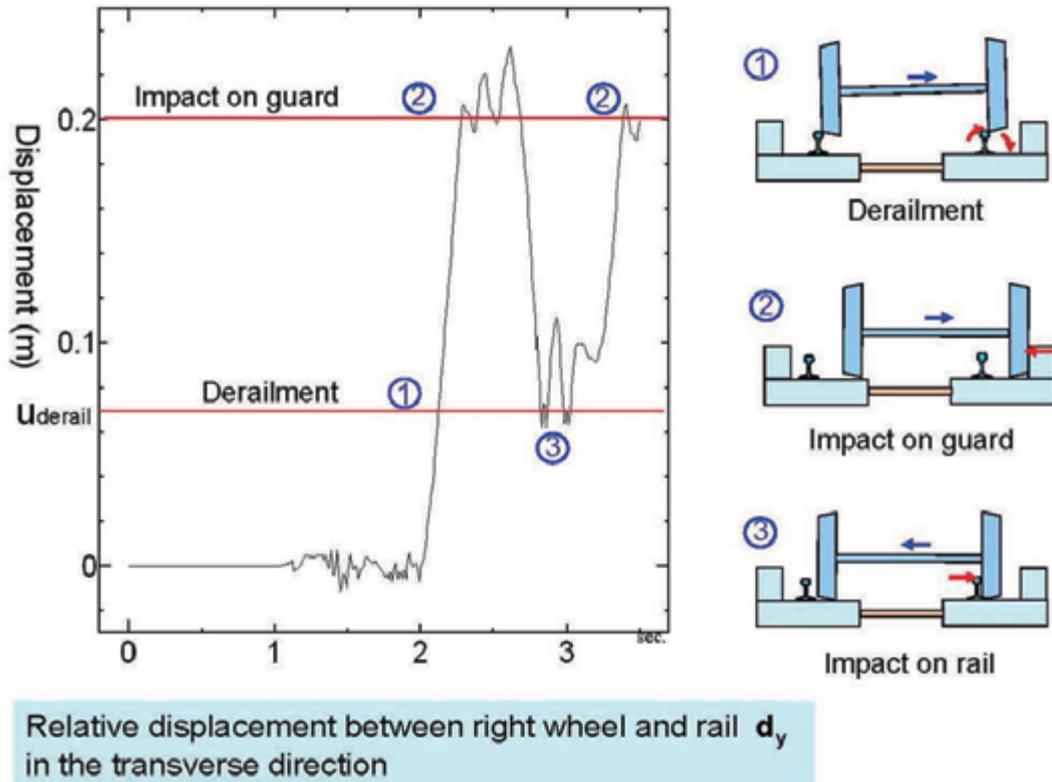


Frequency = 1Hz
 Max. accel. = 4.8 m/sec²
 Waves = 3

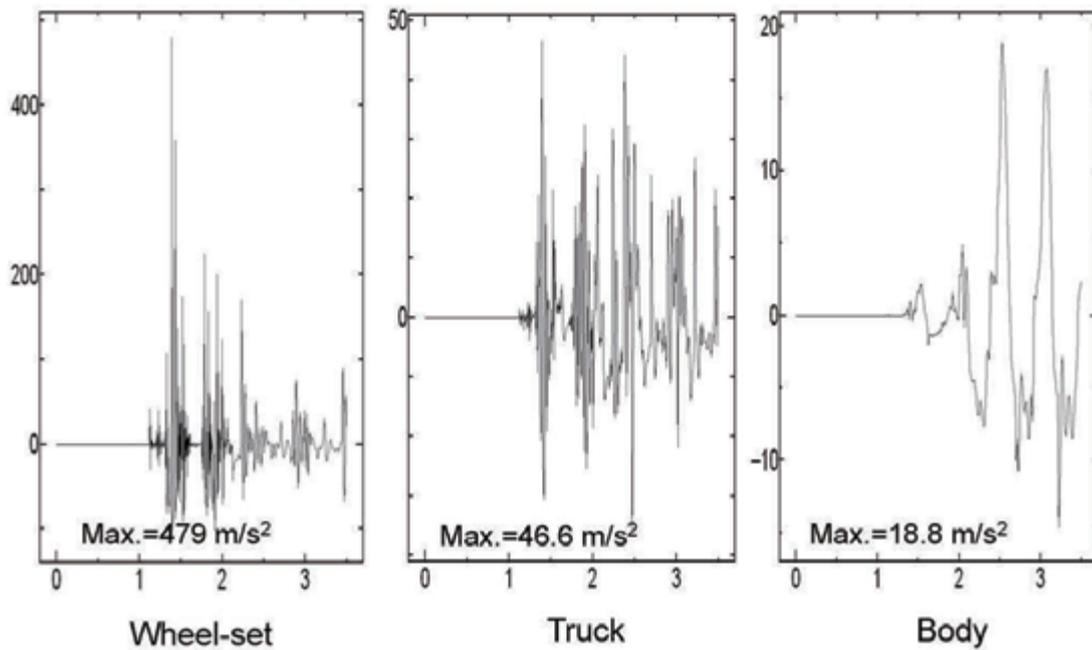


Vertical displacement of right wheel





Acceleration in transverse direction



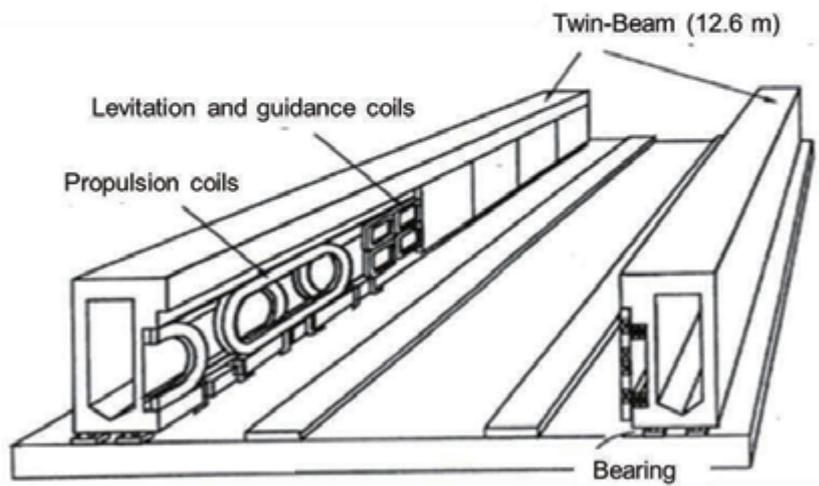
Next generation High-speed railway- MGLEV Train



Superconductive Magnetically Levitated train System

Guideway

- Newly developed Side-wall levitation system using twin-beams
- Due to magnetic forces between SCM (Superconducting Magnet) and ground coils on twin-beam, the train has forces for levitation, guidance and propulsion.

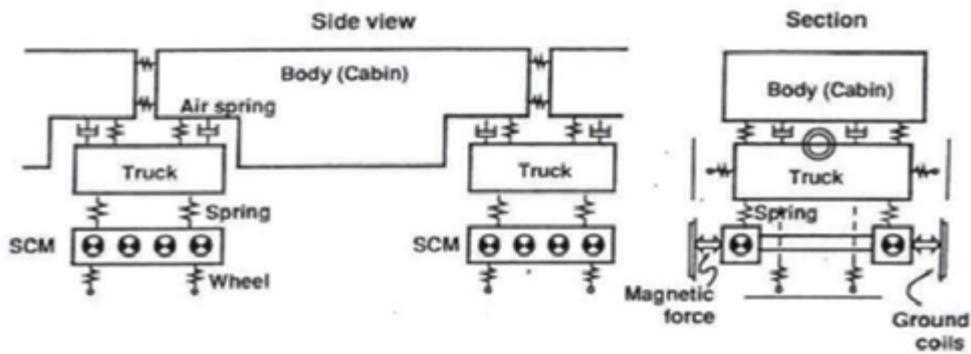


Twin beam guideway structure

Mechanical model of a Maglev train

Components of Maglev train

- Body
- Truck
- SCM
- Wheels under truck in vertical and transverse directions



DIAMAGS - A computer program for the dynamic interaction analysis of a Maglev train and the guideway structure

- Simulation of a Maglev train running on the guideway at the speed of 550km/h has been made to design the railway system



Yamanashi Maglev Test Line (42.8 km)

Visualization of the simulation results for Shinkansen train and Maglev train

Concluding remarks and lessons from experiences

- Basic ideas of the mechanical model and numerical method to solve for the dynamic interaction between a high-speed train and railway structure effectively were discussed.
- Based on the methods the simulation programs have been developed.
- Some examples of numerical experiments were demonstrated.
- Research works have values when implemented in the software and used for the design of various products in industries and society.

Numerical experiments would be effective in designing safe and comfortable high-speed railways requested as the third approach after the experimental and theoretical approaches people have created.

質疑応答

質問者① JAXA 環境試験技術ユニット 村田様

ご講演の中に、新幹線の場合と MAGLEV の場合の事例が出ていたが、地震が起きた時、MAGLEV に電磁力が関与することにより、レールの場合のシミュレーションと比較して何か難しくなったり変わったりすることはあるのか。

発表者

ガイドウェイそのものは地上にあるため、基本的な違いはない。地震波は地盤から入ってくるため、新幹線の場合は橋梁の下部に地震波を与えている。MAGLEV の場合も同様であり、ガイドウェイの下部に入力波を与えてモデル化している。磁力は単に内部のインタラクションの問題であり、運動方程式の中で力として作用している。地震が入った場合にはガイドウェイが揺れることによって、その動きが磁力を通して車体に伝わりそれがまた戻ってくるという非常に複雑な現象が起こっているが、それも今のやり方ですでに数値実験を行っている。

質問者② JAXA 山本理事

新幹線のコンピュータシミュレーションと実際の実験との比較で、モデルの垂直方向変位を表すチャートがあったが、その中で特に上にジャンプしているという波形が時間的に 3 秒くらいのところに立っていた。これは何かある要素・条件を与えたから 3 秒にピークが立つのであって、違う条件を与えると違うところにピークが立つという現象なのか。

発表者

P.20 のシミュレーション結果では、振動数が 1Hz の波を 3 波加えている。ジャンプはその波によってリフティングが起こっていることを示している。ジャンプは第 2 波目位の位置で発生しており、第 1 波目は耐えたが、第 2 波目で脱線して脱線後の運動に入ったということが読み取れる。P.18 でも同様であり、振動台で 0.5Hz で加振していた際、何波か加振しているタイミングで共振現象が起こってリフティングしたということを表している。周波数が変わればピークの応答も変化する。

質問者

一般的な鉄道車両の色々な試験のやり方というのはコンピュータ的な試験に傾斜しているのか、やはりコンピュータもあれば通常の実験も同じような割合で実施されているのか。鉄道と宇宙の比較の意味で、鉄道の世界は徹底的にコンピュータの方にシフトしているというような実態があれば興味深いと思い、質問させて頂いた。

発表者

やはり基本は実際の試験だと考えている。現在も試験は非常に重要であるが、頻度は減っている。ほとんど数値的に処理しておいて、数値実験の怖い点であるデータ間違い等が無いことを確認するために最後は試験を行う、これが私は重要だと考える。新幹線でも基本は実際の試験が中心であった。特に大掛かりな試験は上越新幹線での例で、レールに不整を与えて何回も走行させたり、その他色々な回転を与えたりする試験などを行っていた。これらを経て現在は数値的に解けるものは積極的に行い、それを確認する作業を実地試験で行っている。北陸新幹線も今年三月に開業したが、数値計算の後実際に測定をし、合っているかどうかを必ず **validation** している。これら両方、特にできるだけ試験をやったほうが良いと私は考えている。