SOIL VIBRATION ANALISYS DUE TO THE RAIL BOGIE MOTION

M. Bruner [2], M. F. Crisi[1], G. D'Ovidio[1], G. Valente [1]
Faculty of Engineering, University of L'Aquila, Italy [1]– Faculty of Engineering, University of Rome "la Sapienza", Italy [2]

Abstract: This paper presents a numerical method for analyzing dynamic soil-vibration due to rail transit. The methodology uses two 3D models; the first one is a "rail bogie-track" model rigid body based, which instantaneously provides the loads in the rail-sleeper connections created by the transit. The rail beam is discretized into a number of rigid bodies connected each other by beam elements, and linear springs, connected to the ground and depending on the mechanical characteristics of underground structures and soil. The strengths are the input for the second finite element model which evaluates "soil-structure" interaction to determinate the structural vibrations. The numerical results are performed by modelling a rail bogie of real convoy that transits on section track. The dynamic characterization is developed in frequency and time domains.

Keywords: SOIL-STRUCTURE INTERACTION, RAIL MODEL, DINAMIC ANALISYS, FORCE, LOAD, STRENGTH.

1. Introduction

The vibration caused by the rail traffic represents a significant form of pollution, often resulting in damage to buildings and monuments [3]. The prevention of damage from vibrations and/or earthquakes damage requires a technical approach which becomes more complex with the increasing cultural value [4] of the affected buildings and monuments and the expected time of conservation.

For these reasons we propose a numerical method for modeling the components of rail track strictly connected to the dynamic analysis of the soil-structure interaction produced by external action due to the transit of trains. It is assumed that the convoy is a source of moldable noise, within known ranges that vary with running conditions, loads and amount of wear in the wheel-rail contact.

We analyze the full system (vehicle, guideway, soil and structure) by using two different code model based on rigid body and finite element (FE) analysis respectively; the results of the former are used as input for the latter. We perform a time and frequency domain analysis, based on the use of three dimensional models. The methodology entails the use of two, 3D models linked functionally.

Our methodology, applicable to any ground-building interaction, allows dynamic identification and hence a numerical and experimental comparison of structural behavior in the frequency domain to determine elasticity modules, and damping coefficients in the time domain.

2. Analysis method

The proposed methodology uses two three-dimensional models functionally connected and comparable with experimental data.

The first model, a "wagons-track" model rigid body based, instantaneously provides the forces history in the rail-sleeper connections created by the transit of wagons/trains, which vary according to rail operational features. These forces are the input for the second model "soil-structure" FE based which perform the evaluation of the structural vibrations.

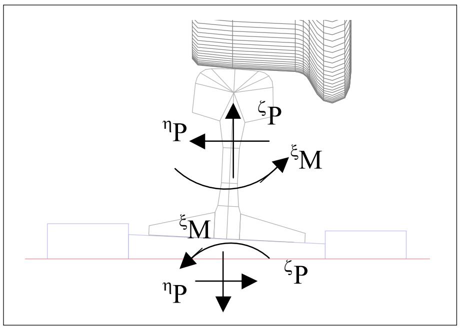

Fig. 1 *Mesh of the S1002 wheel and UNI60 rail and exchanged forces*

Our method is based on the multi-body dynamic analysis of the wagons-track model instantaneously provides at rail-sleeper connections the four force components (ξP, ηP, ζP, ξM) due to the transit of a given convoy traveling along a rail section. In particular, the moment ξM transmitted between rail and sleeper is twisting for rail and bending for sleeper.

As shown in Fig. 1, the same forces are then transferred into the corresponding nodes of sleepers of "soil-structure" model and act as input for the analysis of the structural vibrations of the constructions (buildings, monuments, etc.) included in the same model.

As a result, the analysis provides the values of the spatial components (X, Y, Z) for the kinematic characteristics s(t), v(t), a(t) for all the nodes, and the tensors ε(t), σ(t) for all the elements of the second model.

3. Bogie-track models interaction

The three-dimensional "bogie-track" model faithfully reproduces the following system components:

a) a bogie of convoy; as specific case the Fig. 2 shows a model of a conventional railway two wheelset bolster bogie used in the Roma's Metro between 1985 and 1990;

b) the track (with UNI60 rail) connected to wooden sleepers, laid at a distance of 70 cm, (see Fig. 4). Also this type is modeled according the track characteristics of Roma's Metro [1].

The dynamic interaction between the aforementioned components can be used to instantaneously analyze dynamic interaction between the wheel and the track under varying types of operative conditions.

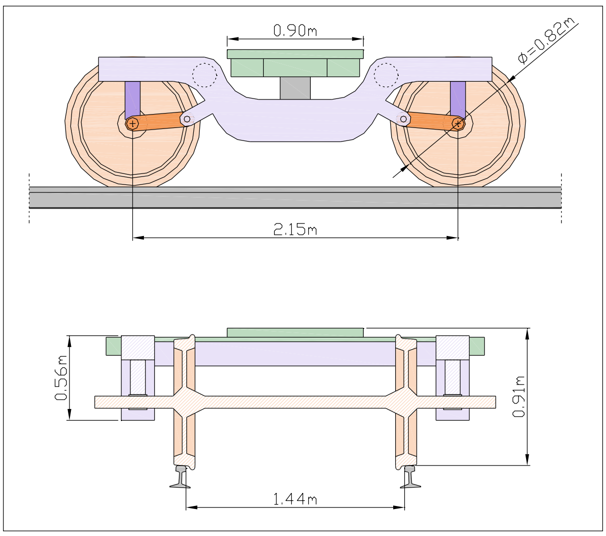

Fig. 2 *Conventional bogie model.*

The parts and loads of the modeled bogie are listed in tab. 1; the mechanical characteristics of suspension are shown in tab. 2.

In the second 3D model, all the involved stiffnesses are taken into account, the ones of the rails, sleepers, ballast, soil and structure.

Table 1: *Bogie parts and vertical loads*

Parts	n.	P [kN]	n·P [kN]
Axle	4	12.87	51.48
Fifth wheel	2	4.84	9.68
Frame	2	5.0	10.0
Engine	2	9.60+4.90	29.0
Ratio axle box	4	22.0	88.0
Actuating arm	4	0.25	1.0
Axle box	8	0.50	4.0
Main shaft	4	0.30+0.73	4.12
Cardanic semishaft	4	0.19+0.21	1.60

Table 2: *Mechanical properties of suspension.*

Suspensions: primary	Stiffness K [N/m]	Damping C [N/(m sec)]	Allowed displ. [mm]
x	3.36×10^5	1.7×10^4	±20
y	3.36×10^5	1.7×10^4	±20
z	7.47×10^5	3.0×10^4	±40
secondary			
x	2.25×10^5	2.33×10^4	±22
y	2.25×10^5	2.33×10^4	±22
z	3.10×10^5	0.635×10^4	-45/+40

4. Beam elements

With reference to the rail track we propose a numerical method for modelling its components strictly connected to already proposed approach focused to the dynamic analysis of the soil-structure interaction produced by external action due to the transit of trains

For each beam element, greater than two for each sleepers span, the local system is defined as follows:

1) the origin O is coincident with the extremity I;

2) the ξ axis starts from I and goes to J;

3) the other two axes (η, ζ) start from O and are principal of inertia for the cross section.

For a generic beam element, and are referring to a local system (ξ, η, ζ), there are:

n. 6 strengths in I (ξF_I, ηF_I, ζF_I, ξM_I, ηM_I, ζM_I), and n. 6 strengths in J of the beam element D=IJ, as Fig. 3 shows;

n. 6 displacement components in I (ξδi, ηδi, ζδi, ξφi, ηφi, ζφi), and n. 6 displacement components in J.

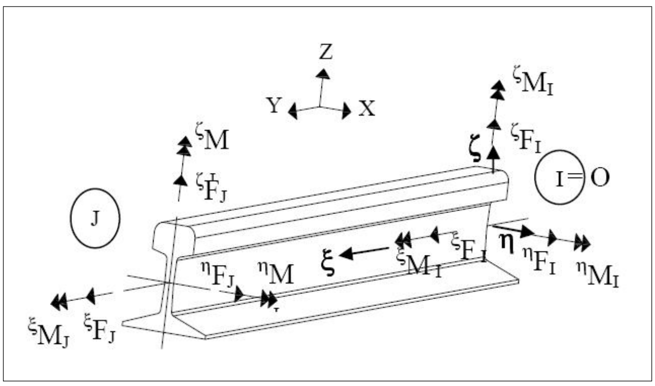

Fig. 3 *Strengths on beam element in the local system (ξ, η, ζ).*

The first model arrives to the rail, and its interaction with the second one is taken into account by means of springs in the connection between rail and sleepers.

The stiffness matrix links linearly the loads in the node J and the relative displacements between the nodes I and J of the beam element D=IJ, in the local system (ξ, η, ζ):

a) ξF_I, ηF_I, and ζF_I are the translational strength components;
b) $\xi\delta_I$, $\eta\delta_I$, and $\zeta\delta_I$ are the translational displacements of the I node with respect to the J node;
c) ξM_I, ηM_I, and ζM_I are the bending and twisting strengths;
d) $\xi\varphi_I$, $\eta\varphi_I$, and $\zeta\varphi_I$ are the relative rotational displacements of the I node with respect to the J node;

Note that the matrix K_{ij}, is symmetric, ($K_{ij}=K_{ji}$).
The code defines each K_{ij} according to the following eight relationships:

$$K_{11} = E\,A / L \quad (4.1)$$
$$K_{22}= 12\,E\,I_\zeta /[L^3\,(1+P_\eta)] \quad (4.2)$$
$$K_{26} = -6\,E\,I_\eta /[L^2\,(1+P_\eta)] \quad (4.3)$$
$$K_{33} = 12\,E\,I_\eta /[L^3\,(1+P_\zeta)] \quad (4.4)$$
$$K_{35} = 6\,E\,I_\eta /[L^2\,(1+P_\zeta)] \quad (4.5)$$
$$K_{44} = G\,K_\xi / L \quad (4.6)$$
$$K_{55} = (4+ P_\zeta)\,E\,I_\eta /[L\,(1+ P_\zeta)] \quad (4.7)$$
$$K_{66} = (4+P_\eta)\,E\,I_\zeta /[L\,(1+ P_\eta)] \quad (4.8)$$

Where:

- E = Young's modulus of the material;
- A = area of the beam cross section;
- L = length of the beam along the ξ-axis;
- I_η , I_η inertia moments of the cross section;
- K_ξ torsional constant of the cross section;
- $P_\eta = 12\,E\,I_\zeta\,\chi_\eta /(G\,A\,L^2)$;
- $P_\zeta = 12\,E\,I_\eta\,\chi_\zeta /(G\,A\,L^2)$;
- χ_η = Timoshenko shear factor in the η direction [2];
- χ_ζ = Timoshenko shear factor in the ζ direction [2].

5. Dynamic interaction

For each crossing joint between rail and sleepers, an elastic linear constraint is introduced in three directions (ξ, η, ζ); the constant coefficients are derived from the analysis of the first model, and are calculated as the ratio between applied forces and the corresponding displacements.

The above four concentrated force components are applied on the sleepers at the connections joint with the rail; the corresponding four displacement components are obtained by the FE analysis. The linear stiffness coefficients are obtained by the four corresponding ratios between forces and displacements.

Consequently, in correspondence of each connection between sleepers and rail of the first model, the four springs values are introduced.

The evaluation of springs constants of rail model are obtained by numerical analysis performed by using the 3D FE model that faithfully reproduces the study area with structure (buildings, monuments etc), rail track (sleepers, ballast, etc) and soil stratification with different Young module values

The springs stiffnesses are evaluated by numerical analysis alone, it is performed on the second 3D FE soil-structure model [6, 7, 8, 9, 10, 11]. It faithfully must reproduce the study area with structure (buildings, monuments etc), rail track (sleepers, ballast, etc) and soil stratification with different Young modulus values.

These four spring values are consequently introduced in correspondence of each crossing joint between rail and sleeper, referring to the local system (ξ, η, ζ).

The displacements δ_X, δ_Y, δ_Z , φ_X are obtained by applying concentrated forces P_X, P_Y, P_Z , M_X on the crossing joints between sleepers and rail, in the absolute referring system XYZ, as in Figure 4. The linear stiffness coefficients are obtained by the following ratios:

$$k_{XX}=P_X/\delta_X \quad (5.1)$$
$$k_{YY}=P_Y/\delta_Y \quad (5.2)$$
$$k_{ZZ}=P_Z/\delta_Z \quad (5.3)$$
$$k_{\varphi X} =M_X/ \varphi_X \quad (5.4)$$

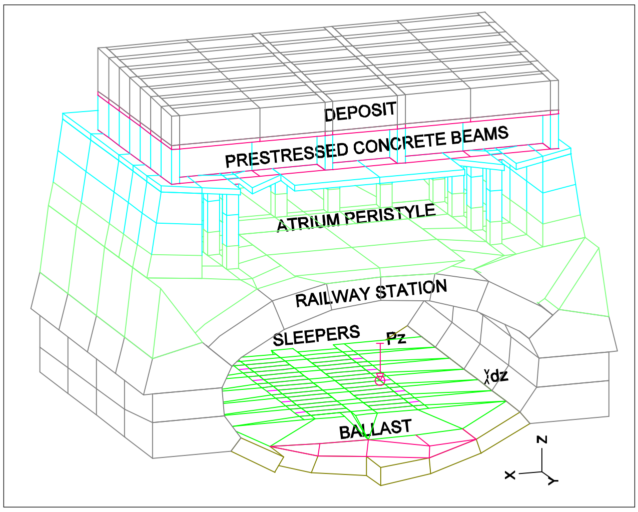

Fig. 4 *Section in the station, load P_Z and its displacement dz*

Our method is based on the dynamic analysis of the soil-structure interaction produced by external action, in this case, the transit of bogie. It is assumed that the bogie transit is a source of moldable noise, within known ranges that vary with running conditions, loads and amount of wear in the wheel-rail contact.

The interaction with the second model is analyzed using a first model that reproduced the technical and performance characteristics of the wheel and the track laid on wooden sleepers, at a distance of 70 cm. The sleepers are modelled as wood made, with dimensions 2.60 x 0.24 x 0.14 m, the rail-sleeper connections are shown in the figures 1. In the study case above mentioned, the spring constants under the rails are defined as:

- k_{XX}= 1.4e+6 kg/cm (5.5)
- k_{YY}= 0.8e+6 kg/cm (5.6)
- k_{ZZ}= 0.7e+6 kg/cm (5.7)

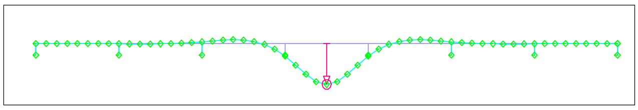

Fig. 5 *Elastic deformations of the beam and its supports.*

Fig. 5 shows the elastic supports and beam deformations due to a generic concentrated load.

6. Dynamic analysis results

The multi-body dynamic analysis of the bogie-track model instantaneously provides the four components of forces [ξP(t), ηP(t), ζP(t), ξM(t)] from the transit of wagon traveling along a given stretch of rail, in relation to the load and running; the transit of the four wheels is shown in Fig. 6;

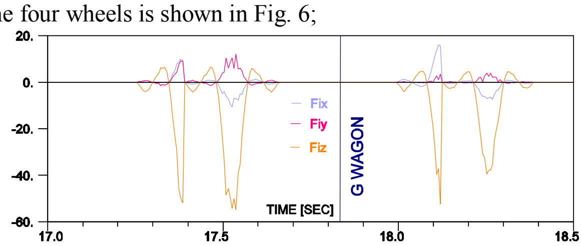

Fig 6. *Typical Force ζP(t) in the connection rail-sleeper, $|\zeta P|_{MAX}$= 40÷57 kN.*

These forces are extracted for the nodes situated at the (i-th) rail-sleeper connections (i=1, .. , n).

The same forces [ξP(t), ηP(t), ζP(t), ξM(t)], changed in sign, are then transferred into the corresponding nodes of the "soil-structure" model and act as input for the analysis of its structural vibrations.

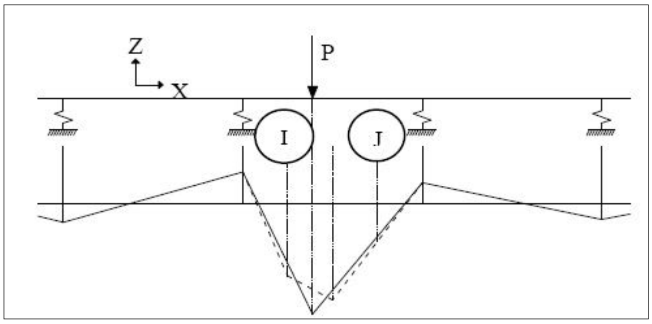

Fig. 7 *Comparison of bending moments: a) real, continuous line; b) code model, dotted line.*

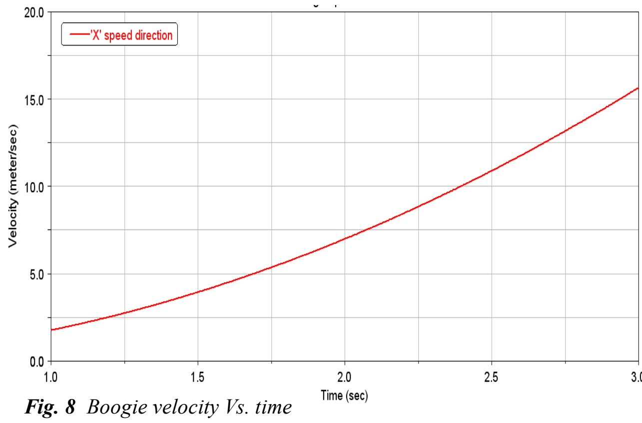

Fig. 8 *Boogie velocity Vs. time*

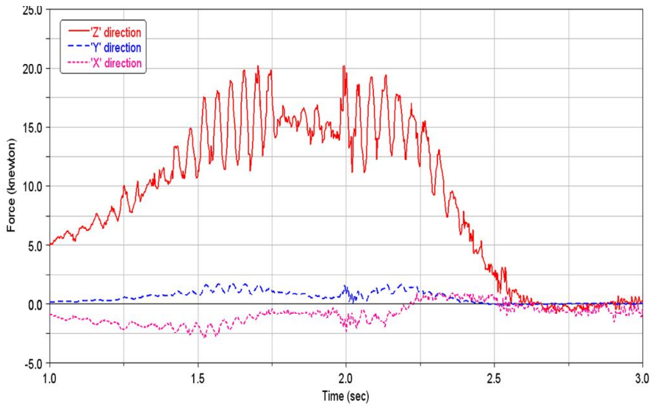

Fig. 9 *Reaction force components on beam spring Vs. time*

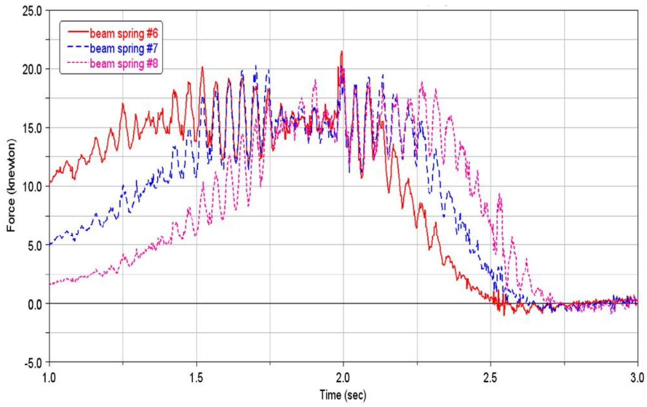

Fig. 10 *Vertical reaction force components on 3 beam springs Vs. time*

As a result, the analysis provides the values of the spatial components (X, Y, Z) for the movement characteristics *s(t)*, *v(t)*, *a(t)* for all the nodes, and the tensors ε*(t)*, σ*(t)* for all the elements for both models.

Fig. 7 shows the comparison for bending moment diagrams between the results obtained from real case (continuous line) and from code model one (dotted line) carried out by using a discretization with four beam elements for each span. It is evident that real and numerical results are in a good agreement.

More in detail Fig. 8 illustrates the bogie speed Vs time. In the Fig. 9 are shown the three spatial force components evaluated on one beam spring vs. time. It is evident that vertical (Z direction) Figures 8, 9 and 10 are referred to the bogie transit, the characteristic of which are listed in tables 1 and 2, along a track section modeled according the above force component is prevalent on the other two (X and Y directions) and it is characterized by a significant ripple the amplitude of which is maximum in correspondence of the wheels transit.

Fig. 10 shows the vertical (Z direction) force components evaluated on three springs consequentiality set along Y direction. In this case you can see the effect summation of force reaction on each spring that punctually causes the soil vibration increasing.

7. Conclusion

A numerical method for dynamic analysis of the soil-structure vibration produced by a rail bogie transit is presented. The dynamic characterization is developed in frequency and time domains by varying the system conditions.

The methodology uses numerical models that can refined by experimental data; the output calculation provides weak vibrations affecting soil and buildings, produced by rail traffic.

The obtained results fully demonstrates the method feasibility and the accuracy of dynamic analysis outputs that allow to calculate and predict the characteristics of motion s(t), v(t), a(t) and the tensorial characteristics ε(t) e σ(t) for all nodes the models.

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