ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
Tome XVIII [2020] | Fascicule 2 [May]

ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
ISSN 1584 - 2665 (printed version); ISSN 2601 - 2332 (online); ISSN-L 1584 - 2665

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CONSIDERATIONS ON POSSIBILITIES, CAPABILITIES AND LIMITATIONS IN MODELING OF COMPLEX MECHANICAL STRUCTURES USED IN RAILWAY ELECTRIC TRACTION, IN VIEW OF TESTING THEIR PERFORMANCE CHARACTERISTICS

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Abstract: The paper presents considerations about the development and validation criteria of analytical models designed to testing the performance characteristics of pantograph–catenary suspension assembly. The first part is a synthetic presentation of specific issues and aspects of the modeling by schematizing of the real physical phenomenon in order to express its mathematical form and to obtain the most accurate modeling of complex structures, such as the catenary–pantograph assembly. In the second part, current models and methods used to evaluate the dynamic response due to the typical catenary–pantograph interaction are analyzed and the efficiency of some of the models and methods used with satisfactory results, as well as their specifically limitations for certain cases are discussed. In order to adopt the elaborated analytical model, the final validation requires both theoretical studies and experimental investigations regarding the reaction of the catenary suspension – pantograph system at the action that intervenes in the operating regime of the real system. The final aim of an efficient modeling process should be useful for the development of engineering tools and techniques designed to obtain an optimal functioning of the catenary–pantograph assembly, both from point of view of the energy transfer and the safety in exploitation.
Keywords: pantograph–catenary suspension interaction, modeling, analytical model

1. INTRODUCTION

In general, the theoretical analysis of the response of a structure to the actions to which it is subjected requires the adoption of modeling by schematizing the real physical phenomenon, in order to express it in mathematical form. In order to obtain the most accurate modeling of the real phenomenon in the case of complex structures, such as that of the catenary–pantograph suspension assembly, it is necessary to analyze specific aspects, such as:

- identification of the main and secondary parameters that influence or determine the maintenance of the optimal functioning of the assembly, in terms of energy transfer and safety in operation;
- establishing the calculation scheme, respectively static and loading schemes of the component elements and of the assembly, taking into account the effect of cooperation between the substructures of the catenary suspension and the pantograph;
- the analysis and connections schematization of the kineto–static interactions between the component elements of the ensemble in terms of the degrees of kinematic freedom – displacements and rotations – followed by the establishment of the limitations and restrictions imposed on them from a technological and functional point of view;
- Elaboration of the mathematical model of the assembly behavior and the designed model validation, based on the comparative critical analysis between the theoretical results and those of the experimental researches.

It is worth mentioning, however, that the efficiency of some of the models designed for certain cases under study is limited, being dependent on a number of particular factors such as: the different possibility of access to the information necessary for the practical use of the respective model, the expected accuracy of the results, the accessibility of the resources specific to addressing such problems, etc.

The current trend of research aimed at modeling structures of the type of catenary–pantograph assembly, is that of exclusively computerized management of the dynamic behavior of the system and the orientation of the research purpose towards obtaining applicable results in industrial practice. The use of hard / soft performance components and systems allows these desires to be achieved, so that, based on scenarios developed for different levels of use – for example, certain modular structures work for the simulation models themselves, and others, for information management, can be used, designed and tested parameterized models, capable of simulating the dynamic behavior of the assembly but also providing the information with practical applicability required.

In order to model the complex structures, the current methods used to evaluate the dynamic response, [1], [3], are those formulated matrix – based on the inertial characteristics of rigidity and flexibility of the component elements subjected to different requests – and solved with different software. Most of them are designed with the method of finite elements which, by discretizing the real structure in a series of substructures and elements connected between them, can lead to the replacement of the systems of differential equations solution with systems of linear equations.

The determination of the mathematical model by using the dynamic system concept is presented mainly in the first three horizontal blocks in fig.1, and customized in the following blocks with the specific details of the catenary–pantograph suspension assembly modeling.

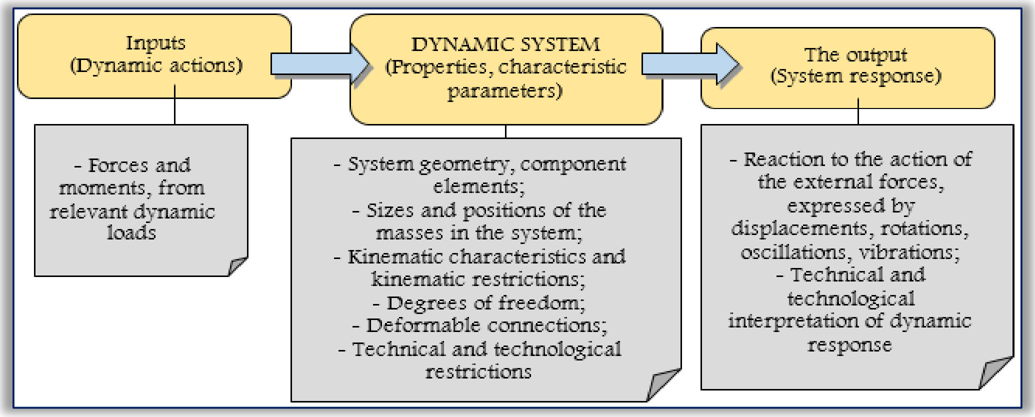


Figure 1. Use of the dynamic system concept in modeling the catenary–pantograph suspension assembly

2. PROBLEM STUDY

≡ Catenary suspension: it can be modeled either by a continuous and finite string of suspended elements at points considered rigid supports, or as a succession of longitudinal frames of flexible elements articulated between them, having fixed vertical supports and from place to place horizontal stiffeners, with the role of ensuring the pickup and transmission of the loads generated by the contact of the catenary with the pantograph's patina.

≡ Pantograph:

» Geometrical model: consisting of a lower and a higher assembly, the lower one having the shape of a frame with variable height and maintaining the current collector pressed on the contact line.

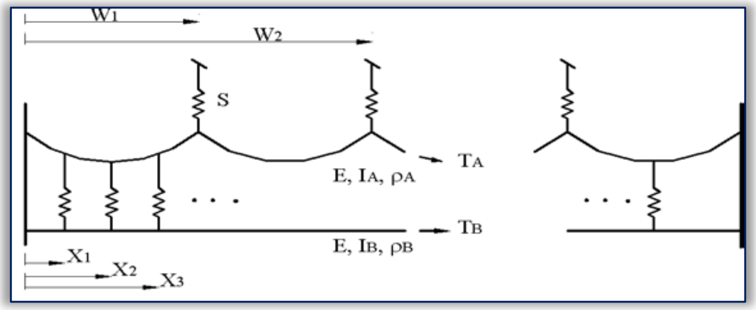
» Physical model: consisting of two masses, the first totalizing the mass of the upper frame elements and the support structure of the current collector and the second, the mass of the lower frame structure.

» The model represented by a moving oscillator along the line, with constant speed: the originality of the model consisting in introducing into calculation the frictional forces between the catenary and the oscillator as well as the possibility of considering the coupled longitudinal–transverse vibrations of the system.

— Catenary–pantograph assembly models

The objectives of the studies undertaken based on the described models of the catenary and the pantograph includes:

» evaluating the effect of catenary structure design and testing the use of materials with a lower cost than of traditional materials that are used;
» examining the effect of the efforts resulting from the catenary bending, on its dynamic performances;
» Analysis of the effect of the defining geometrical parameters and of the inertial characteristics of the pantograph, on the reliability of the entities considered in the study in order to make a set of optimal parameters;
» examining the efficiency of new passive and active pantograph configurations.



S – support stiffness; K - the stiffness of the hinged pendulums; W_j – distance to the j support; X_i - distance to the articulated pendulum i; ρ_A, ρ_B - the density of the two wires; T_A, T_B - mechanical tension in the two wires; EI_A, EI_B - the stiffness module on bending of the two wires
Figure 2. Catenary equivalent mechanical model

The catenary model is developed using modal analysis and includes: the effects of mechanical stresses on wires and deformations from bending, element masses, and stiffness modules on bending, axial deformation rigidity of hinged pendulums and the damping phenomenon of oscillations (fig.2).

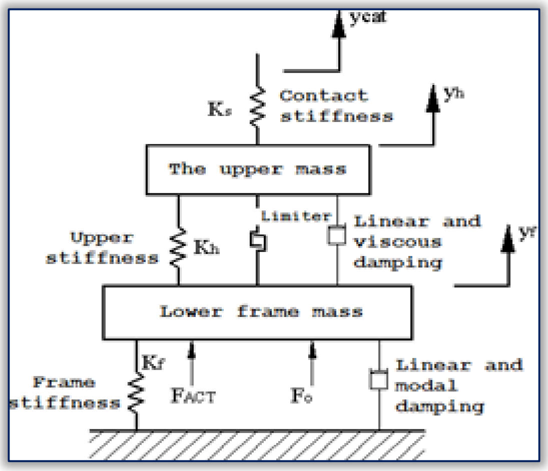


Figure 3. The pantograph equivalent mechanical model, first damping variant

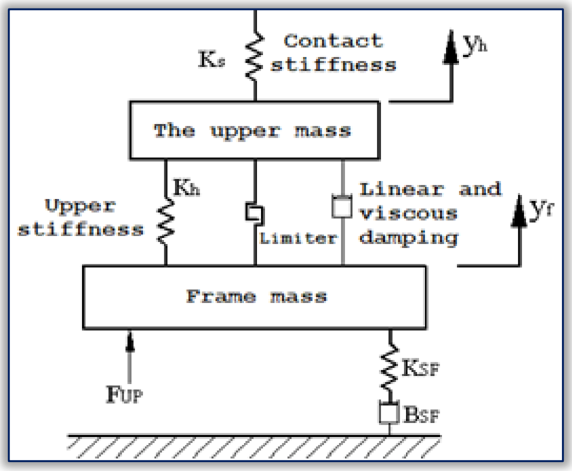


Figure 4. The pantograph equivalent mechanical model, second damping variant

The pantograph model is linear representation type with two masses: one for the skate and another one, for the lower frame (fig.3 şi 4).

The equivalent mechanical model of the pantograph–catenary suspension system is obtained from the coupling of the catenary model with that of the pantograph by the elastic spring K_s, which models the bending rigidity of the skate at the level of contact between the current collector and the contact wire. (fig.5).

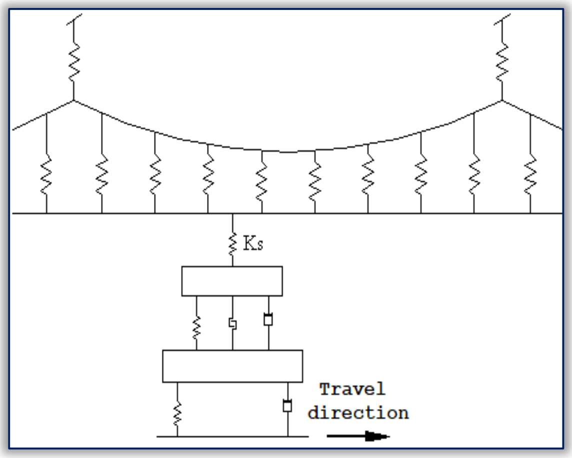


Figure 5. The equivalent mechanical model of the system by coupling the pantograph and catenary model

— Analytical models for testing the performance characteristics of the pantograph

The physical description of the nonlinear analytical model is presented below, for the following variants:

a) *Nonlinear dynamic model* – where the movements of the rigid connection and the absolute movement of the skate are excited by vertical interaction with the catenary;

b) *Static model* – derived from the linear model, where the height of the skate is determined from the equilibrium condition of the loads;
c) *Linear model* – coming from the nonlinear model, to develop the calculation relations of the effective parameters.

≡ **Nonlinear dynamic model**

For the nonlinear analytical model described in Fig. 6, capable of representing a large spectrum of existing pantographs, the degrees of freedom are: θ_1, which defines the angular position of the lower frame connection and y_h, parameter for the absolute position of the head.

The motion equations governing the behavior of the model were obtained in the form of two nonlinear differential equations:

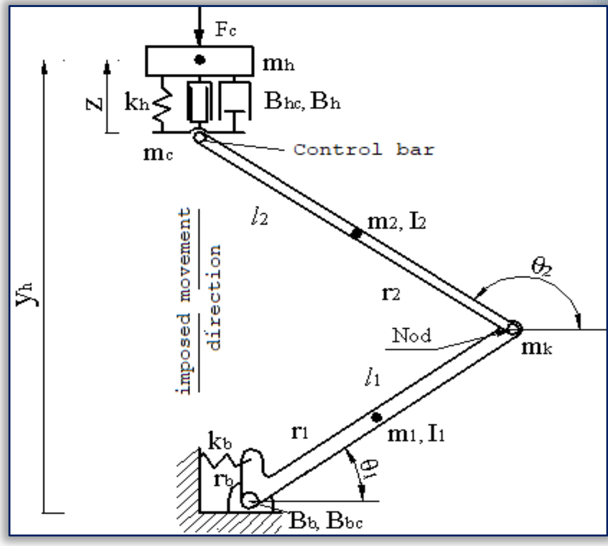


Figure 6. The nonlinear dynamic model of the general pantograph

$$I\ddot{\theta}_1 + C\dot{\theta}_1^2 = Q \tag{1}$$

and

$$m_h\ddot{y}_h + B_h[\dot{y}_h - (l_1\cos\theta_1 - l_1\frac{\sin\theta_1\cos\theta_2}{\sin\theta_2})\dot{\theta}_1] + K_h[y_h - (l_1\sin\theta_1 + l_2\sin\theta_2)] =$$

$$= -F_c - m_h g - B_{hc}\,\mathrm{sgn}[\dot{y}_h - (l_1\cos\theta_1 - l_1\frac{\sin\theta_1\cos\theta_2}{\sin\theta_2})\dot{\theta}_1] \tag{2}$$

where: I – generalized moment of inertia, C – a coefficient of centripetal forces, Q – represents the generalized force.

≡ **Static model**

Static analysis includes gravitational forces acting on all five masses, the horizontal force F_b at the base arc and the force applied for equilibrium, F_c. After algebraic transformations of the relations deduced from the classical static equilibrium conditions, the equation for calculating the force Fc, positioned at the level of the pantograph's shoe to ensure the increase of the uplift force, is:

$$F_c = \frac{F_b r_b \sin(\theta_1+\theta_0) - (m_1 r_1 + m_k l_1) g\cos\theta_1 - m_2 g(l_1\cos\theta_1 - r_2\cos\theta_2\frac{l_1\sin\theta_1}{l_2\sin\theta_2})}{(l_1\cos\theta_1 - l_1\frac{\sin\theta_1\cos\theta_2}{\sin\theta_2})} - m_c g - m_h g \tag{3}$$

where the force in the base arc is determined by the relation:

$$F_b = PRETEN + K_b r_b\cos(\theta_1+\theta_0) \tag{4}$$

≡ **Linear model**

In the literature, most of the models described for the study of pantograph behavior are linear models. Such a model is especially useful in parametric design studies, its validity being verified previously, on a completely nonlinear model. The nonlinear analytical model described in the previous paragraph was linearized to develop the general linear model, presented in fig.7. The linearization was performed in two absolute coordinates: y_h, the position of the shoe mass, and y_c, the vertical height of the frame at the level of the control bar.

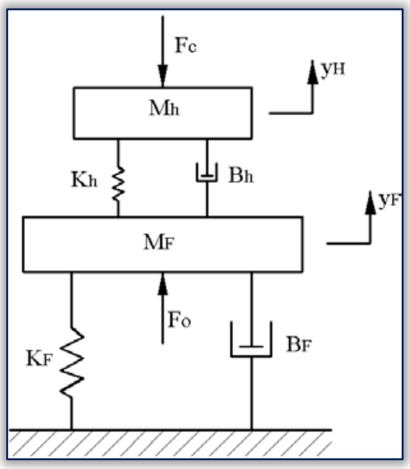
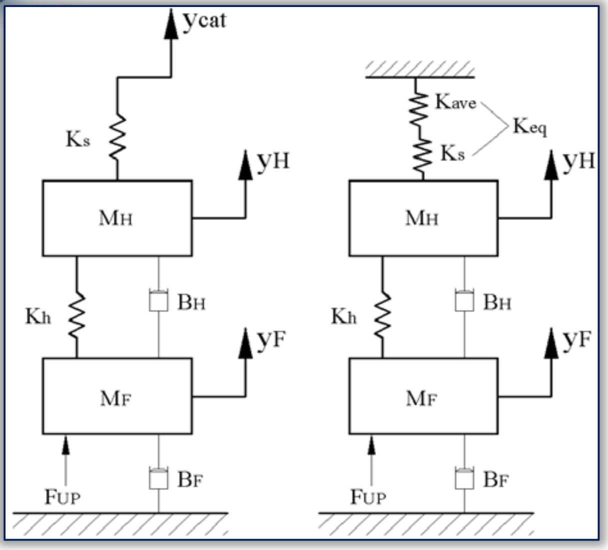


Figure 7. Pantograph linearized model

≡ **Pantograph model with active control**

The basic model used for the active control pantograph, [5], realized in the controller variant with the lower frame control (as it was found that the dynamics of this substructure is largely responsible for most contact losses) is the two–mass model presented in fig. 8a; but, as the height of the wire, y_{cat}, is a size difficult to measure accurately, the catenary modeling was performed by a spring having an elastic constant equal to the average catenary stiffness, k_{ave}, according to the diagram in fig. 8b.



a) Basic model; b) Model adapted to the pantograph with active control

Figure 8. Equivalent mechanical models of the pantograph

3. ANALYSIS. DISCUSSIONS

The main analysis described in references as [2–6], consists in the study of the dynamic behavior of the pantograph model with two masses, similar to the one presented in fig.8. Some of the authors adopt variants of this basic model to analyze special features; for example, in the works mentioned above, the classical linear model in the literature has been modified by including an additional mass to represent the shoe's flexibility, respectively a spring between the frame mass and the vehicle roof to represent the limited stiffness of the frame suspension and its effects on the dynamic behavior of the pantograph.

The values of the used parameters, similar to those used in the linear model study, come from the linearization of the nonlinear model. The comparison between the behavior of the linear model of the pantograph and of the model that includes the effects of nonlinearities is performed on a range of operating heights up to 2m. Although towards the upper limit of the domain, maintaining the frame mass equal to that of the linear model revealed that the simulation results no longer provide a good representation of the pantograph's response, the authors' conclusions are that, for the typical catenary–pantograph interaction, the frequency and amplitude of the disturbances due to the nonlinear effects it is most often located in an area that allows the linear model to be used with satisfactory results.

4. CONCLUSIONS

The essential dependence of the current collector system performance on the problem of the dynamic interaction between the pantograph and the catenary system, justifies the importance of the possibility of predicting the dynamic behavior of the catenary–pantograph suspension assembly in operation.

As a result of the intensification in the last years of the theoretical studies and the experimental investigations undertaken especially by researchers from technologically advanced countries and interested in the railway systems with high speed trains (Sweden, Italy, France, Germany, England, Japan), the mathematical models that were elaborated have proved their relevance by solving, in general, the problems raised by the practice of the current exploitation of the electrification installations in the railway transport..

It is worth mentioning, however, that the efficiency of some of the models designed for certain cases under study is limited, being dependent on a number of particular factors such as: the different possibility of access to the information needed for the practical use of the respective model, the expected accuracy of the results, the accessibility of the resources specific to addressing such problems, etc.

The current trend of research aimed at modeling structures of the type of catenary–pantograph assembly, is that of exclusively computerized management of the dynamic behavior of the system and the orientation of the research purpose towards obtaining results applicable in industrial practice. The use of high–performance hard / soft components and systems allows these desires to be achieved, so that, based on scenarios developed for different levels of use – for example, some modular structures work for the simulation models themselves, and others for information management can be designed, developed and tested parameterized models, capable of simulating the dynamic behavior of the assembly but also providing the information with practical application required.

In order to model the complex structures, the current methods used to evaluate the dynamic response, [1,3,5,10,12], are the ones formulated with matrix – based on the inertial characteristics of stiffness and flexibility of the component elements subjected to different demands – and solved with software. Most of them are designed with the finite elements method which, by discretizing the real structure in a series of substructures and elements connected between them, can lead to the replacement of the systems solutions of differential equations with linear equations systems.

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