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MATHEMATICAL MODELING OF THE RESPONSE OF THE HUMAN LOCOMOTOR SYSTEM SUBJECT TO THE ACTION OF DISTURBING MECHANICAL VIBRATIONS

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ABSTRACT

In this paper, we will follow the configuration and development of a physical model in accordance with the main objectives of the study. The model must be useful in estimating the essential dynamic parameters, specific to the response of a multi-body system under the action of intense and varied external dynamic excitations, such as mechanical vibrations produced by different technical systems, indirect and direct interaction with the locomotor system of the human body. In the first stage, a basic configuration will be considered, which will take into account the functionality of the leg - calf- thigh assembly. In the second stage, the model will be harmonized in accordance with the additional restrictions and demands imposed by the muscular system on the skeletal structure of the modeled assembly. The third stage will consist of the comparative evaluation of the simulated answer, with the data obtained that experimental, in order to validate the conformity of the structure and parameters of the proposed model.

KEYWORDS: whole body vibration, external dynamic excitations, muscular system, validation of numerical results

1. INTRODUCTION

Many researchers have studied the model of the human body under the action of vibrations. For example, the contribution of ankle muscle proprioception to the control of dynamic stability and lower limb kinematics during adaptive locomotion was studied by K.L. Sorensen, M.A. Hollands, and A.E. Patla [1]. Tarabini, M., et al. said ”the human response to vibration is typically studied using linear estimators of the frequency response function, although different literature works evidenced the presence of non-linear effects in whole-body vibration response” and they analyzed the apparent mass of standing subjects using the conditioned response techniques in order to understand the causes of the non-linear behavior [2]. The human body has a non-linear behavior under different vibration conditions that occur while walking [3].

2. METHODS OF CALCULATING

The first stage of modeling is to address the specific movement of the human foot subjected to external actions of a mechanical type, taking into account exclusively its bone system.

The simplified model of the human foot skeleton, in the context of fulfilling the objectives of this study, is presented schematically in Fig. 1, where the parameters have the following meanings, namely: m_1, m_2, m_3 the masses of the three components (respectively thigh, leg, leg), $\varphi_{1,2,3}$ the angles of the three components, evaluated relative to the vertical axis of the coordinate system, F_{ex} the external excitation, applied to the system in a

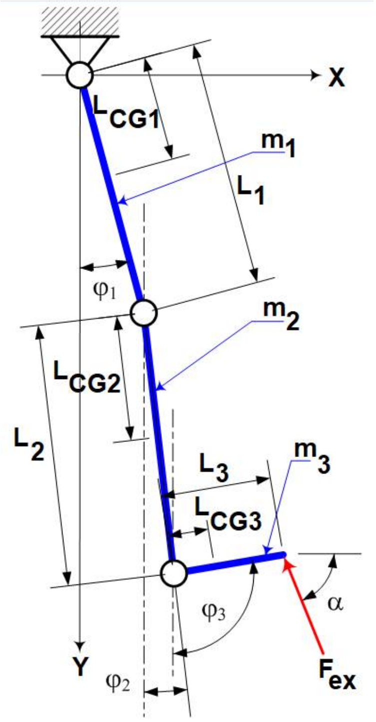


Fig. 1. Diagram of the simplified model for the analysis of the dynamic response of the human foot, subjected to external mechanical actions

direction inclined at an angle α to the horizontal. The hip, the knee, and the leg joint, respectively, were considered, in this first approximation of the model, simple joints of class C5.

The simulations were performed using a single set of characteristic values (corresponding to a single human subject) so that a unitary and relevant comparative analysis of the simulated data with the experimental ones is possible [4].

Although the deviations between the measured and estimated characteristics based on the calculation schemes in the available literature did not exceed 0.56%, the human subject was chosen for the laboratory tests that best corresponded to the theoretically estimated data [5-7]. The actual values used in the simulation on the model in fig. 1 are the following: m_1=7.0kg, m_2=3.25kg, m_3=1.0kg, L_1=0.46m, L_2=0.40m, L_3=0.25m, L_{CG1}=0.22m, L_{CG2}=0.17m, L_{CG3}=0.12m.

The physical model diagrammed in fig. 1, was implemented in a Matlab-Simulink-SimMechanics application, having the structure shown in fig. 2. The final processing of the results was carried out with the help of additional applications developed in the Matlab programming language.

An additional advantage of SimMechanics applications is the possibility to view in real-time the movement of the model implemented in a window specially designed for this purpose - see the image in fig. 3. Under this option, each component element is represented by a series of straight segments that connect the center of gravity and the connection points with the rest of the system.

To evaluate the response of the considered system, the following specific quantities were proposed, namely: kinematic excitation, accelerations of the three components (thigh, leg, sole), and angular variations of the three components, relative to the vertical, considered in the articulation points (hip, knee, and leg joint, respectively) [8, 9].

In fig. 4 the excitation is of kinematic type - imposed harmonic displacement, applied at an angle of 750 to the horizontal direction, having the amplitude of 0.004m and the frequency of

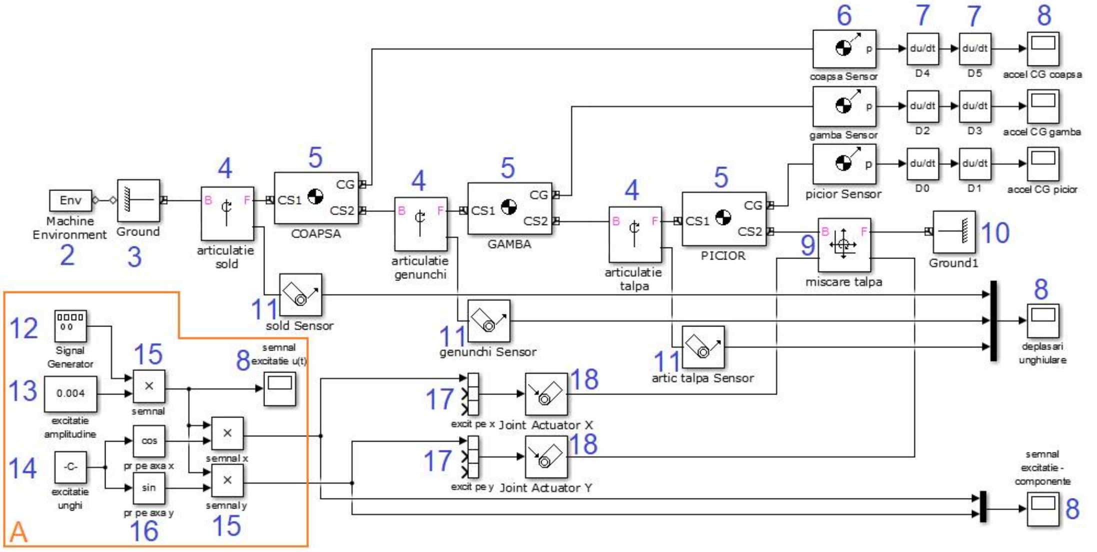


Fig. 2. Working diagram of the Matlab-Simulink application associated with the model in fig. 1

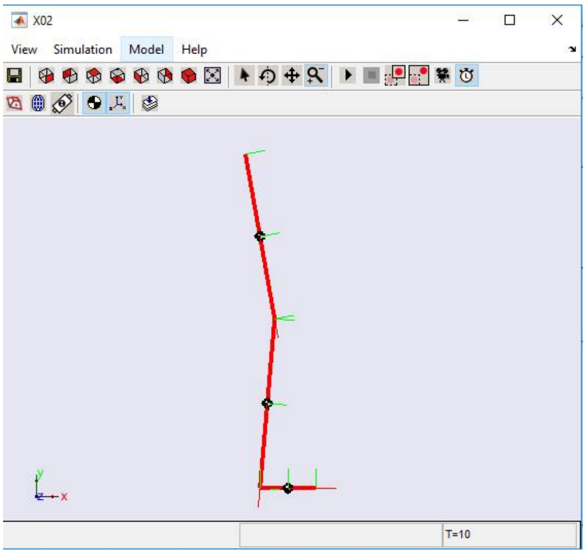
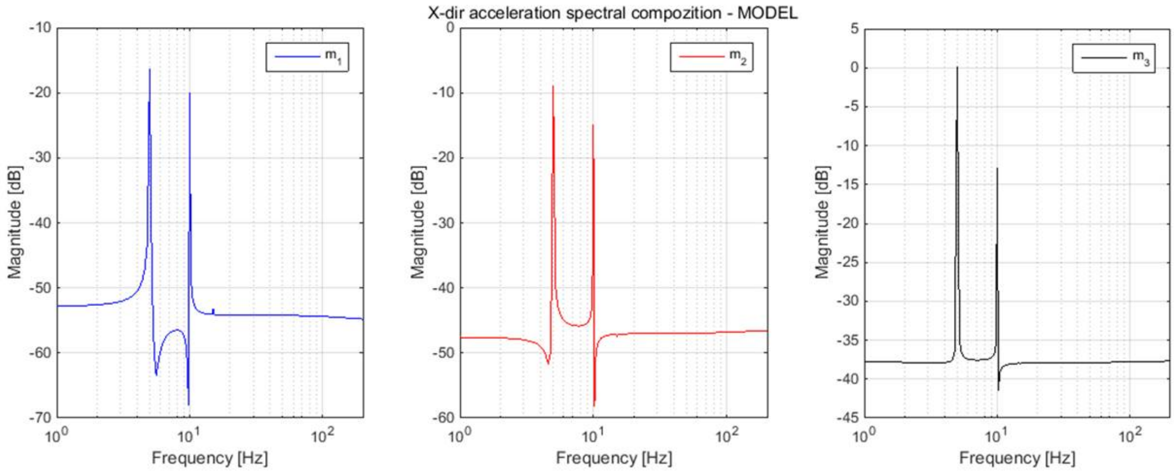


Fig. 3. Matlab-Simulink application window for graphical representation of real-time results (simulation of system dynamics for each step of the calculation algorithm)

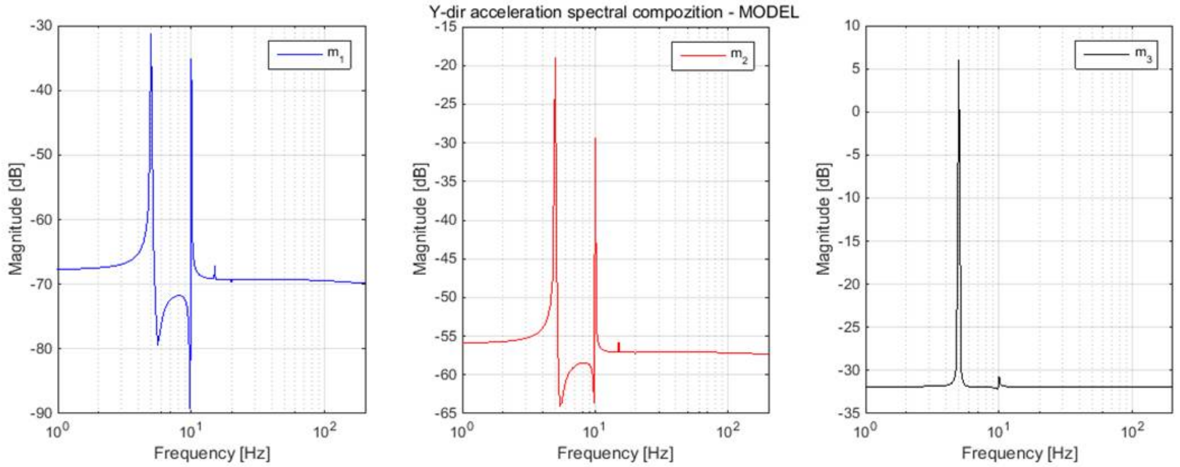
5Hz (which corresponds to a generating source with 300rot/min).

The results obtained, in terms of spectral amplitude as a function of frequency, are presented in fig. 4 - for the horizontal components of the accelerations, in fig. 5 - for the vertical components of the accelerations and, respectively, in fig. 6 - for the variations of the three angular displacements.



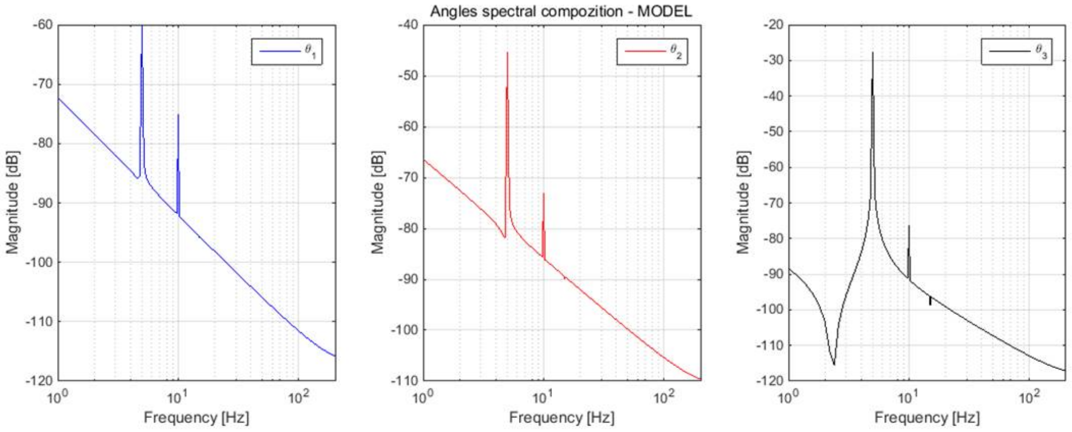
(a) (b) (c)

Fig. 4. The frequency response of the simplified model, in the horizontal direction, for mass m_1 (a), mass m_2 (b), mass m_3 (c)



(a) (b) (c)

Fig. 5. The frequency response of the simplified model, in the vertical direction, for mass m_1 (a), mass m_2 (b), mass m_3 (c)

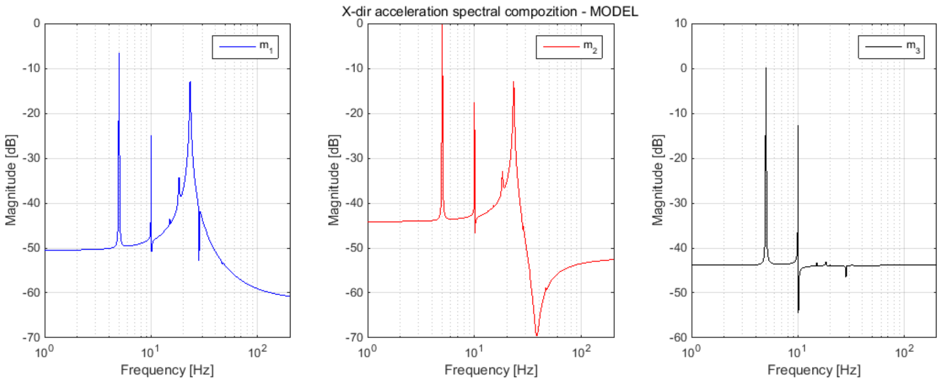


(a) (b) (c)

Fig. 6. The frequency response of the simplified model for rotations φ_1-(a), φ_2-(b), φ_3-(c)

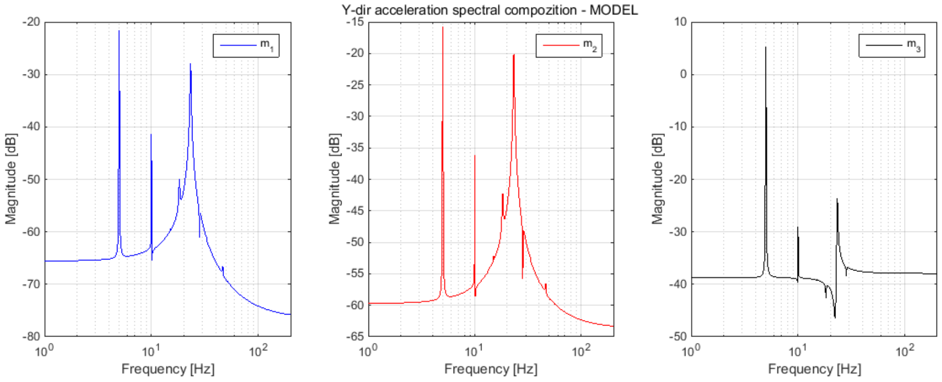
3. PHYSICO-MATHEMATICAL MODEL OF THE HUMAN FOOT WITH THE SIMULATION OF THE ACTION OF THE MUSCULAR SYSTEM

It can be considered that a conservative and, respectively dissipative, equivalence of the simultaneous actions of muscle groups involved in the coordination of the skeletal system, is asufficiently viable option, at least in the context of meeting the objectives of this study. In this sense, the schematization of the initial model (see fig. 1) was completed with three functional modules, of restrictive type for the specific movement of the three joints. These functional modules have the ability to simulate elastic and respectively viscous dissipative.



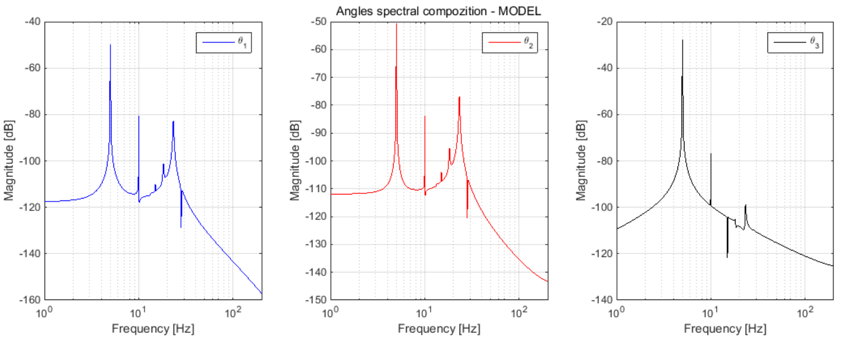
(a) (b) (c)

Fig. 7. The frequency response of the complex model, in the horizontal direction, for mass m_1 (a), mass m_2 (b), mass m_3 (c)



(a) (b) (c)

Fig. 8. The frequency response of the complex model, in the vertical direction, for mass m_1 (a), mass m_2 (b), mass m_3 (c)



(a) (b) (c)

Fig. 9. The frequency response of the complex model for rotations φ_1 (a), φ_2 (b), and φ_3 (c), respectively

To facilitate comparative analysis, the respective excitation parameters are identical to those used in the previous case. The difference is that the duration of the dynamic behavior simulation has been increased, in order to avoid the effects of the transient regime that manifests itself in the first part of the dynamic response.The spectral compositions of the monitored parameters, in this case, were evaluated, and the results are presented respectively in figs. 7-9.

4. CONCLUSIONS: VALIDATION OF NUMERICAL RESULTS THROUGH EXPERIMENTAL RESULTS

In order to validate the simulated results, it was considered an experimental configuration, laboratory, on a human subject with the geometric configuration of the locomotor system corresponding to the values adopted after the initial study. Overview of the experimental configuration current, is shown in fig. 10.

The data acquisition system consists of three triaxial type accelerometers PCB Piezotronics 356A16 and a complex system of acquisition, measurement, and analysis of vibrations transmitted to humans NetdB. Pre-processing and data management was done with dBFA Suite software. Post-processing and data analysis were performed using applications developed in the Matlab environment, in order to facilitate unitary comparative analysis of experimental results with those resulting from simulations on numerical models.

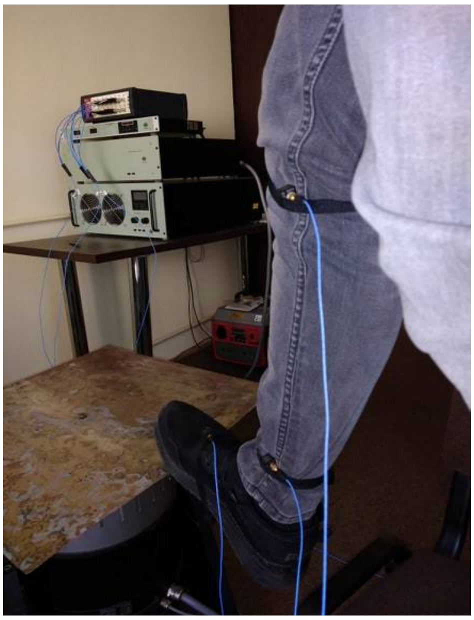
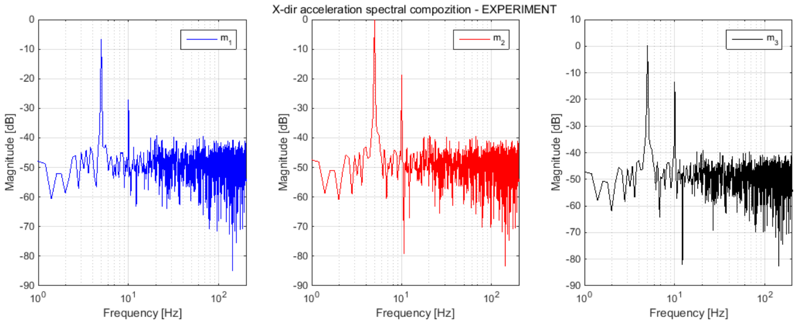
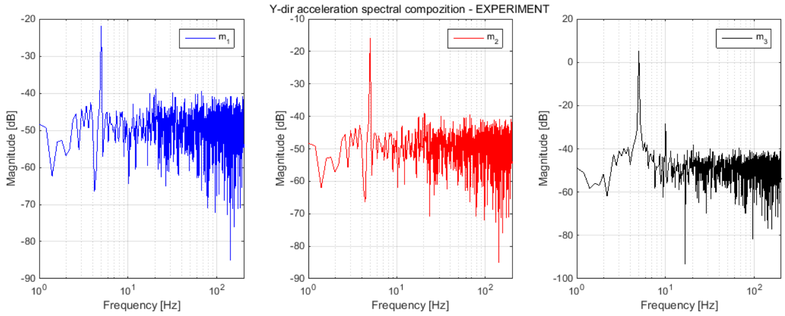


Fig. 10. Experimental configuration used to evaluate the response of the human foot subjected to mechanical vibration excitation



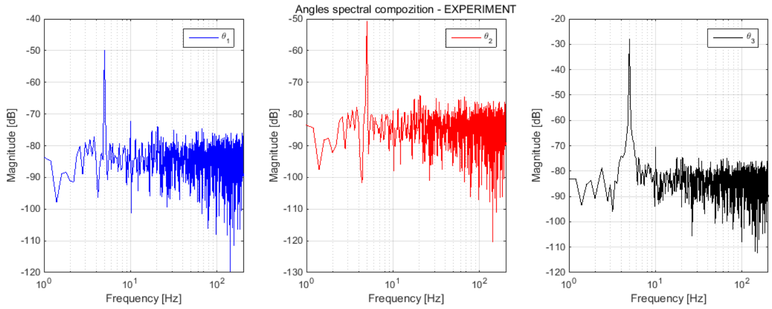
(a) (b) (c)

Fig. 11. Frequency response, obtained by laboratory tests on the real system (human subject), in the horizontal direction, for mass m_1 (a), mass m_2 (b), mass m_3 (c)



(a) (b) (c)

Fig. 12. Frequency response, obtained by laboratory tests on the real system (human subject), in the vertical direction, for mass m_1 (a), mass m_2 (b), mass m_3 (c)



(a) (b) (c)

Fig.13. Frequency response, obtained by laboratory tests on the real system (human subject), corresponding to rotations φ_1 (a), φ_2 (b), and φ_3 (c) respectively

The avoidance of transient regimes was obtained by cutting a time zone corresponding to a quasi-stationary dynamic regime (actually, for analysis, it was considered a duration of five seconds, starting with the tenth second from the moment of initiating the dynamic excitation process).

Analogous to the simulated situations on numerical models, the temporal variations of the monitored signals were analyzed from the point of view of the spectral composition, obviously insisting on the spectral amplitude. The results are shown in fig. 11 - the horizontal component of the accelerations, fig. 12 - the vertical component of the accelerations, and respectively fig. 13 - variations of angular displacements in the joints.

For the simple model, the value of about 20 Hz has a very low contribution in the spectrum, so it could not be identified in all diagrams. However, on the whole, the existence, even sporadic for some values, of the four spectral components indicates the basic spectral structure of the analyzed system (excitation frequency, eigenfrequencies). By introducing, within the complex model, visco-elastic elements that restrict the dynamic behavior of the joints, two effects are obtained in the spectral area, namely: (1) affecting the eigenvalues of the simple model, in a relatively small proportion, but identifiable in the spectrum and (2) the emergence of significant additional components, generated by the conservative terms in the system of differential equations associated with the model. Obviously, in the experimental case, the two dominant spectral components (5 and 10 Hz) are clearly identifiable.

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