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DYNAMIC ANALYSIS OF THE VEHICLE WHEEL GUIDANCE SYSTEM USING VIRTUAL PROTOTYPING TOOLS

BY

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Abstract. The present work deals with the dynamic analysis of a vehicle wheel guidance system by using virtual prototyping software tools. The study is based on the development of a full-vehicle model, which integrates the following specific subsystems: front suspension, rear suspension, steering, car body, and anti-roll bar. The design and simulation of the full-vehicle virtual model is carried out by using the MBS (Multi-Body Systems) software package ADAMS, more specifically the module dedicated to the automotive industry, namely ADAMS/Car, which offers facilities for simulating the complete vehicle under various road conditions and loading states. The results obtained through the dynamic analysis in a virtual environment, which are presented both in the form of in-time variation diagrams and in the form of graphical simulation frames, enable the accurate assessment of the vehicle wheel guidance system behavior, what is found in effective decision-making from the early stages of the design process.

Keywords: vehicle, suspension, steering, dynamics, virtual prototyping.

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1. Introduction

The vehicle wheel guidance (suspension & steering) system is made up of a set of bodies (theoretically rigid), which are interconnected by joints, elastic and dissipative elements. A complex set of external forces (which depend on the loading & running regime) and internal reaction forces (generated by the elastic and damping elements of the suspension, such as springs, shock absorbers, bushings, anti-roll bar, compression & extension bump-stops, tires) act on the system. For the accurate evaluation of the dynamic behaviour, it is necessary to consider the full-vehicle model, including both front and rear guiding systems, due to the mutual influences between them through the car body (Fischer, 2007). In the case of such models, with a large number of degrees of freedom, it becomes practically a necessity to use commercial virtual prototyping software solutions for performing the dynamic simulation, and subsequent optimization as well (Mejia-Gutierrez and Carvajal-Arango, 2017).

Generally, a virtual prototyping platform integrates the following software solutions (Alexandru, 2020): CAD (Computer Aided Design) – to create the 3D solid model of the system, MBS (Multi-Body Systems) – to perform the dynamic analysis of the system, and FEA (Finite Element Analysis) – to convert rigid bodies into deformable parts. The virtual prototyping process usually involves the following stages (Enescu and Alexandru, 2012): modelling (building), simulation (analysis/testing), validation, refining (re-modelling) and optimization. The modeling stage involves making the virtual model of the system, i.e. transposing the specific components (bodies, joints, actuation elements, other force-generating elements) on the computer. The virtual model thus obtained is further analyzed / tested in order to evaluate its behaviour. The results obtained through simulation in a virtual environment are later compared with experimental results in order to validate the virtual model. If the virtual results are not close to the experimental ones, in other words the virtual model is invalid, it is necessary to further refine the virtual model in order to bring it closer to the real physical model (by replacing rigid bodies with deformable parts, adding friction, and so on). Finally, once the virtual model becomes a valid one, it becomes subject to optimization, with the aim of improving the system from various points of view, such as functional or economic aspects.

In the following, the dynamic analysis of a full-vehicle guidance system is approached by using the MBS virtual prototyping package ADAMS of MSC.Software, more specifically the module dedicated to the automotive industry, ADAMS/Car, which offers facilities for simulating the complete vehicle under various road conditions and loading states (Ning *et al.*, 2011).

2. Virtual Prototype of the Full-Vehicle Assembly

The full-vehicle virtual model under consideration includes the following specific subsystems: front suspension, rear suspension, steering, anti-roll bar, car body, and wheels (which belong to the testing rig).

The front suspension subsystem (Fig. 1) is based on McPherson guiding mechanisms. The lower control arms (9, 10) are connected to the wheel-carriers (7, 8) by spherical joints, respectively they are double connected to the car body by revolute joints with bushings. The shock absorber is part of the suspension mechanism, the cylinders (11, 12) being rigidly connected to the wheel-carriers, while the pistons (13, 14) are spherically connected to the car body. The helical springs are mounted between the cylinders of the shock absorbers and the car body, the compression and extension bump-stops being arranged inside the shock absorbers (thus limiting relative displacement of the pistons inside the cylinders).

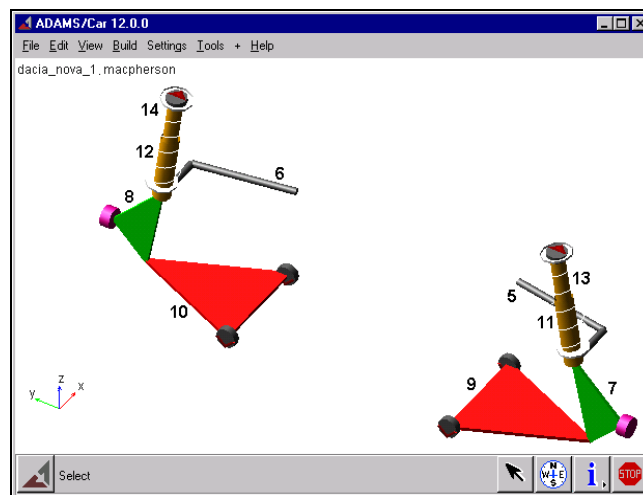


Fig. 1 – Front suspension subsystem.

For the rear suspension subsystem, there is used a beam axle (so called H-axle), which is double-connected to the car body through revolute joints with bushings (Fig. 2). Interface parts connect the flexible part of the axle with the rigid hubs (15, 16) of the wheels. The main movement of the axle (i.e. the vertical travel) is carried out freely, through the articulation mode of the axle to the car body, while the rolling rotation of the axle is carried out through the elastic deformation of both the bushings and the axle. The helical springs and the shock absorbers of the rear axle suspension are mounted, non-concentrically, between the rigid parts of the axle (i.e. the wheel hubs) and the car body.

The theoretical model of the anti-roll bar (Fig. 3) is composed of a torsion spring connecting two rigid bodies materializing the left and right levers (21, 22), which are rigidly connected to the lower control arms of the front suspension mechanism.

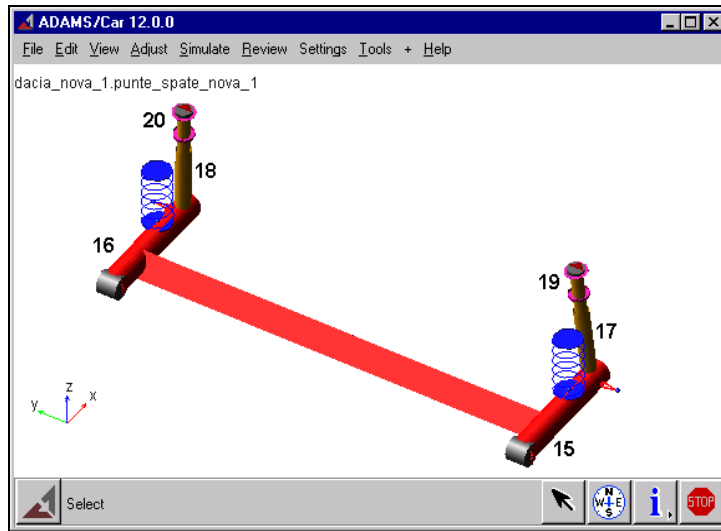


Fig. 2 – Rear suspension subsystem.

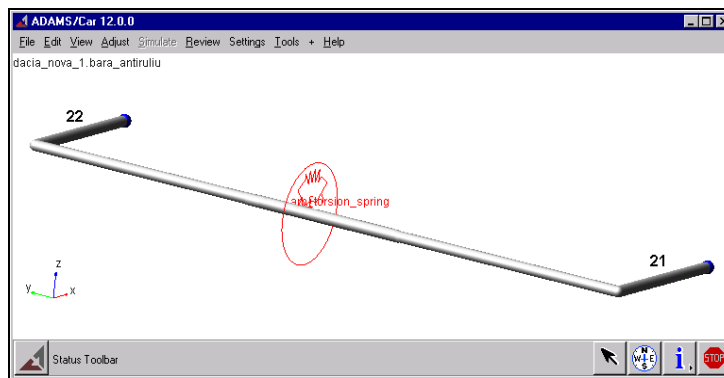


Fig. 3 – Anti-roll bar subsystem.

The steering subsystem (Fig. 4) contains a classical rack & pinion gearbox, as well the transmission from the steering wheel to gearbox. The multi-body system model for this mechanism includes 4 bodies, as follows: steering wheel shaft (1), intermediate shaft (2), pinion shaft (3), and rack (4). The three shafts are connected among themselves through universal (Hooke) joints, while revolute joints are used to connect them to the mount part from the

car body subsystem. The rack executes translational motion along the transversal axis (Y) relative to the car body. The contact between pinion and rack is modeled by a gear joint.

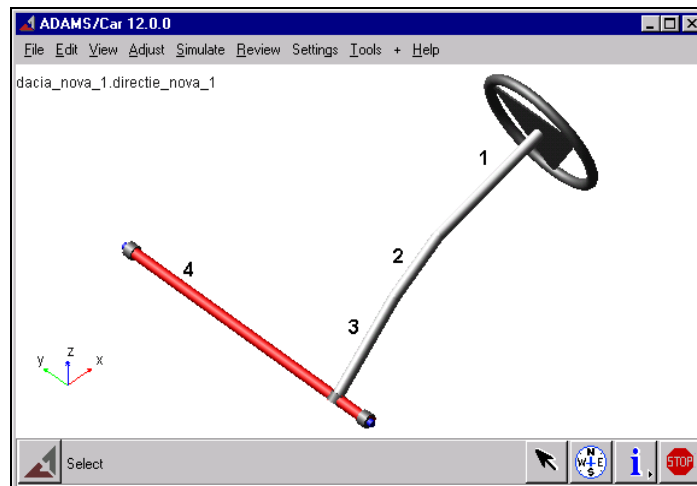


Fig. 4 – Steering subsystem.

The subsystems that define the full-vehicle virtual model are connected through the use of communicators (MSC.Software, 2012). They allow subsystems to exchange information about the topological data (information about bodies and attachments), locations, orientations, etc. Since the data transfer between subsystems is bidirectional, two types of communicators are used: input communicators – request information from other subsystems; output communicators – provide information to other subsystems.

The type of information that is exchanged between subsystems is defined by the class of communicators, the main classes being: Mount - the name of the part (body) that ensures the connection between the subsystems; Marker - point and name of the part that provides information about location and body; Joint - the name of the coupling (geometric constraint); Joint for motion - the name of the joint in which a motion generator (driver) is applied; Location - the location of a point or coordinate system; Part - the name of the part; Orientation - the orientation of a coordinate system; Real / Integer parameter - the name of a variable parameter of real / integer type. For example, a "Mount" class communicator from the steering subsystem provides (output communicator) the name of the rack to which the steering rods from the suspension subsystem will be connected (input communicator), respectively a "Location" class communicator from the suspension subsystem provides the location of the wheel center to which the wheel from the testing subsystem is attached.

Each communicator has a minor role, which defines the position of the communicator as a component of the subsystem, as a whole (for example, front or rear), respectively a major role, which describes the type of subsystem (such as suspension or steering).

Under these conditions, the communicators used to assemble the subsystems of the previously described virtual prototype are presented in table 1, where FS - front suspension, RS - rear suspension, ST - steering, CB - car body, WH - wheel, AR - anti-roll bar, s - single communicator (the others being in pairs left and right).

Table 1
List of communicators used to assemble the full-vehicle subsystems

Communicator		Type (Input - I / Output - O)					
Name	Class	FS	RS	ST	CB	WH	AR
lower arm - car body	Mount	I			O		
damper - car body		I	I		O		
steering rod - rack		I		O			
wheel carrier/axle - wheel		O	O			I	
axle - car body			I		O		
spring plate - car body			I		O		
antiroll bar - suspension arm		O					I
steering column - car body ^(s)					I	O	
rack - car body ^(s)					I	O	
pinion - car body ^(s)					I	O	
wheel center	Location	O	O			I	
toe-in/toe-out angle	Real parameter	O	O			I	
camber angle		O	O			I	

The so obtained full-vehicle virtual model (Fig. 5) is defined by the following:

- generalized coordinates for $n = 27$ mobile bodies: $27 \times 6 = 162$;
- the degrees of freedom removed by the geometric constraints - Σr_g (the pair "i/j" defines the adjacent bodies connected by the joint under consideration):
 - revolute joints - 3/23, 7/24, 8/25, 15/26, 16/27: $5 \times 5 = 25$,
 - translational joints - 4/23: $1 \times 5 = 5$,
 - cylindrical joints - 1/23, 11/13, 12/14, 17/19, 18/20: $5 \times 4 = 20$,
 - spherical joints - 4/5, 4/6, 7/9, 8/10, 5/7, 6/8, 13/23, 14/23, 15/17, 16/18, 19/23, 20/23: $12 \times 3 = 36$,
 - fixed joints - 9/21, 10/22, 7/11, 8/12: $4 \times 6 = 24$,
 - gear joint - 3/4: $1 \times 4 = 4$,

- universal (Hooke) joints - 2/1, 2/3: $2 \times 4 = 8$;
- redundant constraints - R (Haug *et al.*, 1995): 3 (in the steering subsystem).

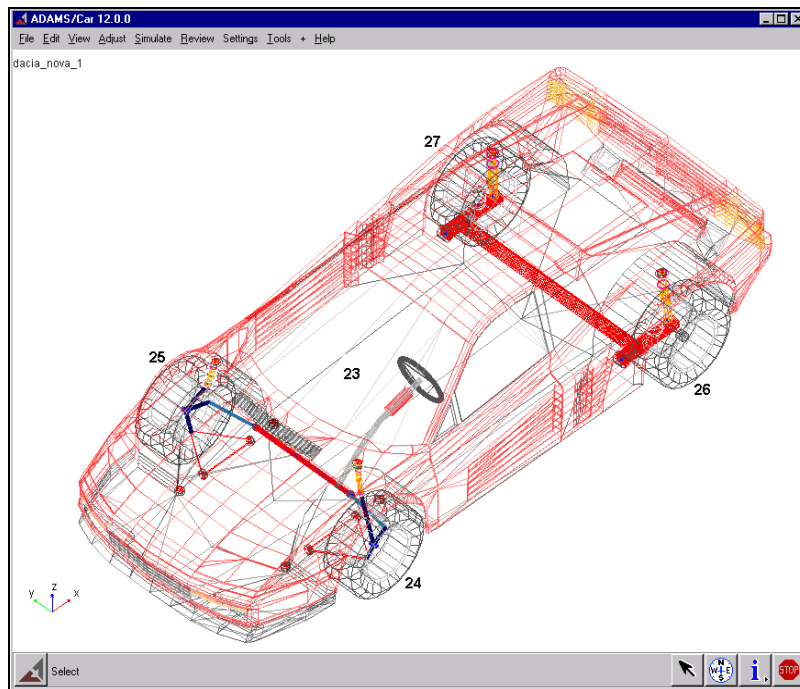


Fig. 5 – Full-vehicle virtual model.

The number of degrees of freedom (i.e. independent generalized coordinates) of the full-vehicle model is determined according to the Gruebler's count (Haug, 1989), $DOF = 6n - (\sum r_g - R) = 162 - (122 - 3) = 43$, which are distributed in the following way:

- 15 active movements (vertical travel of the wheels - 4, steering movement - 1, car body oscillations (linear and angular) - 6, wheels rotations around the spindle axes - 4);
- 20 elastically restricted mobilities in bushings, except for the necessary mobilities;
- 8 passive mobilities - rotations around their own axes (front damper pistons - 2, rear damper pistons & cylinders - 4, steering rods - 2).

The full-vehicle virtual prototype is analyzed / tested in the case of a turning (steering) maneuver on a sinusoidal cycle. The dynamic simulation was performed over an interval of 5 seconds, with the launch of the steering maneuver at the moment $t=2$ seconds, and the vehicle running speed of 90 km/h, while considering a law (function) of rotation of the steering wheel in the variation interval $[0, 90]^\circ$.

Following the dynamic analysis of the full-vehicle virtual prototype, a series of useful results have been obtained in order to evaluate the behavior of the wheel guidance system, of which the following are shown in Fig. 6: a - vertical position/displacement of the car body, b - transversal position of the vehicle, c - roll angle, d - yaw angle, e - roll acceleration, f - yaw acceleration.

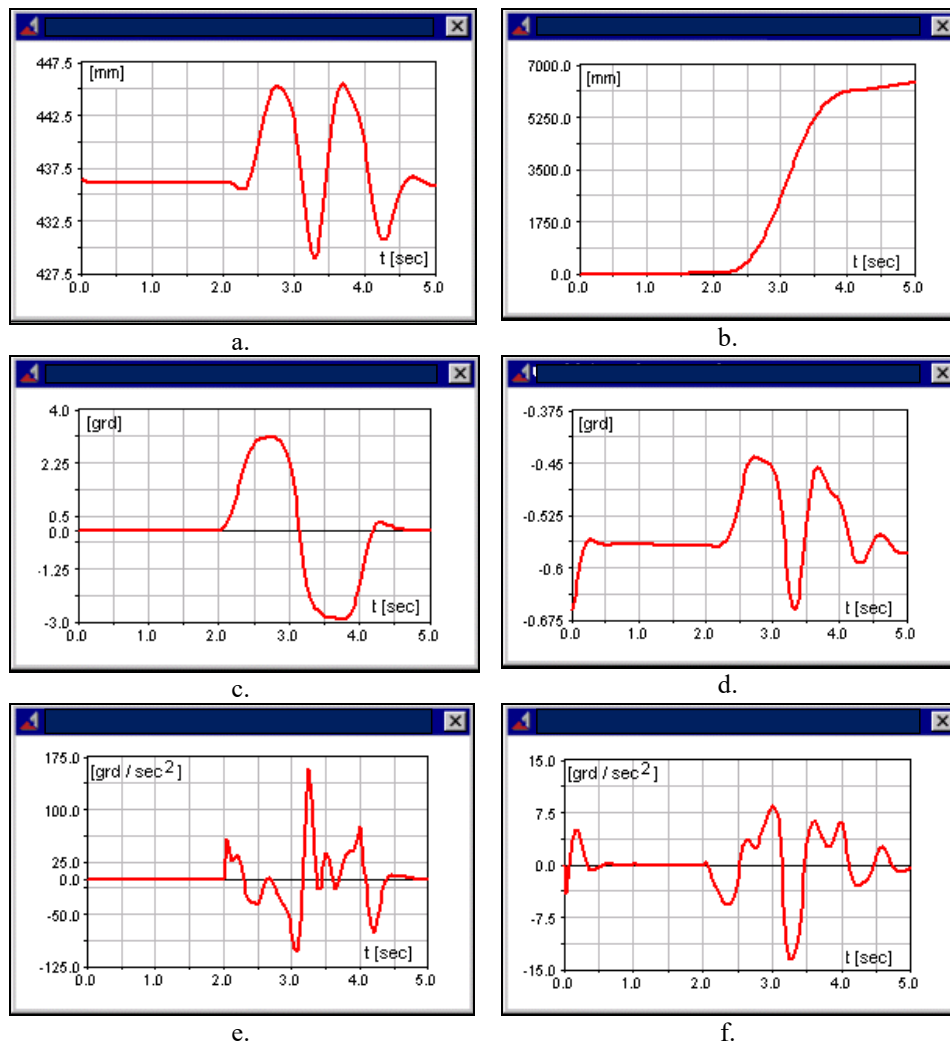


Fig. 6 – Results of the dynamic simulation.

In addition, Fig. 7 shows some representative graphical simulation frames during the dynamic simulation, which were made by means of the ADAMS/Animation post-processing module.

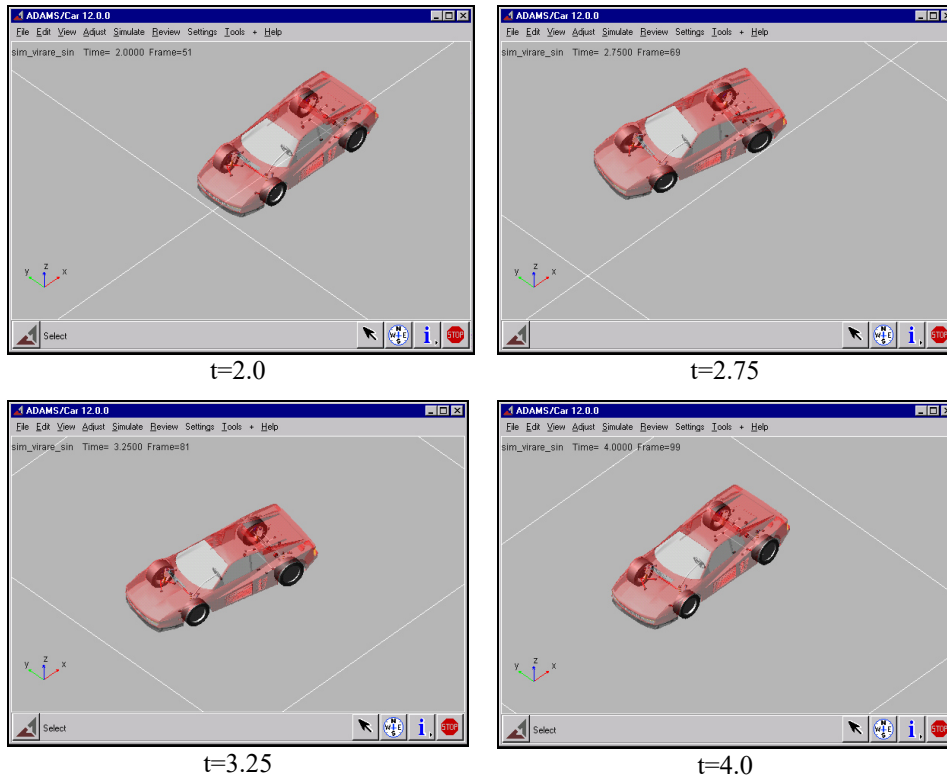


Fig. 7 – Graphical simulation frames.

3. Conclusions

Along with the appearance and development of the MBS software solutions (such as ADAMS), the design of the vehicle wheel guidance systems evolved in a new direction: the design and analysis of complex theoretical models, close to the real models both from the point of view of the system structure and the operating conditions. Real virtual prototypes can be made on the MBS software platform considering the minimization of the cost that would result from the design and testing process of physical (experimental) prototypes.

The application presented in this work is a relevant one from the point of view of the previously mentioned, the dynamic behaviour of the vehicle (in this case, with a focus on the wheel guidance system) being able to be assessed and improved from the early stages of the design process. On the virtual prototype of the vehicle wheel guidance system, various measurements can be made at any location and for any type of parameter (linear or angular movement, force), including parameters that would be very difficult or even impossible to measure on the experimental prototype, either because of the lack

of adequate transducers, or because of the difficulty of mounting them in certain spaces, or insufficient space for their installation.

Further research in the field will be focused on the optimal design (by using virtual prototyping tools like those used in this work) of an innovative suspension system for race (open-wheel) cars.

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ANALIZA DINAMICĂ A SISTEMULUI DE GHIDARE A ROȚILOR AUTO UTILIZÂND INSTRUMENTE DE PROTOTIPARE VIRTUALĂ

(Rezumat)

În această lucrare se abordează analiza dinamică a sistemului de ghidare a roților unui vehicul prin utilizarea instrumentelor software de prototipare virtuală. Studiul se bazează pe dezvoltarea unui model tot-automobil, care integrează următoarele subsisteme specifice: suspensie față, suspensie spate, direcție, caroserie și bară antiruliu. Proiectarea și simularea modelului virtual se realizează prin utilizarea pachetului software MBS (Multi-Body Systems) ADAMS, mai precis modulul dedicat industriei auto ADAMS/Car, care oferă facilități pentru simularea întregului vehicul în diferite condiții de rulare și stări de încărcare. Rezultatele obținute prin analiza dinamică în mediu virtual, care sunt prezentate atât sub formă de diagrame de variație în timp, cât și sub formă de cadre de simulare grafică, permit evaluarea precisă a comportamentului sistemului de ghidare, ceea ce contribuie la luarea de decizii eficiente încă din fazele incipiente ale procesului de proiectare.