Analysis and control of vehicle steering wheel angular vibrations

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Summary :

The steering wheel vibration is analyzed through tests and numerical modal analysis. A dynamic mode is identified as responsible for the sensitivity of vehicle. Control of the phenomenon can be achieved through the mastery of excitation sources and axle design. Dynamic and modal analysis on an Adams model could be used to optimize the axle design in order to decrease the effect of shimming.

Introduction

The phenomenon we've studied deals with steering wheel angular vibrations which appear, in straight line driving case, for speed condition between 90 and 150 km/h, according to the vehicle characteristics.

Beyond the analysis of physical phenomena, the objective of this paper is to highlight the procedures and means which are necessary to handle and to control these vibrations.

To master the phenomenon at the development stage, we have to follow a process of translating complete car specifications into technical requirements for systems and components. The simulation models will allow us to define the technical requirements of each sub-system. The test bench will be necessary to validate these technical requirements.

Phenomenon analysis

Analysis of the phenomenon on a vehicle

The angular steering wheel vibration could be measured in straight line condition, steering wheel free with a reference mass fixed at the bottom of the steering wheel (representing the arm inertia of the driver) - see fig 1.

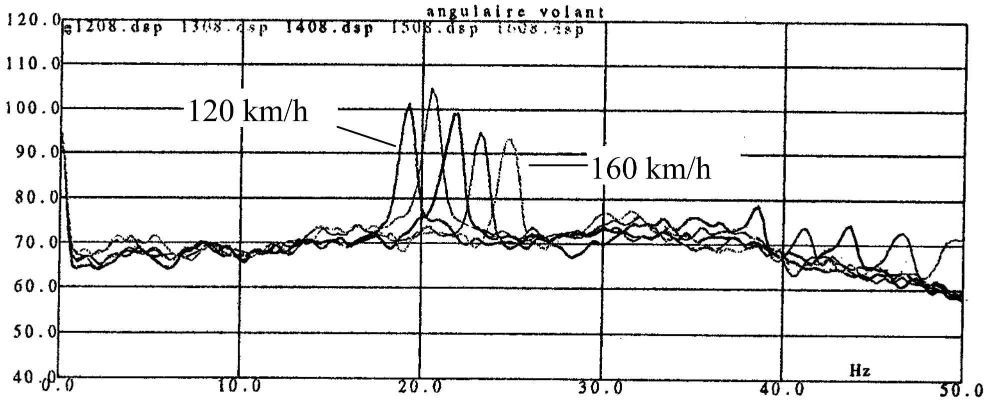

FIG 1 : frequency analysis of the steering wheel acceleration ; 5 measures from 120 km/h to 160 km/h

The two main comments we can do at this step are :

- one or several critical speeds exist
- the vibration level of the phenomenon is variable during a long running test.

Some influence factors are generally observed :

-> Wheel unbalance : the vibration level is all the lower as the unbalance is low.

-> the radial non-uniformity of the tire is unfavorable.

-> the longitudinal flexibility of the front suspension (longitudinal displacement of wheel center for a longitudinal effort applied) moves the critical speed and modifies vibration amplitude.

-> steering friction attenuates the phenomenon.

Analyzing of the phenomenon by simulation

Model definition :

The front suspension has been studied with Adams/Car for kinematic and elasto-kinematic problems. In the model, all parts are described as rigid ones, exepted anti-roll bar. The joints between these parts are defined as non-linear bushings.

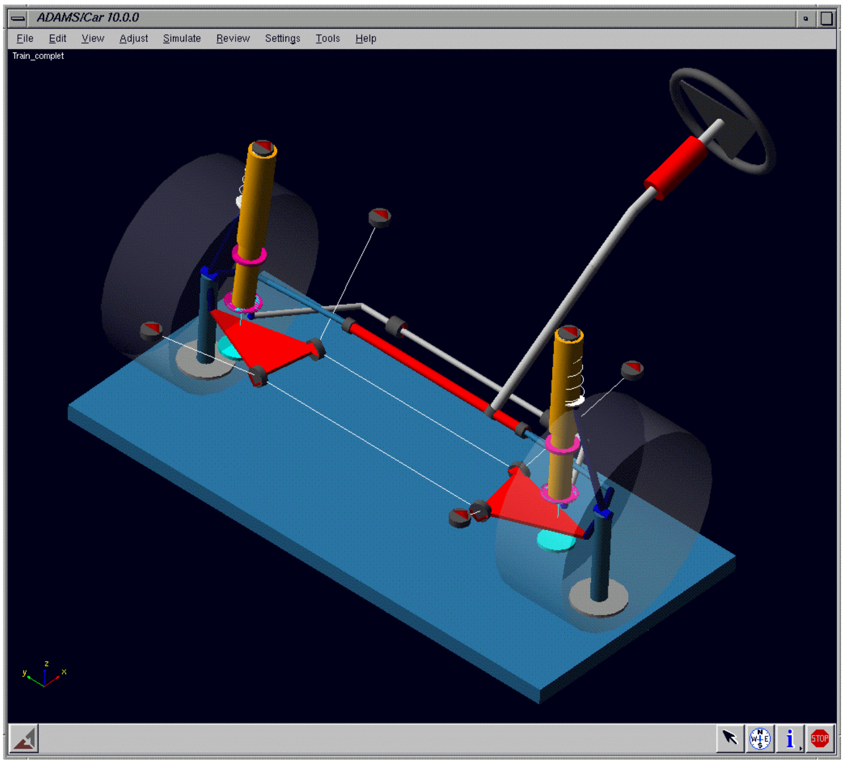

FIG 2 : Adams/Car model

With this model, we compute standard kinematic analysis such as roll center height, toe and camber angles versus wheel travel. We simulate also the axle deformations under static forces load cases.

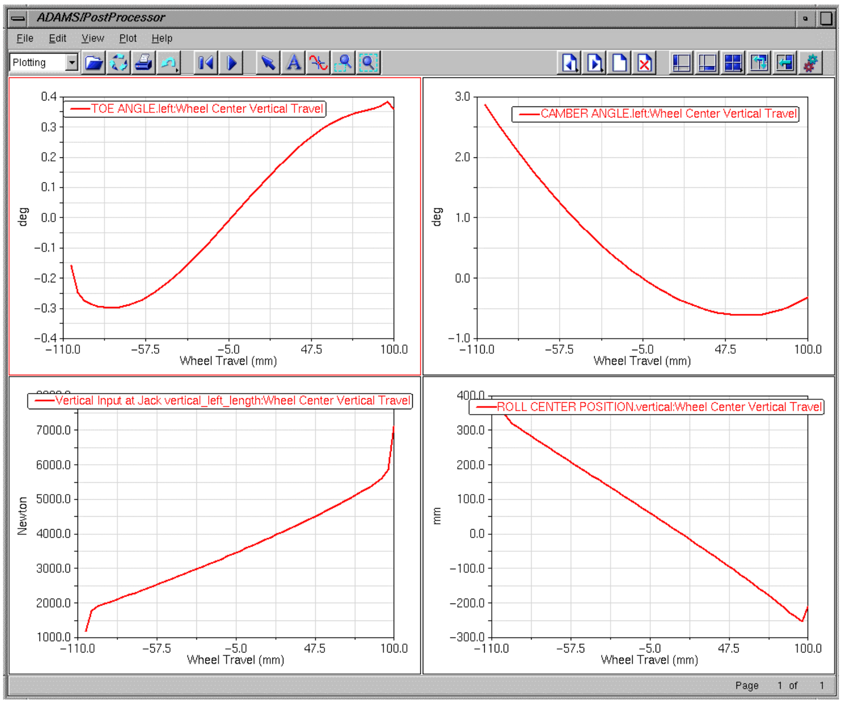

FIG 3 : Standard Adams/Car results

These results are used to validate the sub-system requirements for handling and the impact comfort of the vehicle.

We use the same model for running the modal analysis we need for analyzing the dynamic phenomenon of steering wheel vibrations. A few modifications are necessary to run these analysis, with a specific command file or a customization of the interface, but all the axle data are still parametrized.

Modal analysis :

On this front suspension, just after the first two modes - respectively parallel vertical wheel displacement (12.4 Hz) and opposite vertical wheel displacement (12.7 Hz), modal analysis identified two modes (about 23 Hz) which can be described as longitudinal modes of unsprung masses on the attachments stiffness of the arm on the sub-frame.

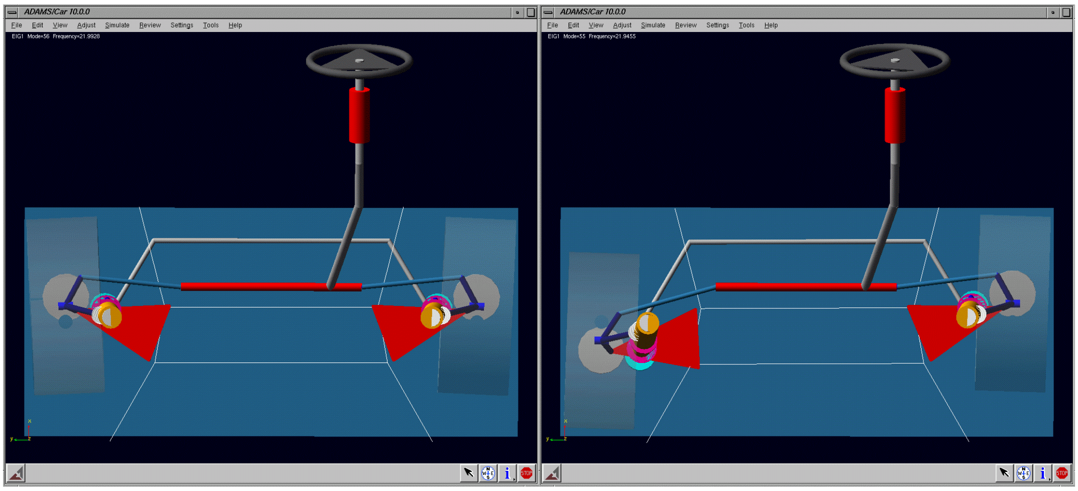

FIG 4 : Longitudinal symmetric and anti-symmetric mode shapes

The deformed mode shape of mode number 4 shows symmetric movements of the wheels, whereas the deformed mode shape of mode number 3 shows anti-symmetric movements of the wheels. The main consequence of this asymmetry is to cause a displacement of the steering rack and then of the steering wheel.

Harmonic response :

In order to compare the sensitivity of different configurations of an axle, during the development phase, we use state matrices (generated by Adams/Linear) in a matlab post-processing to plot some bode diagrams corresponding to each solution.

Interpretation of the phenomenon :

We explain the phenomenon of steering wheel vibrations by observing the similarity of the longitudinal mode frequency of suspension with the critical speed converted in wheel rotation frequency.

The excitation generated by wheel unbalance or radial non-uniformity of pneumatics couples with longitudinal axle modes. When excitation frequency becomes close to the mode frequency, the excitation increase, caused by the dynamic system, manages to overcome steering friction and then causes a steering rack movement.

This analysis allows us to explain some facts we observed during tests :

- The cyclic and random evolution of the phenomenon during the running may be explained by the effect of the symmetric or the anti-symmetric mode, according to phase or opposite phase of right and left wheels excitation (fig 5).
- We notice also by simulation that the disconnecting of the anti-roll bar move the mode from 21.2 Hz to 19.8 Hz. This is consistent with the speed decreasing observed on the vehicle in the same conditions.

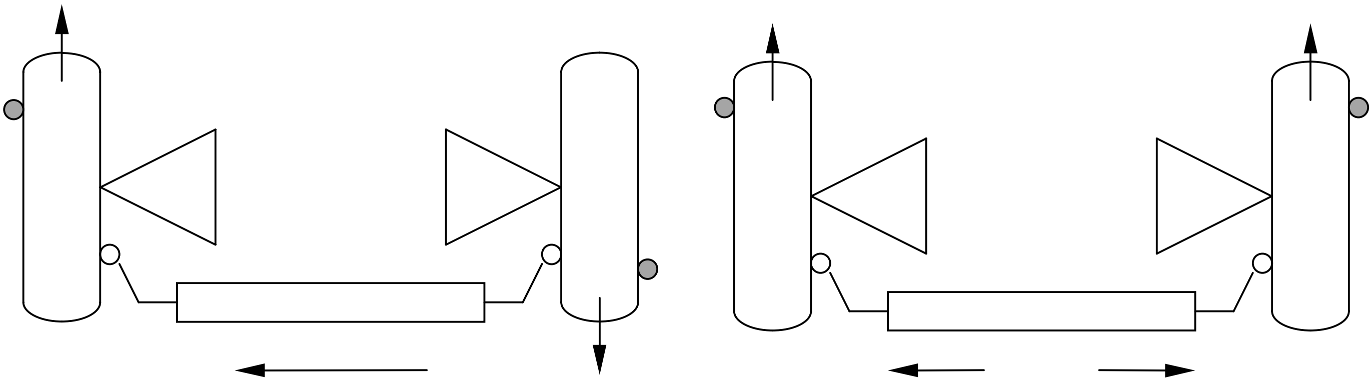

FIG 5 : Effect of phase or opposite phase of the unbalance steering wheel vibrations

Axle development mastering

The phenomenon analysis brings to the light the anti-symmetric longitudinal mode as the main influential factor on steering wheel vibration. Therefore, it is possible, during the development study, to decrease the axle sensitivity to the phenomenon by acting on the frequency and the shape of this particular mode.

Mode frequency :

The excitation force is proportional to the unbalance mass, but also to the square rotational speed of wheel :

$$F = m.\omega^2.r$$

Furthermore, a critical speed of about 130 km/h usually happens on roads like motorways, then in low level of ambient vibrations which makes it easy to detect the phenomenon.

For these reasons, it is preferable to move the critical speed to a lower value (about 90 km/h). Then, excitation force will decrease of about 50% with the same unbalance conditions, while having the mode moved to a frequency range where the vibration environment is more important and consequently able to hide the effect of wheel unbalance.

Transfer function :

We can compare the vibrations amplitudes by using the state matrices generated by Adams/Linear. The bode diagrams of the transfer functions (steering rack force / longitudinal force applied at the wheel center) corresponding to different stiffnesses of the axle bushings allow us to discriminate the design solutions.

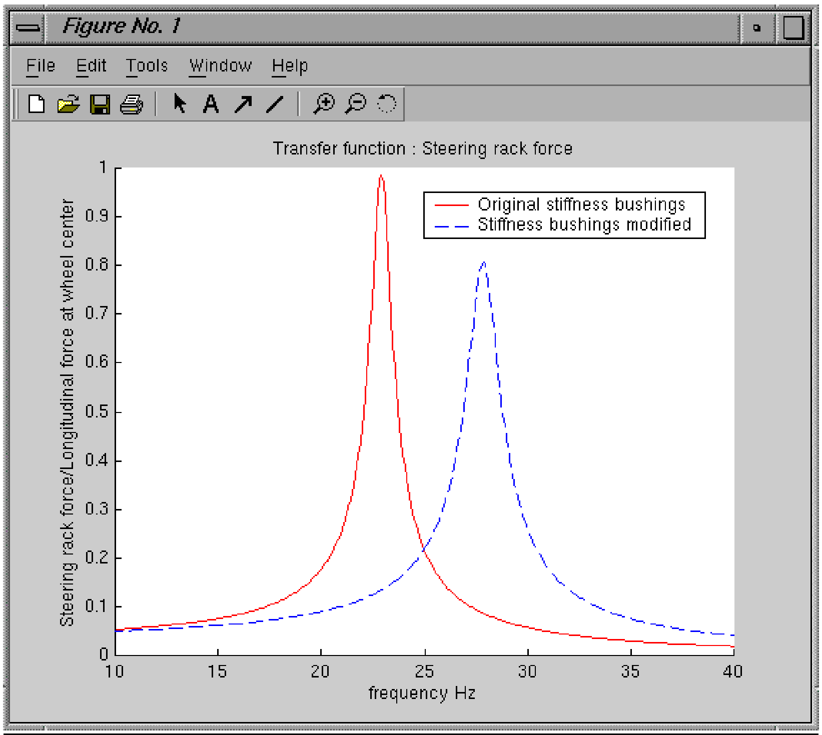

FIG 6 : Transfer functions

Mode shape :

To minimize the anti-symmetric longitudinal mode on steering wheel movement, it is possible to modify the mode shape. This can be realized by acting on the kinematic (geometry) or on the elasto-kinematic of the axle (bushings flexibilities).

Axle kinematic :

Axle geometry influence directly the mode shape, as we can see on the mode shape of an axle where the arm is rectangular, instead of an isosceles one (see fig 7).

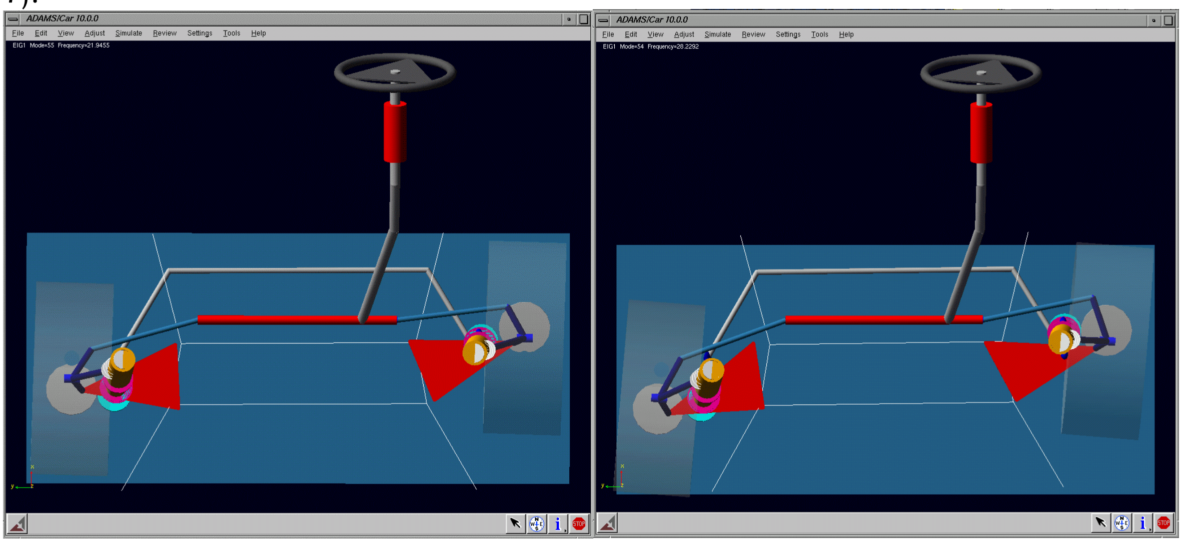

FIG 7 : Kinematic effect

Axle elasto-kinematic :

The influence of flexibilities is shown by a simulation in which the distribution of flexibilities of the bottom arm attachments has been modified. We can see on the deformed mode shape (fig 8) that the steering wheel is quite stable, whereas the wheels movement is important.

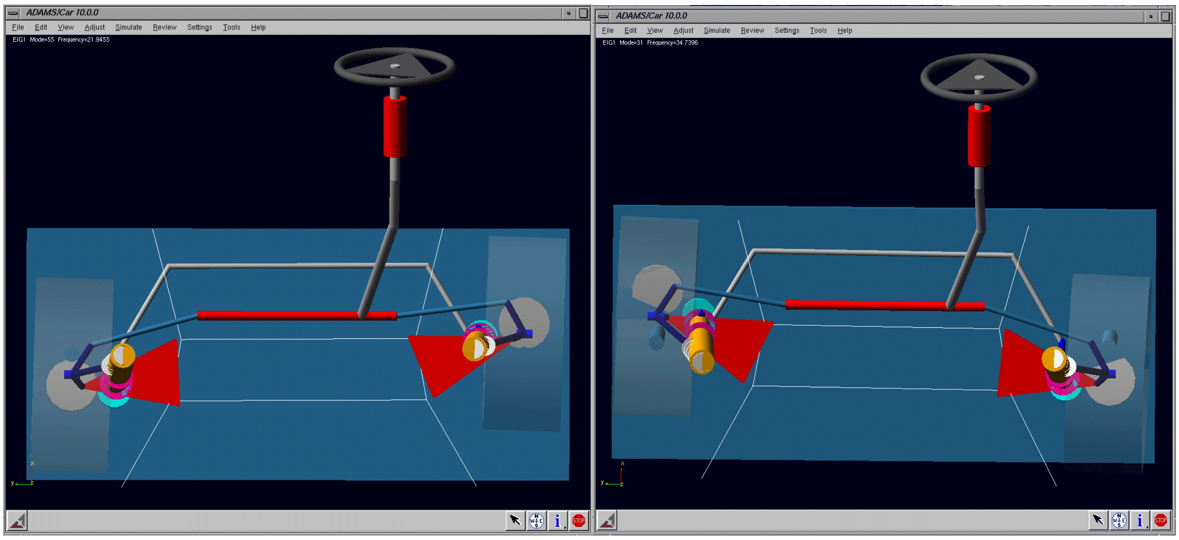

FIG 8 : Elasto-kinematic effect

The modification of geometry and flexibilities also influences road handling capabilities (axle deformations) and comfort (longitudinal impact) of the vehicle. The dynamic behavior of the axle is an additional parameter to take into account in a compromise between comfort and road handling.

Excitation mastering

To master the wheel excitation, it is necessary to master the wheel unbalance, the hubcaps unbalance, the wheel centering and the radial uniformity of the pneumatic.

Wheel unbalance :

According to the vehicle sensitivity, a balancing tolerance (static and dynamic unbalance) is defined by the use of the characterization procedure of the phenomenon on vehicle.

These tolerances are transferred on the compensation plane, and some capable machines, with reference to these tolerances are installed in plants.

Hubcaps unbalance :

Wheel balancing is generally done without any hubcap, but this unbalance can't be negligible (until an equivalent mass of 10 grams at rim edge).

This unbalance can be a consequence of an unsuitable centering position of the hubcap relatively to the wheel, or of a mass dissymmetry, caused for example, by the valve hole.

Wheel centering :

The off centering of the wheel relatively to the hub is an unbalance and radial non uniformity generator.

The geometric tolerance on the central bore of the rim is defined as compared with the external diameter of the hub in order to limit the phenomenon to an acceptable value.

Radial non uniformity of tires :

The radial non uniformity of tires is defined by the variation of vertical force, in the case where wheel center is fixed, during a complete rotation of the wheel.

This variation can be due to geometric defects as well as internal structure defects of the pneumatic.

Control of the phenomenon damping

As the steering rack friction has a softness effect on steering wheel vibrations, the tendency to increase it is all the more important as this parameter, from design, is adjustable on steerings at the end of the fabrication process.

However, it is useful to precise some points :

- First, the major functional parameter is the friction measured at wheel steering. This friction is composed of only 50% or so of the steering rack friction. The remainder is made of the internal friction of the axle in a turning position and of steering column friction (see fig 12).
- A too high friction level is unfavorable to steering wheel torque and to the ability to come back to straight line under return force ; then the steering friction value results from a compromise.
- As it is the case for any friction device, there is an evolution according to the time and use conditions (sliding speed, creep, ageing, wear ...)

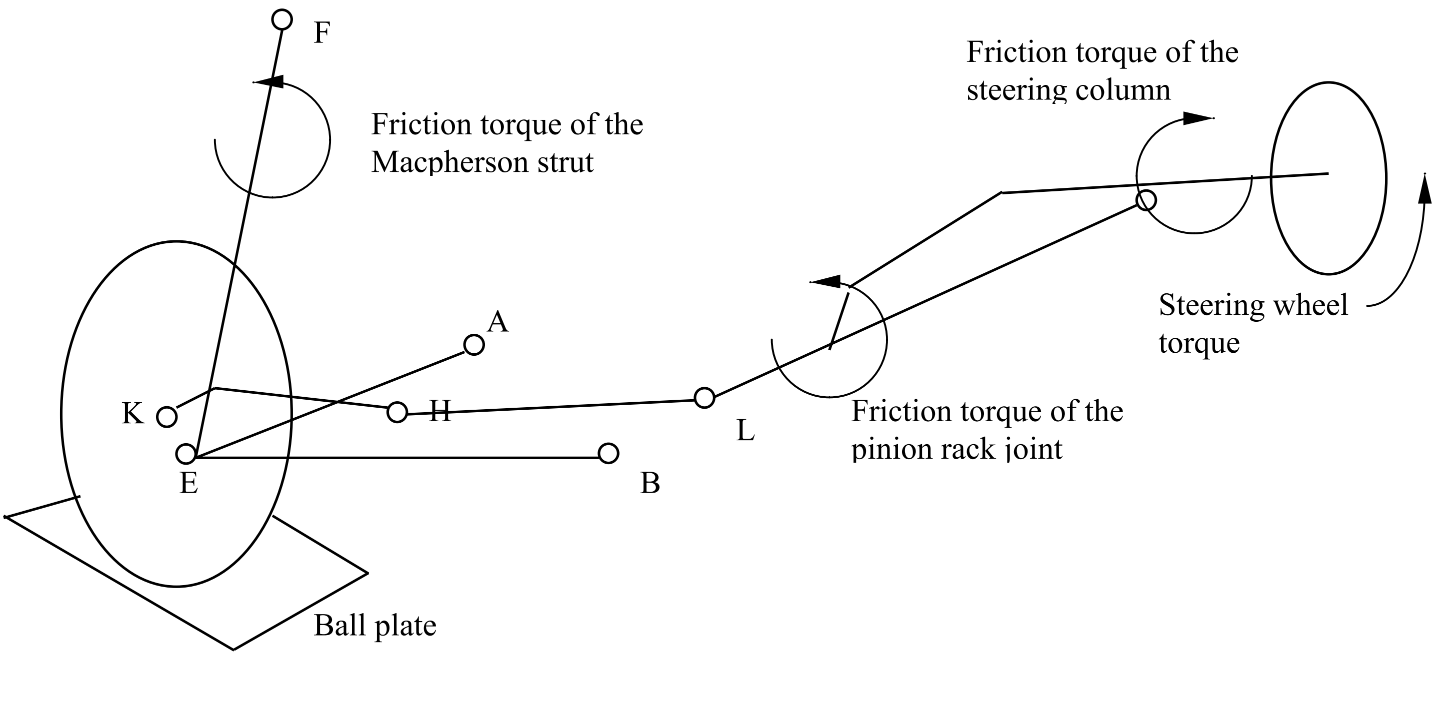

FIG 12 : Steering friction components

Conclusion

The phenomenon of angular steering wheel vibrations is mainly due to a resonance frequency of a front axle mode.

The frequency of this mode and its mode shape have to be taken into account during the design phase. The vehicle is then less sensitive and it is easier to master excitation parameters (wheel unbalance and radial non-uniformity) and to minimize parameters of the phenomenon (steering friction).

However, this consideration of modes must be managed with other technical requirements (mainly handling).

Then, the success conditions are on the one hand to have a strict way of detailing technical requirements (from functional vehicle specification until elementary components), and on the other hand to have computation and test facilities at one's disposal making this procedure possible.