Analysis of sensitivity of the steering system to road roughness

Valerio Bisogno, Pino Giliberti, Agostino Volpe

Elasis S.C.p.A.

Fiat Automotive Research Institute

1. Abstract

Vehicle steering system sensitivity to road roughness is one of the key factors impacting over vehicle quality. This directly affects customer satisfaction. The aim of this study is to understand the sensitivities of a given suspension and steering system with respect to road roughness and develop possible solutions to this problem. Selected one of the cars available on the market, the Flat Trac® Roadway Simulator has been used to reproduce a meaningful manoeuvre (step input on a curve). All the bench tests, made with different vehicle configurations, have indicated that the disturbances on the steer wheel are generated mainly by inertial phenomena (gyroscopic torque on the front wheel) and may be amplified by a high steering ratio. A full vehicle model created by ADAMS reproducing the same manoeuvres has been used to confirm the results and the comparison is made between simulation results and bench test results. Moreover, a theoretic analysis has been made using ADAMS models in order to identify the variable to check during the design of a new front suspension and steering system. On the basis of the simulation results, design suggestions have been made for further vehicle improvement.

2. Introduction

This paper reports the analysis of the influence of vehicle steering system sensitivity to road roughness on two factors mostly important in choosing a new car, that are safety and comfort level. In fact the steering roughness is mainly described as an unacceptable vibration that the driver can feel directly through the steering wheel and steering feeling is one of the first elements the customer uses to express his own judgement about vehicle quality.

The aim of this study is to identify on a car available on the market the main causes of a high steering wheel vibration due to obstacle passing and develop possible solutions to this problem.

The car analysed has a double wishbone suspension on the front, macpherson suspension on the rear and power assisted steering system.

Identified a meaningful manoeuvre at the Alfa Romeo test circuit in Pomigliano d'Arco (step input on a curve), the Flat Trac® Roadway Simulator has been used to reproduce correctly the manoeuvre by testing the car in different vehicle configurations and test conditions. The steering wheel torque (peak and RMS values) has been chosen to measure objectively the vibration during the manoeuvre in order to consider both the maximum value and the damping of the felt disturb.

After formulating some hypothesis about the causes of the disturb, the consequent changes have been really made in the vehicle in order to verify the exactness of hypotheses. Among all the probable causes (resonance of steering shafts, non regular vibrations of suspension, jamming of drive-line) the bench tests have indicated that the disturbances on the steering wheel are generated mainly by inertial phenomena (gyroscopic torque on the front wheel) and may be amplified by a high steering ratio (60 mm/revolution).

The problem has been solved by reducing the propagation of disturbance to steering through a different pump for the power steering system able to maintain constant the oil flow with the revolutions of the engine.

The same tests have been made again using another car available on the market with the same typology of suspension on the front (double wishbone); the bench results have shown that the disturbance on the steering wheel seems to be sensibly reduced.

In order to better understand the phenomenon, two full vehicle models of the cars previously tested (including driveline, steering-line, front, rear and engine suspension units) have been created by ADAMS. They reproduce the same manoeuvre performed on the bench. The model validation, by comparison with experimental data, has guaranteed the reliability of numerical results and allowed the introduction of variations to the original design in order to realize an effective improvement in the vehicle.

The numerical results have confirmed the experimental tests. Moreover, a parametric study has been made in order to identify the variable to check during the design of a new front suspension. Based on the simulation results, design suggestions have been made for further vehicle improvement.

3. Experimental trials

The Flat Trac® Roadway Simulator has been used to perform a manoeuvre able to reproduce the undesirable vibration of the steering wheel. The Flat Trac® Roadway Simulator (fig. 1) is a laboratory-testing machine for automotive performance measurement. It allows most manoeuvres that are conducted on a real test track to be performed indoors, but with more control over repeatability and measurement. The FTRS consists of four flat surface roadway units, each one positioned beneath each tire of a fixed vehicle. Each flat surface roadway unit can present an independent speed and direction to each tire of the vehicle. The system measures the handling characteristics of a running automobile. All four-roadway units are coordinated so that the surface they present to the vehicle is equivalent to a rigid plane, possessing a horizontal velocity vector and instant turning center. The system can also test the vibration and durability characteristics of an automobile due to driving on rough roads; for this reason each roadway unit can be also moved vertically by a hydraulic cylinder at speeds sufficient to simulate the effects of the road roughness. The vehicle is fixed in the horizontal plane and free in the normal suspension directions of vertical, pitch and roll. The control system in the FTRS is responsive enough to perform not only steady state testing manoeuvres, but also dynamic testing manoeuvres. The vehicle is driven either by a human driver or by an autopilot. The autopilot is capable of manipulating all the driver's inputs for the vehicle including throttle, brake, clutch, gear selection and steering.

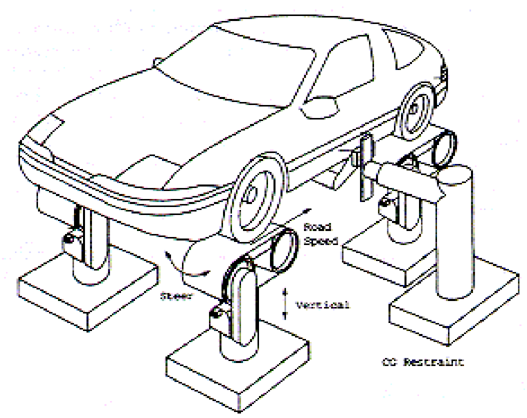


Figure 1, Elements of Flat Trac Roadway Simulation

The manoeuvre considered particularly meaningful in order to reproduce correctly the disturbance on the steering wheel is the following (fig. 2):

- Initial steady state condition
  - Vehicle speed = 120 kph
  - Steering wheel angle = 45deg
- Vertical input given to actuators
  - Vertical displacement = -25 mm
  - Actuation time = 2 s

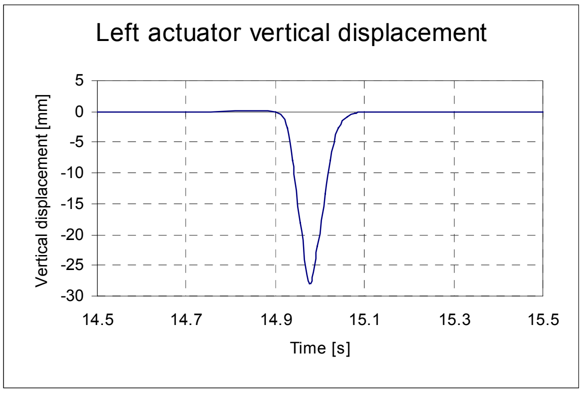


Figure 2, Vertical input given to actuators

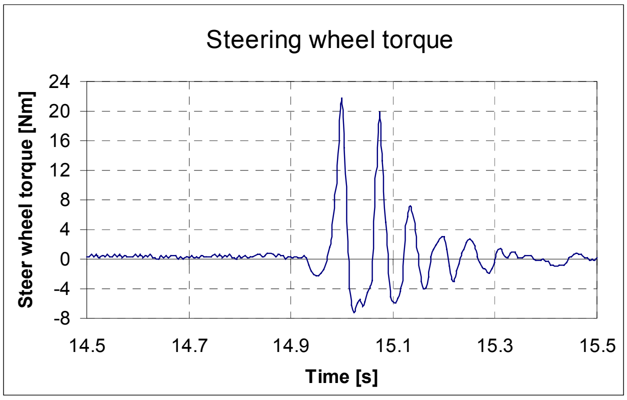


Figure 3, Autopilot's steering wheel torque

The vertical input is given first symmetrically and then separately to the two front wheels.

The first analysed car (Car A) has a double wishbone suspension on the front, macpherson suspension on the rear and power assisted steering system.

The steering wheel vibration is evaluated by locking the steering wheel and measuring the autopilot's reaction steering wheel torque (fig. 3).

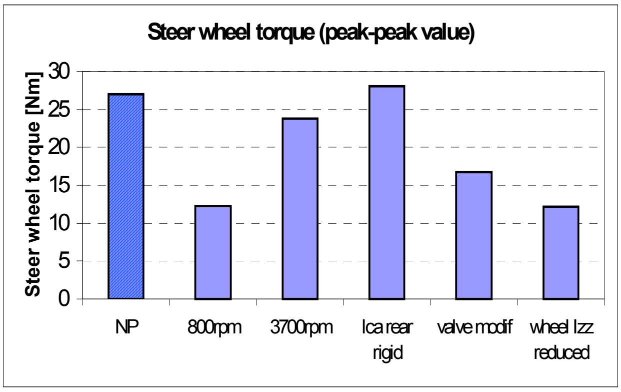
In order to identify the probable causes of the disturb, some hypotheses have been formulated. Among all the probable causes (resonance of steering shafts, non regular vibrations of suspension, jamming of drive-line) the bench tests have indicated that the disturbances on the steering wheel are generated mainly by inertial phenomena (gyroscopic torque on the front wheel) and may be amplified by a high steering ratio (60 mm/revolution).

Excluding the tests that haven't provided considerable results, the useful information made out of the test plan is synthesised as it follows (figg. 4,5):

3.1 Inertial causes (mainly gyroscopic torque)

- Decreasing the inertial moment of unsprung mass (using on the front axle two spare wheels with smaller inertial moment) the disturb is sensibly reduced respect to the normal production configuration;
- The disturbance is maximum when the vertical input is given to the external wheel (unloaded wheel);
- Changing the vertical input given to the actuators of the bench simulator, in particular fixing the vertical displacement (25mm) and decreasing the vertical acceleration from 9g to 3g, the disturb is sensibly reduced. This indicates that the problem depends on the velocity of camber variation rather than camber variation;
- Performing the same manoeuvre (same vertical input) at different vehicle velocity, the steering wheel vibration increases linearly with the velocity.

It has been possible to perform the last two tests because on the FTRS the vertical dynamic is uncoupled with the longitudinal motion (and so with the vehicle speed) despite of what happens on the real road.



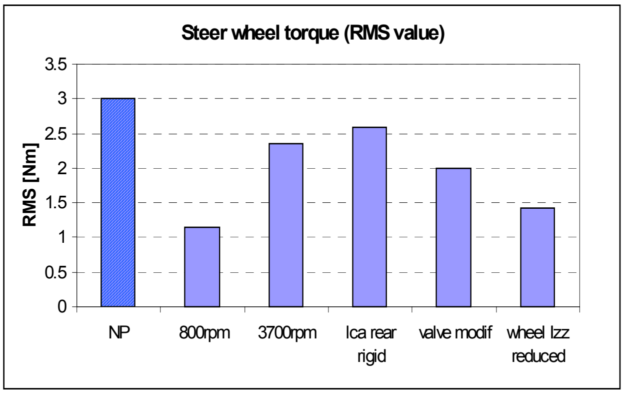


Figure 4, Bench results for Car A (peak-peak)

Figure 5, Bench results for Car A (RMS value)

3.2 High flexibility of rear bushing of the lower control arm

- Substituting the original bushing with more rigid, the disturb one doesn't improve in terms of peak-peak value but the phenomenon is sensibly more damped (RMS of the signal is smaller). This means that the phenomenon is under-damped because of the excessive flexibility of the analysed bushing.

3.3 Optimisation of power assisted steering system

- The high steering ratio due to the power steering system amplifies the disturb;
- Before going on it is useful to notice that the FTRS can work in three different operating modes: 1) <u>*road load*</u>: the auto pilot controls the entire vehicle driver's inputs; 2) <u>*road speed*</u>: the vehicle speed is independent of driving inputs; 3) <u>*belt speed*</u>: the four flat roadway speed are independent of driving inputs. In the last two cases the tyres are driven through the roadway belt by four hydraulic engines. It has been performed a manoeuvre first at 120kph in 5[a] gear and 3700 rpm (road load mode) and then at 120kph in neutral gear and 3700 rpm (road speed mode). Between these two tests there is no appreciable difference in terms of peak-peak value although the steer wheel vibration is more damped. It probably occurs because of different tire forces since in road speed mode there is hardly any longitudinal slip. So performing the manoeuvre at 3700 rpm (the level of assistance minimum) the disturb is maximum. On the contrary repeating the manoeuvre at 800 rpm (the level of assistance maximum) the disturb is sensibly reduced. These tests indicate that the phenomenon is certainly influenced by the power steering system.
- Using a particular control valve on the pump able to maintain the level of assistance constant (constancy of oil flow) with the revolution of the engine, the undesirable vibration of the steering wheel decreases considerably.

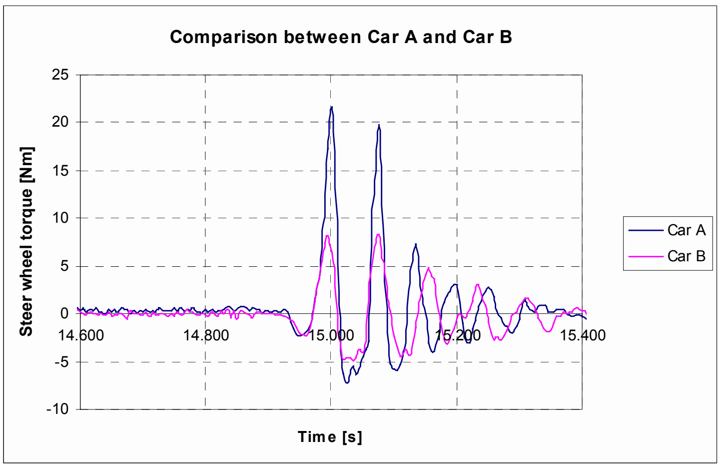


Figure 6, Comparison between the experimental results of the two cars

In order to verify that the steering wheel disturb is not due to the typology of front suspension but to this specific instance, the same tests have been made again using this time another car available on the market (Car B) with the same typology of suspension on the front (double wishbone). The bench results have shown that the disturbance on the steering wheel is sensibly reduced respect to Car A (fig. 6).

4. Modelling and numerical simulation

In order to study the phenomenon in detail, two full vehicle models of the cars previously tested have been created using Adams/Car. The two models are complete with the body, engine, driveline, tyres, front, rear and motor suspension units as well as all their inertial and elastic properties (fig. 7). They have been used to reproduce virtually the same test performed on the test bench.

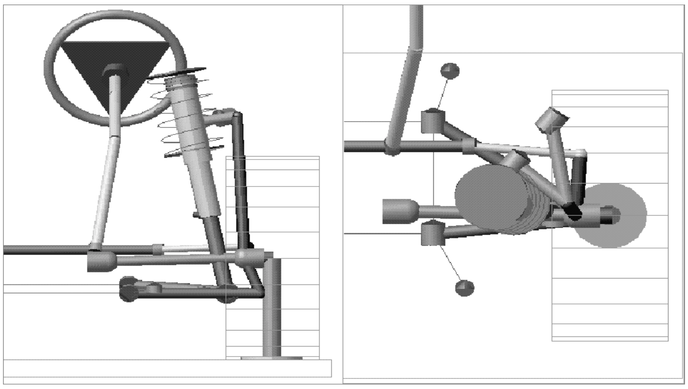


Figure 7, Double wishbone front suspension and steering system of Car A

Before going on it has been verified (using the Car A), the reliability of the model by comparing experimental and numerical results (fig. 8). The differences between them (above all in terms of RMS value) can be justified considering that the inertial and damping property of the steering system (steering wheel, steering shaft and hydraulic behaviour of the power assisted steering) is not exactly reproduced in the model. However the two signals are in good accordance and the model can be considered validated.

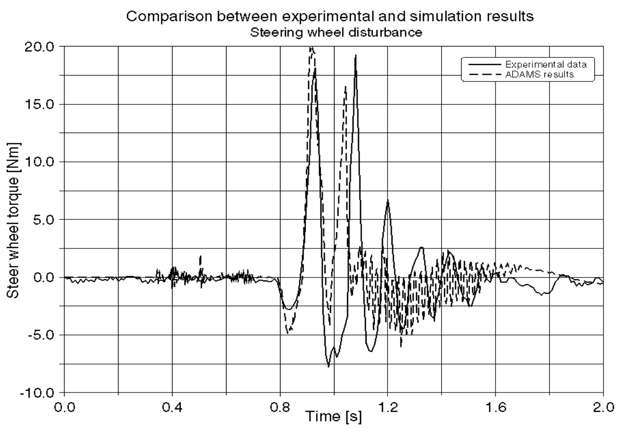


Figure 8, Experimental and ADAMS results

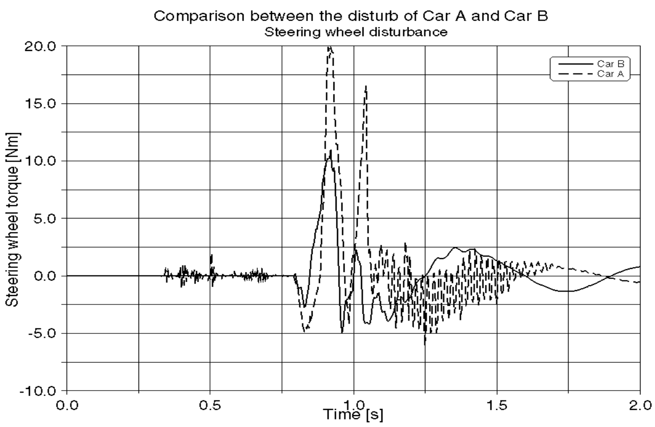


Figure 9, Comparison between Car A and B

Repeating the analysis also on the Car B, a comparison has been made between the two cars: as in the experimental tests, also this time Car B has shown a behaviour about steering wheel vibration clearly better than Car A (fig. 9).

This result confirms the hypotheses formulated on the bench: the disturb is due to gyroscopic causes. In fact during the manoeuvre Car B has a camber variation similar to Car A but the velocity of camber variation is decidedly smaller than Car A (fig. 10). As the gyroscopic torque depends directly on this angular velocity, according to the equation

$$\vec{M} = I\omega \times \dot{\Omega}$$

(where M is the gyroscopic torque around the vehicle vertical axis, $\dot{\Omega}$ is the velocity of camber, I and ω are respectively the inertial moment and the angular velocity of wheel)

it is possible to conclude that the disturb for Car B is less evident as the gyroscopic torque is smaller.

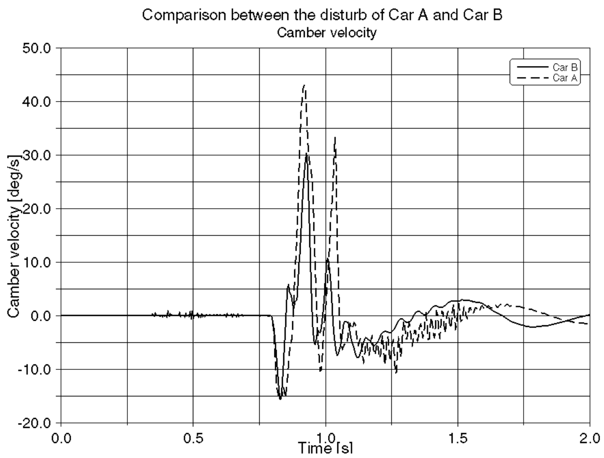


Figure 10, Comparison between camber velocity for Car A and Car B

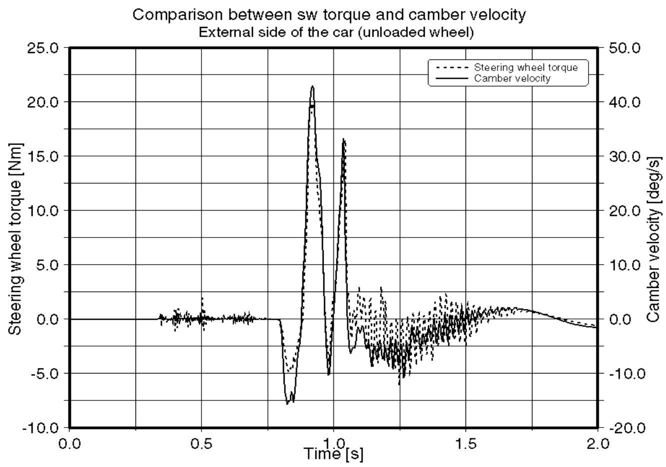


Figure 11, Analogy between SW torque and camber velocity

Moreover, comparing the camber velocity of the two front wheels of Car A, it is possible to notice that the shape of the curve relative to internal wheel (unloaded wheel) is the same as the steering wheel disturb (fig. 11). This confirms the experimental results in which the steering disturb is influenced greatly by the unloaded wheel; it probably occurs because for the loaded tyre the bumpstop works obtaining in this way a more rigid suspension with smaller wheel displacement.

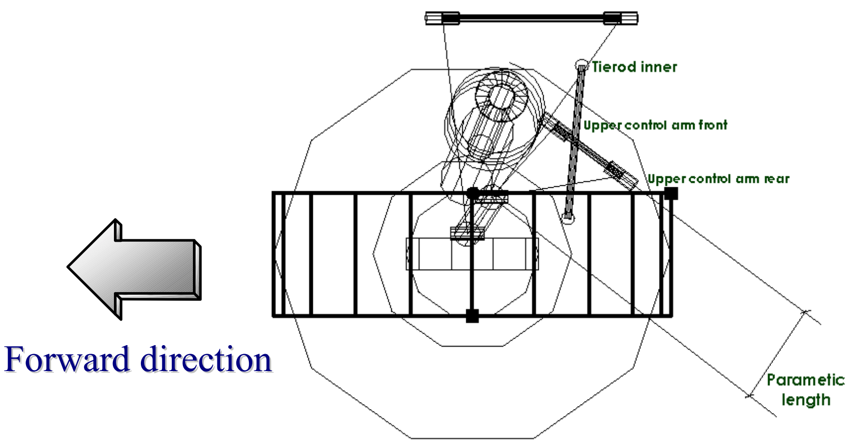


Figure 12, Parametric model of front suspension

At last, it has been created a parametric model of the front suspension of Car A in which it is modified the length of upper control arm (fig. 12). This change is obtained by moving parallelly along y-axis the two points: upper control arm front and rear. This obviously varies both the camber and the toe-in. In order to study the influence of camber independently from the effect of toe-in, it has been moved the position of tierod inner (according to a cubic function) maintaining the toe-in variation constant and independent from upper arm length. Performing the same manoeuvre and increasing the upper arm length, the camber velocity and consequently steering wheel vibration decrease (fig. 13).

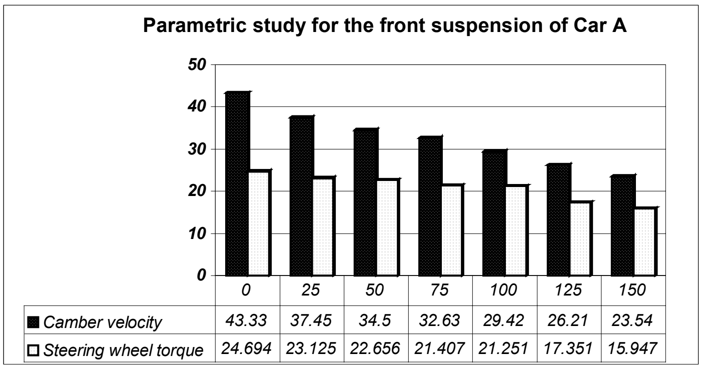


Figure 13, Parametric study for the upper arm length

5. Conclusion

All the tests made, both experimentally and virtually, have indicated that the disturbances on the steer wheel are generated mainly by inertial phenomena (gyroscopic torque on the front wheel) and may be amplified by a high steering ratio. In order to reduce the undesired vibration of the steering wheel it is surely useful to check the velocity of camber variation by designing double wishbone suspension with less difference between upper and lower control arm. Moreover, since the problem is influenced greatly by rebounding wheel while the handling by the loaded tyre, it is possible to optimise the suspension without prejudicing the handling behaviour: it is enough to design a suspension in such a way as to have a small camber variation in rebounding.

If the design restraints don’t allow to modify the architecture of suspension, it is possible to set up the power steering system in such a way as to make gyroscopic effects not so evident to steering wheel. In this way, the problem is not really solved but the automobile is certainly acceptable for both the handling and the comfort level.