DEVELOPMENT OF A SEMI-ACTIVE LATERAL SUSPENSION FOR A NEW TILTING TRAIN

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ABSTRACT

Fiat Research Centre has recently analysed, for a new tilting train, the potential of a semi-active lateral suspension in improving lateral comfort at high speed and during curve transitions.
The paper shows some preliminary results of this numerical investigation and, in particular, highlights the usefulness of integrating a control system design tool, like MATLAB, together with a tool for railway vehicles simulations, ADAMS/Rail. In fact the development of the semi-active lateral suspension requires to analyse the interaction of this system with other on-board controlled systems (tilting system and active hold-off device).
ADAMS/Control module has been integrated in ADAMS/Rail to manage both mechanical and control environments. User-defined irregularities, previously calculated by an external code, have been used for irregular track simulations, with independent spatial displacements on each wheel-set.
Performed analyses carried out with ideal continuos and discrete semi-active systems have given good results, if compared with the performance of a traditional passive secondary suspension.
Further analyses have to be carried on, mainly for developing adequate control algorithms able to manage the critical problem of the commutation-time in real semi-active dampers.

INTRODUCTION

Under competition from other forms of transport, railway operators are seeking to offer their passengers ever-increasing train speed and comfort.
It is known that considerable improvements to train speed and passenger comfort could be obtained by the use of full-active suspensions, in which the energy flow in the suspension is controlled and augmented by an external source, using a technology similar to the one developed in the automotive world.
It is also known that the performance of a semi-active suspension system, in which the energy flow in the suspension is controlled but not augmented, is much better than for a passive system and can approach the performance of a full-active suspension. Moreover semi-active systems are much less complex and hence potentially more reliable: so, they would seem to fit in with railway operators' requirements for very long service life, reliability and low maintenance.
Fiat Research Centre (*CRF*) has recently analysed, for a new tilting train, the potential of a semi-active lateral suspension in improving lateral comfort at high speed (> 150 km/h) and during curve transitions. In fact the target of this railway vehicle is to run at 225 km/h on existing infrastructures while offering high ride-comfort levels.
The new train will be provided of 3 different controlled systems: the tilting system, the *hold-off device* (HOD) and the Active/semi-active Lateral Suspension (ALS) itself. It is quite clear that the presence of these controlled systems requires a deep investigation for understanding their reciprocal interaction in dynamic conditions.

The paper shows some preliminary results of this numerical investigation and, in particular, highlights the usefulness of integrating a control system design tool, like MATLAB, together with a powerful tool for mechanical motion simulation, ADAMS.

MODELLING THE TRAIN

A complete model of a passenger coach has been developed in ADAMS/Rail 9.04.

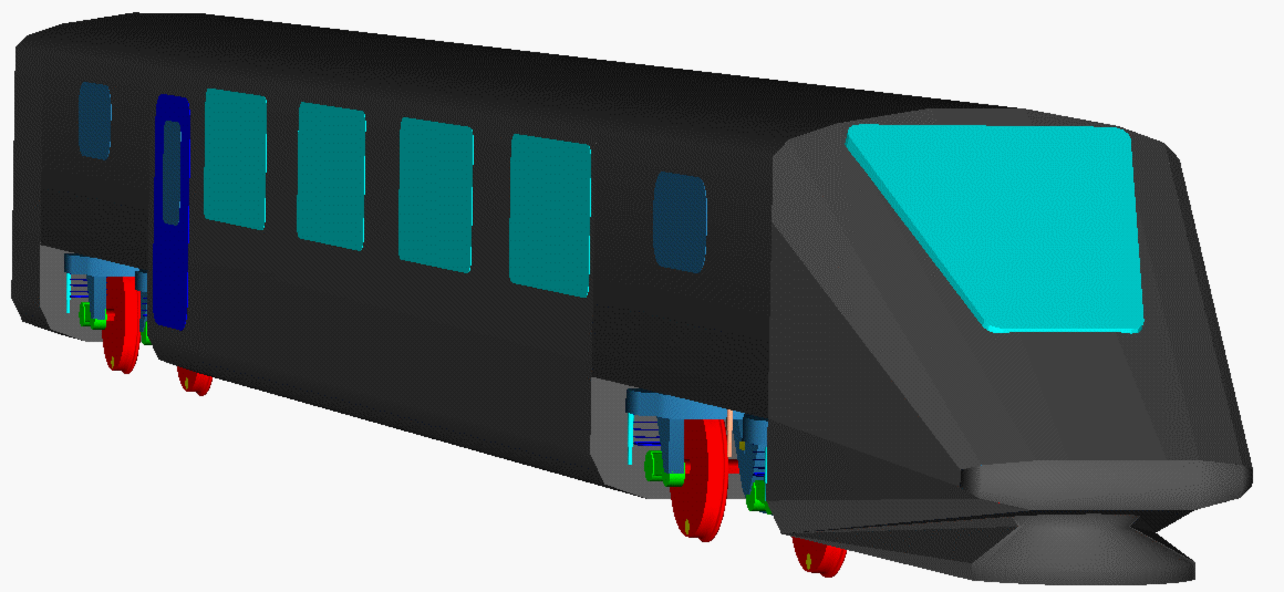

Figure 1 - ADAMS/Rail model of the new tilting train.

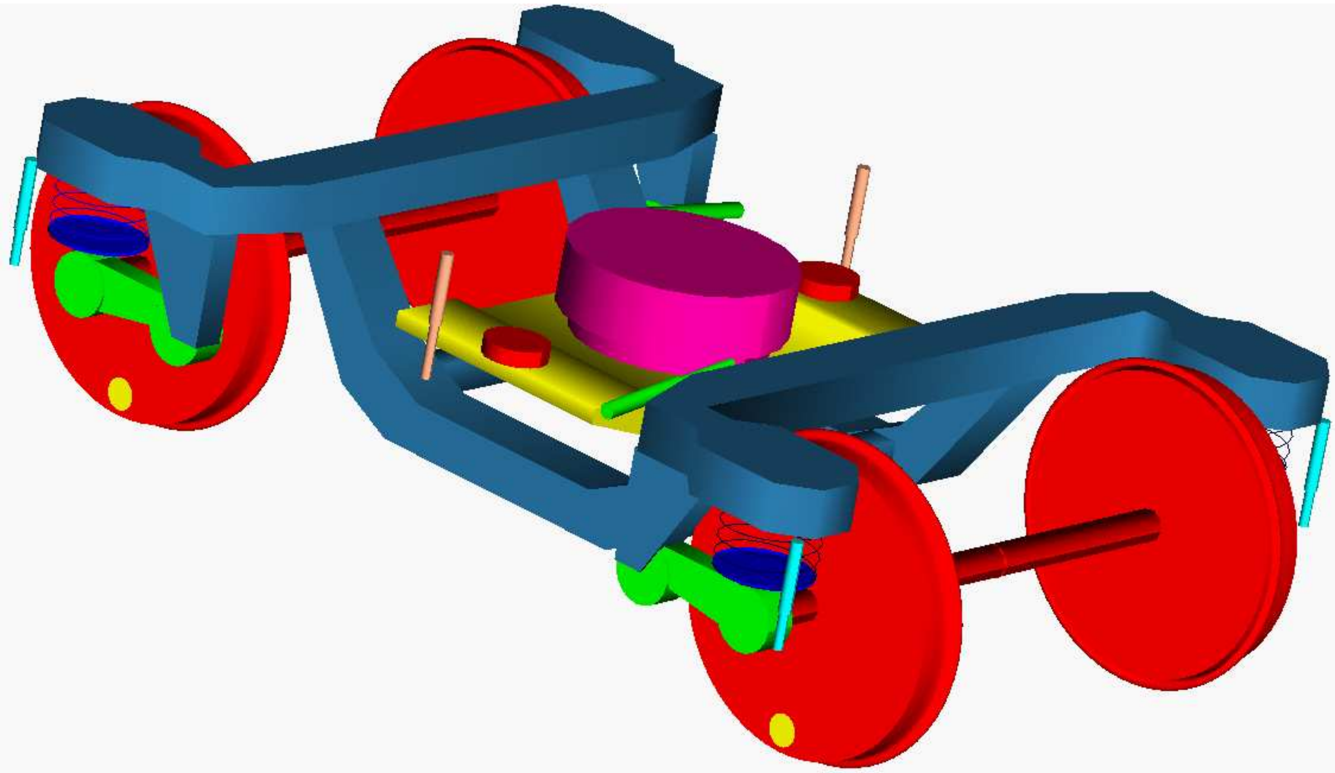

Figure 2 - ADAMS/Rail model of the bogie.

The vehicle model consists of a rigid car body, suspended on bogies having a central air-spring (with non-linear characteristics).

The air-spring lies on the tilting bolster, that is linked to the bogie through a particular mechanism (modelled as a PTCV joint) simulating the tilting system.
The secondary suspension of each bogie is completed with :

- Two vertical passive dampers with non linear characteristic
- Two transversal passive (or active or semi-active) dampers with non linear characteristic
- Two longitudinal passive dampers with non linear characteristic (anti-yaw system)
- Two active actuators (Hold-off device)
- Lateral bumpstops with non linear characteristic

The bogie is linked to wheelsets through the primary suspension, which is made by :

- Four arms linked to wheelsets and to the bogie through non linear bushings.
- Four vertical dampers and four springs with non linear characteristics

Figure 1 and Figure 2 show the complete model of the coach and the bogie.
All analyses, both on curved-track and on irregular straight-track, have been made using rail-wheel contact method "Level 1" of ADAMS/Rail (analytic macro-geometry, no wheel-rail contact forces).

Irregular straight-track analyses

Straight-track analyses have been made using two different types of irregularities:

- standard irregularities, according to ORE176 "Small defects" track
- user-defined irregularities, previously calculated by MODKAT code, passed to ADAMS solver by means of a dedicated user-subroutine; the subroutine provides a set of 6 spatial displacements on each wheel-set, allowing a simulation with *an independent generalised-motions on each wheel-set*

Straight track simulations have been made at high speed (225 km/h) to analyse the lateral behaviour of the train and to investigate the potential benefits of a semi-active system on the lateral ride-comfort.
The RMS value of weighted lateral acceleration (as calculated by ADAMS/Rail post-processor, according to ISO 2631) has been used as lateral comfort index on straight track; the corresponding accelerations have been calculated on the body in three different positions:

- Body floor above front bogie
- Body floor above rear bogie
- Body center of mass

Curved-track analyses

An ideal curved track has been used to analyse the dynamic behaviour of the train on curve entry and exit transitions. The following table summarises the main data of this manoeuvre.

Ideal Curve Manoeuvre	
Curvature Radius (m)	320
Elevation (mm)	150
Curve junction length (m)	60
Curve length (m)	600
Velocity (km/h)	115
Non-compensated lateral Acceleration (m/s^2)	2.0

The peak value of the lateral non compensated acceleration (A.n.c.) has been selected as lateral ride-comfort index for curving manoeuvres; it has been evaluated on the car body in the same positions as in straight-track analyses.

MATLAB/ADAMS INTEGRATION

The development of the semi-active lateral suspension requires to analyse its interaction with the other on-board controlled systems (tilting system and hold-off device). This involves the development of a complex mechanical model and, in the same time, the development of a globally complex control system. Therefor it is evident the advantage of having an integrated environment allowing both time-domain analyses of the mechanical system and control design analyses of all controlled systems.
Finally, the following analysis environment has been chosen:
ADAMS/Rail 9.04 : for modelling the mechanical system and for dynamic simulations.
MATLAB 5.2: for control system analysis.
ADAMS/Controls: for on-line integration of both simulation tools, where ADAMS/Rail model is included as SIMULINK super block.

Two different modes of simulation are possible with ADAMS/Controls:

- Function evaluation mode (continuos) in which an overall integration is performed in the control environment
- Co-simulation mode (discrete) where both systems use their own solvers. This mode has been finally chosen by CRF.

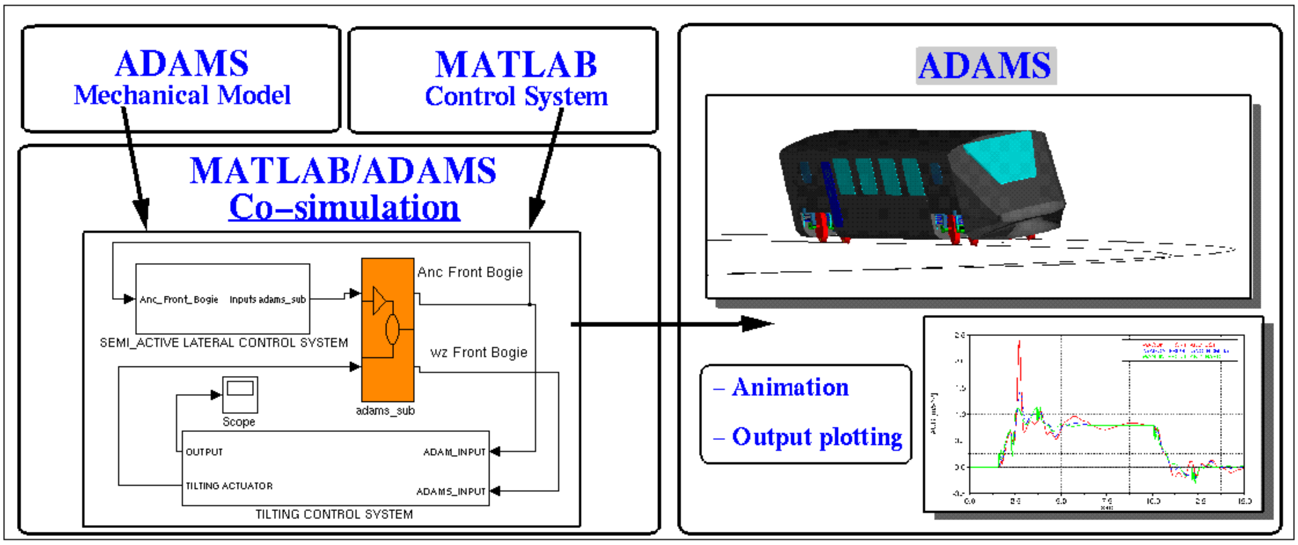

Figure 3 - Operative flow of ADAMS/Rail and MATLAB combined simulation.

Some additional analyses have been performed in order to compare the results obtained from a combined simulation towards the results from a pure ADAMS/Rail simulation. Analyses have underlined the importance of choosing a low ADAMS output-step value (low delta-time) to obtain good results from combined simulation.
Another important aspect of the co-simulation is the total CPU time: using the same control system, it has been assessed that the calculation time for an ADAMS/MATLAB *combined simulation is about 20÷50% larger than for the corresponding ADAMS pure simulation*.

According to the different complexity of the three control systems, it has been decided to develop the tilting system and the semi-active suspension system in MATLAB, while the hold-off device has been modelled using appropriate ADAMS statements.

TILTING SYSTEM

The tilting system allows the train to run a curve at high speed without compromising lateral comfort. In fact, thanks to this system, during a curve the body tilts so as to reduce the non-compensated lateral acceleration.

In early analyses, the electrical tilting system of this new train has been modelled directly in ADAMS in a simplified manner. Successively it has been reproduced in MATLAB in a very detailed manner, very close to the real control system.

The selected tilting algorithm uses the following feedback signals from mechanical model: the front bogie A.n.c., the front bogie yaw velocity (ωz) and the train velocity.

Using these parameters, the algorithm calculates the appropriate tilt-angle and corresponding linear displacements, which have to be applied to the translation joints in the mechanical model.

Fig.4 shows the tilting system block scheme, where it is possible to see the connections with the ADAMS block.

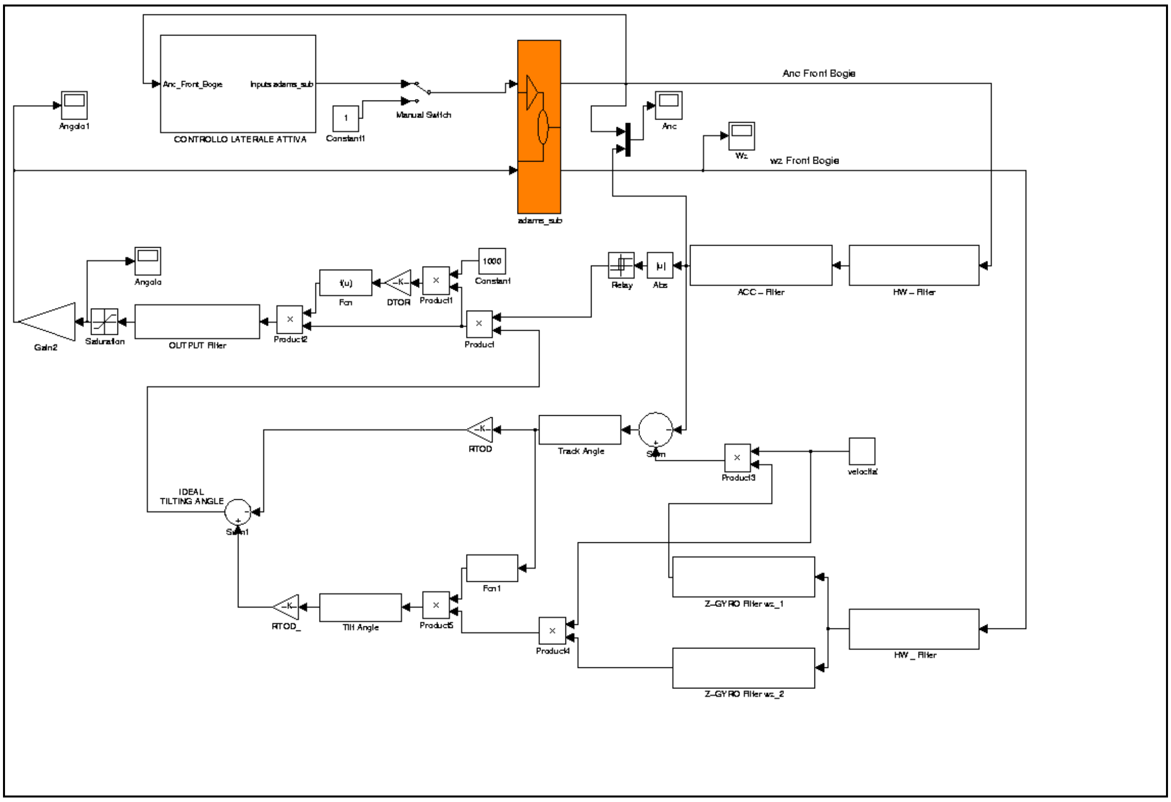

Figure 4 - Block scheme of tilting control.

Optimised tilting law

The tilting control has been analysed with simulations on the above mentioned ideal curve: the influence of tilting system on the transient response of body has been deeply investigated and finally CRF has found an optimal control law for improving the lateral comfort during curve transition.

Performed analyses have shown the importance of having an *early and smooth tilting action for avoiding the contact between body and bumpstops*.

Figures 5 and 6 show the results, in terms of A.n.c., with two different tilting laws.

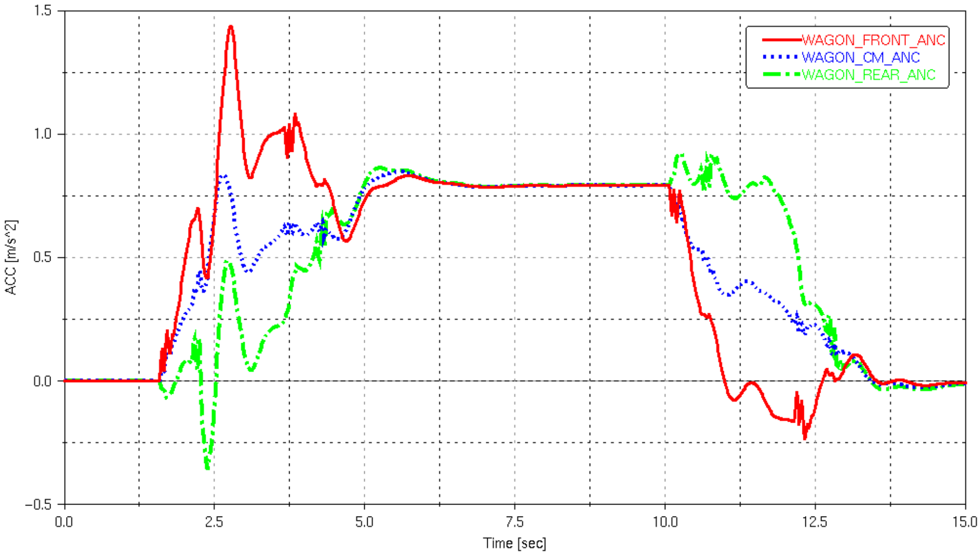

Figure 5 - Body later acceleration with <u>original</u> tilting law.

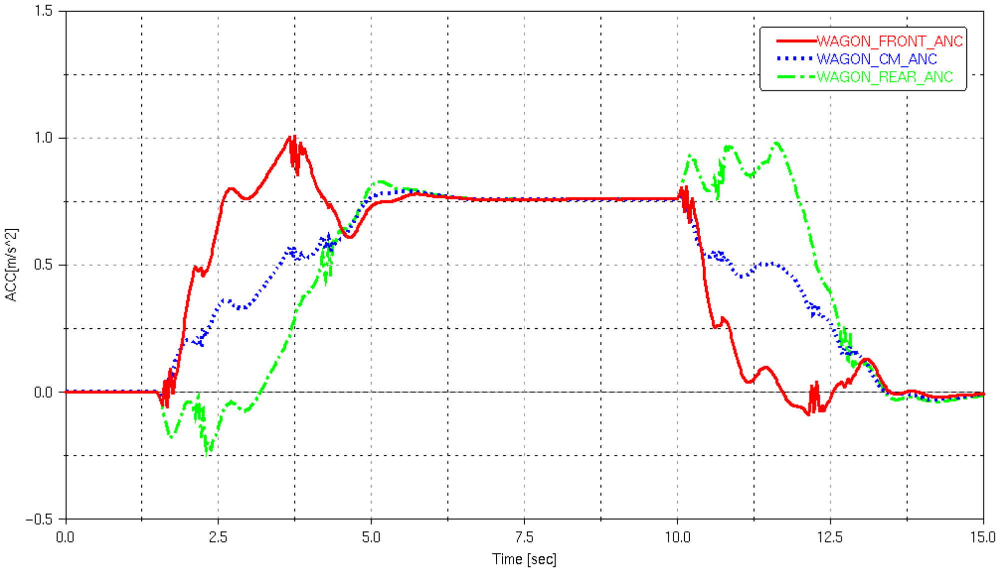

Figure 6 - Body later acceleration with <u>optimised</u> tilting law.

CONTROLLED LATERAL SUSPENSION

The lateral suspension consists of two separate controlled systems:

- the hold-off device (HOD), which is a slow-active positioning device, based on pneumatic actuators, intended to react centrifugal forces during curve manoeuvres, thus reducing the quasi-static lateral displacement of body and also avoiding undesirable contacts with bumpstops.
- the semi-active lateral suspension (ALS), consisting in two fast-controlled hydraulic dampers, placed across the secondary suspension of each bogie, near the central air-spring.

While the HOD is intended to reduce only quasi-static body movements in curve, the ALS systems is a middle/high frequency device intended to control body movements in the frequency range up to 2 Hz, both in curve conditions and, especially, in straight at high velocity.

Active Hold-Off Device

The HOD consists of two actuators per bogie connecting the body with the tilting bolster. These actuators provide a force that has to react the centrifugal force and, therefor, is proportional to body A.n.c. So the system has a closed-loop control feeding back the bogie A.n.c. Then this signal is appropriately elaborated in order to estimate the corresponding body A.n.c.

Thus, for each bogie, the analytic expression of the HOD force is :

$$F = (K * A.n.c.)$$

where K is a proportional constant. Due to the simplicity of this control law, it has been implemented directly in ADAMS using appropriate statements.

Several analyses have been performed in order to investigate the benefits of various HOD control strategies and, mainly, to understand the influence of this device on the overall dynamic behaviour of the train. The results show that the benefits of HOD action are tightly related to the actuation time. While a slow actuator can be useful only in stationary curves for maintaining the relative body-bogie central position, a quite fast actuator could be conceptually useful also during curve transitions.

Apart from the eventual benefits during curve transitions, analyses have shown the necessity of HOD on this train for avoiding bumpstop contacts during stationary curves. Figure 7 shows the simulated lateral displacement of front secondary suspension on curve transition, with/without hold-off device: in the second case the suspension displacement widely exceeds the threshold of bumpstop contact during most of curve duration, clearly resulting in considerable worsening of ride-comfort levels.

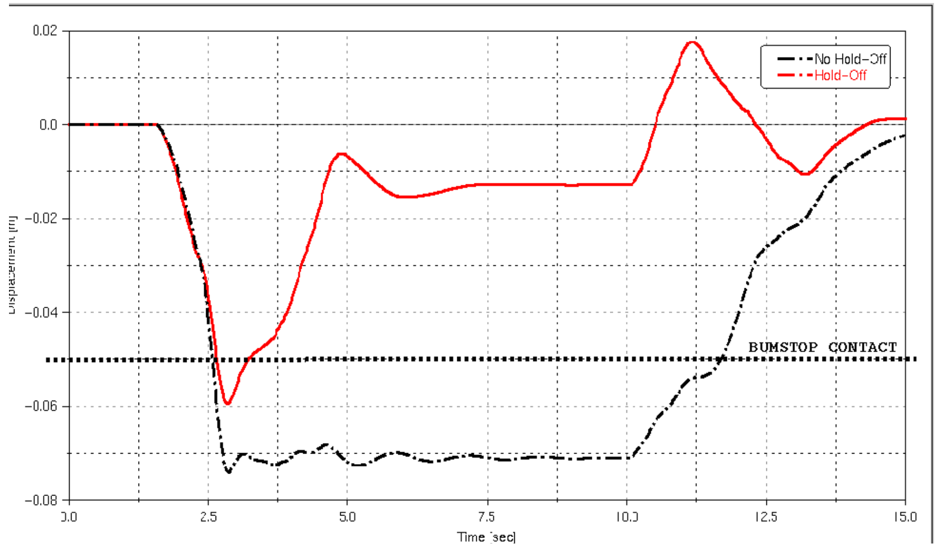

Figure 7 - Secondary suspension lateral displacement with/without Hold-off Device

The frequency response of the secondary suspension, in presence of the stiffening contribution of lateral bumpstops, has been analysed by means of ADAMS/Linear module. Figure 8 shows the scheme of the frequency response analysis (FRF): a force is applied on the bogie as system input and the resultant body displacement is evaluated as output. This force-displacement transfer function is clearly worse (higher) without HOD, due to the contribution of lateral bumpstops in increasing the overall lateral stiffness of secondary suspension.

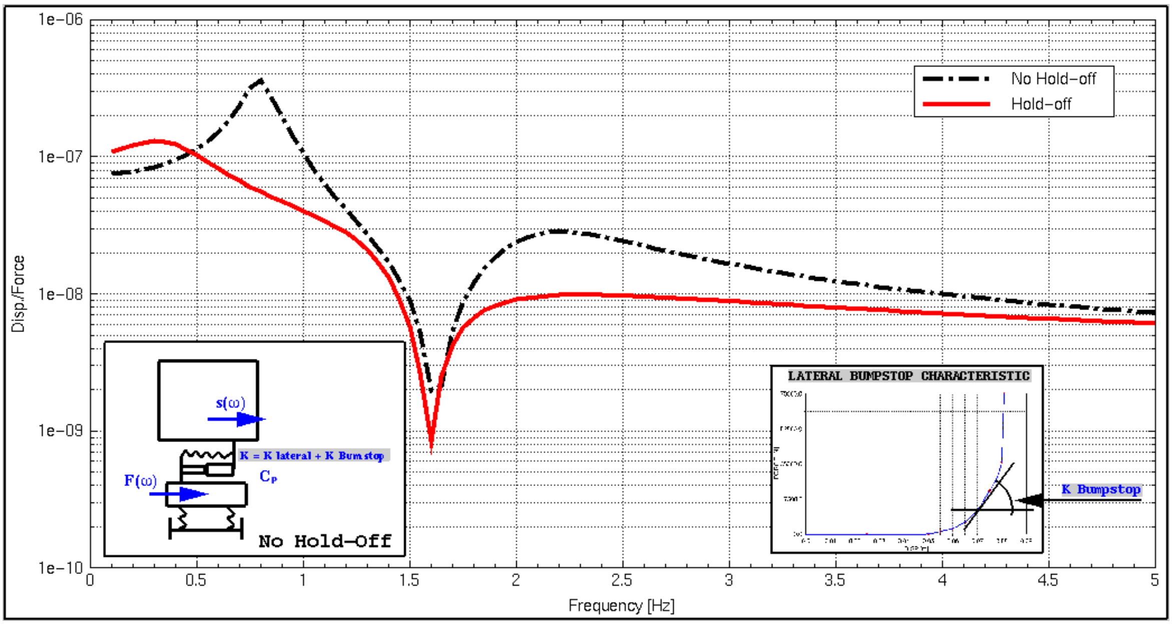

Figure 8 - Secondary suspension isolation with/without hold-off device (Displacement/Force FRF)

Semi-Active Damping System

The semi-active control system has been developed according to the *skyhook strategy*. Following this well-known theory, the controlled damping force is proportional not only to damper stroke velocity (as in passive shocks) but also to the absolute velocity of the suspended mass (body). In other words, while the damping force in passive system is :

$$F_{damper} = C_p * V_{rel}$$

the damping force in the active system becomes:

$$F_{damper} = C_p * V_{rel} + C_{sky} * V_{abs}$$

This force consist of a passive term, which purely dissipates energy, and an active term that can be different from zero even when damper stroke velocity is zero. In this case the system needs an external energy supply.

The ideal semi-active implementation of the previous expression is:

If $(F_{damper} * V_{rel})>0$, then $F_{damper} = C_p * V_{rel} + C_{sky} * V_{abs}$
If $((F_{damper} * V_{rel})\leq 0$, then $F_{damper} = 0$

The control law and the dynamic model of actuators have been implemented in MATLAB environment. Then the potential benefits of the ideal full-active and semi-active lateral system has been analysed by means of co-simulation.

Semi-Active Strategy in Straight.

In straight-track conditions the skyhook strategy has given good results with respect to the passive system. However, for the optimisation of the system performance, it has been necessary to find optimal values for C_p and C_{sky} coefficients.

Therefor a frequency response analysis has been performed on the complete ADAMS/Rail model, with the scope of optimising the control law coefficients for active strategy (Figure 9).

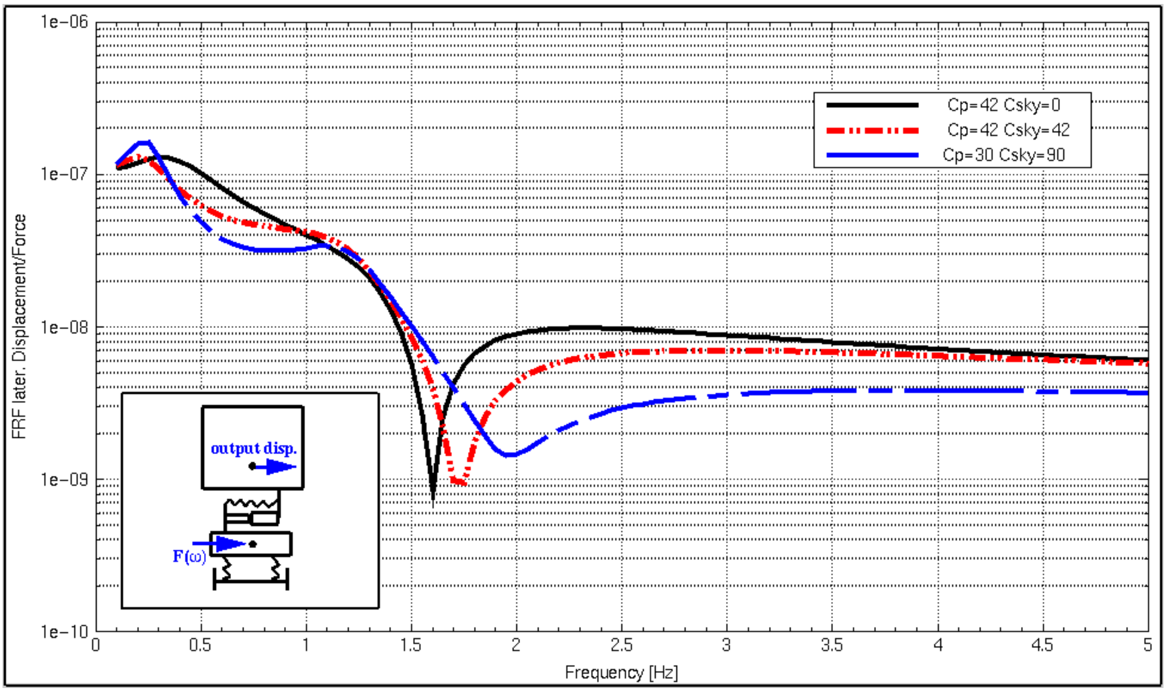

Figure 9 - Optimisation of control law coefficients C_p and C_{sky} for active strategy.

After choosing the coefficient C_p and C_{sky} with linear analyses, several control strategies have been implemented and tested with time-domain simulations using irregular straight-track profile at high speed.

Particular attention has been given to the most promising semi-active dampers which are today under development by European manufacturers of railway shocks:

- Continuos variable dampers
- Discrete 3-steps dampers

Each of these components requires a different control strategy. The main difference between these two kinds of damper is that, while the continuos one can vary its force-velocity characteristic from a lower curve to a higher curve with a large number of intermediate levels, the discrete controlled damper has only 3 force-velocity characteristics. Figure 10 and 11 show the working points on the two semi-active force-velocity characteristics, obtained from a simulation of 20 seconds with irregular straight track input.

Since from a constructive point of view these two controlled dampers are different (e.g. having different servo-valves), also the corresponding commutation times should be expected to be different. But, in any case, first analyses have been performed with the hypothesis of having ideal components, without time-delay during commutation from one characteristic to another.

Therefor, ideal (without actuation-delay) continuos/discrete semi-active systems have been simulated and compared with the passive and the ideal full-active system.

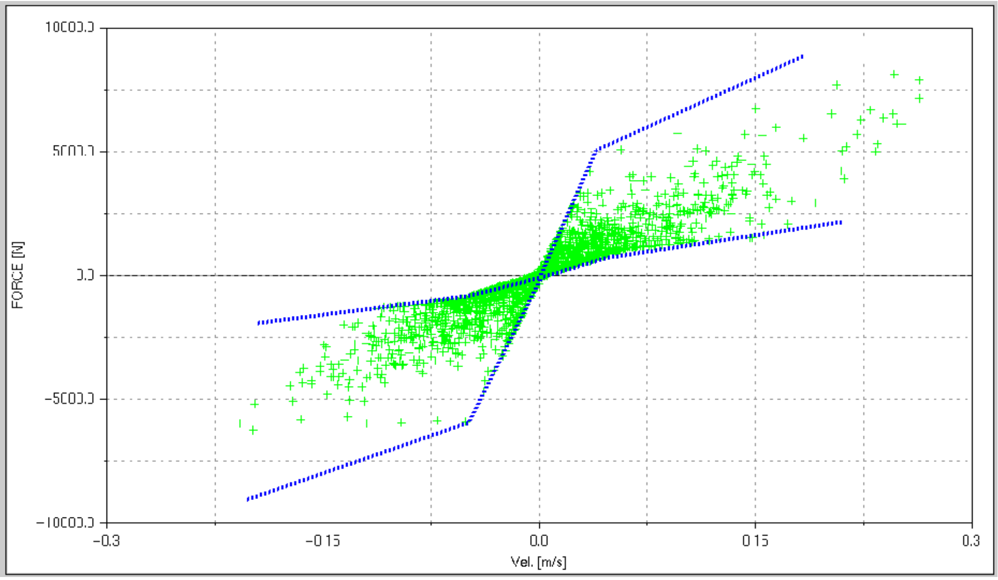

Figure 10 - Working points on force-velocity characteristic for a continuous semi-active damper.

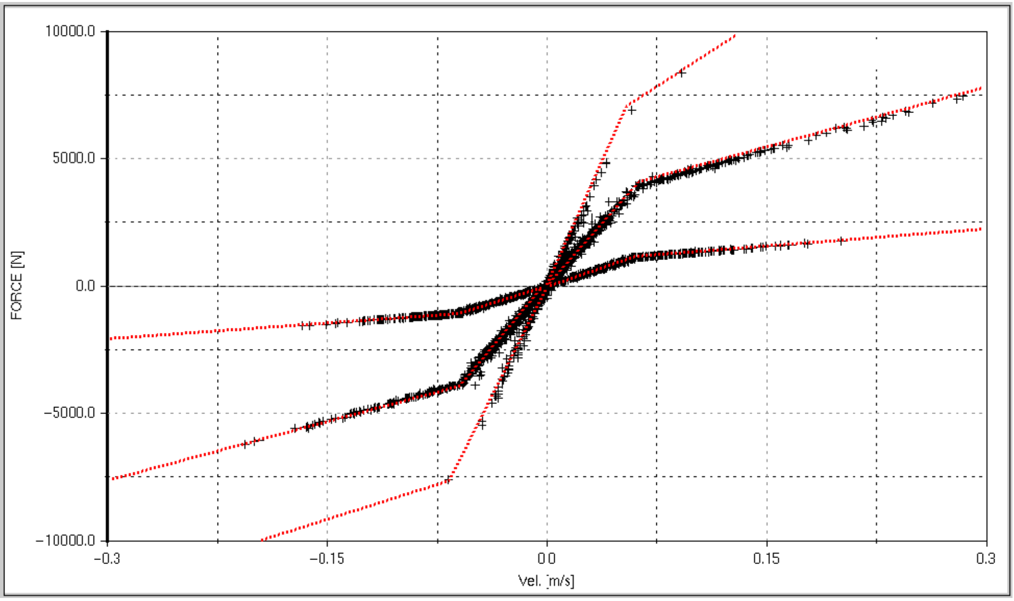

Figure 11 - Working points on force-velocity characteristic for a discrete semi-active damper.

RMS ISO-weighted lateral ride figures have been calculated in three different body positions (front, middle, rear), on irregular straight track with passive, full-active and semi-active lateral suspensions. Obtained results are:

- Improvements of nearly 50% with ideal (no time-delay) full-active system
- Improvements of about 37% with ideal (no time-delay) semi-active system.

The next picture (Figure 13) shows the corresponding spectra (PSD) for above mentioned systems; the results have been obtained after simulations having as input the previously described (user-defined) irregular track.

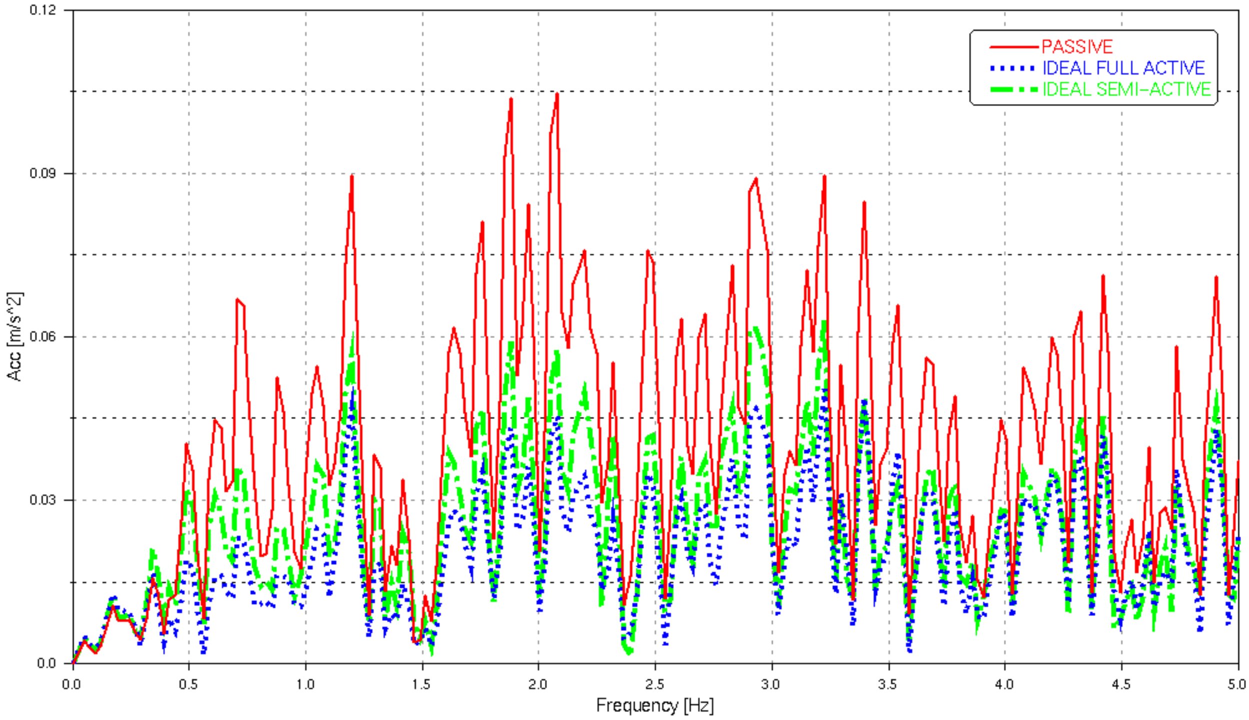

Figure 12 - PSD of responce on irregular track (body lateral acceleration, floor level, front bogie position)

Semi-Active Strategy in Curve Transition.

Some analyses have shown that the *skyhook strategy is not effective during curve transitions*. The reason is quite simple: the basic skyhook strategy aims to control (reduce) the body absolute velocity in spite of other external disturbances; this implies that the corresponding control, during a curve, aims to maintain the body in a rectilinear direction. But, on the other side, the bogie is moving laterally, due to the curved track. Obviously this causes the sudden contact of the body with lateral bumpstops (placed on bogie) and the final result is a worsening in lateral comfort.

This fact suggests the use of other strategies for curve transition. A reasonable idea is, during the curve transient, to keep the body far away from lateral bumpstops by means of an efficient damping action. This force could be provided by a controlled damper with a simple On-Off logic, feeding back the bogie lateral n.c. acceleration.

This on-off strategy has given good results: Figure 13 shows the resultant body behaviour when the damper characteristic is switched from soft to hard, thanks to a simple controller feeding back the bogie A.n.c. signal. In this case the damper with hard characteristic avoids the bumpstop contact and this reduces the overshoot of lateral acceleration, improving comfort.

An interesting aspect of this type of strategy is the *optimal switching time for soft-to-hard transition*. If the transition is too fast (low switching time), the body receives an impulsive force which produces again a peak of body A.n.c.

On the contrary, if an appropriate switching time is used, the damping force becomes smoother and the peak of body A.n.c. due to damper transition becomes much lower (Figure 13).

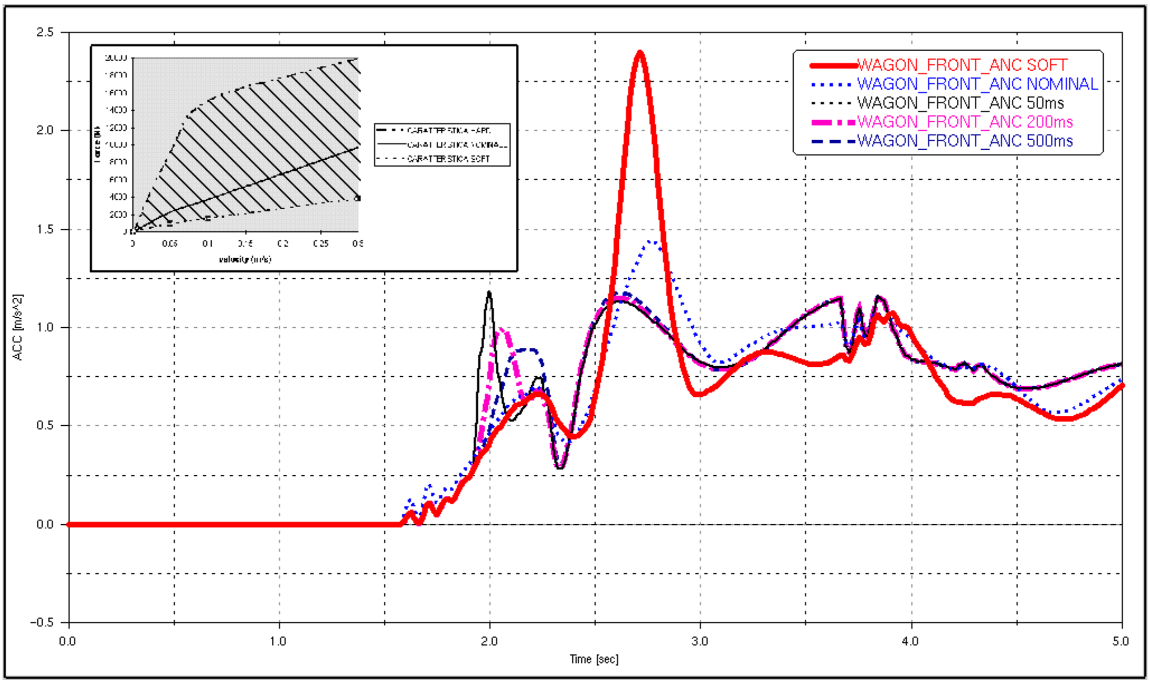

Figure 13 - Body response with different soft-to-hard switching time for semi-active dampers.

In the real system, the problem of switching the damper in a correct time could be critical, especially on the leading coach, where an advance warning of curve transition can not be given. In fact, while on other coaches it is possible to preview the beginning of the curve using transducers fitted in the first coach, on the leading coach the controller can not provide an early damper commutation. So the commutation of controlled dampers can start when the train has already begun the curve manoeuvre.
In this case, it has been assessed that an optimal soft-to-hard switching time has to be found: obtained optimal values are comparable with the time-delay of mid-bandwidth actuators.

CONCLUSIONS AND FUTURE DEVELOPMENTS

Preliminary analyses carried out with ideal (without actuation-delay) continuos and discrete semi-active systems have given good results, if compared with the performance of a traditional passive secondary suspension.
Further analyses have to be carried on, mainly for developing an adequate controller able to manage the critical problem of the commutation-time in real semi-active dampers.
Finally a wide optimisation should be carried out, considering all control parameters and various other vehicle parameters, such as remaining passive dampers, bushings and bumpstops. This could be done by using numerical optimisation techniques and by an extended use of co-simulation method.

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