New developments for tilting trains

Alessandro ELIA / Tilting System Director

Summary

Tilting trains aim to increase service speed on existing conventional lines whilst maintaining an adequate level of ride comfort and obviously in full safety.

This goal can be obtained only through a wide range of product performance improvement:

- tilting system of the train needs to be designed and manufactured according to the most up-to-date technology for electronic, electro-mechanic, communication and sensors
- bogie mechanics, the car body structure and furnishing need to be defined, by the earliest concept phase, in order to be compatible with the required performances.

Furthermore, and as preliminary condition, the tilting train shall be fully competitive in terms of price, LCC, RAMS figures with the existing conventional trains.

The decision of the Customer will be based on the above characteristics and performances, on the additional costs to be planned in order to guarantee the compatibility of the infrastructure and of the maintenance facilities, compared with the expected increase on the final Customer’s demand.

As a consequence, the Tilting System has to be seen as part of a much more complex train’s subsystem, also including bogie concept and calculation, car body structure concept and design, auxiliaries masses and suspensions, damping and transmission characteristic of interiors.

The R&D activity aims to increase performance, in terms of RAMS figures and LCC, and is focused on the most strategic among Tilting Subsystems.

- High Cant deficiency bogies
- TILTRONIX concept and predictive command and control software
- Semiactive lateral suspension
- Active dampers, based on EM actuation technology

As a consequence, the strategic success factor for the Tilting System development and application is a continuous R&D activity, in different directions, aiming in each case to increase performance, to improve RAMS figures and to reduce LCC.

This continuous development activity can be demonstrated through the performances of the new products for EM and hydraulic Tilting train projects (such as West Coast Mainline, Czechia and VR), through the consolidation of experienced solutions (ICE-T, Cisalpino, ICN) and through the development activity of the most strategic amongst Tilting Subsystems:

- High Cant deficiency bogies, tuned according to the required application (narrow curves, high speed, …)
- Hardware configurations flexible to different complexity of applications
- Diagnostic software tunable according to environmental conditions and subsystems’ characteristics
- C&C software predictive or reactive
- Safety issues managed through a dedicated predictive diagnosis
- Semiactive and active subsystems, for improvement of ride comfort.
1. A short Pendolino project history

1.1. The approach, the prototype, first application in Italy and Germany

By late 1960, following the experiences started in France, and contemporarily to the activities in Canada, England and in Japan on metric gauge, the former «Divisione Ferroviaria» of Fiat begun to approach the concept of tilting systems. From day one, the goals of this project were clearly defined: to improve service speed on regional lines, with quite poor track quality whilst maintaining full safety and a comfort level compatible with what was then on offer.

This activity started in Italy around 1966, up to mid 1970, through an analysis of then-existing rules and specifications, the development and tests on tilting devices, and the assessment of development potentiality of light power-distributed rolling stocks.

The first tilting unit was built and tested in early 1970, the first EMU in service, the ETR401 (see slide 1), was delivered in 1975.

The series production of the electro-hydraulic tilting system started in the late 1980s with the ETR450, based on ETR401, with improved traction technology and digital tilting control.

The bogie concept, with minimized masses, hold-off pneumatic system and rod configuration for tilting mechanism, anticipates the actual product configuration of electro-hydraulic tilting. The fleet of 15 ETR450 trains, each of 9 coaches, entered into service in 1988. The total mileage is now more than 35 millions train x km, with about 10 millions passengers.

The VT610, the last product in the line of ETR401/ETR450, was delivered in the early 1990s: it can really be considered, from the viewpoint of tilting and ride performance, to be the best and most advanced product of the line.

1.2. The Electro-Hydraulic Pendolino®

The new bogie was developed in 1991 and the ETR460 train has been in service since 1994. The bogie architecture (see slide 2) is basically unchanged (low weight per axle, low bogie masses, hold-off pneumatic, tilting rods over secondary suspension, distributed power, traction motors suspended underframe), but the following improvements were introduced:

- tilting system totally underfloor
- body bolster simplified connection (four screw groups)
- redesigned axlebox guide
- simplified bogie frame concept

Traction concept and car body design were significantly improved:

- DC/AC traction power systems, designed for bi-current and three-current solutions.
- wider modular carbody, in large extrusions profiles
- pressure tightness, in two different options (pressure-sealed, pressurized)
- tilting concept improvements, for hardware (transmission lines, sensors) and software (diagnostic, tilting signal)

The modular trainset concept allows different trainset compositions and features, which can be adapted according to the customers' requirements; different base modules are available for different compositions:

- Traction unit 2MW for design speed of 200, 220 or 250 km/h (end- or intermediate unit)
- Driving trailer
- Intermediate trailer
- Two-cab traction unit.

The test and service experience in different European countries had very important influences in new products and developments of electro-hydraulic Pendolino®, started by early 1990.
2. The Tilting command concept

See Slide 3: The tilt angle must reproduce the applied Cant Deficiency without any delay. The reference signal is measured through the acceleration of a non-tilting part of the vehicle (bogie frame).
Filtering introduces a delay between the acceleration signal and the starting point of the curve. Since the cut-off frequency is very low, this delay is not acceptable for a comfortable tilting behavior.
An actuation only based on accelerometer readings would ask for unacceptable threshold levels to avoid wrong tilt activation due to high dynamics; this would cause further delays that would more and more compromise the tilt performance.
Therefore, a different sensor type was introduced to have an anticipated signal: a gyroscope, fast-reacting on transition ramps and not influenced by lateral dynamics of the vehicle.
The gyroscope is mounted to measure the roll angular velocity of the bogie frame. During the transition phase, the gyro signal is up, like a step, and the information of curve beginning is immediate.
This information is sent to the on-board computer that starts to tilt following the transition's geometry, through a tuned algorithm. After a short time, the system actuates adding the accelerometer signal.
On the cars following, the reference signal is basically the acceleration, taking advantage of the distance between the vehicles.
3. **Tilting bogies**

The rotation of the carbody on a tilting train is obtained through different kinematic solutions and different kind of actuators as well.

From the point of view of the actuation technology, which is related to the mechanical device able to deliver the tilting force to the carbody, two solutions have been developed by Fiat Industrie Ferroviarie, the hydraulic and the electromechanical ones.

The components, which are part of the electromechanical and of the Hydraulic Tilting Systems, are shown in slides 4 and 5.

### 3.1. **Hydraulic tilting bogie.**

See Slide 4: Four single effect actuators, two for each bogie of the same carbody, are required to rotate the carbody. The Hydraulic Tilting Actuator is a telescopic hydraulic cylinder driven by a hydraulic pump and a closed loop servo-system.

The kinematics mechanism associated with the hydraulic actuation is of «Pendulum» type. The body bolster (blue part), which is fixed to the car-body, is connected through four rods (red part) to bogie bolster (violet part).

The hydraulic actuators (in blue) deliver the forces to rotate the carbody in respect to the bogie.

A tilting vehicle must be able to negotiate curves at higher speed: therefore, the secondary suspension is subject to higher centrifugal lateral force, which would cause high lateral displacements of the carbody. This could have a negative impact on the swept envelope of the carbody and on passenger comfort.

In order to compensate such a lateral displacement, a pneumatic device called «Active Lateral Suspension» acts between bogie frame and bolster, reacting the centrifugal force. This force applied compensates and counteracts the effect of the secondary suspension flexibility in respect to the lateral displacement of the bogie bolster. The force compensation is tuned at optimal value from tare and fully laden charge conditions.

The «Pendulum» kinematics solution allows a very easy stabilization of the pantograph in respect to the catenary: the Pantograph is connected to a mechanical structure suspended on the secondary suspension and it doesn’t tilt.

### 3.2. **Electro-mechanic tilting bogie.**

See Slide 5: The electro-mechanical tilting bogie in existing projects has the so-called “Roller” link between the tilting bolster and the bogie frame associated with the electromechanical actuation.

The tilting bolster (green part) has two inclined sliding guides coupled with two rollers (blue elements). A special profile defines the mathematical relation between the force delivered by the actuator and the tilting angle, in order to optimize the auto-centering of the carbody.

The tilting bolster can rotate clockwise or counter clockwise rolling on two rollers by a tilting angle, up to 8 degrees.

Uplift safety is guaranteed by stops (red elements) between the bogie frame and the tilting bolster.

The Electromechanical Tilting Actuator consists of a planetary roller spindle moved by a brush-less motor (yellow element), which is driven by an Electric Power Unit, which controls, through a closed loop servo system, the rotation of the motor itself and consequently the variable length of the spindle.

Two double effect actuators, each installed on one bogie of the same carbody, provide to rotate every vehicle of the train.

The bogie frame has been remodeled to receive the tilting bolster. A single air spring provides the secondary suspension, roll stiffness is guaranteed by two roll bars.
A kinematics system provides longitudinal traction link and drives anti-yaw dampers. This system is designed to uncouple the anti-yaw position from the tilting angle.

All elements over the tilting bolster must tilt during curve negotiation. The secondary suspension is not laterally deformed by centrifugal force because tilting is compensated. The secondary suspension being tilting-compensated, its lateral displacement under centrifugal effect is very limited: no Active Lateral Suspension is required by swept envelope. This notwithstanding, where very high levels of comfort are required, the Active Lateral Suspension is added in order to minimize the lateral acceleration and the lateral jerk transmitted to the carbody.

The “Rollers” kinematics cannot allow a simple mechanical connection of the pantograph to a non-tilting part of the bogie. Therefore, the stabilization of the pantograph in respect to the catenary is obtained by means of an active electromechanical servo-system (see slide 5). In this way, the position of the pantograph with respect to the catenary can be centered taking into account the roll of the carbody.

A safety issue is applied in tilting control system, because any fault in pantograph control must be managed according to safety rules.

The pantograph is mounted on the roof of the carbody through a sliding frame. This frame is tilted in the opposite direction of the carbody in order to assure a stable position of the pantograph in respect to the catenary regardless of the tilted position of the carbody. The tilting mechanism of the pantograph consists of a brush-less motor, driven by a computerized electronic box, which transmits to the sliding frame of the pantograph the movement by means of a transmission belt.

In case of the failure of the tilting system, by disactivating the motor, the pantograph is automatically centered in respect to the carbody by means of two proper recovery springs.

3.3. **Self-centering effect.**

One of the most important performances of tilting systems is the intrinsic self-centering capability in case of fault (see Slide 6). During the tilting phase, the position of the center of gravity (on which weight it acts) is kept approximately at the same position.

The tilting angle center move along a curve during the body-car rotation but its position guarantees the stability, because the reaction $w' = w$ tends to re-center the tilted body-car. The relative position guarantees under all conditions, that a force is produced to move the body-car to a neutral position ($0^\circ$).

The torque effect $T_{Act}$ applied by the actuator is reacted by $w'$ and $w$ torque effect. No reaction is transmitted to bogie; therefore, effects to wheel/rail are negligible.
4. **Tilting control system**

The master unit on the leading vehicle receives data from the sensor on the bogie and creates the reference tilting command. (See slide 7)

The tilting command is transmitted to the following cars via serial lines.

The tilting command is adapted according to train speed variation and delayed considering train speed and distance between vehicles.

The control system is a closed loop between the tilt command and the real tilt angle measured by a suitable sensor (rotational or linear) mounted between the tilted and non-tilted bolsters.

The servo-valve receives a command that is the difference between the reference command and the measured tilt angle.

The reference signal is defined by the tilting logic as described in chapter 2.

The same logic is applied on the electro-mechanical system, but quantities are different.
5. **ALSTOM tilting trains in the world (see slide 8)**

The tilting technology allows the trains on which it is adopted, to offer not only higher speeds but also better comfort without any limitation in terms of safety.

In addition to the above, tilting trains can run on traditional tracks, not needing very expensive dedicated new lines which have a high impact on the environment.

The tilting technology is today very sound and experimented thanks to many years of studies and many millions of kilometers covered by hundreds of tilting trains in regular revenue service in different European countries.

The expected future trend of the market for what will concern the acquisition of new trains is giving very positive signals in favor of the tilting trains.

We can conclude by saying that the tilting technology born in the early 1960’s and considered at the time just as a theoretical exercise, has reached, during the last fifteen years a sound and reliable level of industrial application.
6. **Product’s improvements**

Tilting trains must be a competitive product able to run in full safety, with remarkable comfort level on existing lines and up to high speed on dedicated lines. This challenging target asks for continuous R&D activity, focused in different subsystems, aiming to increase performance, to improve RAMS figures and to reduce LCC.

This continuous development activity will be demonstrated through the new products for EM and hydraulic Tilting trains projects (such as West Coast Mainline, Czechia, VR and of course the tilting TGV), through the performance tuning and consolidation of experienced solutions (ICE-T, Cisalpino, ICN) and through the development activity of the most strategic among Tilting Subsystems.

R&D activities are based on the following items:

- Development of High Cant deficiency bogies, with EM actuators and tilting mechanisms based on rods (see slide 9).
- TILTRONIX concept, which include a predictive command and control software, based on existing hardware and sensors, coupled with the well-known reactive one (see slide 10).
- Semiactive subsystems, for improvement of ride comfort, particularly in lateral direction (see slide 11).
- Active dampers, based on EM actuation technology (see slide 12).