Methodology for the Validation of Loads in Rational Turning Analysis

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Abstract

An aircraft with a non-conventional landing gear configuration requires a methodology for the validation of the turning loads. This is the case of the A400M aircraft in which the main landing gear (LH and RH) consists of three independent articulated-type struts positioned along the aircraft longitudinal axis. The intention of this report is to demonstrate that the methodology followed in the A400M for the validation of the models providing lateral loads in the turning analysis is the correct one.

Aircraft regulation CS25 [7] (paragraphs CS25.495/CS.25.503) is not entering in how the tyres mechanics affects the lateral load sharing in a multi-leg landing gear. In fact it considers an equal share of the lateral loads between the legs taking into account a constant lateral load - vertical load relationship. This approach is far away from the physics of the manoeuvre. Firstly, because experience indicates that load sharing is affected by the steering angle. Secondly, because the relationship between the lateral load and the vertical load depends of the side slip angle and the vertical load.

Consequently, it was decided to build rational models that approach real dynamic of the aircraft complying with the aircraft load factors required by CS25 [7]. Tests were performed on tyres, landing gears and on the aircraft for the validation of the loads models.

The methodology presented here is concluded to be valid since good relationship between models and tests was achieved.

0. Nomenclature

α = tyre side slip angle
δ = Tyre vertical deflection
δ_y = Tyre lateral deflection
CR = aircraft turning centre of rotation
CS25 = EASA Certification Specifications for Large Aeroplanes
CS25TM = Turning Model complying with CS25.495 requirement.
Fy = Normal lateral load on ground-tyre contact point
Fz = Vertical load on ground-tyre contact point
GVT = Ground Vibration Test.
J = Jacobian matrix
K_y = Lateral tyre stiffness
L = the Lagrangian.
LH = left hand
LMLG = Left Main Landing Gear
LR = right hand
NLG = Nose Landing Gear

Q = external applied forces
q = the column matrix of n generalized coordinates of the rigid bodies
RMLG = Right Main Landing Gear
RTM = Rational Turning Model
T = kinetic energy of the mechanical system
V = speed vector
Venergy = the potential energy of the mechanical system
XGPS = horizontal coordinate in ground reference system
YGPS = lateral coordinate in ground reference system

1. Introduction

The objective of this paper is to describe the methodology followed in the A400M for the validation of the rational turning models. These models were used to calculate the aircraft loads required by civil requirements (CS25 [7] plus special conditions) and the aircraft operational limitations when the aircraft is performing military missions with weights above the one used for the civil certification.

During the A400M flight test campaign developed between December 2009 (First Flight) and August 2013 (delivery of the first A400M to the French Military Air Force), a huge amount of data were collected to validate the models used for the load calculation. Two aircraft assembled at Seville Final Assembly Line were instrumented at airframe and at landing gear levels with the purpose of the aircraft load validation.

A set of the tests performed at Airbus Facilities were dedicated to validate the rational turning model. High speed turns performed in the runway and slow speed turns performed in the tarmac have been done to validate the dynamics of the aircraft through a range of different speed conditions.

Two different activities were required with the turning models: the first one was to obtain the limit loads for aircraft design in accordance with civil requirements. The second one was to define aircraft operational limitations when the operating weights are higher than the civil certified one. This led to the construction of two different models: one that complies with what is specified by the civil rules and another one that approaches (as much as possible) to the real dynamics of the aircraft in turning manoeuvres. The first model was called CS25TM model and the second one is called Rational Turning Model (RTM).

For the construction of these models, the following was used: the airframe structural model that was validated by ground vibration tests developed in Seville [2, 3], the landing gear models that were validated by drop tests developed in Toulouse and the tyre models that were validated through qualification tests developed at Dunlop facilities and tyre tests developed in Châteauroux.

Another important reason to have two models is the computation time. Although the results of the CS25TM can be obtained from the RTM, the simulation time of the CS25TM is much less than the RTM. The reason for that is the RTM is more complex than the CS25TM.

2. Modelisation

The most important part of both models is the modeling of the main landing gear configuration. Each main landing gear (LH and RH) consists of three independent articulated-type struts positioned along the aircraft longitudinal axis. All these struts have a twin wheel arrangement and are fitted to the main fitting by a trailing arm assembly (Figure 1b). Three shock absorbers units connect the trailing arms to landing gear fixed structure. The NLG has a conventional telescopic configuration. A picture can be seen in figure 1a.

Due to the special configuration of the main landing gear, the share of the lateral load among main gear tyres is not complying with what is required in CS25.495, CS25.503 [7]: the lateral load is not constant value multiplied by the vertical load. Consequently, it was necessary to raise special conditions for turning and pivoting loads that replace the requirement CS25.495, CS25.503. To show compliance with the requirements a model was developed when the aircraft

aircraft is executing a steady turn with the loads factors defined by CS25 plus including the following characteristics:

1. The aircraft Landing gear spring curves and landing gear kinematics
2. Reliable tyre friction characteristics
3. Airframe and landing gear flexibility when significant
4. Aircraft rigid body motion.

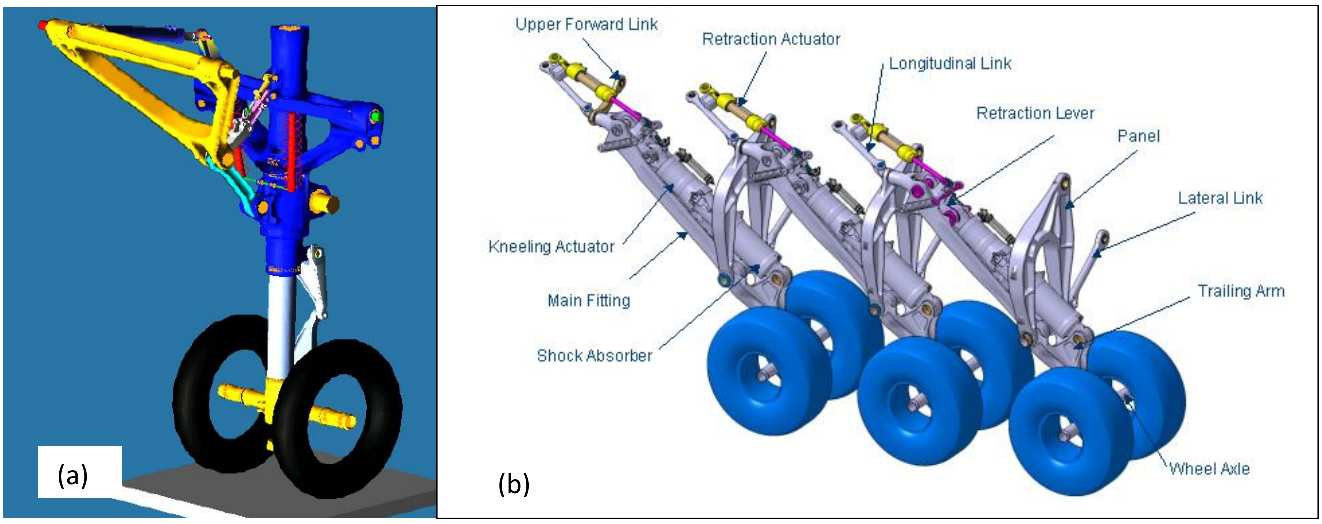


Figure 1. (a) Nose Landing Gear ADAMS model. (b) Main Landing Gear Main Parts.

Based on those requirements, CS25TM is composed of a rigid aircraft body (in point 3 is demonstrated that flexible body is not needed) plus a flexible landing gear body. The kinematic of the model has 47 degrees of freedom: 6 degrees of freedom associated to the aircraft body, 7 degrees of freedom associated to the oleos (piston-cylinder displacement), 6 degrees of freedom associated to the MLG trailing arms (rotation) and 14x2 degrees of freedom associated to the lateral and vertical tyre deflection. The connection of the landing gear kinematic to the fixed structure was performed through the bearings (simulated as a cylindrical joints) of the trailing arm and the shock absorber body. A force is simulated between the piston the shock absorber piston and cylinder is acting depending on the shock absorber stroke according to shock absorber spring curve. No damping was taken into account as it is simulated an aircraft steady condition. The tyre mechanics (Figure 2) was simulated taken into account the vertical tyre-load spring curve, the lateral tyre stiffness and the normal lateral forces (Fy). The normal lateral forces depend on the side slip angle (α) and the ground vertical load. The side slip angle was calculated computing the angle between the wheel plane and the speed vector (V) associated to the tyre-ground contact point.

$$F_y=F_y(\alpha, F_z)$$

$F_z=F_z(\delta)$, where F_z is the vertical load and δ is the tyre vertical deflection.

$F_y=K_y(\delta)\cdot\delta_y$, where F_y is the normal lateral load and δ_y is the tyre lateral deflection. K_y is the lateral tyre stiffness. The lateral tyre stiffness depends also on the vertical load.

This model included the capability of braking on each of the MLG pair of wheels and to simulate the thrust on each of the engines. Rolling friction was simulated as well.

As required by the CS25 rule, no aerodynamic forces were taken into account.

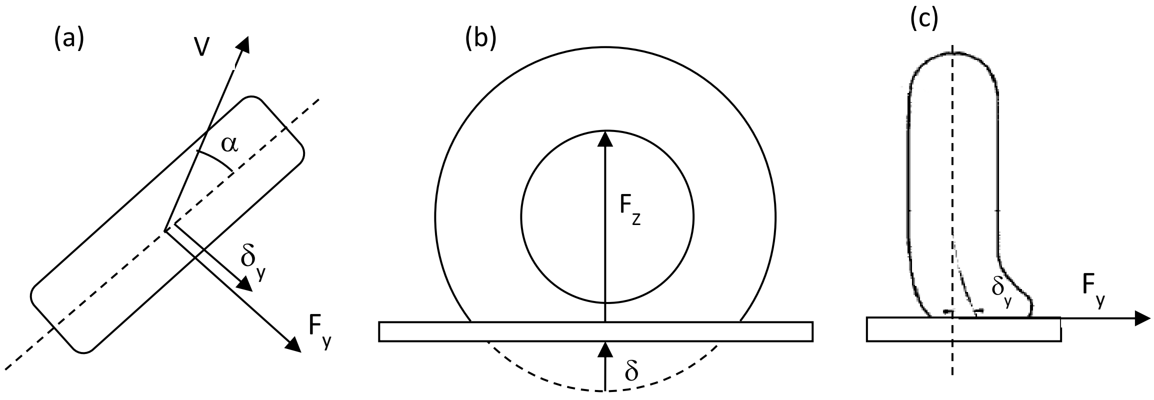


Figure 2. Panel (a), (c) shows parameters related to into account for lateral behavior of the tyre. Panel (b) shows parameters taken into account in the vertical behavior of the tyre.

The dependency of the lateral force of the tyre in relation to the side slip angle was obtained via dedicated tests. For a given vertical load specified in the tests, lateral loads were measured from 0 deg to 30 deg of side slip angle and then plotted. A generic curve is shown in Figure 3. At angles near to α=0, the curve has a linear tendency till some angle in which the curve bends to reach a maximum Fy for a specific αmax, and afterwards the tendency is to decrease. Knowing that the models could enter in the zone of loads above 30 degrees of side sleep the curves were extrapolated considering that the lateral load is maintained constant from the last tested point. This approach is conservative from the point of view of load calculation since it is possible to achieve greater load factors than in the real manoeuvre if the tyre enters in the side slip region above 30 degrees.

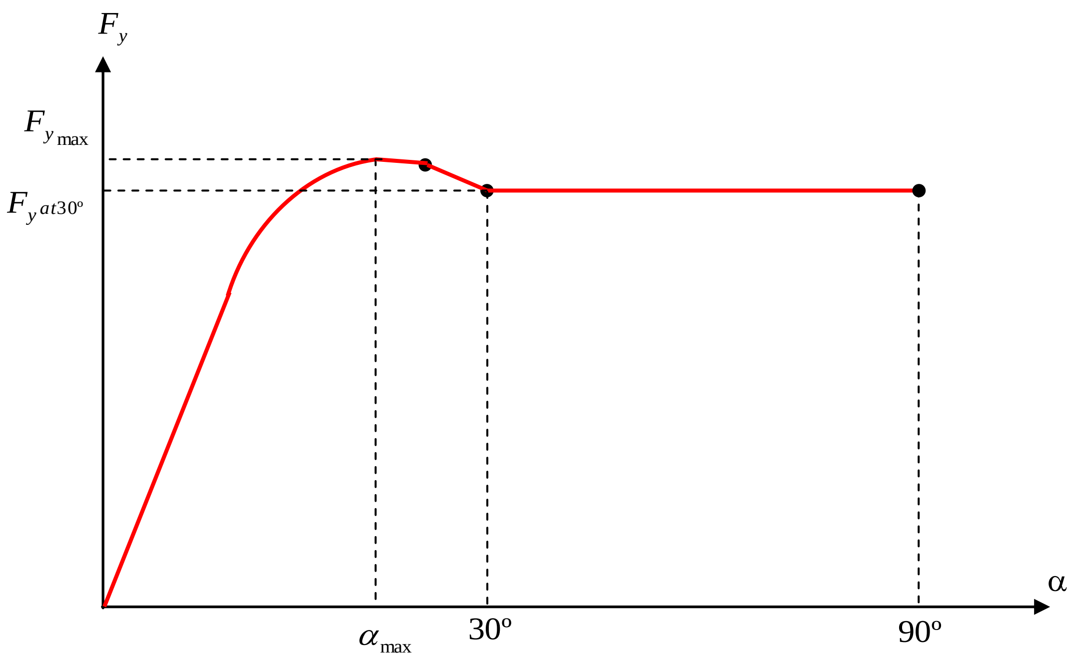


Figure 3. Generic lateral normal force for a given ground vertical load versus side slip angle.

The RTM was developed in MSC/ADAMS software (see Figure 4). It is composed of a flexible airframe body plus flexible landing gear bodies. The kinematic is solved in the same way as CS25TM. The landing gear mobile parts (Shock absorbers and trailing arms) are connected to the fixed landing gear structure (main fitting and panels) meanwhile cylindrical joints. Shock absorber characteristics as damping and spring curves were simulated. Same tyre mechanics as the CS25TM were used. The loads coming from the tyre ground contact point are transmitted to the axle generating forces and moments as can be seen in Figure 5. No aerodynamic forces were taken into account in this model so that the generation of the aircraft lateral forces is produced only by the tyres. The thrust is simulated in order to achieve the necessary speed at the turning manoeuvre. In order to control the possible trajectories of the aircraft on ground it is simulated the steering control system. The maximum steering rate has been limited taken into account the steering system capability. Braking capability was introduced by simulation of the braking torques at the main landing gear wheels. The combination of the braking force and the lateral force at the tyre contact area is limited by the tyre-ground friction of the runway.

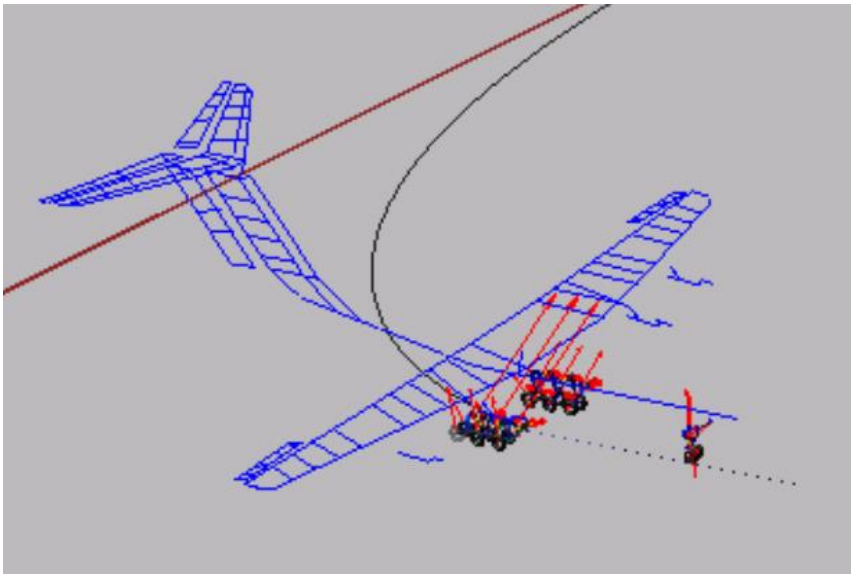


Figure 4. Picture of the MSC/ADAMS model

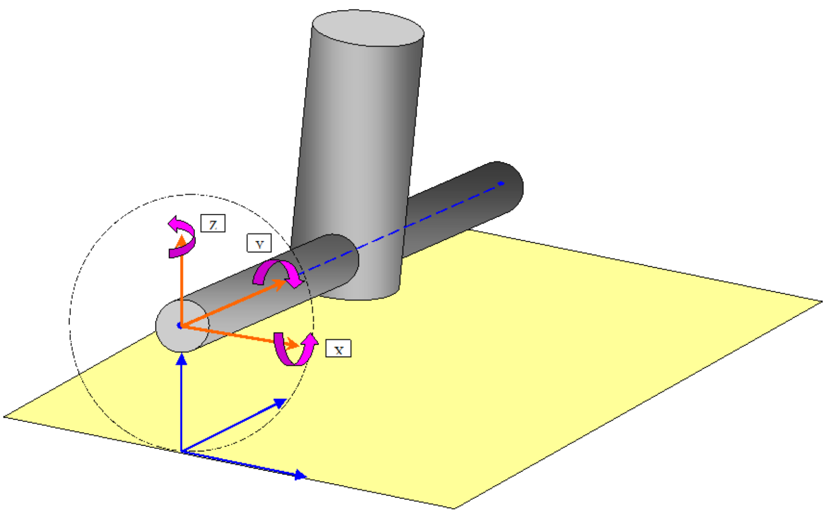


Figure 5. Transmission to the axle of the forces generated at tyre-ground contact point.

3. Validation

The first validation exercise was to check that the results of the two models were the same when simulating the same aircraft load conditions. As the CS25TM can be considered a particular condition of the RTM, it was easy to put inputs at the RTM that was equivalent to the CS25TM. For this task, it was necessary to make rigid the airframe flexible body and to simulate a steady condition with the same lateral load factor and steering angle. As a result of this analysis it was compared the tyre loads of both models. The tyre load difference between the models was less than 3% so it was considered that the models were equivalent.

The RTM was used also to check if the airframe flexibility is significant in the tyre load calculation. Comparing results of this model with the airframe rigid and the airframe flexible, it was concluded that the differences are negligible in the load results. This is an important result since computation time of the CS25TM is much less than the RTM.

RTM and CS25TM were built with elements that were validated separately: the airframe structural dynamic that was validated through a GVT ([2], [3]), the landing gears that were validated through a dedicated drop tests and the tyre mechanics that was validated through qualification and specific tyre tests. Afterwards, flight tests with fully instrumented aircraft were performed to validate the full integrated aircraft models.

Considering that aircraft structural dynamic has a negligible effect on the ground load calculation over the landing gears when the aircraft is performing the turning manoeuvres, validation of the airframe structural dynamic is not treated in this report.

3.1. Landing Gear Model Validation.

A series of drop tests were conducted to validate the landing gear models used in the ground load calculation. Drop test results were used to adjust the spring curves, friction and damping characteristics of the shock absorbers. Figure 6 represents the typical flow chart during the drop test validation. Normally, by changing the size of the shock absorber orifices is achieved an adjustment of the dynamic response of the landing gear in terms of vertical load and shock absorber stroke. The matching of the shock absorber spring curve is achieved adjusting the polytropic coefficient of the nitrogen. Figure 7 represents a comparison between the theoretical model of the main landing gear and the tests after the shock absorber parameters adjustments.

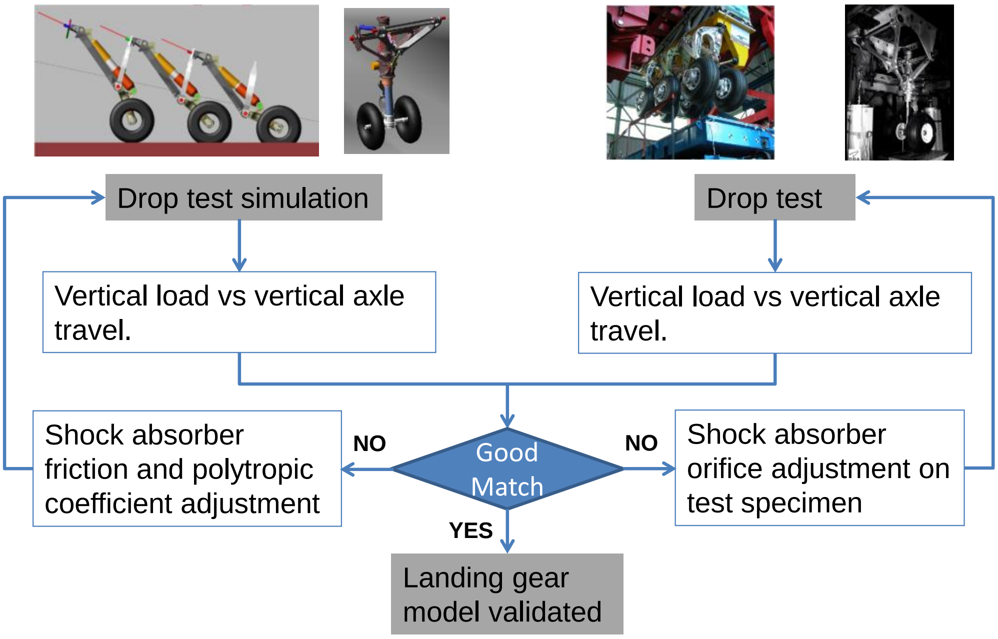


Figure 6. Landing gear validation flow chart.

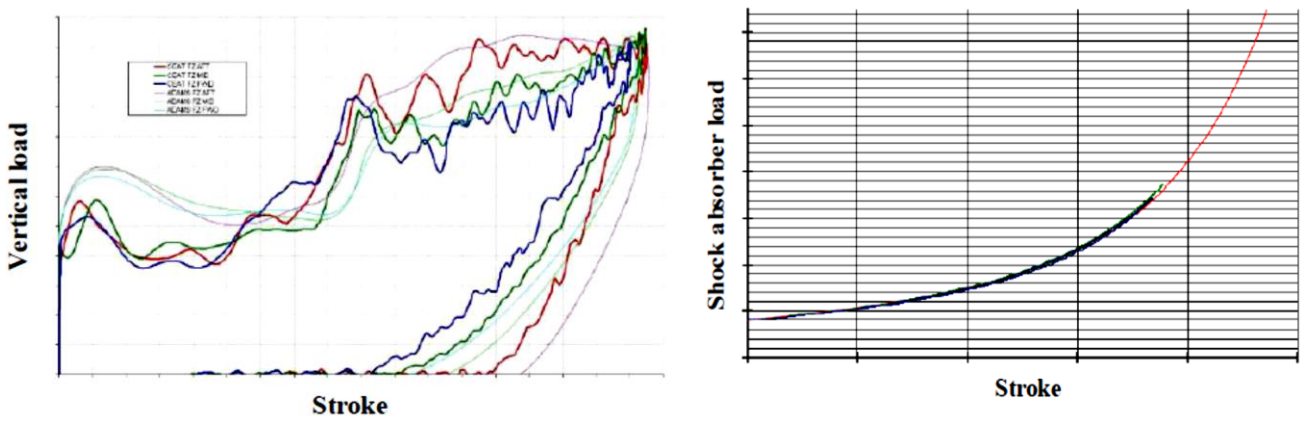


Figure 7. Shock absorber damping and spring curve adjustment.

3.2. A400M tyre model validation tests.

Tyre mechanics is the most important parameter during the turning load validation. Due to this reason is necessary to develop tests that capture in an accurate manner the mechanical response of the tyres.

During the qualification tests (Figure 8), it was obtained the vertical load vs tyre deflection curves for different tyre pressures. These curves did play an important role in the vertical load distribution between each of the legs.

Airbus Teratyre test rig (Figure 8) was used to obtain the lateral load response of the tyre versus the side slip angle. This parameter is the main contributor to the lateral load factor achieved by the aircraft during a turning manoeuvre. Before the test was developed, theoretical values of this parameter [4] were used in a preliminary design phase.

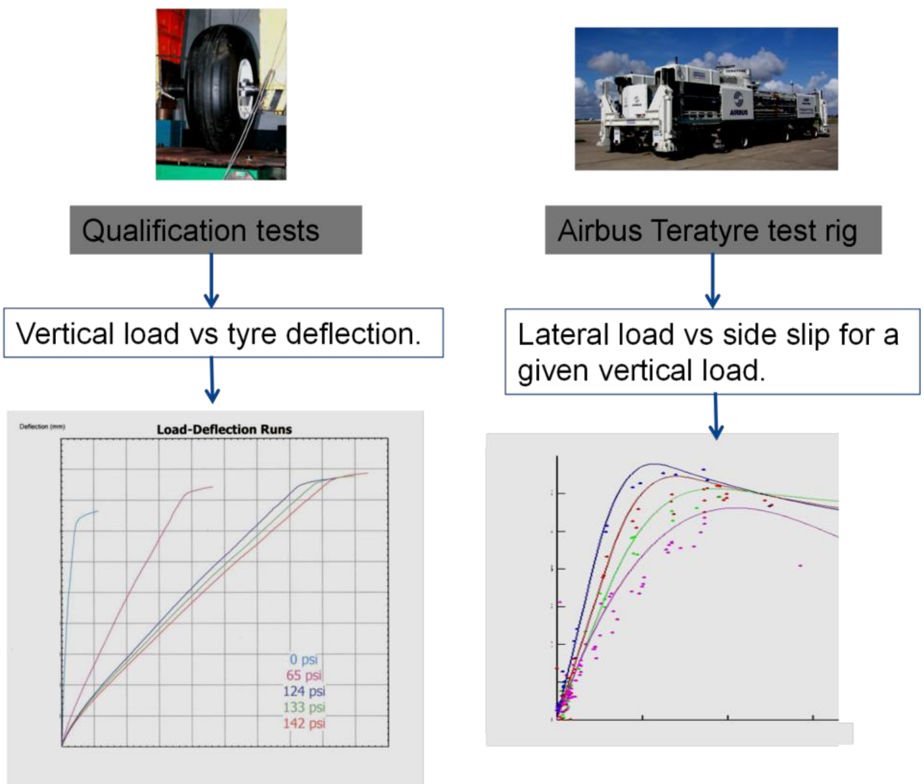


Figure 8. Test developed to obtain tyre mechanical charateristics.

3.3. A400M Flight Test for CS25TM and RTM model validation

A lot of parameters were instrumented in the aircraft to monitor the loads that occurs during the flight test campaign [5]. Part of this instrumentation were used in the validation of RTM and CS25TM. Here bellow it is explained the parameters used in the validation:

- Load factors at the centre of gravity.
- Angular accelerations and angular speeds at the centre of gravity.
- Linear speed at the centre of gravity.
- Aircraft position of the centre of the gravity.
- Pitch, roll and yaw of the aircraft.
- Landing gear loads. 60 parameters were used to obtain pintle and axle loads on each main landing gear side. 13 parameters were used to obtain pintle and axle load on nose landing gear.
- Shock absorber pressures and strokes.
- Accelerations at the wheel axles.

Although the complete models were built with elements validated separately, some aircraft tests at Airbus facilities were performed in order to check the integration of them and if there is a need for a simulation of the surface conditions (profile roughness). A series of steady turns with different aircraft mass, centre of gravity positions and steering angles were performed for the validation of the models. Thanks to the flight tests, final validation of the models CS25TM and RTM can be achieved. In Figure 9 can be seen the turning models validation flow charts.

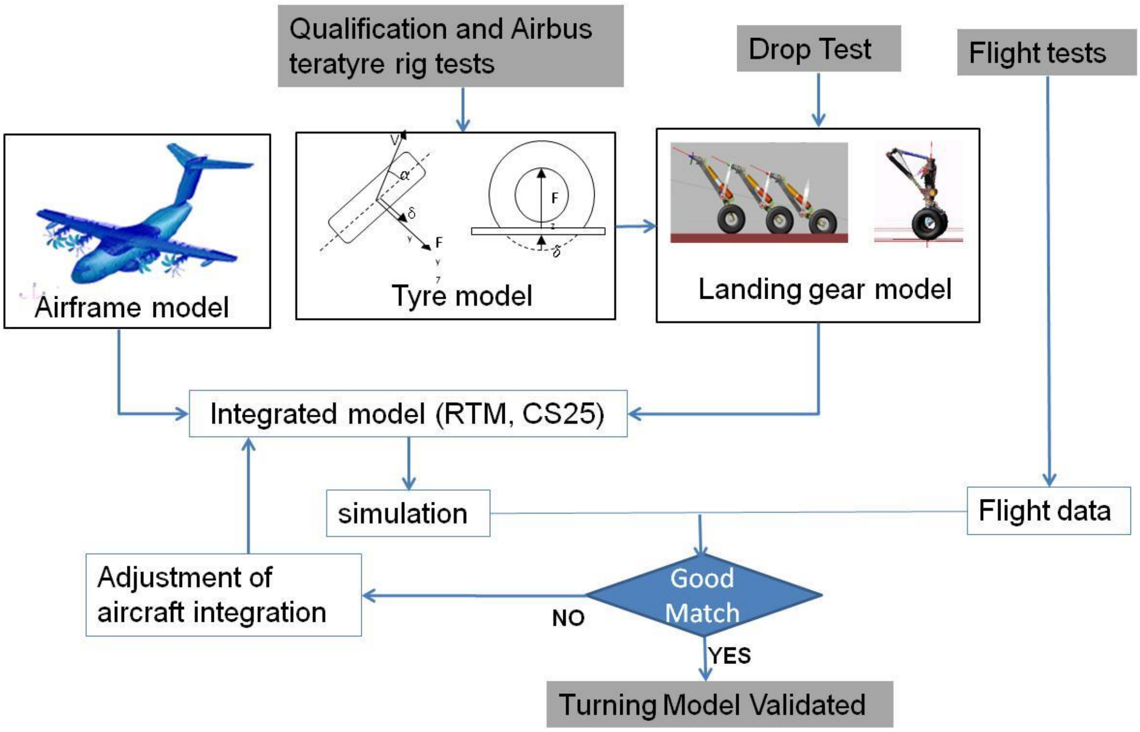


Figure 9. Turning model validation flow chart.

Due to the main landing gear configuration of the A400M, with the three legs equally spaced along the fuselage, it is important to know how the lateral loads are shared between the legs. To know this load distribution the load measurements on the lateral links (Figure 1b) has been used. As it can be seen in the Figure 10a, there is a time range in which the load measurement is stable. The values associated at this range of time are used for the comparison. The centre of rotation of the manoeuvre (Figure 10b) is adjusted by comparing the side slips coming from the tests and the side slips coming from the model (Figure 10c).

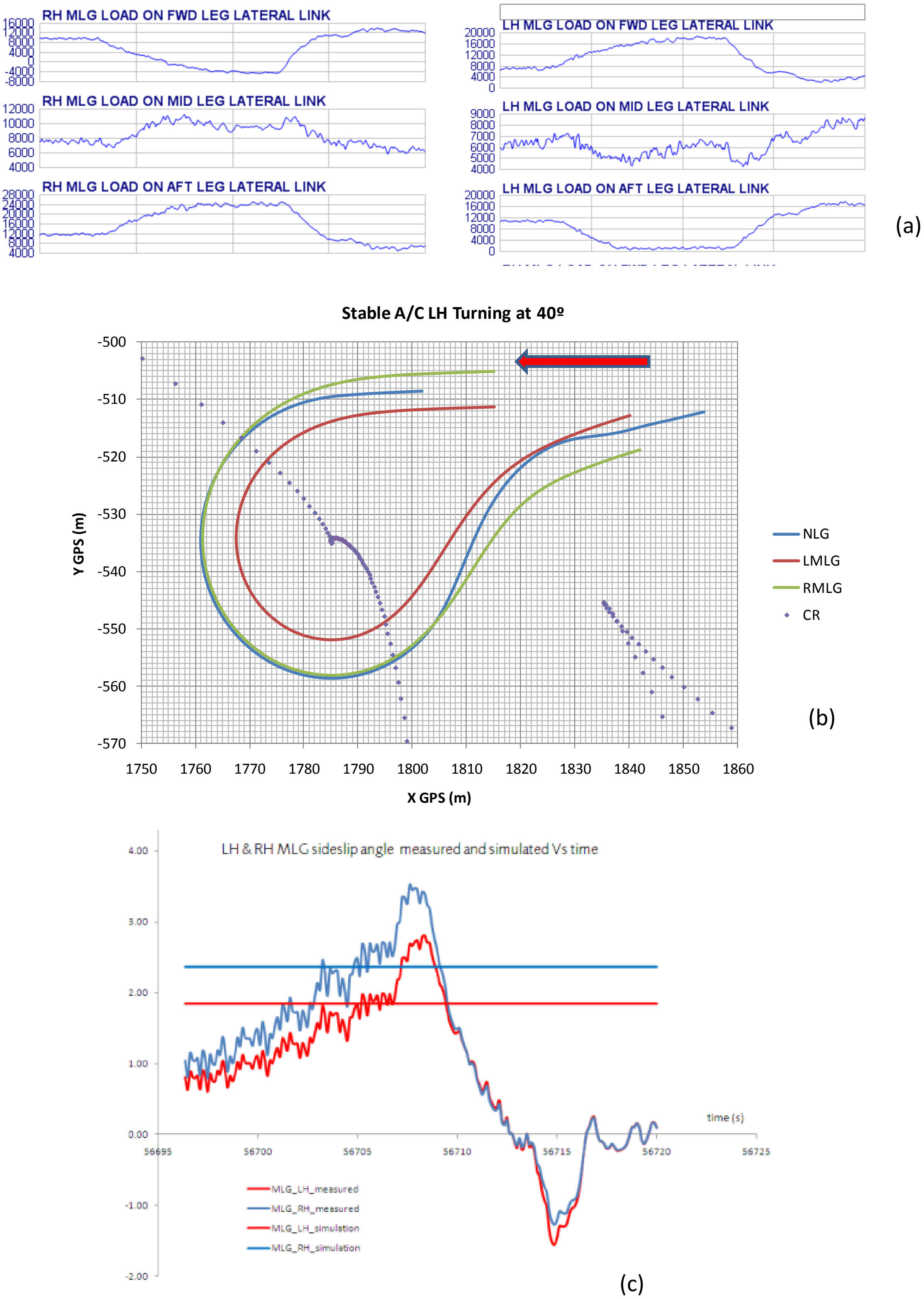


Figure 10. Panel (a) shows the lateral links load measurements on both Left and Right Hand Side Main Landing Gear (LH and RH MLG). Panel (b) shows the trajectory of points (dotted curve) on the landing gears in order to adjust the centre of rotation (CR). Panel (c) shows a comparison of the side slips coming from flight tests and the model.

3.4. CS25TM validation.

The CS25TM load calculation was built using in house software. The model consists on a set of algebraic equations (1) that is solved using the Generalized Reduced Gradient method (GRG) [1]. The Generalized Reduced Gradient method (GRG) to find the solution of the system equations.

$$\{\mathrm{F}(\{\mathrm{x}\})\} = \{0\} \tag{1}$$

The GRG method was built to minimize a function that it is subjected to restrictions in which the variables can be between a lower and upper boundary.

$$\{x^{\mathrm{k}}\} = \{\mathrm{x}^{\mathrm{k}-1}\} - [\mathrm{J}]^{-1}(\{\mathrm{x}^{\mathrm{k}-1}\}) \cdot \{\mathrm{F}(\{\mathrm{x}^{\mathrm{k}-1}\})\} \tag{2}$$

Where {x} is the vector solution of the non linear equations. The equations to be solved are represented by the vector {F({x})}. J is the Jacobian matrix associated.

Specific tests were requested in the flight test campaigns to validate the CS25TM. For these tests different aircraft configurations were tested:

- Light and heavy aircraft mass.
- Forward and rear centre of gravity position.
- Differential braking and symmetrical thrust.
- Differential braking and differential thrust.
- Different steering angles.

Since the model is calculating an aircraft steady condition, the tests were required so that the aircraft reach stabilised turns. In Figure 11, there is a comparison between the test and the simulation after the model adjustments. It corresponds to a braked pivot manoeuvre with a steering angle of 65 degrees. In these example the minimum turning radius is achieved leading to maximised lateral loads. Brakes were applied on the left hand side main landing gear. Braking forces were applied on the wheels of the model till the load difference in the longitudinal links between the model and test is adjusted.

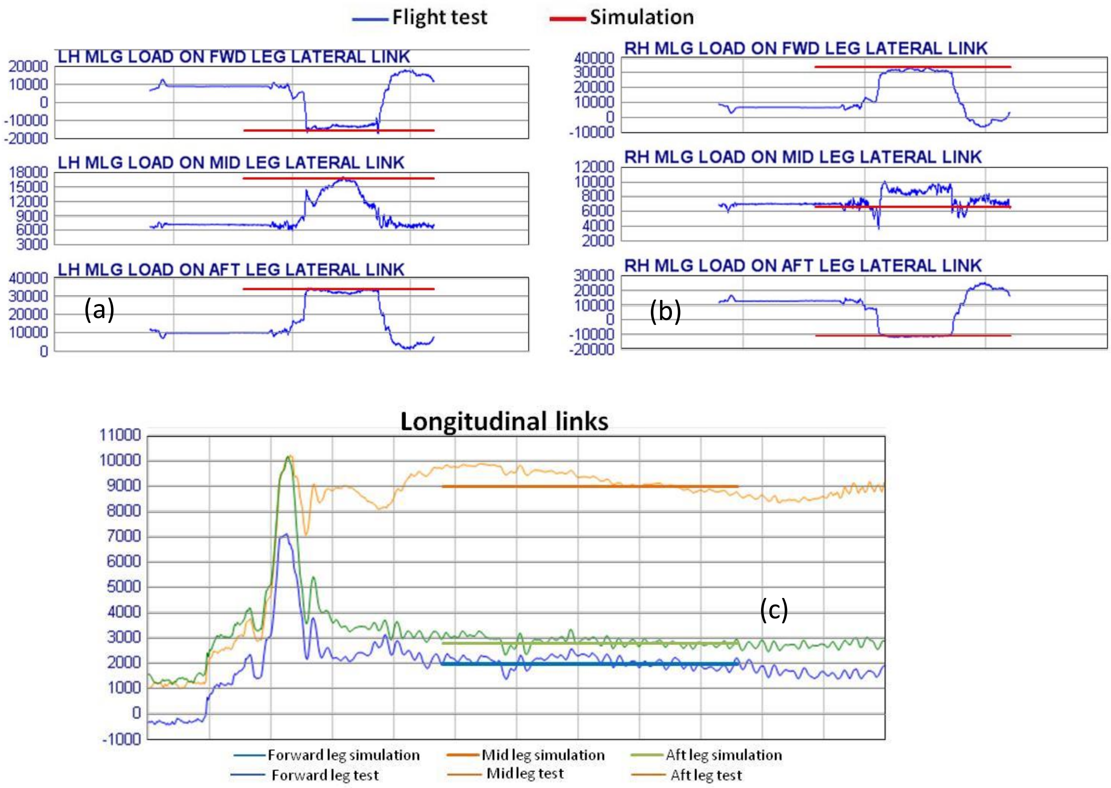


Figure 11. Comparison between the test and the simulation after the model adjustments: (a) for the lateral links of the left hand side main landing gear, (b) for the lateral links of the right hand side main landing gear, (c) for the longitudinal links of the left hand side main landing gear (the braked one).

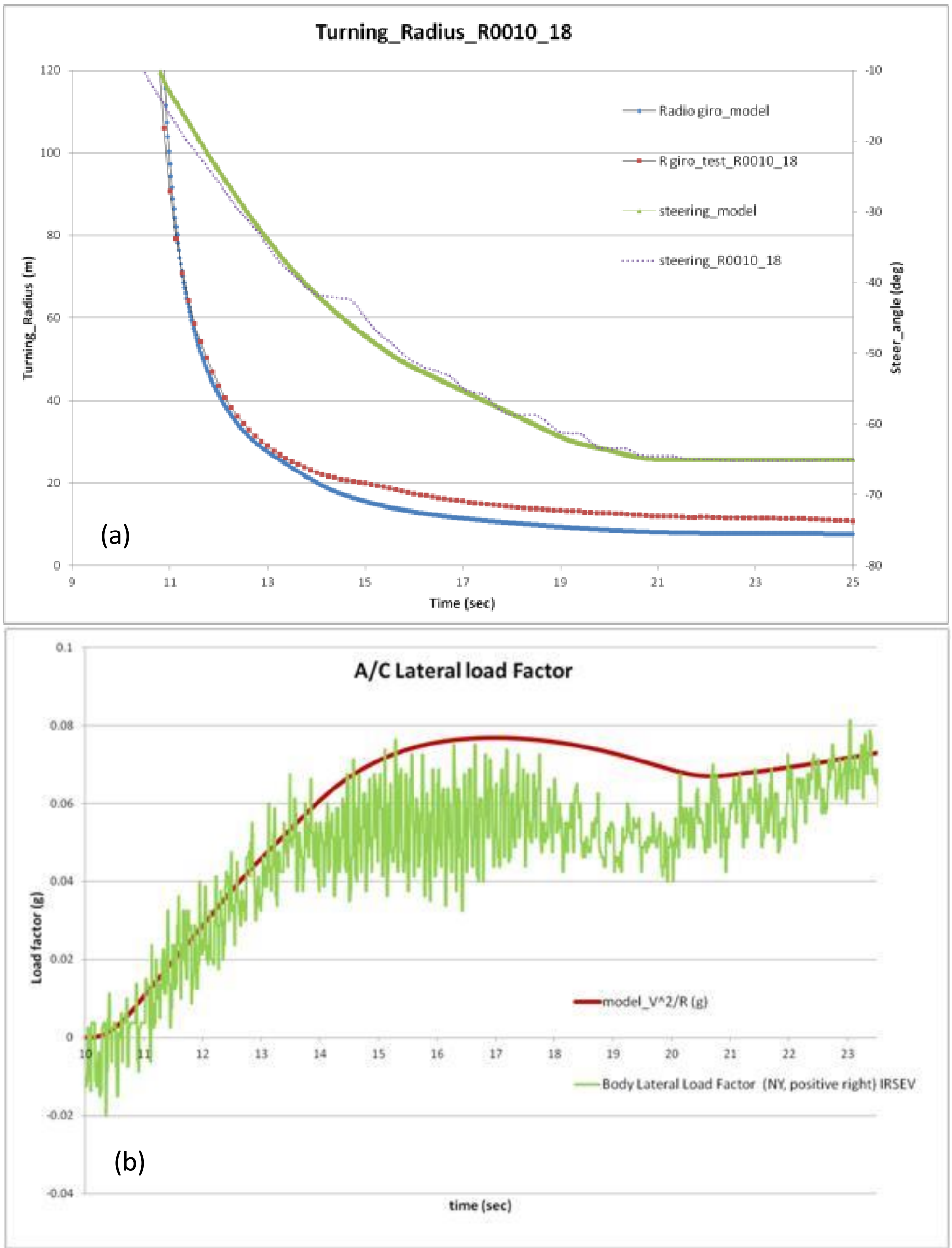
3.5. RTM validation

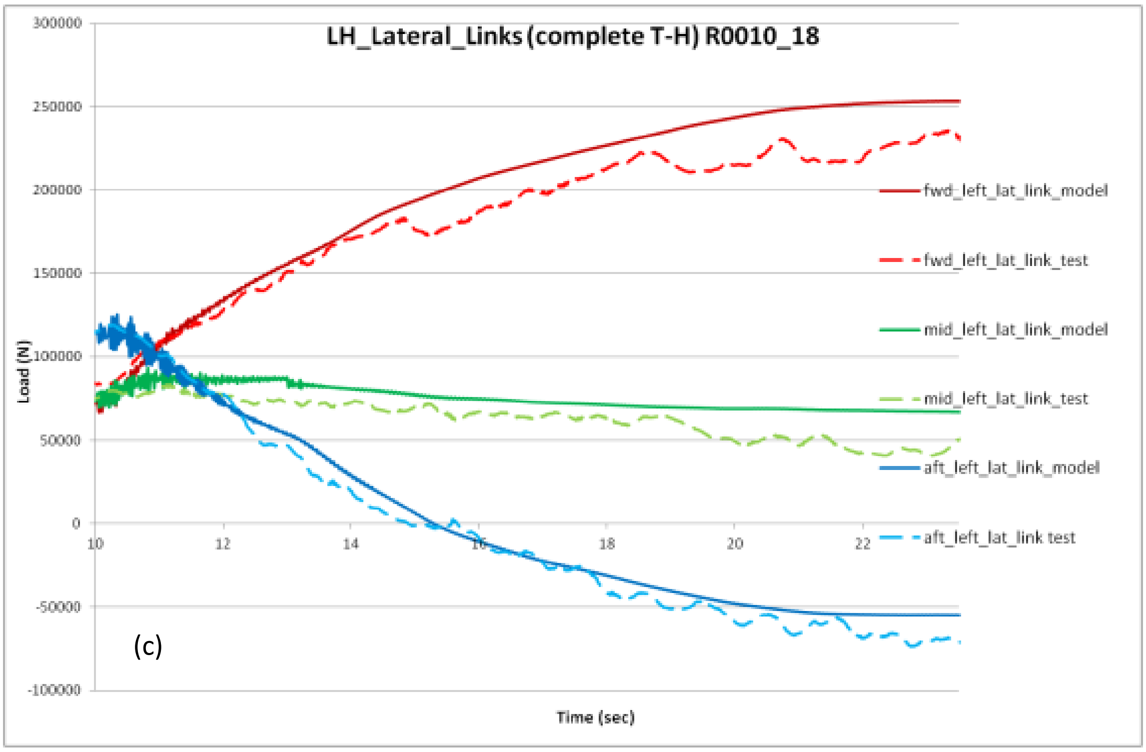
The RTM model simulation was built using MSC.ADAMS. The Euler-Lagrange equations are used by ADAMS/Solver [6] to generate the equations of motion:

$$\frac{d}{dt}\left[\left(\frac{\partial L}{\partial \dot{q}}\right)^{T}\right]-\left(\frac{\partial L}{\partial q}\right)+\Phi^{\mathrm{T}}\lambda=\mathrm{Q}$$

q is the column matrix of n generalized coordinates of the rigid bodies which describe the configuration of the system at any given instant in time. L defines the Lagrangian, which is the difference between the kinetic energy (T) of the mechanical system and the potential energy (Venergy). The first term represents the inertial forces; the second term represents the potential forces; the third term represents the constraint (i.e., joints and motions) forces, and Q represents the externally applied forces.

Same flight tests used for the validation of the CS25TM were used in the RTM model. In this case also the dynamic behaviour was also validated. In Figure 12, there is a comparison between the simulations and the tests. It corresponds to a slow turning without differential braking and differential thrust. As it can be seen in the figure there is a good match between the test and the results. Consequence of this comparison is that the lateral load sharing between the legs is simulated in an accurate manner.





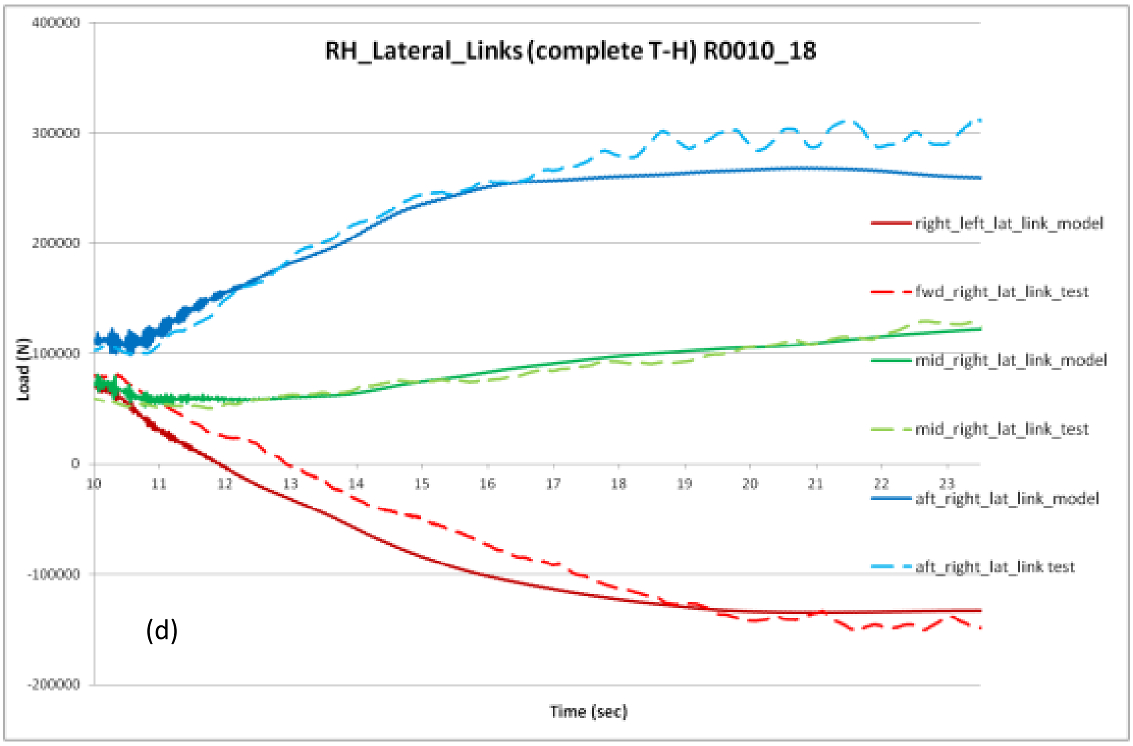


Figure 12. Comparison between simulation and test after model adjustments for the RTM model: (a) steering angle input and turning radius comparison. (b) Lateral load factor at the centre of gravity comparison. (c) Left Main Landing Gear Lateral Link Loads comparison. (d) Right Main Landing Gear Lateral Link Loads comparison.

4. Conclusion

The methodology presented here has been used for the validation of the models that simulate the turning manoeuvres performed by the A400M aircraft. The intention of this report is to demonstrate that the methodology followed here is right for the validation of the turning model used in the load calculation. Two models were built during A400M program development: CS25TM and RTM. In both models the main issue was related to the non-conventional main landing gear configuration. The main gear consists of three independent articulated-type struts positioned in the aircraft longitudinal axis. Each of these struts has a twin wheel arrangement and is fitted to the main fitting by a trailing arm assembly. Due to this configuration, when the aircraft is performing a turning, the lateral load reacted by the main gear is distributed between each of the legs depending on the tyre and landing gear mechanics, the ground surface conditions and the landing gear flexibility.

In order to check if the airframe flexibility has an impact in the simulation results some analysis with a rigid airframe and with a flexible airframe were performed. The comparison between flexible and rigid results showed that there was no influence of the airframe flexibility on the results.

For the validation of the models it was necessary to perform drop tests, tyre tests and full aircraft tests. The landing gear model was validated through drop tests, in which it is adjusted the shock absorber spring curves, damping and friction. The lateral load versus side slip curves and the vertical load versus tyre deflection were obtained from Teratyre and qualification test respectively. Finally to check the aircraft integration of the tyres and the landing gear validated models, it was performed some full aircraft tests. With these tests it was also confirmed that the effects of surface profile roughness are negligible, so the simulations can be done using a flat runway.

Considering that there is a good relationship between models and tests it is concluded that the methodology for the Validation of Loads in Rational Turning Analysis is valid.

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