Thermo-mechanical modelling of the aircraft tyre cornering

Lama Elias-Birembaux, Iulian Rosu, Frédéric Lebon

Machine Dynamics Research
2013, Vol. 37, N° 1
pp. 29-36

Thermo-mechanical modelling of the aircraft tyre cornering

Lama Elias-Birembaux, Iulian Rosu, Frederic Lebon

LMA CNRS UPR 7051, Université Aix-Marseille, Centrale Marseille
31Chemin Joseph Aiguier, 13402 Marseille Cedex 20 France

elias, rosu, lebon@lma.cnrs-mrs.fr

Abstract

Some numerical models are proposed for simulate the aircraft tyre behaviour on the ground in critical situations. Fully coupled thermo-mechanical analysis procedures taking into account finite deformation, dynamics and frictional contact are studied. The proposed models are compared with experimental data such as contact area, lateral and longitudinal stiffnesses, surface temperature evolution due to friction, self-alignment torque, and lateral friction coefficients. A good agreement is observed at low speed (less than 70 km/h). Thus, the model is extrapolated to high speeds and seems able to predict results in cases for which it is not possible to obtain realistic experimental data.

Keywords: aircraft tyre, Finite Element Method, thermo-mechanical modelling

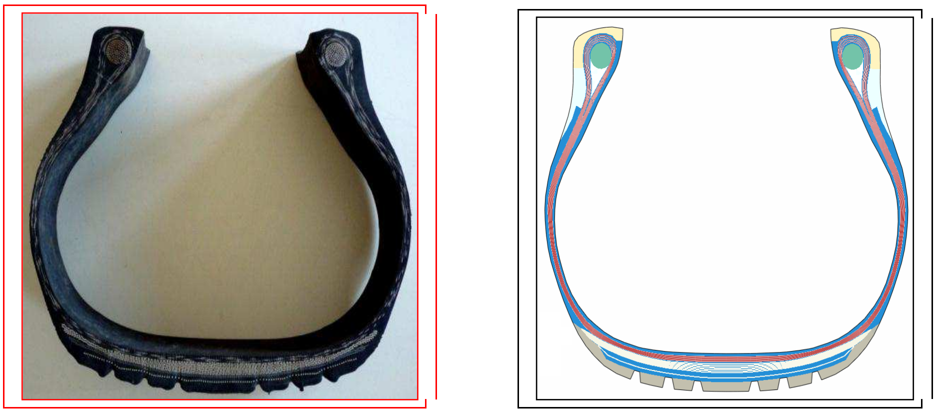
1. Introduction

Landing and take-off operations are the most critical phases of an aircraft flight. Indeed, the high speed, the violent impact when the aircraft touches the ground, the need of braking efficiently, the ground irregularities, the climatic conditions (crosswind, contaminations, etc.) as well as other parameters can make these ground manoeuvres very complex.

Knowing at each time the forces in the contact patch allows controlling the behaviour at the tire/ground interface. For aeronautical applications, the experiments realized on real tire, at moderated speeds (less than 70 km/h), help to analyse the tire/ground behaviour in this reduced field. However, numerical models based of Finite Element method are fundamental methods to predict the tyre behaviour at higher speed, taking into account the high non-linearities related to materials, and coupled phenomena (contact with friction, thermal-mechanical couplings, and internal dissipation).

2. Modelling of tire aircraft by Finite Element Methods

In this study, finite element analyses were performed in several steps. In the first step, the tyre was modeled under inflation pressure using an axisymmetric 2-D model. A 3-D model was then developed for performing static vertical loading simulations. To study the lateral, torsional and longitudinal stiffnesses of tire, a quasi-static analysis was performed after the static analysis. Recently a fully coupled thermo-mechanical 3-D model was also realized to predict the tire behaviour during landing and taking-off operations: an improved geometry description was introduced, materials behaviours were identified, experimental determination of rubber properties was validated, and Mooney-Rivlin model was used to characterize the hyper-elasticity of rubber. The visco-elasticity properties of rubber were also taken into account.



(a) (b)

Fig.1. 2-D tire structure: (a) real cross-section of tire (b) 2-D axisymmetric FE model

All the finite element computations were realized using ABAQUS/Standard Version 12-EF on an HP server with Two Xoen quad-core processors cadenced at 3 GHz, using the parallel code version.

The 3-D model was created by rotating the axisymmetric 2-D model around the tire axis. In the 2-D model (fig.1 (b)) CAX4T(H) and CAX3T elements from

ABAQUS element library were selected to represent all the rubber parts of the structure. These are four and three-node coupled temperature-displacement elements without twist and with constant pressure. The reinforcement materials were modeled by SFMAX1 Rebar elements (two-node linear axisymmetric surface element with twist).

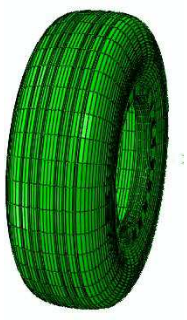


Fig.2.3-D fully coupled thermo-mechanical model

3. Static simulation

3.1. Cross section mesh

In previous papers (Kongo at al. 2012, Kongo et al. 2013), some simulations are presented and analyzed in detail. The main defect of these simulations is the rather low number of elements constituting the mesh. In this part a new refined mesh was realized for the 2-D Element Finite model of tire (Fig.3, second part). This operation was necessary to analyze the mesh sensibility, thus the number of elements was increased in the contact area, and a higher number for circumferential elements was used for the 3-D modelling. Total run time for a complete static analysis with this refined cross section mesh is still little expensive for industrial applications. This new strategy will be adopted in all our future analyses, both for static and dynamic simulations.

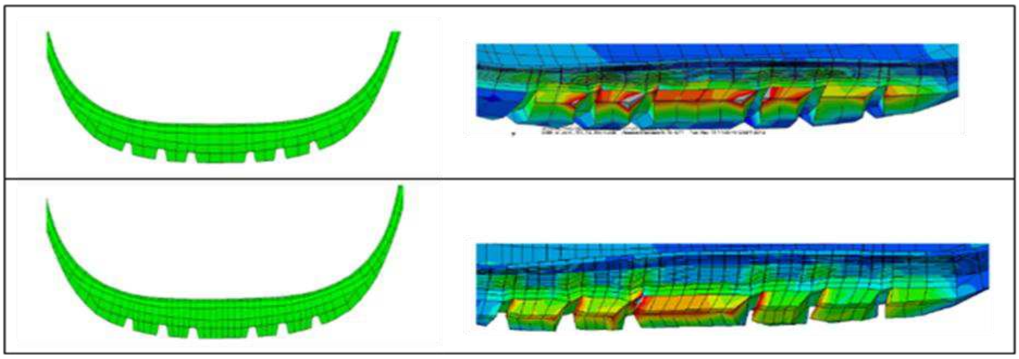


Fig.3. Comparison between old (Kongo et al. 2012) and new refined cross mesh for 2-D FEM model.
At left side: cross section mesh before and after refinement.
At right side: cross treads stress before and after refinement.

3.2. Contact area

In this study, the inflation analysis of the axisymmetric new model was followed by a 3-D quasi-static analysis of a vertically loaded tyre. Simulations were performed under static vertical loads Fz ranging from 0.125 to 0.75 % of f_0. The inflation pressure p_0 was equal to 17.2 bars and the static friction coefficient µ was equal to 0.65. f_0 stands for a reference value of the vertical load. The (Fig.4) shows the numerical evolution of the contact area with regard to the vertical loading in comparison with the experimental results.

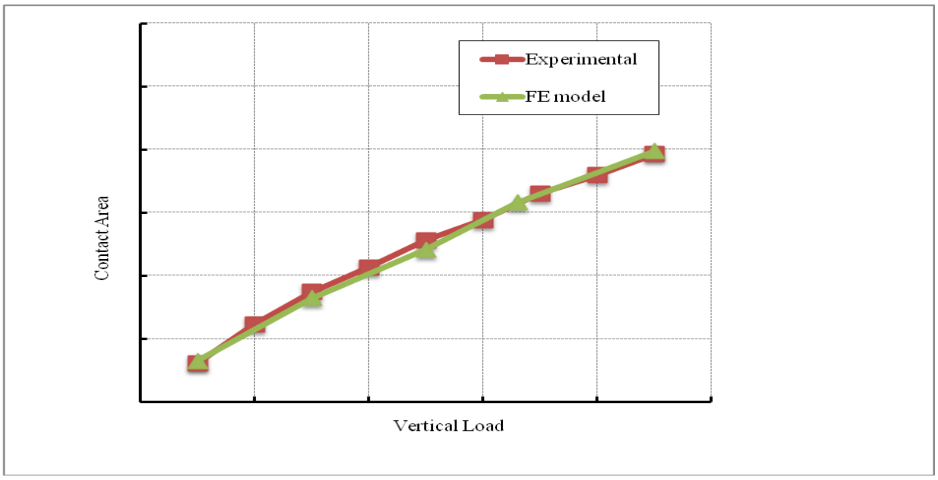
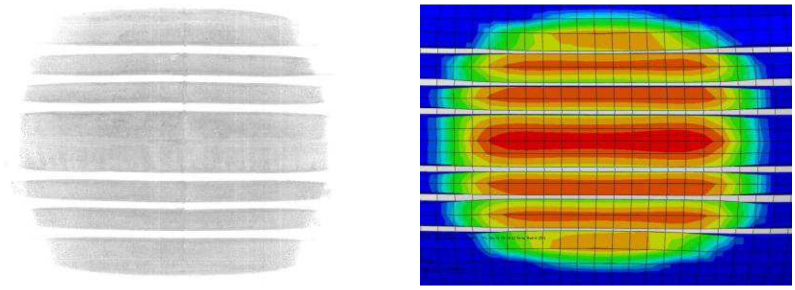


Fig.4. Evolution of contact area in the case of a grooved tire



(a) Experimental (b) Numerical

Fig.5. Experimental and Numerical footprints at F3 of loading

As we can see in (Fig.5), a good agreement is observed between numerical and experimental data; footprints were measured in the case of a grooved tire.

4. Dynamic simulations

When we study tire yawed rolling, it is relevant to well estimate the Self Aligning Torque and the ratio, lateral force/ normal force. They respectively express the ability of a tyre to turn back to its steering direction when it is no longer steered and the lateral grip potential of the rubber/ground couple. Indeed, the ratio μ_Y (between the lateral force and the vertical one) defines the equilibrium which exists between steering lock action and the trajectory of the vehicle. During μ_Y upward phase, there is equilibrium; more the pilot turns the wheel, more β increases. It corresponds to pseudo-sliding in the contact patch up to β_{max} (usually around β=4 to 7° for automobile pneumatics, around 15 to 25° for aircraft).

In this study, mechanical and fully coupled thermo-mechanical analyses are developed to predict the friction ratio μ_y and the self-aligning torque M_z. A classical rolling (CR) method based on a Lagrangian formulation was studied, thus from an observer point of view, the tyre mesh (51circumferential elements) is rotating and moving forward. A variable friction coefficient μ (P,T) depending on pressure and temperature was used in the thermo-mechanical model, real viscosity parameters were also introduced in this model. Concerning the mechanical model, a fixed friction coefficient μ_0 was adopted. These simulations (for both models) require two numerical steps, an acceleration step from zero to a given velocity and a rolling cornering step at a constant given velocity and a given slip angle.

4.1. Experimental vs Numerical simulations

4.1.1. Self aligning torque/ lateral friction coefficient

Mechanical and thermo-mechanical analyses were investigated; these studies concerned a grooved aircraft tire. Fig.6 shows the evolution of the self aligning torque M_z versus the slip angle. In order to show the influence of the temperature on the lateral friction coefficient μ_y and on the self-aligning torque M_z, purely mechanical, and thermo-mechanical models were performed under the same loading conditions and for the same slip angles. Results were compared with experimental data. In the case of the pure mechanical simulation without any temperature dependence, we can observe that the lateral coefficient μ_y (Fig.7) reaches a plateau equal to μ_0 with respect to the Coulomb's friction low. β_{max}, the angle for which the self-aligning torque is maximum, seems to be in good agreement with experimental data. The self-aligning torque M_z increases up to β_{max} at which the full grip potential is reached. The self-aligning torque M_z decreases when $\beta > \beta_{max}$, and tends to negative values.

In the case of a thermo-mechanical approach, the dependence of the lateral friction coefficient on the temperature (Fig.7) resulted in a decrease in μ_y beyond the β_{max} value. The self-aligning torque M_z (Fig.6) falls quickly toward null values.

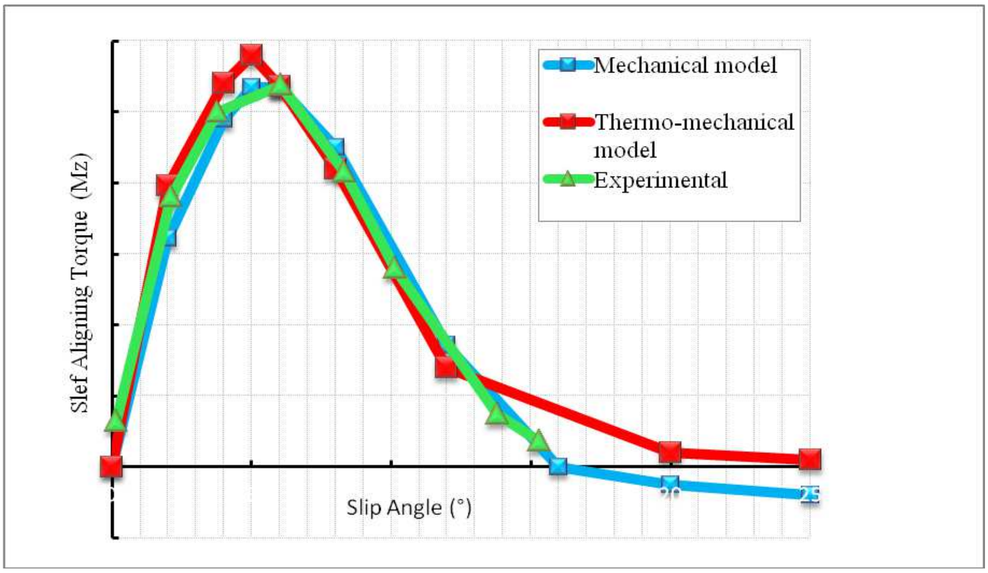


Fig.6. Comparison between experimental data, mechanical and thermo-mechanical models
Self aligning torque M_z,
Under given loading conditions (vertical load, pressure and velocity)

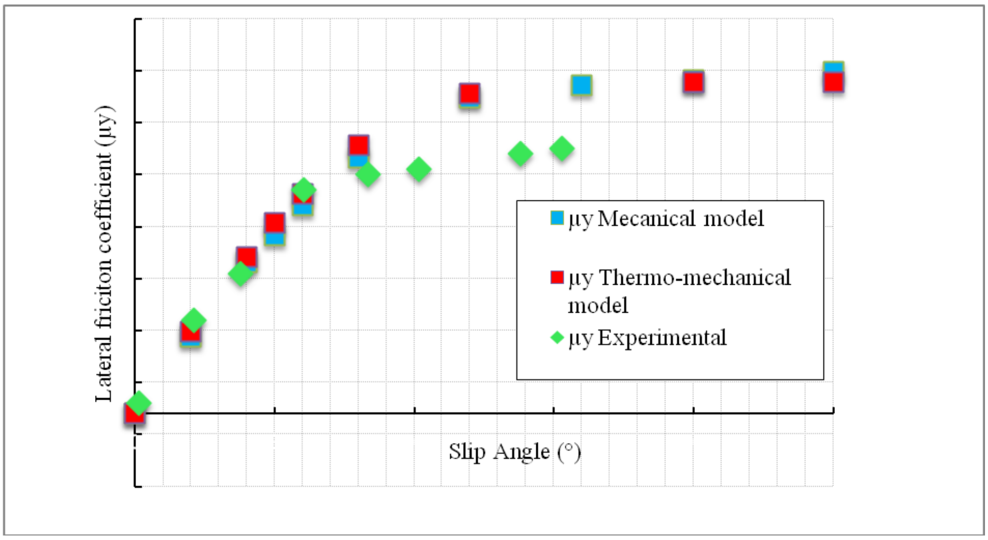


Fig.7. Comparison between experimental data, mechanical and thermo-mechanical models
Lateral friction coefficient μ_y,
under given loading conditions (vertical load, pressure and velocity)

4.1.3. Temperature evolution of an aircraft tire thermo-mechanical approach

Cornering rolling is obtained by imposing longitudinal and lateral velocities (related to a slip angle β). Figure 8 shows the temperature distribution at the tyre tread.

After a few seconds of rolling in cornering, an increase of the temperature occurs on tire tread and especially on groove sides; a warming zone is observed on the entire contact zone. However a slight diffusion of temperature is observed after a short period of rolling. We note also the role of a thermal barrier presented by the reinforced zones. Recently different experimental and numerical tests were performed; their purpose was to verify the behaviour of rubber during cornering rolling. These studies confirmed the necessity of taking into account the frictional heating of rubber and also the heating produced by energy dissipation (visco-elasticity properties).

Fig.9 shows a rolling cornering case of an aircraft tyre at a low velocity and for a small slip angle; a good agreement seems to be obtained between the thermo-mechanical model and experimental data.

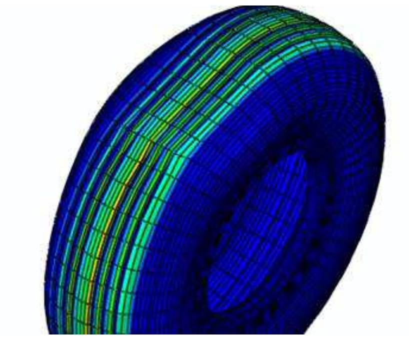


Fig.8. Temperature gradient for a cornering simulation at given velocity and slip angle

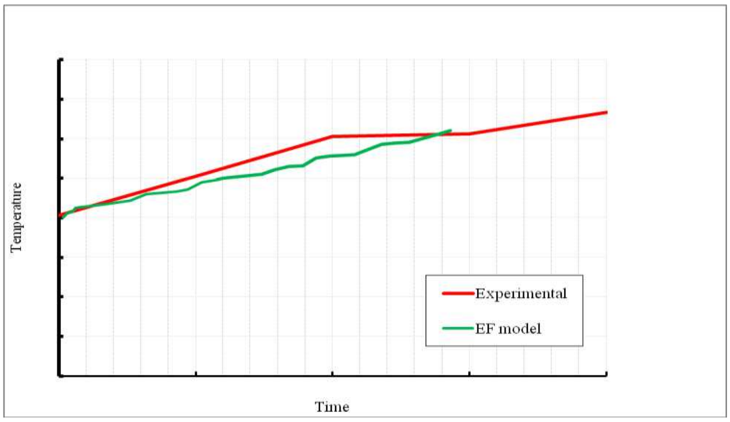


Fig.9. Temperature evolution: comparison between thermomechanical FEM and Experimental data for a cornering simulation of an aircraft tyre for given velocity and slip angle

6. Conclusion

In this paper, we have proposed some numerical models to simulate the aircraft tyre behaviour in cornering. Fully coupled thermo-mechanical analysis procedures taking into account finite deformation were studied. The proposed models have been compared with experimental data such as contact area, lateral and longitudinal stiffnesses, surface temperature evolution due to friction, self-alignment torque, and lateral friction coefficients. A good agreement was observed at low speeds (less than 70 km/h) and the model seems to be able to predict results at high speeds, in which case it is not possible to obtain realistic experimental data. In the future, we intend to improve the models introducing more complex constitutive equations coupling thermo-mechanical effects, particularly taking into account viscosity, internal dissipation, etc. Other kind of experimental devices will be proposed in order to confirm the validity's domain of our models in various critical situations.

References

Kongo Kondé, A.., 2011,*"Modelisation du roulement d'un pneumatique d'avion "*, PhD thesis, Aix-Marseille University.

ABAQUS/Standard., 2012, *"Theory Manual and Example Problems"*, Release 6.12.

Kongo Kondé, A., Rosu, I., Lebon, F., Brardo, O., Devésa, B., 2013, On the modelling of aircraft tire, *Aerospace Science and Technology*, **27**, 1 (2013) 67-75

Kongo Kondé, A., Rosu, I., Lebon, F., Brardo, O., Devésa, B, 2012, Thermo-mechanical analysis of an aircraft tore cornering using coupled ale and lagrangian formulations, *Central European Journal of Engineering*, V3, 191-205.

McAllen, J.M., **Cuitino, A.M., Sernas, V.,** 1996, "*Numerical Investigation of deformation characterisations and heat generation in Pneumatic Aircraft Tires, Part I. Mechanical Modelling, Part II. Thermal Modelling"*, Finite Element in Analysis and design, 23, 241-263.

Mc Carthy, J.L., Tanner J.A., 1983, "*Temperature Distribution a Aircraft Tire at Low Ground Speed*", NASA Technical Paper 2195.

Clark, S.K., Dogde, R.N., 1982, "*Heat Generation in Aircraft Tires under Free Rolling Conditions*", NASA Contractor Report 3629.