Use of simulation techniques to improve tractor operator safety

Mangialardi L.[1], Pascuzzi S.[2], Soria L.[1]
[1]*Politecnico di Bari, DIMeG – Mechanical Design Section*
V.le Japigia 182 – 70126 Bari, ITALY
Tel. +39 080 596 2710 – 2813, Fax +39 080 596 2810 – 2777
lmm@poliba.it, soria@poliba.it
[2]*University of Bari – PRO.GE.SA. – Mechanics Section*
Via Amendola 165/A – 70126 Bari, ITALY
Tel. +39 080 544 2214, Fax +39 080 544 2214
simone.pascuzzi@agr.uniba.it

Abstract

In the automotive sector, virtual prototyping allows to reduce time and costs of designing. Crash tests can be simulated by computer models, by using multibody-FEM techniques and, among the solvers available on the market, Madymo (TNO Automotive Safety Solutions - NL) has been developed for being particularly suitable for studying problems of impact and crash mechanics. Born as a general-purpose multibody code, Madymo includes (i) powerful routines of contact detection, (ii) libraries of numerical dummies (which reproduce the dynamical behaviour of the real instrumented dummies, with the aim of evaluating injuries to the occupants) and (iii) the principal active and passive safety systems as different kinds of belts and airbags.
We have extended, to our knowledge for the first time, these techniques of numerical simulation to work accidents, analysing the reliability of safety systems aimed at protecting workers and proposing an original approach for their functional design and optimisation. In this paper, the results pertinent to the roll-over of a wheeled tractor with narrow track, placed on a sloping ground, is presented as an application, with the purpose of evaluating the safety performance of a pelvic restraint system.

Keywords: roll-over, restraint systems, dummies, injuries, functional design**.**

Introduction

Agricultural and forestry tractors are often involved in accidents, even fatal, caused by the overturning of the vehicle (Ispesl 2002, Comer *et al.*, 2003). With the aim of reducing and limiting the number of work accidents, the European Community directive concerning the homologation of agricultural and forestry tractors for road circulation (EC 2003, EEC 1979, EEC 1986, EEC 1987, ISO 1989, OECD 2005) has compelled manufacturers to equip the tractor with a ROPS and a seat belt anchorage. Pelvic restraint systems are, hence, installed on the tractors, fastened to the driver seat or, less frequently, to the tractor chassis (Molari and Rondelli, 2007). During tractor roll-over, this type of seat belt restraints the driver movements inside the clearance zone maintained by the ROPS (Nichol, 2005). Seat belts are an important tool for protecting drivers also when involved in on the road head-on collisions (Myers, 2002).

In this area of high scientific interest, we propose a new approach to the analysis of the effectiveness and to the optimal functional design of different type of operator restraint systems, based on multibody techniques. The performance comparison is indeed made by evaluating the driver biological injuries (NHTSA, 1998; Ambrosio, 2001; EuroNCAP, 2004), by means of the multibody-FEM code Madymo (MAthematical DYnamic MOdels), produced by TNO Automotive Safety Solutions (NL). In this environment, the analysis of problems of impact dynamics is allowed thanks to powerful routines of contact detection. More over several types of numerical dummies of different complexity are made available to the user, as models of seat belts and airbags (TNO Automotive Safety Solutions, 2007). In particular, the numerical dummies allow to simulate the dynamic behaviour of the real instrumented dummies, commonly used in the crash tests for road vehicles. As it is well known, dummies present suitable joints calibrated on the basis of the knowledge obtained in the field of biomechanics, through tests carried out on volunteers and dead bodies.

For such reasons Madymo is commonly utilised for safety problems concerning road vehicles, to design the structures and the active and passive safety devices aimed at the protection of the occupants. This approach clearly allows to lower the times and, above all, the costs of designing, as the experimental study carried out through crash tests is reduced only to the final validation of prototypes.

In a very original way, we propose to extend these techniques to the field of workplace accidents and safety, by analysing the reliability of the systems aimed at protecting workers, with the aim of improving their performance (Mangialardi and Soria, 2005). In this paper, in particular, the results pertinent to the roll-over of a wheeled tractor with narrow track, placed on a sloping ground, where the resultant of weight forces falls outside the supporting convex polygon, are reported. The purpose is to evaluate, by means of the proposed approach, the safety performance of a pelvic restraint system.

Materials and methods

<u>*The tractor*</u>

The 3D multibody model of the tractor considered in the paper is represented in Figure 1, where the inertial reference frame utilised is also reported. It is a narrow track wheeled tractor equipped with two ROPS safety frames. The model is composed by seven parts, the body frame, the four wheels, the front and the rear safety ROPS. Moving from the drawings of a commercial model, selected among the ones available on the market, the geometry of each part has been reproduced in Madymo, by using native hyper-ellipsoidal surfaces.

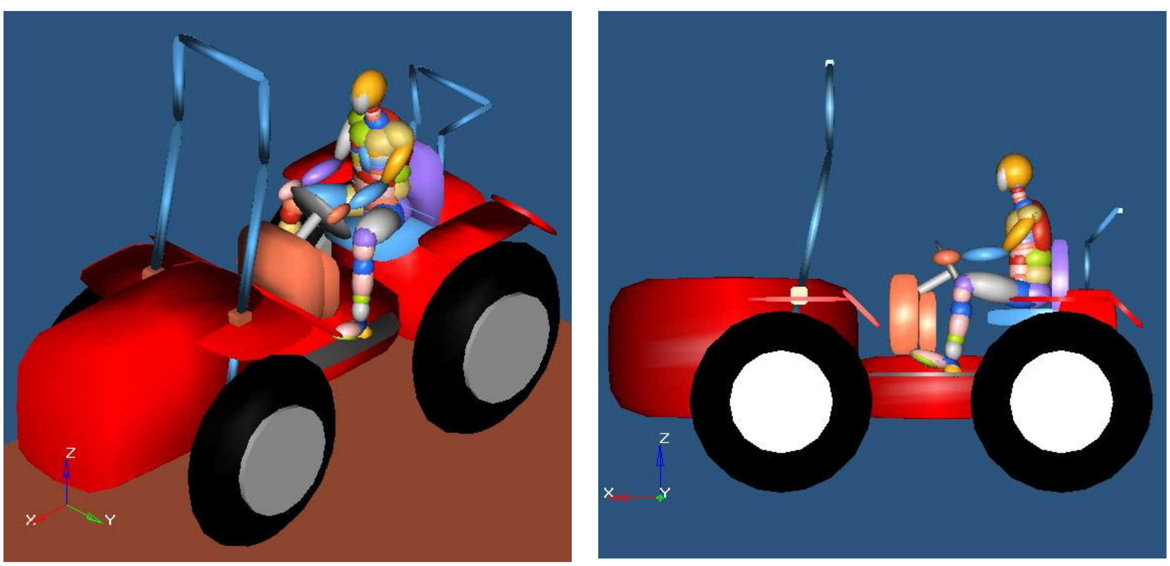

Figure 1. 3D and lateral view of the dummy-tractor model

To each of these surfaces a body reference frame is rigidly connected and the whole spatial distribution of the mass (centre of gravity and inertia tensor) is declared with respect to this frame. The entire tractor model is then obtained by constraining the parts each other, by means of kinematic joints. The safety frames are supposed to be fixed to the body frame, by means of two brackets. Each of the four wheels is connected to the body frame by a cylindrical joint. The whole tractor model is then declared in the input scenario by means of a free joint.

When the tractor does not have any contact taking place with the ground, e.g. in a particular phase of the accident, the model has, in conclusion, 10 degrees of freedom (d.o.f.), the 6 rigid body motion d.o.f. and the 4 wheel rotations.

The ground

The accident scenario is more over composed by the ground where the tractor is leant on by unilateral contacts. Each part of the tractor could actually come into contact with the ground during the accident dynamics. These situations can be foreseen by simply declaring into the Madymo input file all the possible contacts that the solver could have to detect during the numerical simulations. The resultant number of d.o.f. that characterises the scenario in each instant of time depends, indeed, by the contacts taking place at that time.

In the paper, as anticipated, a typical roll-over accident is considered, and the ground is supposed to be composed of three planes of different slope (Figure 2). At the beginning of the simulated dynamics, the tractor is positioned on the plane having the highest slope, in a way that the resultant weight force is able to make the tractor rolling over.

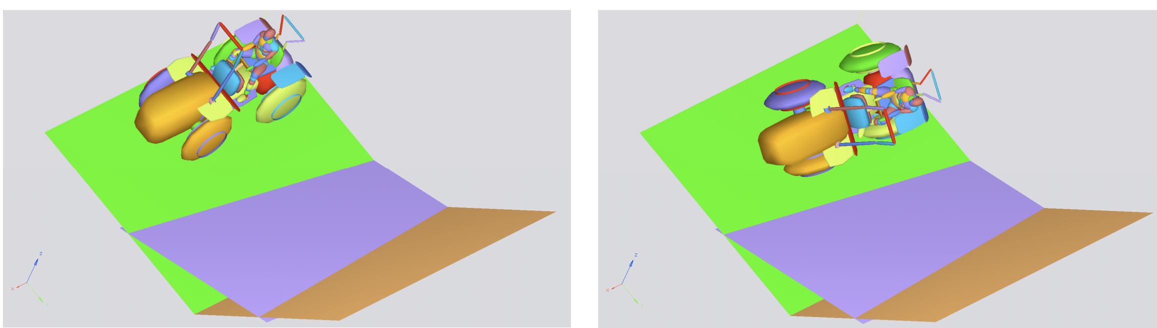

Figure 2. The initial position of the simulations (on the left) and an intermediate instant of time (on the right)

The dummy

The tractor operator is simulated in the scenario by means of a numerical dummy chosen among the ones available in the Madymo libraries, the Hybrid III 50th percentile male dummy, which is the most frequently utilised in the crash tests and in all the NCAP programs (New Car Assessment Programs). The dummy numerical models available in the Madymo libraries are multibody systems, composed by simple geometry bodies and/or FEM models assembled with kinematics joints and restraints, which reproduce the connections present in the instrumented dummies usually employed in the crash tests.

The evaluation of biological damages by multibody techniques: The injury parameters

By means of Madymo, an estimation of the biological damages that occur to the occupants can be obtained through the evaluation of the values of the so-called injury parameters. Therefore the injury severity can be evaluated by utilising the corresponding injury criteria, i.e. by comparing the calculated value of each parameter with a certain threshold value. This thresholds have been established with the progresses made in the field of biomechanics, by carrying out experimental test campaigns on volunteers and dead bodies.

The injury parameters and the corresponding criteria utilised in the paper have been (NHTSA, 1998; Ambrosio, 2001; EuroNCAP, 2004):

- the Head Injury Criterion (HIC) for the estimation of head injuries. It is evaluated by means of a suitable integral average of the head centre of mass acceleration in a time window of not more than 36 ms. The criterion threshold value is 1000 $(m/s^2)^{2.5}s$ during an impulsive frontal shock. It has to be stressed that head sudden rotations are not considered in HIC evaluation.
- the Neck Injury Predictor (N_{ij}) for the estimation of neck injuries. It is evaluated by the calculation of the forces and moments acting on the occipital region. The values achieved by these quantities are put in a suitable dimensionless form by using critical values, that depend on the dummy typology and on the neck loading conditions. They do exist four types of N_{ij}, indeed, one in each of the possible cases, tension – extension (N_{TE}), tension – flexion (N_{TF}), compression – extension (N_{CE}), compression – flexion (N_{CF}). In all the cases, to not have severe damages to the neck, it has to be $N_{ij} < 1$.

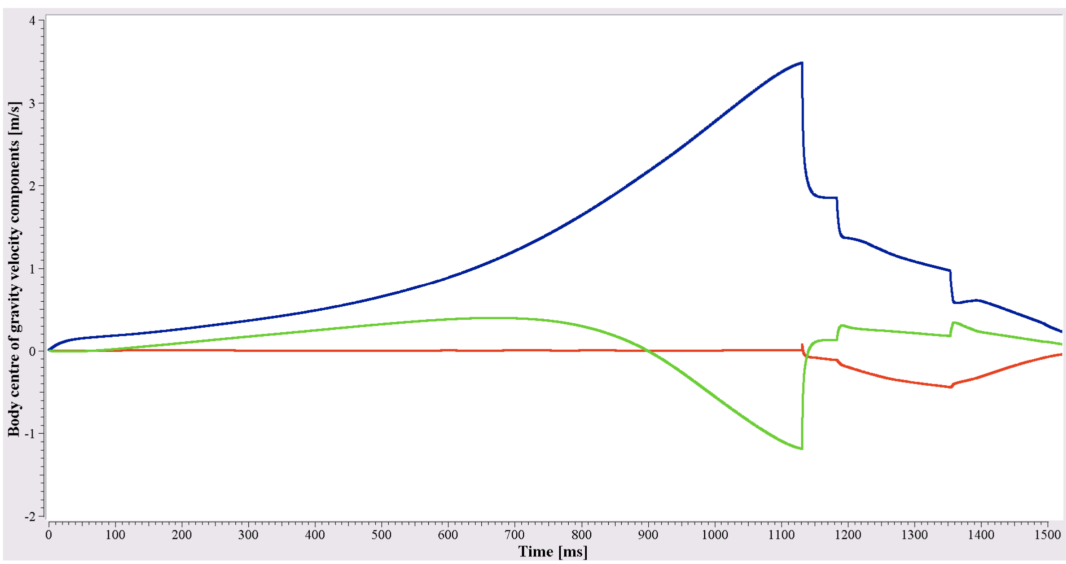

Figure 3. The components of the centre of gravity velocity vector of the tractor body [m/s] as functions of time [ms] (red along the *x*-axis, blue along the *y*-axis, green along the *z*-axis)

- the 3 ms Criterion (3ms) for the estimation of damages occurring to thorax. Thorax injuries are the most critical after head injuries. To not have severe damages, the thorax centre of mass has not to undergo an acceleration higher than 60 g for a time longer than 3 ms.
- the Femur Force Criterion (FFC), for the estimation of femur damages. It allows the evaluation of femur traumas by calculating the longitudinal force acting on each femur. The criterion threshold value is 10 kN.

- the Tibia Index (TI), for the estimation of tibia damages. Moving from the forces and moments acting on the inferior parts of the legs, it is evaluated in a way similar to N_{ij}. The threshold values are 0.4 or 1.3, respectively, for a highly secure or for a less certain estimation of the tibia injury severity.

Results

The roll-over kinematics

In Figures 3 and 4 the main kinematic quantities are represented. They are the velocity vector of the centre of mass of the tractor body and its angular velocity vector. The main shock coming to the system when it hits the ground on its side happens at time $t^* \approx 1130$ ms from the beginning of the simulation. In correspondence of this instant of time, indeed, one can see a fast variation of all the components of the two quantities. Other shocks follow the first one and can be, of course, singled out in the two diagrams in a similar way. In figure 5 the snapshot of the time t^* is reported.

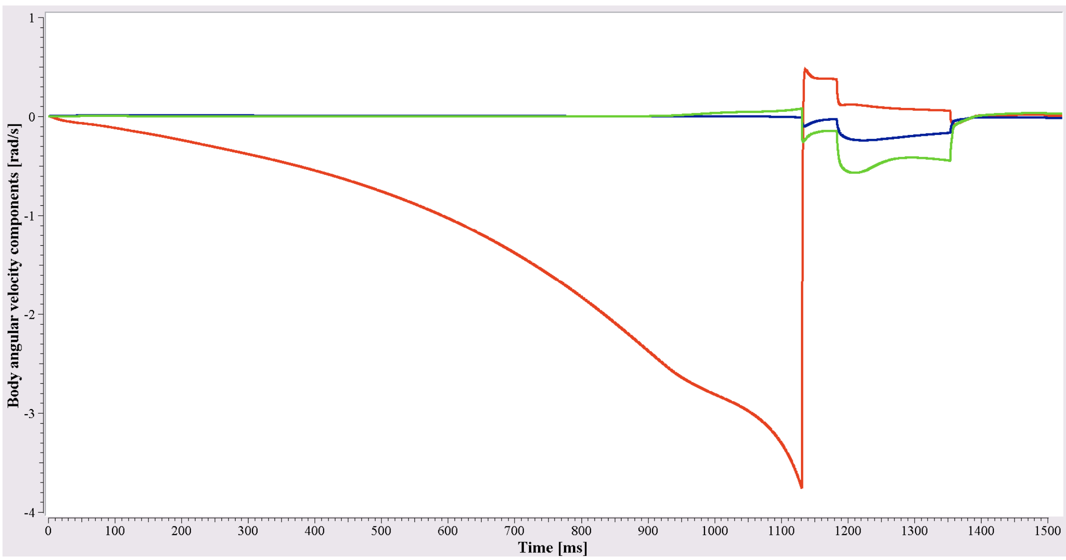

Figure 4. The components of the angular velocity of the tractor body [rad/s] as functions of time [ms] (red along the *x*-axis, blue along the *y*-axis, green along the *z*-axis)

In figure 6 the final time of the simulations is represented. In this Figure the reader is able to see all the parts of the system which are in contact with the ground. The algorithm utilised to detect a contact is, indeed, basically related to the evaluation of the virtual relative penetration between two interacting parts. This quantity allows the evaluation of the reactive forces due to the contact, since a spring-damper system is considered acting at the contact point. It is useful to stress that, indeed, the body surfaces are supposed to have hyper-ellipsoidal form just because in this way the contact region is in each case reduced to a single contact point as the body stiffness approaches infinity. The stiffness and the damping coefficient have, hence, to be accurately chosen by the user, by modelling the dynamical response of the considered contact, in term of relative compliance and energy dissipated. This allows, in a certain, approximated way, to take into account the plastic deformations of hitting parts by choosing the relative penetration equal to the depth of the plastic damages.

The biological traumas coming to the operator

The functional design of the passive protective devices can be carried out by comparing the operator biological traumas in the cases he is restrained with different kind of systems or not restrained at all. In this section the comparison between the case of operator restrained with a 2-point pelvic belt and the non-restrained operator will be shown. In Table 1 one can see the values of several injury parameters in both the cases. In particular the biological damages in absence of restraining systems are severe as expected. Injury parameters overcome the corresponding threshold values in the cases of the head, the neck, the thorax and the tibias.

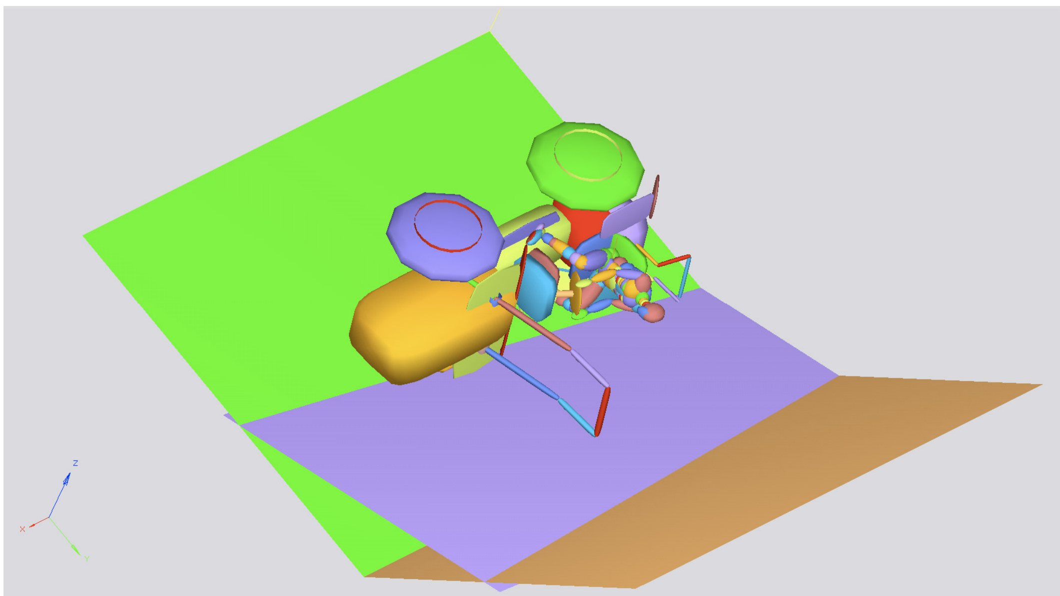

Figure 5. The instant of time in which the main shock takes place (1130 ms)

The possibility offered by the pelvic belt of confining the operator in its safety volume reduces a lot all the injuries, as also expected. In this case, indeed, the criteria threshold is overcome only for the tibias, but less than in the case of non-restrained operator.

Table 1. Comparison of the main injury parameters in the cases of (i) non-restrained dummy and (ii) dummy restrained by a 2-point pelvic belt

Injury Parameter	Injury Criteria	non-restrained	2-point pelvic belt
HIC $[(m/s^2)^{2.5}s]$	< 1000	1465.4	124.65
N_{TE}	< 1	1.1144	2.2696E-01
N_{CF}		5.5008E-02	9.6685E-03
3 ms $[m/s^2]$	< 60 g	718.92	110.42
FFC [kN]	< 1E+04	1.9145E+03	4.0524E+02
TI	< 0.4	1.2021	6.0736E-01

To completely avoid also this kind of injuries a side-bag could be employed, with an opportune counter-reacting structure.

Conclusions

A multibody approach aimed at the functional design and performance optimisation of safety restraint systems for tractor operators is proposed in the paper. To our knowledge, for the first time a similar approach is utilised in the field of work accidents and, in particular, accidents related to the utilisation of agricultural machines. As an example of this possibility, the scenario of a typical roll-over accident has been reproduced in the commercial multibody-FEM Madymo environment (TNO Automotive Safety Solutions - NL).

We show how it is possible to evaluate the severity of the injuries happening to the operator, which becomes the fundamental parameter that the performance of a safety restraint device depends on. By comparing the amount of biomechanical damage to the operator, in the cases different protective systems are employed, is indeed possible to evaluate the safety performance of each device and, hence, to proceed to its optimal functional design.

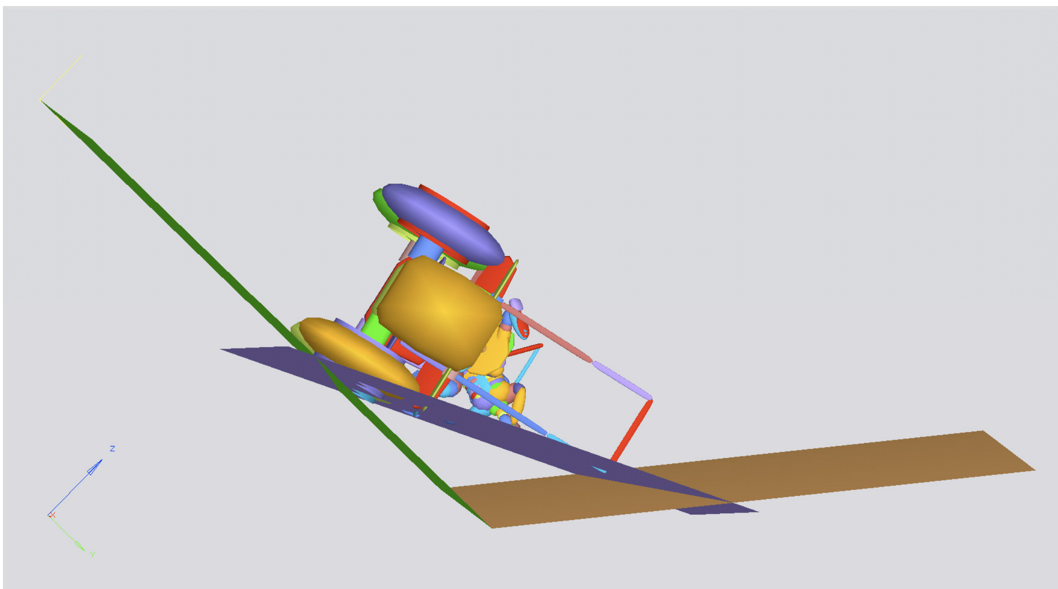

Figure 6. End of the simulation: it is possible to visualise the contacts between the dummy-tractor system and the ground

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