BIOSYSTEMS ENGINEERING 127 (2014) 79–91

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Comparison between a rollover tractor dynamic model and actual lateral tests

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ARTICLE INFO

Article history:
Received 24 January 2014
Received in revised form
7 August 2014
Accepted 20 August 2014
Published online 16 September 2014

Keywords:
Energy
Tractor
Mathematical model
Dynamic behaviour
Rollover
ROPS

Despite the progress in tractor design with respect to safety, one of the most dangerous situations for the driver under operating conditions on agricultural machines is the lateral rollover. Several accidents involving tractor rollover have indeed been encountered, requiring the design of a robust Roll-Over Protective Structure (ROPS). A mathematical model representing the behaviour during a generic tractor lateral rollover, with the possibility of modifying the geometry, the inertia of the tractor and the environmental boundary conditions is herein proposed. The purpose was to define a method allowing the prediction of the elasto-plastic behaviour of the impacts occurring in the rollover phase. In particular, this paper proposes a tyre impact model capable of analysing the influence of the wheels on the energy to be absorbed by the ROPS. Different tractor design parameters that affect the rollover behaviour, such as mass and dimensions, were considered and their influence on the energy absorbed by the ROPS was determined. The model was designed and calibrated with respect to the results of actual tests carried out on a narrow-track tractor. The results of the model showed a good match with the dynamic behaviour and energy absorbed by the ROPS in experimental lateral rollover tests. This should permit good prediction of the amount of energy to be absorbed in some accident situations, and therefore assist in the design of protective structures.

1. Introduction

The problem of tractors and agricultural machinery overturning has been studied over the years and different operating conditions can lead to a high risk of instability and, hence, consequent rollover situations. Rollover accidents have been investigated in depth since the 1930s, with a peak of interest in the 1970s (Chisholm, 1972). Renewed attention in recent years has considered the evolution of tractor design (shape and overload masses) (Harris, McKenzie, Etherton, Cantis, & Ronaghi, 2010). The difficulty in avoiding fatal tractor accidents has led to the introduction of Roll-Over Protective Structures (ROPS), not to prevent rollovers but to reduce injury to the operator involved in the accident. The first mandatory requirement for ROPS tested on agricultural tractors was introduced in Sweden in the 1950s (Moberg, 1964); subsequently, many countries followed, encouraged by the first standardised testing procedure of the Organisation for Economic Co-operation and Development (OECD) (OECD

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http://dx.doi.org/10.1016/j.biosystemseng.2014.08.010

Nomenclature

Tractor parameters

- R — Rear and front tyre radius (0.430 m)
- N — Rear and front tyre width (0.265 m)
- T — Rear and front wheel-track (1.110 m)
- W — Wheelbase (1.390 m)
- P — Horizontal distance ROPS impact point-external wheel (0.140 m)
- H_{CM} — Height of the centre of mass (0.600 m)
- H_{imp} — Height of ROPS impact point (2.140 m)
- I_z — Moment of inertia along the Z axis (223.75 kg m^2)
- m — Tractor mass (1478 kg)
- g — Gravitational acceleration (9.81 m s^{-2})
- s — Ground slope (12 deg)
- θ_1 — Angle between the CM and the point of unstable equilibrium (36.9 deg)
- θ_2 — Angle between the ROPS point of impact and the ground (93.7 deg)
- θ_3 — Angle between the ROPS point of impact and the y axis (6.2 deg)
- CP1 — The lower part of the wheels (first centre of rotation)
- CP2 — The upper part of the wheels (second centre of rotation)
- CP3 — ROPS impact (third centre of rotation)

Variables

- $\vec{F}$ — Vectors of body external force (N)
- $\vec{T}$ — Vectors of body external moments (N m)
- $\vec{p}$ — Vectors of linear momentum (kg m s^{-1})
- $\vec{L}$ — Vectors of angular momentum (kg m^2 s^{-1})
- I_{CP} — Moment of inertia for any impact point (kg m^2)
- $\vec{v}_{CM}$ — velocity of the centre of mass (m s^{-1})
- $\vec{\omega}_z$ — The body angular velocity (rad s^{-1})
- $v_{\perp 3}$ — Velocity of impact ROPS-ground
- v_x — Component of $v_{\perp 3}$ parallel to the ground
- v_y — Component of $v_{\perp 3}$ orthogonal to the ground
- E_{ROPS} — Strain energy to be absorbed by the ROPS
- KE — Kinetic energy (J)
- KE_A — Actual kinetic energy (J)
- KE_C — Computed kinetic energy (J)
- PE — Potential energy (J)
- LE — Deformation energy and/or energy loss due to heat or friction (J)
- b — Horizontal distance between the axis of rotation and the CM (m)
- $\vec{l}_{CP}$ — Distance between the impact point and the centre of mass (m)
- Φ — Angle between the gravitational acceleration vector ($\vec{g}$) and $\vec{l}_{cm}$ (deg)
- ψ — Angle between two $\vec{l}_{CP}$ consecutive (deg)
- γ — Angle between the velocity vector *before* impact and the x axis (deg)
- α — Angle between the velocity vector *after* impact and the x axis (deg)
- k_e — The springback factor (elastic return) (–)
- k_g — The energy factor absorbed by the ground (–)
- k_w — The elasticity factor of the wheels (–)

Abbreviations

- CM — Centre of mass
- CP — Generic contact point

Code 3, OECD 1967). Continuing research activities on the subject of tractor rollover have led to the definition of additional OECD normalised testing procedures (OECD ROPS Codes, 2013). Official ROPS tests are normally based mainly on the energy to be absorbed by the ROPS, defined according to the reference mass of the tractor (Rondelli & Guzzomi, 2010). However, ROPS are verified in terms of strength through test criteria based mostly upon studies carried out more than thirty years ago (Boyer, Chisholm, & Schwanghart, 1976; Chisholm, 1977; Chisholm & Seward, 1976; Moberg, 1973; Schwanghart, 1982). Over the years, many research approaches have involved the development of mathematical models dedicated to understanding rollover dynamics via computer simulation. Since 1920, the static and dynamic behaviour of tractors has been investigated (McKibben, 1927). Research increased in the 1960s as a result of the introduction of computers, with the first examples of numerical modelling applied to the tractor, mainly based on the Newtonian approach or the Lagrange method (Kim & Rehkugler, 1987). Tractor lateral rollover (Schwanghart, 1971, 1973; Davis & Rehkugler, 1974a, 1974b; Chisholm, 1979a, 1979b, 1979c, 1979d) and longitudinal overturning (Goering & Buchele, 1967; Koch, Buchele, & Marley, 1970; Smith & Liljedahl, 1972) were simulated. Research continues to investigate the real behaviour and the energy dynamics during tractor rollover (Ahmadi, 2011; Guzzomi, Rondelli, Guarnieri, Molari, & Molari, 2009; Lenain, Hugo, & Langle, 2010; Scarlett & Reed, 2009; Silleli et al., 2007, 2008). These approaches have been based on a totally rigid body, mainly based on a simulation software approach requiring computing skills, but with little relevance to the framework of testing procedures. The ROPS approach has also been considered with respect to small agricultural vehicles, such as lawn mowers (Wang, 2005). Computer-based dynamic simulation modelling techniques, validated by practical rollover trials, have been employed to investigate small vehicle lateral rollover behaviour, with particular respect to the onset of vehicle lateral instability and the energy levels likely to be absorbed by the vehicle ROPS during the overturn event (Scarlett et al., 2006). Studies have been carried out using Finite Element in order to predict ROPS deflection, without carrying out actual tests (Alfaro, Arana, Arazuri, & Jarén, 2010; Arana, Alfaro, Arazuri, Ponce de León, & Jarén, 2011; Harris, Mucino, Etherton, Snyder, & Means, 2000; Wang, Ayers, & Womac, 2009).

The deflection of the mechanical part of the tractor (depending on shape and material) and the amount of energy to be absorbed during a shock must be known for design purposes when a generic tractor is being considered. An analytical model is extremely important for safety in agriculture in order to assess the risks for the operators. Their