Non-Collision mitigation and vehicle transportation safety using integrated vehicle control systems with modular model

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Abstract

A vehicle frontal collision can be divided into two main stages, the first one is a primary impact, and the second one is a secondary impact. The primary impact indicates the collision 42 J. Traffic Transp. Eng. (Engl. Ed.) 2017; 4 (1): 41e60 between the front-end structure of the vehicle and an obstacle (another vehicle in this paper). The secondary impact is the interaction between the occupant and the restraint system and/or the vehicle interior due to vehicle collisions

Introduction

Vehicle dynamics control systems (VDCS) exist on the most modern vehicles and play important roles in vehicle ride, stability, and safety. For example, anti-lock brake system (ABS) is used to allow the vehicle to follow the desired steering angle while intense braking is applied (Bang et al., 2001; Yu et al., 2002). In addition, the ABS helps reducing the stopping distance of a vehicle compared to the conventional braking system (Celentano et al., 2003; Pasillas-Lepine, 2006). The active suspension control system (ASC) is used to improve the quality of the vehicle ride and reduce the vertical acceleration (Alleyne and Hedrick, 1995; Yue et al., 1988). From the view of vehicle transportation safety, nowadays, occupant safety becomes one of the most important research areas and the automotive industry increased their efforts to enhance the safety of vehicles. Seat belts, airbags, and advanced driver assistant systems (ADAS) are used to prevent a vehicle crash or mitigate vehicle collision when a crash occurs. The most well-known pre-collision method is the advance driver assistant systems (ADAS). The aim of ADAS is to mitigate and avoid vehicle frontal collisions. The main idea of ADAS is to collect data from the road (i.e., traffic lights, other cars distances and velocities, obstacles, etc.) and transfer this information to the driver, warn the driver in danger situations and aid the driver actively in imminent collision (Gietelink et al., 2006; Seiler et al., 1998). There are different actions may be taken when these systems detect that the collision is unavoidable. For example, to help the driver actively, the baking force can be applied in imminent collision (Jansson et al., 2002), in addition, the brake assistant system (BAS) (Tamura et al., 2001) and the collision mitigation brake system (CMBS) (Sugimoto and Sauer, 2005) were used to activate the braking instantly based on the behaviour characteristics of the driver, and relative position of the most dangerous other object for the moment. Vehicle crash structures are designed to be able to absorb the crash energy and control vehicle deformations, therefore simple mathematical models are used to represent the vehicle front structure (Emori, 1968). In this model, the vehicle mass is represented as a lumped mass and the vehicle structure is represented as a spring in a simple model to simulate a frontal and rear-end vehicle collision processes. Also, other analyses and simulations of vehicle-to-barrier impact using a simple mass spring model were established by Kamal (1970) and widely extended by Elmarakbi and Zu (2005, 2007) to include smart-front structures. To achieve enhanced occupant safety, the crash energy management system was explored by Khattab (2010). This study, using a simple lumped-parameter model, discussed the applicability of providing variable energy-absorbing properties as a function of the impact speed. In terms of the enhancing crash energy absorption and minimizing deformation of the vehicle's structure, a frontal structure consisting of two special longitudinal members was designed (Witteman and Kriens, 1998; Witteman, 1999). This longitudinal member system was divided into two separate systems: the first, called the crushing part, guarantees the desired stable and efficient energy absorption; the other, called the supporting part, guarantees the desired stiffness in the transverse direction. For high crash energy absorption and weight efficiency, new multi-cell profiles were developed (Kim, 2002). Various design aspects of the new multi-cell members were investigated and the optimization was carried out as an exemplary design guide. The vehicle body pitches and drops at fontal impact are the main reason for the unbelted driver neck and head injury (Chang et al., 2006). Vehicle pitch and drop are normally experienced at frontal crash tests. They used a finite element (FE) method to investigate the frame deformation at full frontal impact and discussed the cause and countermeasures design for the issue of vehicle body pitch and drop. It found that the bending down of frame rails caused by the geometry offsets of the frame rails in vertical direction during a crash is the key feature of the pitching of the vehicle body. The effect of vehicle braking on the crash and the possibility of using vehicle dynamics control systems to reduce the risk of incompatibility and improve the crash performance in frontal vehicle-to-barrier collision were investigated (Hogan and Manning, 2007). They proved that there was a slight improvement of the vehicle deformation once the brakes were applied during the crash. A multi-body vehicle dynamic model using ADAMS software, alongside with a simple crash model was generated in order to study the effects of the implemented control strategy. Their study showed that the control systems were not able to significantly affect the vehicle dynamics in the offset barrier impact. In addition, it was found that in offset vehicle-tovehicle rear-end collision, the ABS or direct yaw control (DYC) systems can stabilize the vehicle. However, these control systems affected each other and cannot work together at the same time. The behaviour of a vehicle at high-speed crashes is enhanced by using active vehicle dynamics control systems (Elkady and Elmarakbi, 2012). A 6-degree-of-freedom (6-DOF) mathematical model was developed to carry out this study. In this model, vehicle dynamics was studied together with a vehicle crash structural dynamics and a validation of the vehicle crash structure of the proposed model was achieved. Four different cases of VDCS were applied to the model to predict the most effective one. An extension to this study, an occupant model has been developed and the effect of VDCS on the occupant kinematics has been analysed (Elkady and Elmarakbi, 2012). The main aim of this research is to investigate the effect of the VDCS on vehicle collision mitigation, enhance vehicle crash characteristics, and improve occupant biodynamics responses in case of 50% vehicle-to-vehicle offset crash scenario. For that purpose, different seven cases of VDCS are applied to the vehicle model, there are three new cases which are not mentioned in the previous publications.

Methodology of modular model

The aim of this paper is to investigate the effect of vehicle dynamics control systems (VDCS) on both the collision of the vehicle body and the kinematic behaviour of the vehicle's occupant in case of offset frontal vehicle-to-vehicle collision. A unique 6-degree-offreedom (6-DOF) vehicle dynamics/crash mathematical model and a simplified lumped mass occupant model are developed. The first model is used to define the vehicle body crash parameters and it integrates a vehicle dynamics model with a vehicle front-end structure model. The second model aims to predict the effect of VDCS on the kinematics of the occupant. It is shown from the numerical simulations that the vehicle dynamics/crash response and occupant behaviour can be captured and analysed quickly and accurately. Furthermore, it is shown that the VDCS can affect the crash characteristics positively and the occupant behaviour is improved

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Vehicle dynamics/crash model

Using mathematical models in crash simulation is useful at the first design concept because rapid analysis is required at this stage. In addition, the well-known advantage of mathematical modelling provides a quick simulation analysis compared with FE models. In this paper, a 6-DOF vehicle dynamics/crash mathematical model, shown in Fig. 1(a), has been developed to optimize the VDCS, which will be embedded in the control unit, in impending impact at offset vehicle-to-vehicle crash scenarios for vehicle collision mitigation. The ABS and the ASC systems are co-simulated with a full car vehicle dynamic model and integrated with a front-end structure. It is worthwhile mentioning that vehicle components, which significantly affect the dynamics of a frontal impact, are modelled by lumped masses and nonlinear springs. In this full-car model, the vehicle body is represented by lumped mass m and it has a translational motion in longitudinal direction (x axis), translational motion on vertical direction (z axis), pitching motion (around y axis), rolling motion (around x axis), and yawing motion in case of offset collision (around z axis at the point of impact). Four spring/damper units are used to represent the conventional vehicle suspension systems. Each unit has a spring stiffness ks and a damping coefficient c. The subscripts f, r, R and L denote the front, rear, right and left wheels, respectively. The ASC system is co-simulated with the conventional suspension system to add or subtract an active force element u. The ABS is cosimulated with the mathematical model using a simple wheel model. The unsprung masses are not considered in this model and it is assumed that the vehicle moves in a flat-asphalted road, which means that the vertical movement of the tyres and road vertical forces can be neglected. To represent the front-end structure of the vehicle, four non-linear springs with stiffness ks are proposed: two springs represent the upper members (rails) and two springs represent lower members of the vehicle frontal structure. The subscript u denotes the upper rails while the subscript l denotes the lower rails. The bumper of the vehicle is represented by a lumped mass mb and it has a longitudinal motion in the x direction and rotational motion for the non-impacted side of each bumper.

improve the crash performance in frontal vehicle-to-barrier collision were investigated (Hogan and Manning, 2007). They proved that there was a slight improvement of the vehicle deformation once the brakes were applied during the crash. A multi-body vehicle dynamic model using ADAMS software, alongside with a simple crash model was generated in order to study the effects of the implemented control strategy. Their study showed that the control systems were not able to significantly affect the vehicle dynamics in the offset barrier impact. In addition, it was found that in offset vehicle-tovehicle rear-end collision, the ABS or direct yaw control (DYC) systems can stabilize the vehicle. However, these control systems affected each other and cannot work together at the same time. The behaviour of a vehicle at high-speed crashes is enhanced by using active vehicle dynamics control systems (Elkady and Elmarakbi, 2012). A 6-degree-of-freedom (6-DOF) mathematical model

The general dimensions of the model are shown in Fig. 1(a), where lf, lr, l and h represent the longitudinal distance between the vehicle's CG and front wheels, the longitudinal distance between the CG and rear wheels, the wheel base and the high of the CG from the ground, respectively. a is the distance between the centre of the bumper and the right/left frontal springs; b is the distance between the CG and right/left wheels. The free body diagram of the mathematical model is shown in Fig. 1(b), which represents the different internal and external forces applied on the vehicle body. Fs, FS, Fb, Fz and Ff are frontend non-linear spring forces, vehicle suspension forces, braking forces, normal forces and friction forces between the tyres and the road due to vehicle yawing, respectively. 2.1.1. Equations of motion of vehicle-to-vehicle crash scenario The model in the case of offset frontal vehicle-to-barrier is thirteen DOF namely longitudinal and vertical movements, pitching, rolling and yawing motions for each vehicle body, the longitudinal movement of the two bumpers as one part, and the rotational motion for the non-impacted side of each bumper. The two bumpers of each vehicle are considered as lumped masses, and dealt as one mass to transfer the load from one vehicle to another.

There are different types of forces which are applied on the vehicle body. These forces are generated by crushing end structure, conventional suspension system due to the movement of the vehicle body and the active control systems such as the ABS and ASC. The free body diagram shown in Fig. 1(b) illustrates these different forces and their directions. To simulate the upper and lower members of the vehicle front-end structure, multi-stage piecewise linear for cede formation spring characteristics are considered. The nonlinear springs used in the multi-body model ADAMS (Hogan and Manning, 2007) are taken to generate the n stage piecewise spring's characteristics as shown in Fig. 4(a), while the general relationship between the force and the deflection, Fig. 4(b), is used to calculate the force of the vehicle's front-end. The suspension forces of the vehicle body are also calculated. The detailed equations of these forces and the validation of the vehicle dynamic secrash model was established in a previous study by the authors (Elkady and Elmarakbi, 2012). The validation is performed to ensure the validity of the model and is accomplished by comparing the mathematical model results with real test data and the results of the former ADAMS model. The validation showed that the mathematical model results are well matched with the other results. 2.2. Multi-body occupant model In this section, occupant biodynamic is considered by modelling the occupant mathematically in order to be integrated with the vehicle mathematical model. The occupant model is proposed to be three-body model to capture its dynamic response, rotational events of the chest and head, due to different crash scenarios. The restraint system consists of seat belt, front and side airbags is presented by different spring-damper systems. The occupant biodynamic model shown in Fig. 5 is developed in this study to evaluate the occupant kinematic behaviour in full and offset frontal crash scenarios. The human body model consists of three bodies with masses m1, m2 and m3. The first body (lower body/pelvis) with mass m1, represents the legs and the pelvic area of the occupant and it is considered to have a translation motion in the longitudinal direction and rotation motions (pitching, rolling and yawing) with the vehicle body. The second body (middle body/chest), with mass m2, represents the occupant's abdominal area, the thorax area and the arms, and it is considered to have a translation motion in the longitudinal

Conclusions

All the directions and a rotation motion around the pivot between the lower and middle bodies (pivot 1). The third body (upper body/ head), with mass m3, represents the head and neck of the occupant and it is considered to have a translation motion in the longitudinal direction and a rotational motion around the pivot between the middle and upper bodies (pivot 2). A rotational coil spring is proposed at each pivot to represent the joint stiffness between the pelvic area and the abdominal area and between the thorax area and the neck/ head area. The seatbelt is represented by two linear spring damper units between the compartment and the occupant. The frontal and side airbags are each represented by two linear spring-damper units. 2.2.1. Equation of motion (EOM) of the human body model Fig. 6(a)e(c) shows the side, top and front views of the occupant model, respectively. POI in Fig. 6(b) means point of impact. For each figure, the positions of the occupant's three bodies are illustrated before and after the crash.

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