Quad bike frame dynamic load evaluation using full vehicle simulation model

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Abstract. The paper describes a quad bike multi-body model intended to extract maximum dynamic forces acting on the vehicle frame. This complex full-vehicle model includes all essential systems such as suspension, steering, frame, power train, brakes, payload, as well as tire-road interaction model. A number of the quad bike operation events has been simulated. Time histories of the forces acting on the vehicle frame and tire contact patch have been analyzed and load cases with maximum forces have been extracted for subsequent finite-element analysis of the frame. In case the sufficient number of the events is simulated, the load cases can be used in the design optimization process, such as topology optimization, at early stages of the frame development.

1. Introduction
A quad bike frame is a load-bearing structure intended to withstand numerous load cases during vehicle ride. Strength and reliability of this particular structure could be predicted by finite element methods [1]-[3]. These strength calculations should be performed for all possible loads, which are usually dynamic. The purpose of this study is to evaluate these dynamic loads acting on a quad bike frame by using full-vehicle simulation model capable of capturing full range of environment conditions in which the quad bike is operated. The more ride situations are simulated in virtual tests, the higher the reliability of the quad bike and of its frame can be guaranteed.

Another purpose of dynamic load evaluation models is to use the mat the early stage of the frame design process. Modern methods, like topology optimization, provide calculation of the beneficial and reliable load paths for the frame structure only when all major loads are known in advance.

2. Quad bike multi-body dynamic model description
The quad bike and its dynamic model are shown in Figure 1. The model consists of front and rear suspensions, steering, power train, driver and passenger, front and rear payloads, load-bearing frame. The model has been built under the following assumptions: all the parts of the model are rigid; joints are frictionless; roadbed is rigid; driver, passenger and payload are not moving relative to the quad bike during ride. The quad bike model was built in an all-purpose multi-body dynamics software [4]-[9].

The models of the suspensions and steering system are shown in figure 2. The front and rear suspensions are double wishbone suspensions with telescopic hydraulic shock absorbers and springs. The rear suspension is equipped with an anti-roll bar [10]-[12].
Figure 1. Quad bike (left) and its multi-body dynamic model with driver, passenger and payloads (right)

Power train model shown in figure 3 consists of a power unit and transmission. The power unit includes an engine, a CVT (continuously variable transmission) and a transfer case. The CVT, transfer case gear ratios and engine’s torque-speed curve are defined in the model by means of an external DLL file.

Figure 2. Front and rear suspensions model with steering model

Figure 3. Power unit and transmission model

The engine torque is calculated as a function of the transmission rotation speed and accelerator pedal rate and is applied to the front and rear final drives, modelled as rigid bodies with gear coupling ratios. Final drives models also include a locking differential. Torque-speed curves for the power unit and CVT unit are shown in figure 4.
Figure 4. Torque vs rotation speed curves at different accelerator rates for power unit coupled with CVT.

Figure 5. Damping curve, [N·sec/mm vs mm/s] for suspension.

Figure 6. Spring stiffness curves, [N/mm vs mm] for front (Csus1) and rear (Csus2) suspensions.

Suspension-frame joints are modelled using standard bushing elements with no friction or damping. Stiffnesses of the bushings are shown in Table 1.

| Table 1. Suspension-frame joints bushings stiffness |
|-----------------------------------------------|
| Linear stiffness, N/mm | Angular stiffness, N·mm/rad |
|---|---|---|---|
| Radial | Axial | Bending | Torsion |
| 10000 | 1000 | 1000 | 0 |
Tire-road interaction model choice is very important. After analysis of numerous types of these models [13]-[19] we have chosen Pacejka’s MF-Tire interaction model described in [20], [21], [22]. Its reaction forces are shown in figure 4.

![Tire-road interaction model](image)

**Figure 7.** Tire-road interaction model

Dynamic loads acting on the quad bike frame are evaluated for the following events:
1. Static equilibrium on a flat road (a reference loadcase);
2. Maximum straight-line acceleration forward and subsequent emergency braking;
3. Moving over a 30 deg ramp;
4. Moving on a road with a side slope;
5. Cross-axling;
6. Vertical loading with acceleration 3g (jump simulation);
7. Winching;
8. Towing;
9. Bumping into an obstacle;
10. Loading the quad bike frame sidestep by the combined weight of the driver and passenger.

The list of events considered as loadcases could be extended as the experience of the quadbike operation in different conditions is being gained.

3. Simulation results
Every simulated event listed above produces dynamic force time history in the contact tire patch, suspension, frame, steering joints, etc [22]. For instance, cross-axlings shown in figure 8 results in the tire contact patch force time histories presented in figure 9. These graphs can be used to determine maximum reactions acting on the wheels of the vehicle during the event. Corresponding force acting on the frame in the frame-strut joint of the front left suspension at the same timeframe as in figure 9 is shown in figure 10. Figure 11 zooms this graphs for the time period from 29 to 31 sec during which the cross-axling takes place. As one can see, at a time t=29.84 sec, the front left and rear right wheels are lifted (their contact patch forces are set to zero), and the other two wheels are under increased load.
Figure 8. Cross-axling simulation at a time = 29.84 s. Blue arrows show reaction forces in the tire contact patch, red arrows show drive torques applied to the wheels.

This combination of the contact patch reactions corresponds to a quite heavy loadcase for the vehicle, at which its frame is simultaneously being bented in longitudinal direction and twisted. Analysis of the force time histories depicted in figure 8 and 9 shows that one event can produce several loadcases: loads acting on the frame and at different joints have multiple peaks at different time moments. Therefore, the whole cross-axling event should be represented as several loadcases, at which the worst combination of the rear and front wheel vertical, longitudinal and transversal forces with the corresponding gravity and inertia forces acting on the whole vehicle takes place.

Besides the maximum loads that determine ultimate strength of the quadbike frame, it is also possible to simulate regular vehicle rides. Figures 11 and 12 present an uneven road cruising event and the time history of the contact patch and strut-frame joint forces during this ride. These time histories can be used for further fatigue calculations of the vehicle frame.
Figure 9. Tire contact patch forces:
- a – front left wheel, b – front right wheel, c – rear left wheel, d – rear right wheel
- $F_x$ – traction force, $F_y$ – lateral force, $F_z$ – vertical reaction

Figure 10. Force magnitude vs time in the frame-strut joint of the front left suspension
Figure 11. Tire contact patch forces during cross-axling:
a – front left wheel, b – front right wheel, c – rear left wheel, d – rear right wheel – Fx – traction force, – Fy – lateral force, – Fz – vertical reaction

Figure 12. Uneven road cruising event at a time = 81.5 sec
4. Conclusions and discussion

Analysis of the time histories of the forces in the tire contact patch and suspension-frame joints allows detection of the quasi-static load cases with maximum forces during the event. This maximum loads can be transferred to finite element analysis software for the frame strength estimation. In practice, it is convenient to use inertia relief technique and special scripts to transfer loads from multi-body model to finite element model, as described in [3]. This script-based automation allows performing stress analysis of many load cases without tremendous time-consuming handwork. Calculated loads can also be used in design optimization process, like topology optimization, at early stages of the frame development.

It is also handy to use full vehicle dynamic model to determine the time histories for the forces acting on the vehicle and its frame during regular ride for further fatigue analysis.

The simulation technique described in this paper produces vast amount of data containing time histories of the forces acting on the vehicle frame in every joint during an event. Moreover, the number of events can be also quite big consequently multiplying the amount of data. Automated analysis of this data for extracting maximum loads acting on the vehicle frame presents a problem which has not been fully solved by now.

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