An estimation model of suspension loads in explicit multibody simulation

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Abstract. Explicit simulation is an extensively tool used by automotive designer both for car-performance analysis in standard operating condition and both in drive-simulator, whom exploits the computational ability of this codes to operate in real-time. The computational capability of these simulation tools however implies a reduced set of information available in simulation results. Regards automotive sector, with a particular focus on suspension system, the confined number of information in structural terms (states of solicitation on components and constraint) can be a strong limitation in their massive use. In this context, the objective of this activity is to propose a calculation method, as simple as accurate, that foresees to characterize the suspension by an implicit multibody model, and then using the information already available in explicit multibody model (wheel motion and external forces at the contact patch) allows estimating whichever force in all points of the suspension. The results obtained with the proposed method were compared with those outcoming from ADAMS/Car supplying in all cases, good results.

1. Introduction

The use of multi-body codes for the analysis and optimization of mechanical system is a common practice both in industrial and academic sectors. Multi-body codes allows simulating whichever mechanical system being useful for example for the design, the health monitoring and the optimization process[1,2].

Today, two different approaches can be used: implicit and explicit [3,4]. Implicit multi-body codes allows modelling whichever mechanical system (linear or not-linear) introducing, if desired, flexible bodies [5–7] while explicit one are customized for a particular application allowing modelling a particular mechanical system starting by a reduced set of information. The most important advantages of the latter is the computational efficiency that allows them to be used also in real-time[8,9].

The enormous modelling possibilities offered by implicit multi-body codes are reflected into an high complexity resulting, generally, time consuming. Due to the important advantages of explicit multi-body codes, especially in terms of computational effort, their use in industrial context is undoubtedly wide-spread. However, their simplicity goes beside a reduced set of information in post-processing that may be fundamental.

With reference to automotive sector [5,10–13], a set of crucial information are loads in all joints of the suspension and steering system [14,15]. An exact assessment of this loads would allow to make fatigue design and verification much accurate, keeping into account specific
phenomena that, sometimes, are not considered [16–18]. Moreover, a correct knowledge of joint loads obtained by adopting explicit multibody simulations beside efficient methods for fatigue life estimation may be a key factor with respect to competitors [19].

In this context, the objective of this activity is to propose a method, to be used within explicit multi-body codes, able to address joint loads of a suspension system. The challenge was to propose an efficient method without increasing the computational capability of explicit multi-body codes. To this aim, the proposed method born by the analogy between a suspension system and a lumped mass system. The proposed approach links the wheel center motion and forces at contact patch, data already available in explicit multi-body codes, to each reaction forces and in whichever reference system through non-linear function that must be determined by a characterization process.

The proposed method, certified through a test-case, supplies encouraging results estimating exactly all forces in the whole set of considered joints.

2. The basic idea

The basic idea from which the proposed methods has been developed is the analogy between a lumped mass system and a suspension system [4,20] as shown in Fig. 1.

![Figure 1. Analogy between a suspension system and lumped mass system. (a) Lumped mass system; (b) schematic suspension model.](image)

By the equation of motion of the mass 2 (Eq. 1), the total force acting on the mass can be obtained as linear combination of three components: inertial, viscous and elastic.

\[ F = m_2 \cdot \ddot{x}_2 + c_2 \cdot (\dot{x}_2 - \dot{x}_1) + k_2 \cdot (x_2 - x_1) \]  

(1)

Knowing the relative motion of the wheel center (data already available within explicit multibody codes) and the constant terms \(m_2, c_2\) and \(k_2\) it is possible to address the total force. Previous statement can be applied also to the suspension model shown in Fig. 1 (b). The equation of motion (Eq. 2) allows addressing the total acting on a generic joint.

\[ F = g_1 \cdot \ddot{x}_2 + g_2 \cdot (\dot{x}_2 - \dot{x}_1) + g_3 \cdot (x_2 - x_1) + \sum_{i=4}^{n} g_i \cdot F_{ext,i} \]  

(2)

\(n\) represents the number of external forces applied at the contact patch that must be accounted due to their contribution to the total reaction force. External forces to be considered are the following:

- Lateral force at contact patch:
• Longitudinal force at contact patch;
• Aligning torque;
• Overturning moment;
• Rolling resistance torque;

Comparing Eq. 1 with Eq. 2 the constant terms $m_2$, $c_2$ and $k_2$ are substituted by non-linear functions $g_1, \ldots, g_n$. All these functions $g_1, \ldots, g_n$ are the key factor of the proposed method. As shown in the next section, such relations must be determined through a characterization process of the suspension system.

3. The proposed estimation model

As briefly described in previous section, the proposed approach is aimed to estimate suspension loads exploiting some information already available within explicit multibody codes. Starting by an implicit multibody model of the suspension system it is possible to assess the necessary functions $g_1, \ldots, g_n$ to estimate all the desired suspension loads. Once these are known, the evaluation of reaction forces in whichever joint of the suspension can be made directly by explicit multibody simulation (Fig. 2).

![Flowchart of the proposed method](image)

**Figure 2.** Flowchart of the proposed method. In white the characterization process. In grey the estimation approach once the black box is known.

The crucial part of the proposed method is therefore the characterization process aimed to obtain the necessary functions $g_1, \ldots, g_n$ to link each effect to the force acting on the $i$-th joint. To obtain all the functions necessary to couple each contribution to the total force acting on a joint, the implicit multibody model of the suspension must splitted in 4 “sub-model”: elastic, viscous, inertial and cinematic. The first three models are used to estimate the functions $g_1, \ldots, g_3$ coupling the displacement, velocity and acceleration to the total force, while the cinematic model is used to determine the function $g_4, \ldots, g_n$ coupling each of the external force to the desired reaction force. Exciting each of the previous sub-model on a test rig with an appropriate excitation and measuring the force on each joint, it is possible to find the relative function.

The definition of the excitation is thus a fundamental aspect. For the elastic, viscous and inertia effect, a sinusoidal function is used. The amplitude of the sine must be such to cover the entire travel of the suspension while the angular frequency must be such to obtain the maximum acceleration of the wheel center. For what concern the external forces, the characterization process foresees to stand statically the suspension system over a test rig applying, for each
relative position, each of the external forces singularly. In such a way it is possible to map the entire travel of the suspension coupling, for each relative position, all the external forces to the total force on the joint.

An important consideration must be made. The presence of anti-roll bar and steering system made, de facto, the suspensions system to be not independent. Due to this, it is fundamental to evaluate functions teeing the wheel center motion of the left wheel center to the reaction forces of a joint on the right suspension system and vice-versa.

Moreover it is important to state that the ”black box” is valid for only one component of the reaction force and for only one joint. This means that each component of the force and each joint must have its own set of functions $g_1, \ldots, g_n$.

4. Test case

With the aim to test the proposed method, an implicit multibody model of a full vehicle was realized in Adams/Car. In such a way it was possible to have simultaneously both the input for the proposed model (wheel center motion and forces at contact patch) and the reaction forces on all joint to be used as benchmark. A race car was simulated on a full track composed by all the typical characteristics such as curbs, chicane, strong breaking and acceleration (both lateral and longitudinal). The considered race car is equipped with double wishbone suspension both at the front and rear side. Moreover, anti-roll bar and steering system are considered (Fig. 3).

![Car suspension models](image)

**Figure 3.** Car suspension models used in test case and joints considered for suspension loads estimation and comparison. (a) Front suspension; (b) Rear suspension.

The considered joints are those shown in Fig. 3 namely ”LCA dx rear” and ”UCA sx front”. Both joints coupled the suspension arms to the chassis of the vehicle. The choice of the selected joints was totally arbitrary but it results useful to certify the accuracy of the proposed estimation model when anti-roll bar and steering system are mounted on the vehicle.

The main characteristics of the suspensions systems used in this activity are summarized in Tab. 1.

According to the parameters shown in Tab. 1 it was possible to generate suitable excitations for the characterization process. Following the procedure introduced in previous section, thus exciting both systems on the test bench (test-rig) it was possible to obtain all the non-linear function $g_1, \ldots, g_n$ to use for the estimation of suspension loads.

4.1. Results and discussion

This section shows the results obtained with the proposed method comparing them with those out-coming directly from an implicit multibody simulation.
|                                | Front suspension | Rear suspension |
|--------------------------------|------------------|-----------------|
| Stiffness of shock absorber    | 150              | 150             |
| Preload of shock absorber      | 4260             | 5800            |
| Travel of shock absorber       | 35               | 50              |
| Antiroll bar stiffness         | $6 \cdot 10^4$   | $7 \cdot 10^4$  |

Fig. 4 compared real and estimated time-histories of vertical, lateral and longitudinal force components obtained for a complete track lap for all the considered joints. It is important to refresh that "real" loads are those obtained from the implicit multibody simulation, that in this activity, are considered as reference.

![Figure 4.](image)

Fig. 4. Comparison between observed and estimated forces with the proposed estimation model. (a) Joint "UCA sx front"; (b) Joint "LCA dx rear".

As visible from Fig. 4 the proposed method allows estimating accurately the joint loads in whichever joint and in any reference system even if suspension system are not independent. To give a numeric evaluation of the effectiveness of the proposed method, Tab. 2 shows the
maximum percentage error between estimated and observed joint loads for both front and rear suspension system.

**Table 2.** Maximum percentage error between the estimated and observed joint loads.

|                  | UCA sx front | LCA dx rear |
|------------------|--------------|-------------|
| Longitudinal force | 1.60         | 0.65        |
| Lateral force     | 1.70         | 1.20        |
| Vertical force    | 0.70         | 0.87        |

As shown in Tab. 2 the maximum percentage error is lower than 2% certifying in such a way the accuracy of the proposed estimation method.

5. Conclusion

Thanks to the extremely modelling simplicity and computational quickness, explicit multibody codes are effectively supplanting implicit codes. The major drawback of using this simulation approach is however the reduced amount of information available in postprocessing that in some cases are crucial. In this context, the present activity proposes a method that, starting from the information already available in the explicit multibody codes, allows assessing joint loads for a car suspension. The main section of the proposed method is the characterization process of the suspension system, that allows defining a set of functions able to uniquely link the wheel center motion and forces at contact patch to the joint forces. The proposed method, tested through a test-case, provides excellent results being able to faithfully estimate the forces on all the considered joints.

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