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Optimization of mechatronic systems: application to a modern car equipped with a semi-active suspension

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1. Abstract

The research aims at developing a global mechatronic approach to model, simulate and optimize complex industrial applications. The approach is illustrated with an application: the simulation and the optimization of a modern car (an Audi A6) equipped with a semi-active suspension. A non-linear controller has been desined to control the motion of the vehicle. An optimization procedure is used to find simultaneously the best properties of the passive elements (spring stiffness, etc.) and of the controller parameters (e.g. heave, pitch and roll gains, cut frequency . . .) in order to improve the comfort of the passengers while preserving the car ride and handling performances. Two different modeling and optimization approaches are used and compared. The first one is realized in the MATLAB-SIMULINK environment. The chassis model is built with a symbolic multibody modeler, ROBOTRAN, while the hydraulic actuators, the sensors and the controller are integrated using S-functions. Optimization is also carried out in MATLAB using a genetic algorithm (GA) and other algorithms available in MATLAB libraries. On the other hand, the second approach relies on a multibody model based on the Finite Element method (SAMCEF-MECANO) whereas the optimization is realized with BOSS QUATTRO, an open optimization tool.

2. Keywords: Multidisciplinary optimisation, Mechatronics, Multibody systems, Control, Vehicle, Industrial applications.

3. Introduction (1 page)

To be reworked by Pierre. Comments by everybody are welcome.

In the last decades, machines have turned from purely mechanical systems to complex mechatronic systems, which involve interacting mechanical and electrical components with electronic devices, software and control systems. This enhancement of the mechanical functions with control and computer sciences allows to achieve better motion and vibration control. Mechatronics finds also its roots in new business challenges: mass customization and globalization. New products are customized and designed from cross-over of existing systems. Plenty of models are based on a small number of platforms. The mechatronic approach is very modular by nature. This helps companies to deliver new products or updates in a short time and at lower prices, and with excellent quality and reliability in order to success in the market. This approach is now so successful that mechatronic systems find nowadays numerous applications in robots, machine tools, and transportation systems.

As physical prototypes are expensive and time-consuming, virtual prototyping and simulation tools are very attractive to design mechatronic products with minimal prototyping and time [3]. However the task is not easy, because mechatronic machines are quite complex systems with a lot of couplings between the different components. Therefore, it is necessary to address the simulation of the full mechatronic system instead of considering each single part (structure, mechanism, electric drives, hydraulic systems, sensors, etc.) to predict accurately the system performances [4]. As mechatronic systems involve many engineering disciplines, a *multi-disciplinary approach* is compulsory.

Designing a mechatronic system is carried out as a *multilevel approach*, following a top-down approach [2]. Functional definitions and specification of the product leads to define the system and then the subsystems and components characteristics. Generally speaking, detailed designs of components is realized with simplified models or reduced-order models of other components. For instance, the synthesis of the *control system* is mostly based on reduced-order models of the other components. Conversely, the performance verifications and real-time control follows the opposite way in a bottom-up process.

Finally, simulating the systems and components for different set-ups is very important to guarantee right system performances, to save money and to reduce time to market for new products. As coupling effects make difficult to understand all interactions, optimization techniques are naturally nice tools to provide rationale solutions to these complex design problems. It is now a modern trends to try to combine an *upper optimization layer* on integrated simulation of the controlled mechatronic system to determine the best design parameters.

The work presented in this paper follows the approach that has been drawn. In the framework of an Inter University Poles of Attractions (IUAP5/06, Advanced Mechatronic Systems) sponsored by the Belgium Federal Government, three Belgian universities active in the mechatronic field collaborate to develop and exchange methods and software tools for modeling, control and optimization of mechatronic systems. The main goal of the research is to emphasize a *global mechatronic approach* to solve and optimise complex industrial applications. This paper presents one of the demonstrators that have been selected: the optimisation of a modern car equipped with a semi-active suspension.

In this study two different approaches are used and compared to realize the modeling and the optimization. At first a MBS modeling approach based on a symbolic tool is used. The behaviour models of the MBS, the hydraulic actuators, the sensors and the controller are integrated in the MATLAB-SIMULINK environment using S-functions. Optimisation is also carried out in the same environment. Because the evaluation procedure is fast, a genetic algorithm (GA) is used in a first step, but later other algorithms will be used and compared. The procedure is fast to set-up and the GA algorithm allows exploring the entire parameter workspace to detect the global optimum. On another hand, the second approach relies on a multibody simulation tool based on the Finite Element (FE) approach (here SAMCEF-MECANO) whereas the optimisation is realized with SAMCEF-BOSS QUATTRO, an open optimisation tool. This last approach is rather general, for instance one can take benefit of the large library of optimisation strategies and algorithms (e.g. GCMMA, GA) available in BOSS QUATTRO, but it leads to more complicated and time consuming models.

The paper is organized as follows. In section 4, the different component models are described: The vehicle chassis and the hydraulic systems of the semi active shock absorbers. Section 5 gives an overview of a control system that has been tailored by one of the partner. Then in section 6, the optimization problem of maximum confort is formulated while the numerical results are presented in section 7. Finally the conclusions are given.

4. Model (2 pages)

To be completed by Paul, Pierre, Olivier and Jean Francois

4.1. Vehicle model

For complex multibody systems, a modeling software is helpful to formulate automatically the equations of motion from a high-level description. Among the computer modeling methods, *symbolic methods* allow to build equations of motion in symbolic format, whereas *numerical methods* produce the equations of motion as complex numerical procedures. The symbolic format has the advantages of portability and efficiency, and it provides interesting insights in the analytical structure of equations. However numerical procedures are able to deal with more general class of problems, and they are especially suitable to model the dynamics of a flexible mechanism with complex topology in a systematic way.

4.2. Shock absorber model

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5. Controller (2 pages)

To be completed by Jan and Christophe. Probably on the basis of [1]

6. Optimization (1 page)

Pierre has to formulate the optimization problem.

7. Numerical applications (2 pages)

To be completed by Pierre (for ULG) and by Jean-Francois (for UCL)

Here are presented the results of two optimization processes: the first one tries to make an Audi A6 more comfortable while the second one tries to improve its handling performances.

7.1. Comfort optimization of an Audi A6

The goal of this first optimization process is to improve by simulation the comfort of passengers of an Audi A6 equipped with semi-active suspensions. Practically, the behaviour of this car is simulated during 12 seconds on a given-roughness road profile which is different for each wheel (see Figure 1). This profile is made of a stochastic filtered white noise whose amplitude does not exceed 4.2 cm. As explained above, the complete model consists in the mechanical model of the car and the hydraulic model of the suspensions which are controlled by feedback. The controller receives the vertical acceleration of the body corners and the velocity of the dampers and computes the input current of the electro-valves of the suspensions (see Figure 2). Six parameters of the controller are tunable: the heave, pitch and roll integral gains, the cut frequency, a proportional pitch gain and the current bias. The optimization process consists in finding their best values.

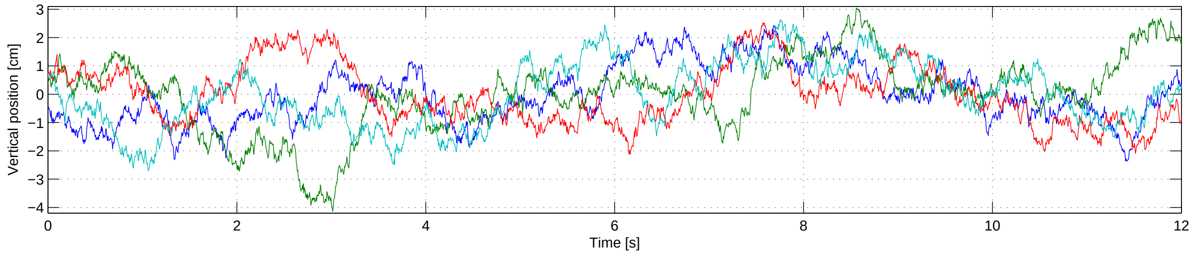

Figure 1: Stochastic road profile

The comfort of passengers is supposed to be in close relation with the vertical acceleration of the car body. The comfort indicator is thus the mean value of the RMS vertical acceleration measured at the 4 body corners. The objective function f_c to minimize is:

$$f_c(\mathbf{x}) = \frac{1}{4}\sum_{i=1}^{4} \frac{\sqrt{\int_{2}^{12} a_i^2(\mathbf{x},t)\ dt}}{10} \tag{1}$$

where $\mathbf{x}$ is the vector of the six controller parameters and a_i is the vertical acceleration at the i^{th} body corner. Remark that this indicator is not observed from the beginning of the simulation to let the car behaviour stabilize during 2 seconds.

Since the optimization of closed-loop mechanical systems is rather difficult, a penalty technique is used as suggested in [5]. The objective function is thus penalized each time the mechanical model cannot be assembled or when a damper length exceeds its limit. This penalty is computed proportionally to

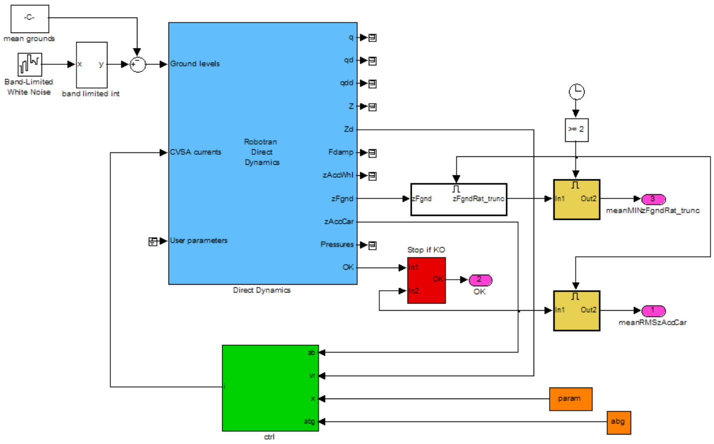

Figure 2: Simulink model diagram

the discrepancy of the parameters from a chosen standard value. This method enables the optimizer to explore the entire parameter space.
Because of the non-linearity and discontinuities of the objective function, a classical genetic algorithm is used. Thanks to this stochastic method, the global optimum is approached. Then, a second optimization process is worked out with the deterministic method of Nelder-Mead to refine the solution. All of this is performed in the Matlab-Simulink environment using the genetic Matlab Toolbox. The Figure 3 compares the simulations of the car behaviour with the optimum controller, with a standard controller and without controller. 7.2. Handling optimization of an Audi A6

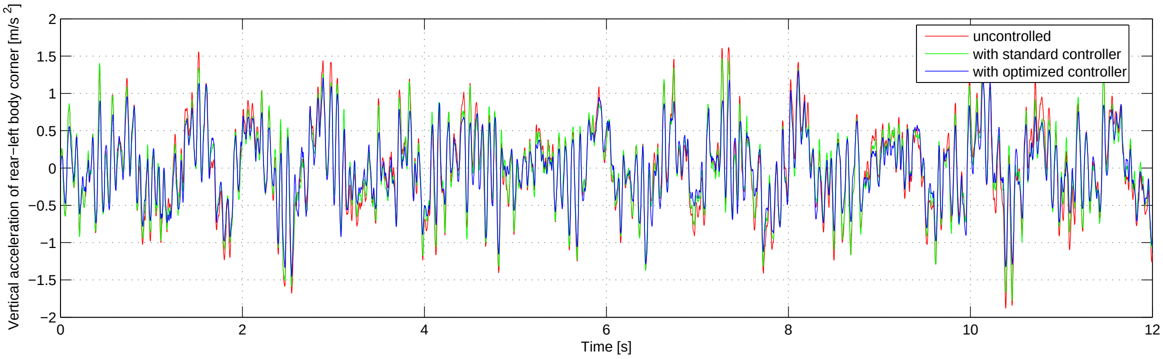

Figure 3: Comparison between car comfort performances with optimized controller, standard controller and without controller

The optimization method is the same as for the comfort optimization. Only the objective function is different. The handling performance of the car can be evaluated on basis of the vertical ground reaction force on each wheel. This dynamic force is compared with the static force which is the vertical reaction force on the wheel at equilibrium on a flat ground as illustrated on Figure 4. When the wheel leaves the ground, the force becomes negative. Therefore, if the dynamic force is lower than the static force, the wheel tends to lose its adherence. The objective function f_h to maximize is the minimum value of the ratio between static and dynamic ground forces at each wheel (see Figure 4):

$$f_h\left(\mathbf{x}\right) = \frac{1}{4}\sum_{i=1}^{4}\min_{2\leq t\leq 12}\frac{F_i^{dynamic}\left(\mathbf{x},t\right)}{F_i^{static}} \tag{2}$$

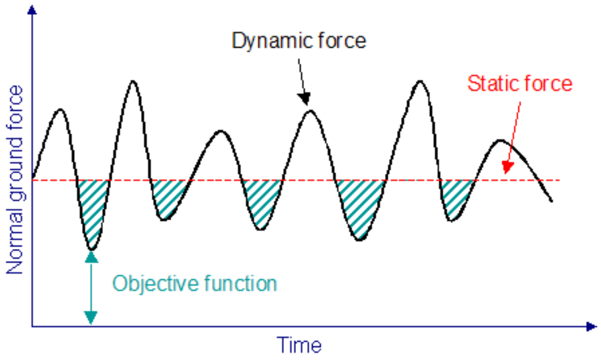

Figure 4: Example of static and dynamic contact forces

As for the comfort optimization, the results of the handling optimization are shown on Figure 5. Finally, both optimization results are summarized in Table 1.

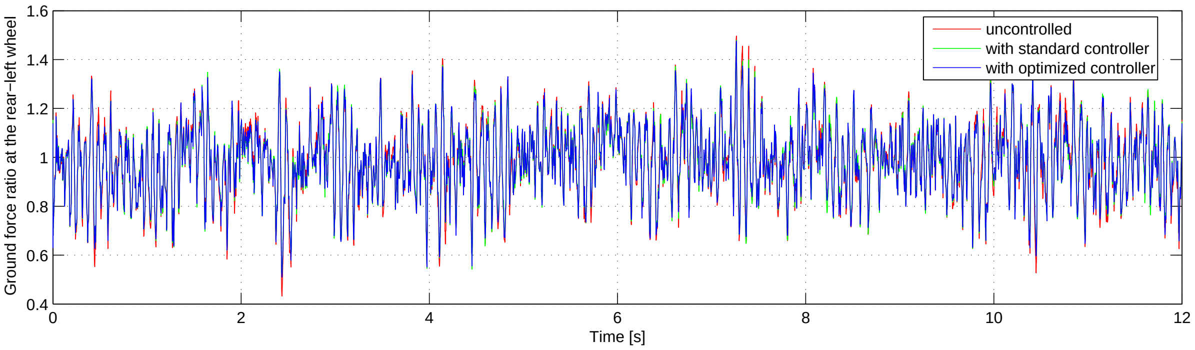

Figure 5: Comparison between car handling performances with optimized controller, standard controller and without controller

	Comfort RMS accelerations $[m/s^2]$	Handling Min Ground force ratio [%]
without controller	0.52	53.7
with standard controller	0.46	58.2
with optimized controller	0.41	59.0

Table 1: Numerical results of comfort and handling optimizations

8. Conclusions (1 page)

Pierre and Paul have to agree on a general conclusion

9. Acknowledgements

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10. References

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