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Investigations on a Level Set based approach for the optimization of flexible components in multibody systems with a fixed mesh grid

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ABSTRACT

This paper considers the optimization of flexible components in mechanical systems thanks to a "fully integrated" optimization method which includes a flexible multibody system simulation based on nonlinear finite elements. This approach permits to better capture the effects of dynamic loading under service conditions. This process is challenging because most state-of-the-art studies in structural optimization have been conducted under (quasi-)static loading conditions or vibration design criteria and also because this "fully integrated" optimization method is not a simple extension of static optimization techniques. The present paper proposes an approach based on a Level Set description of the geometry. This method leads to an intermediate level between shape and topology optimizations. Gradient-based optimization methods are adopted for their convergence speed. Numerical applications are conducted on the optimization of a connecting rod of a reciprocating engine with cyclic dynamic loading to show the feasibility and the promising results of this approach.

1 INTRODUCTION

In the field of structural optimization, the component-based approach is the most common way to obtain an optimal design. Nowadays, the maturity of sizing and shape optimizations has reached an industrial level while topology optimization is still more employed as a pre-design tool in the industry. Even though the majority of loads are dynamic in the real world, structural optimization has been applied to the design of components under quasi(-static) loading conditions or vibration design criteria due to the difficulties of dealing with dynamic response optimization.

Recently, the component-based approach has been extended towards a system-level approach which relies on a multibody system (MBS) simulation to capture the behavior of the whole system. This extension is important because in topology optimization problems, Bendsøe and Sigmund (2003) pointed out that the optimal design may be very sensitive to the support and loading conditions. This system-level approach with the MBS simulation allows capturing precisely the dynamic loading exerted on the considered component and allows the effectively desired optimization.

At the beginning of the optimization of mechanical systems, based on the well established optimization techniques, the considered component was isolated from the system and then multiple static postures were selected for the optimization process (Saravanos and Lamancusa, 1990). The generality of this approach is quite restrictive. Considering a high-speed system, the overall system motion can not be represented by only a few postures. Moreover, the coupling between rigid and elastic motions are omitted which causes an inaccuracy on the displacements and on the stresses. Finally, the multiple static postures do not account for a time-dependency.

At the present time, to carry out the dynamic optimization of a component, the dynamic multibody system problem is reformulated as a set of static problems. This method is based on two steps: firstly, a MBS simulation precomputes the loads applied to each component and secondly, each component is optimized independently using a quasi-static approach. A set of equivalent static load cases should therefore be defined in order to mimic the precomputed dynamic loads (Kang et al, 2005). Several works have been realized using this two-steps method (Oral and Kemal Ider, 1997; Häussler et al, 2004; Kang et al, 2005; Hong et al, 2010). Häussler et al (2001) showed that it is important to consider the changes of the boundary conditions and system behavior during the optimization process since these are subject to significant changes.

Recently, a strong tendency to merge both finite element (FE) analysis and MBS simulation into an unified code has been followed. The integrated simulation tools resulting from this tendency allow analyzing the deformations of mechanism undergoing fast joint motions. An example of this type of software is SAMCEF Mecano based on the work of Géradin and Cardona (2001).

Brüls et al (2011) took advantages of the evolution of numerical simulations and topology optimization codes in order to design optimal structural components loaded during the MBS motion. The method has been validated and they showed that, in order to obtain an integrated approach, it is convenient to work with an optimization loop directly based on the dynamic response of the flexible multibody system. The dynamic effects are naturally taken into account with this approach. Running on from this work, Duysinx et al (2010) investigated the "fully integrated" optimization problem of flexible components under dynamic loading conditions. The approach was illustrated on numerical applications of mass optimization of robotic arms subjected to constraints on the trajectory tracking. From these studies, it results that the optimization of MBS is not a simple extension of structural optimization. The coupled problem between vibrations and interactions within the components generally results in complex design problems and convergence difficulties. The design problem is complicated, and naive implementations lead to fragile and unstable results. To overcome this problem, the formulation of the MBS optimization problem has been investigated and the conclusion is that it is crucial to formulate the problem in a suitable way to obtain good convergence properties (Tromme et al, 2011). Furthermore, the way that time-dependent constraints are taken into account is fundamental for the convergence of the problem. Finally, whether a feasible starting point is available or not, gradient-based solvers can converge efficiently or not.

Compared to the Equivalent Static Loads method, the "fully integrated" optimization method introduces a strong coupling between the dynamic MBS simulation and the optimization process which enables to define realistic dynamic loading depending on the design variables and to use real dynamic criteria for the optimization problem. Moreover, the sensitivity analysis can be directly treated within the flexible MBS simulation code.

In this study, we continue with the "fully integrated" approach to treat the MBS optimization problem. The innovative part is that we propose an approach with an implicit representation of the boundaries thanks to a Level Set description of the geometry (Osher and Sethian, 1988). This approach leads to an intermediate level between shape and topology optimizations.

In shape optimization, a major problem is the mesh distortion which occurs during the optimization process. The regularly distributed mesh at the initial design is often distorted after a few iterations and therefore, the accuracy of the solution decreases. While several adaptative mesh-regenerations have been developed, the re-meshing operations consume CPU time and these techniques can produce discontinuities in the objective function and/or constraints which is not desired for gradient-based algorithms (Van Keulen et al, 2005).

Topology optimization has been developed in order to determine the optimal design of a component without any *a priori* on the component shape (Bendsøe and Kikuchi, 1988). Topology optimization only requires the definition of a design domain, the boundary conditions and the load cases which brings this type of optimization as the most powerful method while it is also more complex than sizing or shape optimization. One of the advantages of topology optimization is that it works with a fixed mesh grid and that this grid is kept unchanged during all the optimization process. A design variable is associated to each element and the material properties of each finite element are modified according to these design variables. In consequence, the number of variables can rapidly be very large and an excessive number of design variables can complicate the optimization process and lead to many local optima. The feasibility of manufacturing the optimal design without any post-processing is often not possible.

The proposed approach tries to gather the advantages of both methods in order to work with a fixed mesh grid and therefore avoiding the mesh distortion but also to have a precise description of the component geometry with CAD entities. In static structural optimization, Kim and Chang (2005) worked with a fixed mesh grid to realize "Eulerian shape optimization" where the geometry was defined explicitly. Numerical applications are carried on the optimization of a connecting rod in a reciprocating engine with cyclic dynamic loading to illustrate the feasibility and the promising results of the proposed method.

2 LEVEL SET DESCRIPTION OF THE GEOMETRY

2.1 Level Set method

The Level Set method is a numerical technique for tracking interfaces and shapes. Usually, the geometric description of interfaces is based on an explicit definition. However, Osher and Sethian (1988) suggested that for tracking an interface, an implicit representation can be used. They proposed to introduce a smooth scalar function $\phi(\mathbf{x})$ defined on all $\mathbf{x} \in R^n$ which is used to represent an interface Γ of dimension $n-1$ as the set corresponding to $\phi(\mathbf{x}) = 0$. In other words, the interface is implicitly defined as the zero-level of a higher dimension scalar function.

To illustrate this statement, we will consider the example of a square plate with a circular hole at its center. To define the interface Γ corresponding to the boundary of the circular hole with a radius r, a possibility is to introduce the following function $\phi(\mathbf{x})$:

$$\phi(\mathbf{x}) = \sqrt{x^2+y^2} - r \quad (1)$$

$$\Gamma = \{\mathbf{x} \in R^2 | \phi(\mathbf{x}) = 0\} \quad (2)$$

Figure 1 illustrates the situation where one can observe the function $\phi(\mathbf{x})$ with its zero-level contour. In the present study, the analytical expression of $\phi(\mathbf{x})$ is directly treated while this can be quite restrictive. In order to partition the domain Ω into Ω^+, Ω^- and $\partial\Omega$ corresponding respectively to the region outside the interface, inside the interface and the interface itself, the sign of $\phi(\mathbf{x})$ is analyzed:

$$\begin{array}{ll} \text{if } \phi(\mathbf{x}) > 0, & \text{then } \mathbf{x} \in \Omega^+ \\ \text{if } \phi(\mathbf{x}) < 0, & \text{then } \mathbf{x} \in \Omega^- \\ \text{if } \phi(\mathbf{x}) = 0, & \text{then } \mathbf{x} \in \partial\Omega \end{array} \tag{3}$$

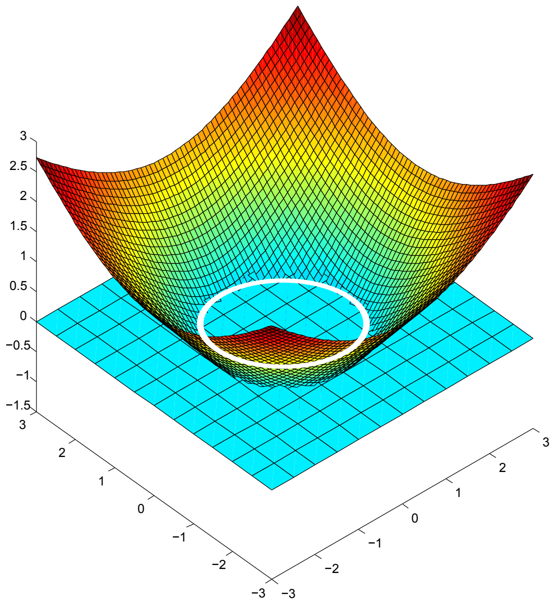

Figure 1. Implicit representation of an interface. Definition of a hole in a square plate thanks to a Level Set.

2.2 Geometry representation

Once the Level Set has been defined, the next step is to partition the design domain, i.e. the mesh grid.

In the proposed method, a pseudo-density variable μ_e is associated to each finite element as in topology optimization. These design variables are used to determine the material properties by the use of the SIMP law (Bendsøe, 1989). Hence, if we consider a material with a density ρ^0 and a Young modulus E^0 [MPa], the material properties of each finite element is defined as:

$$\begin{array}{rcl} \rho_e & = & \mu_e \rho^0 \\ E_e & = & \mu_e^p E^0 \end{array} \tag{4}$$

for e = 1,... N_e where N_e is the number of elements and where the exponent p is the exponent of the SIMP law which introduces a penalization of intermediate densities. The value of the pseudo-densities μ_e is comprise in the interval [μ_{min},1], where μ_{min} is a small value (e.g. 0.001) but not 0 to avoid numerical problems.

In order to partition the domain into three sub-domains, the value of $\phi(\mathbf{x})$ is computed for each node of the finite element mesh. Three situations can occur for each finite element. The first possibility is to have only positive values. In this case, we consider that the element is in the domain Ω^+ and solid material properties are associated to this element, the pseudo-density value is 1. In the opposite case, where only negative values of the function $\phi(\mathbf{x})$ are obtained, we consider that the element is in the domain Ω^- and the value μ_{min} is given to the pseudo-design variable in order to get void material. This partition is illustrated in Figure 2.

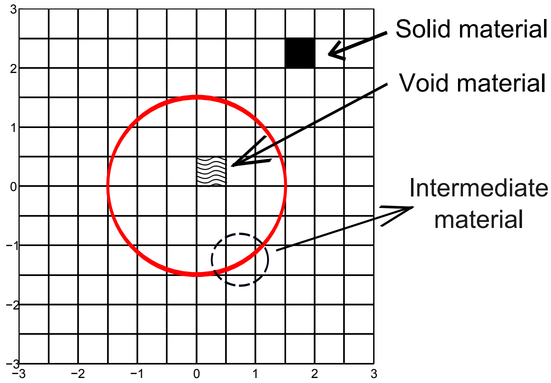

Figure 2. Partition of the design domain - Material distribution - SIMP law.

The situation is more complex when positive and negative values of $\phi(\mathbf{x})$ are obtained. This implies that the element is cut by the interface. In the present approach, the mesh is not refined near this zone in order to represent accurately the boundary. The mesh is kept unchanged and an intermediate material is defined for this element. The intermediate material is related to the percentage of material present in the element where this quantity of material is denoted by μ_e. In order to compute this percentage, as the values of $\phi(\mathbf{x})$ are known for each node, a linear interpolation inside the element is created which allows determining approximatively the percentage of material. Afterwards, thanks to the SIMP law, the properties of the intermediate material are computed.

3 FLEXIBLE MULTIBODY SYSTEMS SIMULATION

3.1 Equations of motion of flexible multibody dynamic systems

In the “fully integrated” optimization method, flexible multibody systems are modeled using a nonlinear finite element formulation as suggested by Géradin and Cardona (2001). The formulation is based on an inertial frame approach. Absolute nodal coordinates which correspond to the displacements and the orientations of each node of the finite element mesh are gathered in the vector $\mathbf{q}$.

If the multibody system is not constrained, its motion is obtained by solving the following equation:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} = \mathbf{g}(\dot{\mathbf{q}}, \mathbf{q}, t) = \mathbf{g}^{ext} - \mathbf{g}^{int} - \mathbf{g}^{gyr} \tag{5}$$

where $\mathbf{M}$ is the mass matrix, $\ddot{\mathbf{q}}$, $\dot{\mathbf{q}}$ and $\mathbf{q}$ are respectively, the accelerations, the velocities and the displacement, and $\mathbf{g}$ gathers the external, the internal and the complementary inertia forces. It should be noted that the mass matrix can depend on the generalized coordinates.

Kinematic constraints, denoted by $\mathbf{\Phi}(\mathbf{q}, t) = 0$, are added to equation (5) and insure typically the connection of the different bodies thanks to joints. These kinematic constraints impose a set of nonlinear equations between absolute nodal coordinates.

The resolution of this constrained dynamic problem is realized thanks to an augmented Lagrangian approach where two terms related to the constraints including a penalty factor p and the Lagrangian multipliers $\boldsymbol{\lambda}$ are added. After some developments, the equations of motion take the general form of a differential algebraic system (DAE)

$$\begin{aligned} \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{\Phi}_q^T(\mathbf{q}, t)(k\boldsymbol{\lambda} + p\mathbf{\Phi}) &= \mathbf{g}(\dot{\mathbf{q}}, \mathbf{q}, t) \\ k\mathbf{\Phi}(\mathbf{q}, t) &= 0 \end{aligned} \tag{6}$$

where k is a scaling factor and with the initial conditions

$$\mathbf{q}(0) = \mathbf{q}_0 \text{ and } \dot{\mathbf{q}}(0) = \dot{\mathbf{q}}_0 \tag{7}$$

3.2 Time integration

To solve the set of nonlinear differential algebraic equations (6), Géradin and Cardona (2001) suggested the use of the generalized-α method developed by Chung and Hulbert (1993). Arnold and Brüls (2007) have demonstrated that, despite the presence of algebraic constraints and the non-constant character of the mass matrix, this integration scheme leads to accurate and reliable results with a small amount of numerical damping. At time step $n + 1$, the numerical variables $\ddot{\mathbf{q}}_{n+1}$, $\dot{\mathbf{q}}_{n+1}$, $\mathbf{q}_{n+1}$ and $\boldsymbol{\lambda}_{n+1}$ have to satisfy the system of equations (6). According to the generalized-α method, a vector $\mathbf{a}$ of acceleration-like variables is defined by the following recurrence relation

$$(1 - \alpha_m)\, \mathbf{a}_{n+1} + \alpha_m \mathbf{a}_n = (1 - \alpha_f)\, \ddot{\mathbf{q}}_{n+1} + \alpha_f \ddot{\mathbf{q}}_n, \tag{8}$$

with $\mathbf{a}_0 = \ddot{\mathbf{q}}_0$.

The integration scheme is obtained by employing $\mathbf{a}$ in the Newmark integration formulae:

$$\mathbf{q}_{n+1} = \mathbf{q}_n + h\dot{\mathbf{q}}_n + h^2 \left(\frac{1}{2} - \beta\right) \mathbf{a}_n + h^2 \beta \mathbf{a}_{n+1} \tag{9}$$

$$\dot{\mathbf{q}}_{n+1} = \dot{\mathbf{q}}_n + h\,(1 - \gamma)\, \mathbf{a}_n + h\gamma \mathbf{a}_{n+1} \tag{10}$$

where h denotes the time step. If the parameters α_f, α_m, β and γ are properly chosen according to Chung and Hulbert (1993), second-order accuracy and linear unconditional stability are guaranteed. Going one time step further requires to solve iteratively the dynamic equilibrium at time t_{n+1}. This is performed by using the linearized form (Eq. 11) of equations (6) and by employing the Newton-Raphson method. The iterations try to bring the residual $\mathbf{r} = \mathbf{M}\ddot{\mathbf{q}} - \mathbf{q} + \mathbf{\Phi}_{\mathbf{q}}^T(k\boldsymbol{\lambda} + p\mathbf{\Phi})$ and $\mathbf{\Phi}$ to zero.

$$\begin{aligned} \mathbf{M}\Delta\ddot{\mathbf{q}} + \mathbf{C}_t\Delta\dot{\mathbf{q}} + \mathbf{K}_t\Delta\mathbf{q} + k\mathbf{\Phi}_{\mathbf{q}}^T\Delta\boldsymbol{\lambda} &= \Delta\mathbf{r} \\ k\mathbf{\Phi}_{\mathbf{q}}\Delta\mathbf{q} &= \Delta\mathbf{\Phi} \end{aligned} \tag{11}$$

where $\mathbf{C}_t = \partial\mathbf{r}/\partial\dot{\mathbf{q}}$ and $\mathbf{K}_t = \partial\mathbf{r}/\partial\mathbf{q}$ denote the tangent damping matrix and the tangent stiffness matrix respectively.

4 OPTIMIZATION OF FLEXIBLE MULTIBODY SYSTEMS

4.1 Formulation of the MBS optimization problem

The general statement of an optimization problem corresponds to the minimization of an objective function $g_0(\mathbf{x})$ subjected to some constraints $g_j(\mathbf{x})$ which typically insure the feasibility of the structural design and some design requirements. The vector $\mathbf{x}$ contains the design variables which are the parameters that are modified during the optimization process. Side-constraints limit the values taken by the design parameters and generally reflect technological considerations.

$$\begin{aligned} &\min_{\mathbf{x}} g_0(\mathbf{x}) \\ &s.t. \begin{cases} g_j(\mathbf{x}) \leq \overline{g}_j, & j = 1, \ldots, m \\ \underline{x}_i \leq x_i \leq \overline{x}_i, & i = 1, \ldots, n \end{cases} \end{aligned} \tag{12}$$

This general formulation allows using different types of optimization algorithms to solve the problem and there is no need to develop specific method. Moreover, this formulation provide a general and robust framework to the solution procedure.

In our case, the function $g_j(\mathbf{x})$ are structural properties and responses like mass, displacements at each time step and stresses for instance. The design variables x_i are the parameters defining the Level Sets.

The formulation of a MBS optimization problem is critical in order to obtain good convergence properties. It is fundamental to formulate the problem in a suitable manner (Tromme et al, 2011). In this study, we only consider local formulations which state that the structural responses are considered at each time step. Introducing the function $\Delta l(\mathbf{x}, t)$ corresponding to a structural response and the definition of the mass of a component

$$m = \int_{V_E} \rho\, dV \tag{13}$$

where V_E is the volume of the considered component, the optimization problem formulation adopted here (Eq. 14) is to minimize the mass while the constraints have to be verified at each time step.

$$\begin{aligned} &\min_{\mathbf{x}} m(\mathbf{x}) \\ &s.t. \;\; \Delta l(\mathbf{x}, t) \leq \Delta l_{max} \\ &\forall t \in [0, T]. \end{aligned} \tag{14}$$

4.2 Optimization algorithm

In this paper, only mathematical programming methods which require to compute the derivatives of the design functions are considered. These methods have been widely employed to solve large scale structural and multidisciplinary optimization problems with conclusive results. Their major advantages are their very high convergence speed and the limited number of iterations and function evaluations required to obtain an optimal solution. The inconvenient of these methods is that they provide local optima due to the local convergence properties of gradient-based algorithms. The robustness of these methods can be a source of difficulties when dealing with highly nonlinear behavior.

The algorithm adopted for this study is GCM (Bruyneel et al, 2002) which is an extension of the algorithms CONLIN (Fleury and Braibant, 1986) and MMA (Svanberg, 1987) based on the sequential convex programming approach. This approach relies on two concepts. Firstly, the original problem which is highly nonlinear and implicit with respect to the design variables is replaced by a sequence of explicit and convex subproblems based on local approximations of design functions. Secondly, each local convex subproblem is solved efficiently using fast and effective mathematical programming algorithms such as Lagrangian maximization (dual method) or interior point methods. Figure 3 illustrates the sequential convex programming approach.

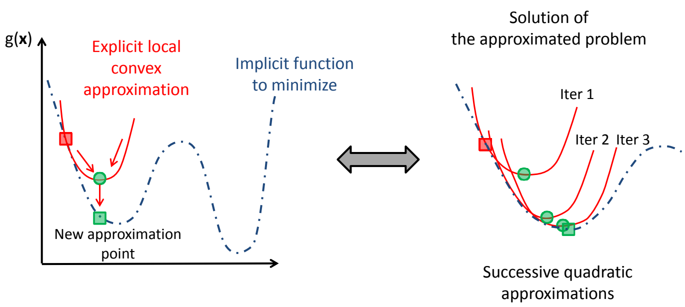

Figure 3. Sequential convex programming approach.

4.3 Sensitivity analysis

When dealing with gradient-based optimization methods, a sensitivity analysis is required to compute the first order derivatives of the structural responses and to provide them to the optimization algorithm. Indeed, the process needs them to determine the descent direction. The sensitivity analysis is a crucial step in the optimization process because it can drastically increase the computation time, especially when the number of variables is large.

While a semi-analytical sensitivity analysis will require less computational efforts in comparison to a finite difference scheme, this second approach is considered in this study. In this case, the sensitivity analysis requires one additional simulation per perturbed design variable and therefore, the CPU time is more important. However, despite its relative computational inefficiency, this method is easy to use in order to carry out our investigation. Furthermore, the task is automatically handled by the task manager of BOSS Quattro (Radovcic and Remouchamps, 2002). Semi-analytical sensitivity analysis of flexible multibody systems has been investigated by Brüls and Eberhard (2008).

5 NUMERICAL APPLICATIONS

5.1 Modeling of a slider-crank mechanism

The numerical application is devoted to the optimization of a connecting rod within a slider-crank mechanism, which models a single-cylinder of a four-stroke internal combustion diesel engine (Fig. 4). The material is steel with a Young modulus of $E = 210$ [GPa], a Poisson ratio of $\nu = 0.3$ and a volumic mass of 7800 $\left[\mathrm{kg/m^3}\right]$. The considered rotation speed of the crankshaft is quite high, 4000 [Rpm], because at this rotation speed, the dynamic loading due to inertia forces represents about 15% of the loading at the top dead center (explosion).

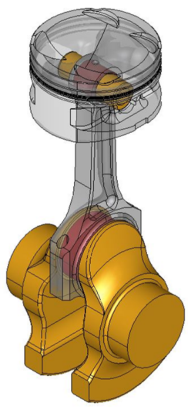

Figure 4. A 3D view of a slider-crank mechanism modeling.

The numerical simulation is conducted by imposing the rotation speed of the crankshaft. A kinematic simulation leads the rotation speed from 0 to 4000 [Rpm] in 0.01 [s]. After, the dynamic analysis is performed where a first period of 0.0025 [s] is needed to stabilize the dynamic response and then, the rotation speed stays at 4000 [Rpm] during one cycle (0.03 [s]) where the gas pressure is introduced. One cycle corresponds to a rotation of 720 [°] of the crankshaft. The pressure gas is known from experimental measurements of a real diesel engine at 4000 [Rpm] and is introduced as an external force in the multibody system. For the time integration, the Chung-Hulbert scheme is used with a time step of 0.001 [s] for the stabilization part while a time step of 0.00025 [s] is adopted for the second part of the dynamic analysis with a spectral radius of $\rho_\infty = 0.0101$.

Since a 2D model has been considered, the connecting rod is modeled by shell elements with a transfinite mesh (thickness of 10 [mm]) allowing getting a mesh grid while the crankshaft is considered as rigid. The piston is represented by its mass (0.456 [Kg]) and by a cylindrical joint. The components are linked with ideal kinematic joints. The finite element model is illustrated in Figure 5 and the geometry and the dimensions of the connecting rod are given in Figure 6.

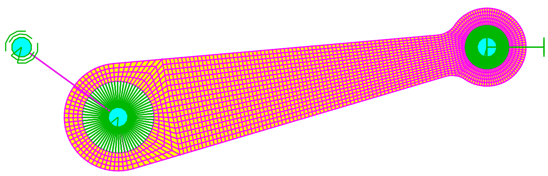

Figure 5. Finite element model of the slider-crank mechanism.

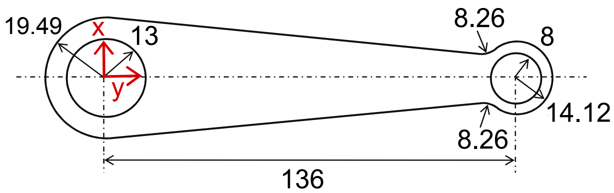

Figure 6. Geometry and dimensions of the connecting rod.

In order to obtain the highest compression ratio, the distance between the piston and the valves has been reduced at the maximum at the top dead center. In consequence, the elongation of the connecting rod have to be accurately analyzed to avoid the destruction of the engine.

In this paper, the geometry of the connecting rod is not completely defined by a Level Set description. The external contour is defined by a traditional explicit formulation while only internal holes are defined with a Level Set description.

5.2 An ellipsoidal hole

The first numerical application considers the introduction of an ellipsoidal hole near the center of the connecting rod (Fig.7). The position of the ellipse center is (x=0; y=67.8 [mm]) with the reference system defined in Figure 6. The level Set is introduced with the following definition of $\phi(\mathbf{x})$:

$$\phi(\mathbf{x}) = \sqrt{\frac{(x-c_x)^2}{a^2} + \frac{(y-c_y)^2}{b^2}} - c \quad (15)$$

where the ratio a/b is kept constant during the optimization and the design variable is c. The values of a and b are 0.05 and 0.3 respectively.

Initially, there is no hole and the connecting rod has a mass of 295.7 [g]. With this initial design, the maximal elongation of the connecting rod is 12.51 [μm] while the maximal authorized value is 15 [μm]. Therefore, the mass can be decreased.

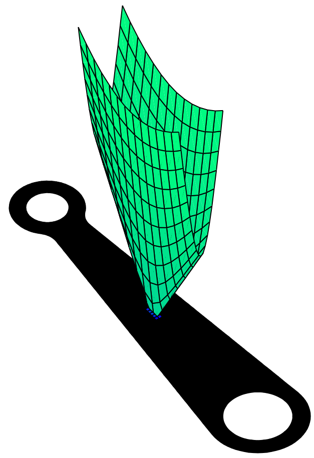

Figure 7. Level Set creating an ellipsoidal hole.

As explained previously, the optimization problem is formulated as the minimization of the mass while the constraint denoted by $\Delta l(\mathbf{x}, t)$ and corresponding to the connecting rod elongation here, is considered at each time step (Eq. 14).

The optimal design is obtained after 7 iterations and a gain of 8.9% has been obtained. Figure 8 shows the convergence history and the optimal design is illustrated in Figure 9. Even if the boundary does not appear clearly in Figure 9, the boundary of the hole is defined by a CAD entity and as the parameters are known precisely, the manufacturing of the component does not require an interpretation of the resulting design.

Table 1. Optimization results - An ellipsoidal hole.

	Initial Value	Optimal value
Mass	295.7 [g]	269.35 [g]
Elongation	12.51 [μm]	14.99 [μm]
Design variable c	0	0.08505

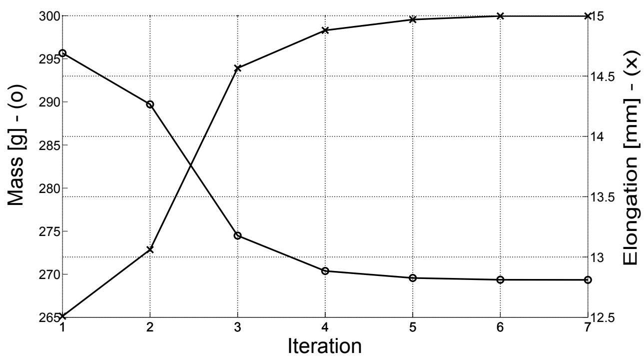

Figure 8. Evolution of the mass and of the connecting rod elongation with an ellipsoidal hole at its center.

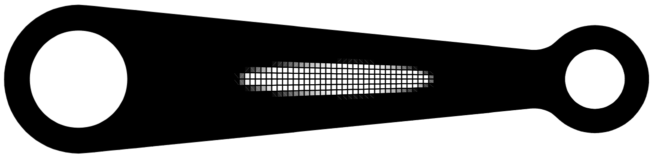

Figure 9. Optimal shape of the connecting rod with an ellipsoidal hole at its center.

5.3 Modification of the topology

The second numerical application illustrates the use of several Level Sets in order to create more holes in the structure. The different Level Sets are coupled together with basic mathematical operations. While in the previous case only one Level Set was introduced, this numerical application considers the introduction of three Level Sets which offers the possibility of creating three ellipsoidal holes. Their definitions are based on equation (15) and the ratio a/b is also constant. Table 2 gathers the parameter values. To keep the symmetry of the connecting rod, a constraint imposes the same evolution on the design variables c_2 and c_3. The optimization problem is formulated as for the previous case.

Table 2. Parameter values - Second numerical application.

	c_x	c_y	a	b
Level set 1	0	0.1307	0.075	0.3
Level set 2	-0.002	0.0925	0.07	0.28
Level set 3	0.002	0.0925	0.07	0.28

The optimization process convergences smoothly and in only 6 iterations (Fig. 10). The results are gathered in Table 3 and one can observe that the optimal mass is a little bit heavier than for the previous case due to the fact that the positioning of the Level Sets is less favorable. It would make sense to introduce the position of the Level Sets in the design variable set.

In this application, it is interesting to note the merging of two holes during the optimization process which therefore modifies the component topology. Figure 11 illustrates the topology modification where at the beginning of the optimization process, three holes are present in the component but after a few iterations, two holes merge. This results from the Level Set method for the description of the geometry which takes naturally into account the possibility of merging entities. The different Level Sets are insensitive to the topology modification of the component as they are simply coupled by mathematical operations. With classical shape optimization techniques, the component topology is fixed and cannot be modified during the optimization process.

Table 3. Optimization results - Second numerical application.

	Initial Value	Optimal value
Mass	295.7 [g]	273.2 [g]
Elongation	12.51 [μm]	14.87 [μm]
Design variable c_1	0	0.03236
Design variables c_2 and c_3	0	0.04524

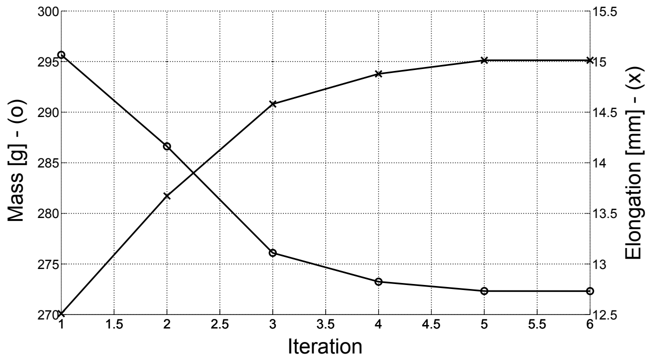

Figure 10. Evolution of the mass and of the connecting rod elongation - Second numerical application.

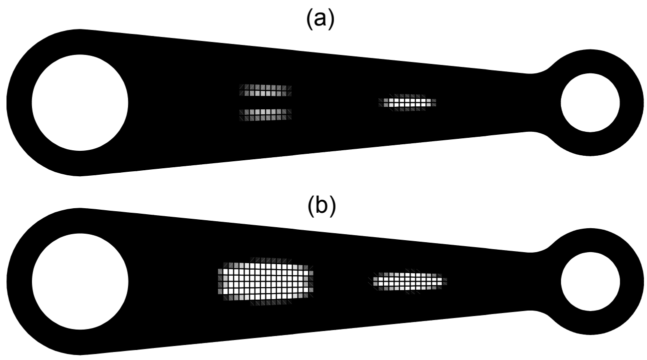

Figure 11. Topology modification - Merging of two holes - Second numerical application: (a) After 2 iterations, (b) Optimal design.

6 CONCLUSIONS AND PERSPECTIVES

This paper has been devoted to the investigation on a Level Set approach for the optimization of structural components carried out in the framework of flexible multibody system simulation. This approach leads to an intermediate type of optimization between shape and topology optimizations and tries to gather the advantages of both while avoiding their drawbacks.

The “fully integrated” optimization method for the optimization of MBS follows a natural evolution of virtual prototyping and computational mechanics where an important effort is dedicated to determine as precisely as possible the dynamic loading conditions. Thanks to the flexible MBS simulation based on nonlinear finite elements, the dynamic coupling between large overall rigid-body motions and deformations is properly taken into account. Moreover, with this "fully integrated" optimization method, the objective function and the design constraints can be formulated with respect to the real dynamic responses.

Concerning the optimization part, the Level Set approach takes naturally into account the possibility of creating, removing and merging holes in the component. The limitation compared to topology optimization is that the different holes must be introduced before the optimization and that the optimization process is not able to add new holes. The proposed approach offers a description of the geometry based on CAD entities which is very useful for the manufacturing process. Furthermore, the mesh distortions are avoided by the use of a mesh grid which is fixed during the optimization process. Finally, even though a pseudo-density variable is associated to each finite element, even if the mesh is very fine, this is not a problem because the effective design variables are the parameters defining the Level Sets.

The numerical applications illustrate that the proposed approach exhibits interesting results. However, as the number of Level Sets have to be introduced *a priori*, this can be considered as a drawback of this method and leads to an optimization type less general than topology optimization. However, Allaire et al (2002) have shown that the Level Set method can be used to realize topology optimization.

In the future, it would be very profitable to develop a semi-analytical sensitivity analysis since an additional simulation is needed for each design variable with the finite difference scheme and that is time consuming. Another advance could be to introduce a sufficiently large mesh grid and to define the whole component geometry implicitly thanks to mathematical operations between the different Level Sets. As seen in the second numerical application, it would be interesting to include the position of the Level Sets in the design variable set. Finally, a special attention should be devoted to the stress analysis of the boundary elements with intermediate materials for the optimization process and their effects on the design.

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