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Suspension mechanism simulation and optimization considering multiple disciplines †

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Abstract

A new method in suspension mechanism design considering two coupled disciplines, dynamics and structure, has been proposed in this paper. One of the decomposition methods widely used in multidisciplinary design optimization (MDO)--collaborative optimization (CO) has been used in this work. CO is a bi-level optimization architecture that preserves the autonomy of individual disciplines. In subsystem level, these two disciplines share the same model from CAD models in preprocess stage. Data file and interface have been explained and implemented in detail. The result obtained has shown that it works well and the time cost is less than before.

Keywords: Collaborative optimization; Interface-based simulation; Share model; Suspension mechanism

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1. Introduction

An automobile suspension is a multidisciplinary complex system. In this paper, we just consider the mechanism layout, which is part of the active suspension system. Traditional design methods always only consider the dynamic [1], structure [2] or control performance [3] of the suspension. But the design result according to one discipline may not satisfy the demand of other disciplines, which likely results in a waste of resources and the extension of the design cycle. According to the design characteristics of the suspension mechanism system, the ideal design method is to integrate different disciplines to realize speedy design with smallest volume, least mass and the best performance.

A suspension is just one of many engineering design problems that involve the optimization of an objective function subject to a set of constraints belonging to N different design disciplines. These problems are known in the literature as MDO problems. Several computational and organizational aspects characteristic of MDO problems suggest the use of decomposition algorithms to solve them [4].

CO is a promising decomposition algorithm introduced by Braun [5] and further developed by Sobiesky [6] to solve the general (non-convex) MDO problem. There are many applications in the aviation industry. In Budianto's research, a study of collaborative optimization as a systematic, multivariable, method for the conceptual design of satellite constellations is presented [7]. Perez presented an integrated control-configured aircraft design-sizing framework that overcomes the challenges that the flight dynamics and control integration present when included with the traditional disciplines in an aircraft sizing process [8]. During these applications, there are two ways in subsystem level analysis: CAE analysis and approximation method. Because of the difficulty and time cost of the computation, some of the applications used the approximation method instead of direct CAE analysis. Jun used CO to design the aircraft wing. The

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genetic algorithm is widely used for the system level optimization while the gradient-based method as a subspace optimization algorithm. The response surfaces are exploited to realize CO in subspace in some research work [9]. When using CO even every MDO algorithm, emphatically, is not a push-button design. Hence, the human interface is crucially important to enable engineers to control the design process [10]. It is necessary to establish a platform that enables data transmission between different commercial unidiscipline software and realize the MDO. Lin proposed a platform that integrated aerodynamic, propulsion and structure disciplines to design a missile based on MDO framework iSIGHT [11]. Chen developed an email-based communication technology of global coordinative optimization of distributed structural system [12]. The application of CO in automobile field is few. Bao-gui proposed a CO integration platform that had successfully tested the whole vehicle virtual model in crash, aerodynamic and NVH (Noise, Vibration and Harshness) disciplines [13]. MDO through CO method and multidisciplinary integrated simulation is a new attempt in active suspension design.

The remainder of this article is organized as follows: Section 2 provides CO methodology to solve the discrepancies of the disciplines. Section 3 describes the subsystem detailed analysis and shows the coupling variables. In section 4, we state the implementation of this process for which concurrent design is used and two CAE models sharing the same CAD model has been proposed to improve the design efficiency. Section 5 is the conclusion.

2. Collaborative optimization

With recent advances in the field of MDO, it is possible to transfer the traditional vertical design process into a horizontal process, enabling concurrent analysis and design. Among many MDO methods, CO is recognized as a suitable method to design and optimize multidisciplinary coupling problems.

The CO method consists of a two-level optimization architecture. The subsystem must satisfy all of the disciplinary constraints. To achieve its design task with given target variables from the system, the subsystem can choose their local variables freely. However, when there is not enough degree of freedom in choosing local variables, the subspaces are also allowed to change their target copies with minimum departure from their target variables. The task of the system is to adjust the target variables so that all subspaces can achieve their own task, while minimizing the system-level objective.

At the system level (SL), the collaborative optimization objective is stated as:

$$\begin{aligned} &\text{Find } x_{sl} \\ &\text{to minimize } f(x_{sl}) \\ &\text{subject to } J_i^*(x_{sli}, x_i^*) = \sum_{j=1}^{m} (x_{slij} - x_{ij}^*)^2 \le \varepsilon \\ &\qquad i = 1, \ldots\ldots, n \end{aligned} \tag{1}$$

Where $f(x_{sl})$ represents the system-level objective function, which is also the design objective function. J_i^* represents the compatibility constraint for the i th subsystem (of the total n subsystems) optimization problem, and the x_i are the i th subsystem design variables whose dimension is m . Variables with a superscript asterisk indicate optimal values for the subsystem level optimization. Note that the system level constraint assures simultaneous coordination of the coupled disciplinary values.

The lower-level objective function is formulated such that it minimizes the interdisciplinary discrepancy while meeting local disciplinary constraints. At the disciplinary level, the i th subsystem optimization is stated as:

$$\begin{aligned} &\text{Find } x_i \\ &\text{to minimize } J_i(x_{sli}^*, x_i) = \sum_{j=1}^{m} (x_{slij}^* - x_{ij})^2 \\ &\text{subject to } g_i(x_i) \le 0 \end{aligned} \tag{2}$$

Where g_i is the specific disciplinary constraint; variables with a superscript asterisk indicate optimal values for the system level optimization.

Considering the condition of three variables and two disciplines as an example, the process of CO is illustrated in Fig. 1 [14]. In the figure below, three coordinate axes represent the values of designed variables X , Y and Z . The two surfaces α and β represent the constraint of two disciplines. Our goal is to find the minimum value of object function ω . From Fig. 1 (a), we can clearly find the optimal point is point 0 that located on the intersection of two constraint surfaces. Point 1 represents a set of system-level design variables that are given as the

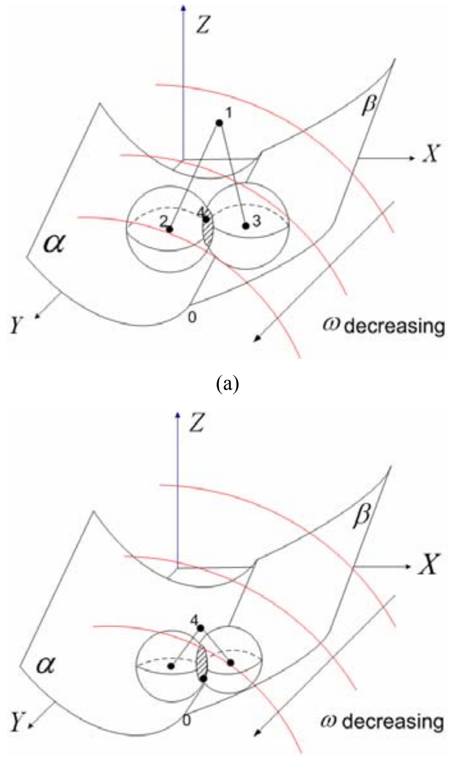


Fig. 1. Process of CO.

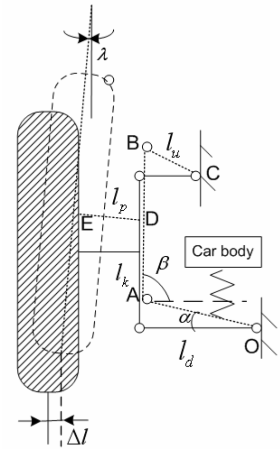


Fig. 2. Dynamic analysis of a double wishbone active suspension.

initial value. Then it will go to subsystem level. In order to satisfy the constraint, we need to find the closest point to point 1 on the two surfaces according to geometrical meaning of Eq (2). The result of this step is point 2 and 3. Then in system level, the geometry meaning of the constraint is two spheres. The optimal point is among the intersection of these two spheres. We can get point 4 here that is closer to the optimal solution. Then continue the iteration to get closer to and arrive at point 0 (Fig. 1 (b)).

3. Subsystem-level design and analysis

In performing this analysis, it is assumed that the mass of the members is negligible compared to that of the applied loading. Friction and compliance at the joints are also assumed negligible.

3.1 Dynamic subsystem

Fig. 2 shows the double wishbone suspension structure. The length of upper and lower wishbone is l_u and l_d . l_k and l_p represent the length of the kingpin and knuckle. The height of the wheel is h. We need to measure the angle of wheel plane λ and horizontal slip of the wheel Δl . When the wheel is beating from top to bottom, we just need to design the length of every rod and make a correct layout. Then we can make the changes λ of Δl and in the scope of the limit.

Now we will deduce the relationship between λ , Δl and wheel structure.

When the wheel beats from top to bottom, the upper and lower wishbone will rotate around rotation center. The angle of rotation is a very complex and nonlinear function so we cannot get them easily. We will use $\alpha(l_u,l_d,l_k)$ and $\beta(l_u,l_d,l_k)$ to express them. We define that the projective length on the ground of OA, AD, DE, BC are $l_d^{'}$, $l_k^{'}$, $l_p^{'}$ and $h^{'}$. According to the geometrical relationship from Fig. 2, we can easily deduce the following formula:

$$
\begin{aligned}
&l_d^{'} = l_d\cos\alpha(l_u,l_d,l_k)\\
&l_k^{'} = \frac{1}{2}l_k\cos\alpha(l_u,l_d,l_k)\\
&l = l\cos\lambda\\
&h^{'} = \frac{1}{2}h\sin\lambda\\
&\Delta l = (l_d + l_p) - (l_d^{'} - l_k^{'} + l_p^{'} + h^{'}) = (l_d + l_p) - (l_d\cos\alpha\\
&(l_u,l_d,l_k) - \frac{1}{2}l_k\cos\alpha(l_u,l_d,l_k) + l_p\cos\lambda + \frac{1}{2}h\sin\lambda)
\end{aligned}
\tag{3}
$$

From Eq. (3), we can consider that Δl is related to l_u l_d l_k and l_p . The height of tire h is also in the function but we do not consider it as a design variable. The slip displacement of wheel Δl should be not more than 5mm, that is $\Delta l \le 5mm$. This is the allowable displacement of elastic deformation.

3.2 Structure subsystem

To the structure discipline, load is the force F_s (Fig. 3 (a)) [15]. Assume F_w is the wheel load.

When the free body diagram of the wheel and knuckle is considered (Fig. 3 (b)), the directions of F_w and F_B are known and together establish the point of concurrency P, for the three forces that act on the body. If the magnitude of F_w is known, the magnitudes of F_A and F_B can be determined from the triangle of forces through: $\frac{F_w}{l_k}=\frac{F_k}{l_u}=\frac{F_A}{\sqrt{l_u^2+l_k^2}}$ (Fig. 3 (c)). For the free body diagram of AO (Fig. 3 (d)), the point of concurrency is at P_2 and with F_A, F_s and $\theta(l_u,l_k)$ known, F can be found from the second triangle of forces (Fig. 3 (e)).

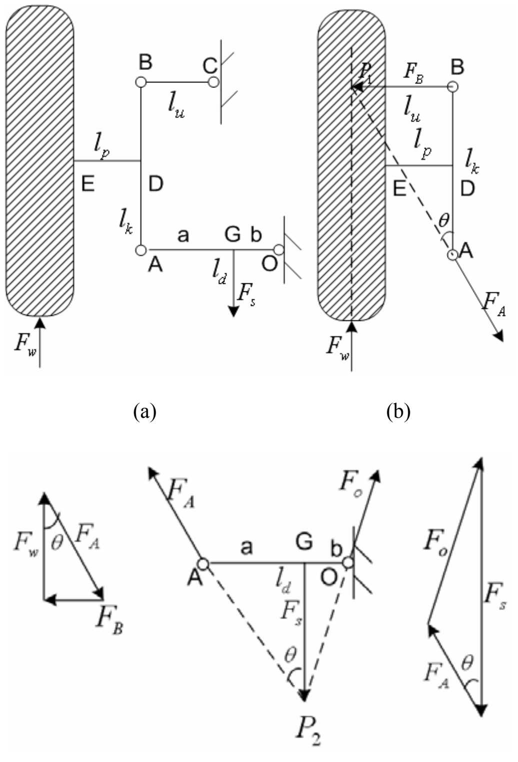
To the lower wishbone OA, the load and geometry parameter is shown in Fig. 3 (d). According to the model, we can get the formula from the mechanism handbook [16]. The cross-section G is the dangerous one because it is located at the maximum bending moment (absolute).

$$\begin{aligned} F_A &= \frac{F_s a^2}{2l_d^3}(3l_d - a)/\cos\theta(l_u,l_k) \\ M_{\max} &= \frac{F_s a^2}{2l_d^3}(3l_d^2 + a^2 - 4al_d)/\cos\theta(l_u,l_k) \\ \sigma_d &= \frac{M_{\max}}{W_z} \le [\sigma_d] \end{aligned} \tag{4}$$

Where $W_z=\frac{I_z}{y_{\max}}$ represents the flexural coefficient of the cross-section; I_z denotes the moment of inertia to the neutral axis that is related to the geometry of the cross-section; $y_{\max}$ represents the maximum displacement from the point of stress tensor to the neutral axis. To the plastic deformation for ductile material such as metal, we use the von Mises yield criterion. The von Mises yield criterion, as a function of the principal stresses, is defined as [19]:

$$\sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \le [\sigma] \tag{5}$$

In the formula, σ_1, σ_2, σ_3, $[\sigma]$ are fist, second, third principal stress and yield stress. The cross-section G can be considered that only the first principal stress works. The constraint is that maximum stress tensor is smaller than the yield one $1-\frac{\sigma_d(l_d,l_u,l_k,a,d_d)}{[\sigma_d]}>0$.



(a) (b)

(c) (d) (e)

Fig. 3. Force analysis of a double wishbone active suspension.

To the upper wishbone CB, we can make the analysis similar to OA:

$$\begin{aligned} F_B &= F_A\tan\theta = \frac{Fa^2}{2l_d^3}(3l_d - a)\sin\theta(l_u,l_k)/\cos^2\theta(l_u,l_k) \\ M_{\max} &= \frac{Fa^2 l_u}{2l_d^3}(3l_d - a)\sin\theta(l_u,l_k)/\cos^2\theta(l_u,l_k) \\ \sigma_u &= \frac{M_{\max}}{W_z} \le [\sigma_u] \end{aligned} \tag{6}$$

The moment of inertia is similar to the expression above. We can consider that the stress tensor of CB is related to design variables l_d,l_u,l_k,a,d_u. The constraint is that maximum stress tensor is smaller than the yield one $1-\frac{\sigma_u(l_d,l_u,l_k,a,d_u)}{[\sigma_u]}>0$.

Considering kingpin and knuckle as a whole, we can also get the constraint as $\sigma_k(l_k,l_p,d_k,d_p)\le[\sigma_k]$.

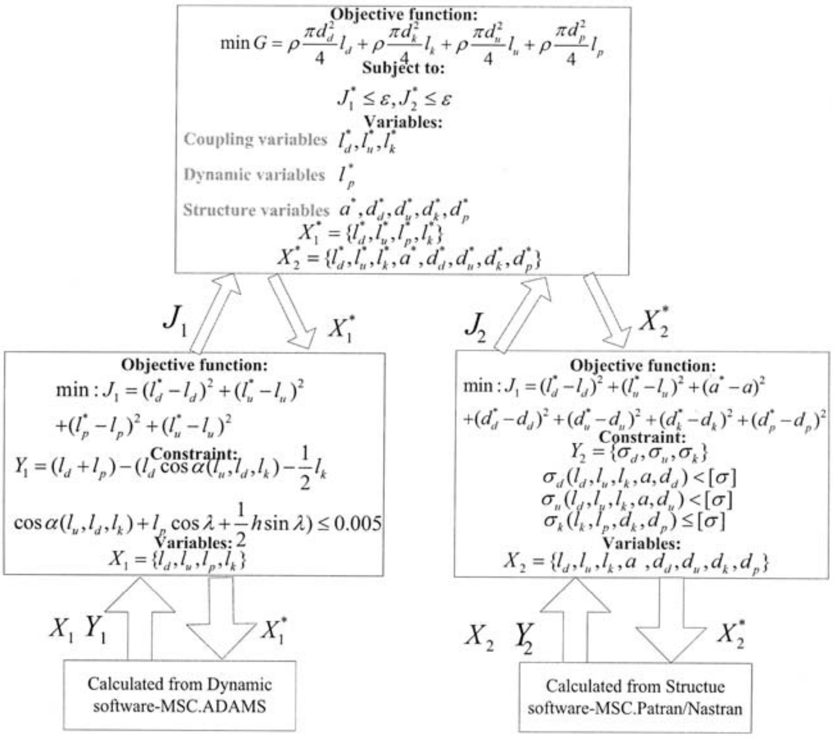


Fig. 4. Expression of coupling problems of structure and dynamic discipline in CO.

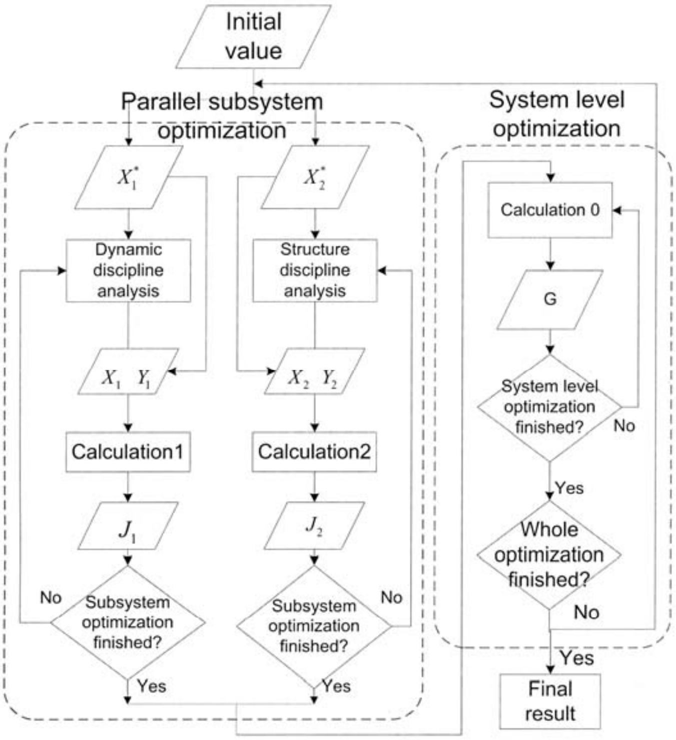


Fig. 5. Process of implementing using iSIGHT.

Through the analysis, we can use the CO method to solve the structure and dynamic coupling problems. The analysis result is summarized in Fig. 4.

4. Implement of active suspension system

4.1 Process of implement

The process of implementation is shown in Fig. 5. First, the initial values of X_1^* and X_2^* are distributed to the subsystem level, then parallel optimization is performed. In subsystem optimization, disciplinary analysis is to get values of design variables X_1, X and state variables Y_1, Y_2 which are used to calculate the discrepancies J_1, J_2 with X_1^*, X_2^*. After subsystem optimization, we will go to system level. J_1, J_2 are transmitted to system calculation to compute the system objective function G. When the minimum design can not only satisfy the system constraints but also subsystem discrepancies, the whole optimization has been finished.

4.2 Data transmission of disciplinary interaction

One of the most challenging aspects of multidisciplinary design and optimization is the sharing of disciplinary data between the various analysis codes. MDO frameworks iSIGHT is chosen to build up the MDO model. iSIGHT can parse different notepad type files generated from commercial software such as Pro/ENGINEER, Patran, and ADAMS and store the values of variables we need in its ".desc" file. When we utilize Pro/ENGINEER to construct the two-wishbone suspension model, a rod is just used instead of a wishbone for simplification. The model constructed in Pro/ENGINEER can be used in Patran and ADAMS. Through this kind of sharing model, the speed of design and optimization can be improved significantly. In the optimal cycle, we cannot run the CAD/CAE software every time by Graphics User Interface (GUI). Instead, we execute command files that automatically record every operation step, save the command flow the first time, and modify them according to our need. The data transmission among every step is shown in Fig. 6 and details are explained below:

In structure discipline, the steps are shown as below:

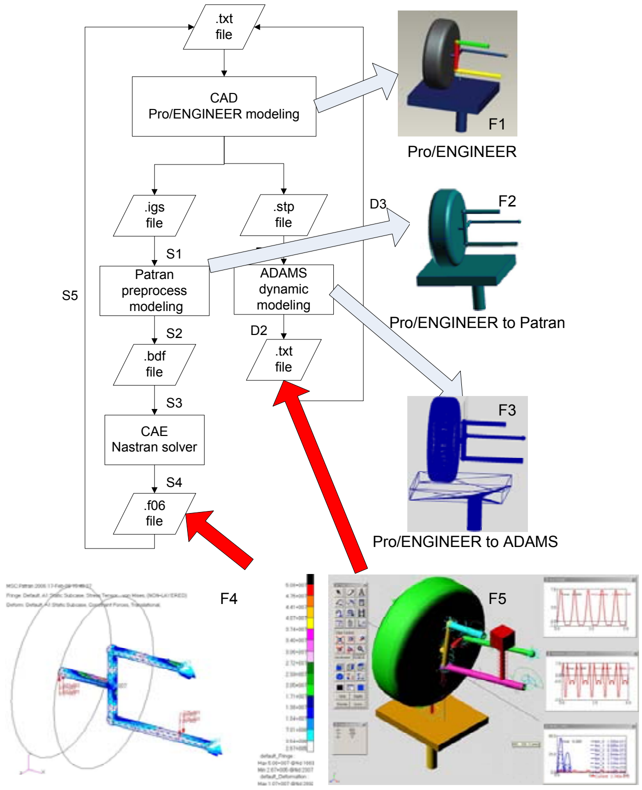


Fig. 6. Automatic data transmission in iteration.

Table 1. Result of the optimization.

Parameter	Initial value	Min value	Max value	Optimization result	Unit
l_u	35	26	38	36.26	cm
l_d	50	40	58	41.65	cm
l_k	32	28	40	31.28	cm
l_p	26	20	30	24.50	cm
d_u	40	30	50	38.05	mm
d_d	40	30	50	41.60	mm
d_k	40	35	45	34.80	mm
d_p	40	35	45	40.40	mm
a	40	35	50	33.60	cm
Δl	12.5			1.8	mm
$\sigma_{\max}$	57			50.8	MPa
G	14.3033			11.0826	Kg

S1: CAD model import to Patran

The CAD model constructed by Pro/Engineer (F1) can store many kinds of data types such as".igs" file—iges format, ".stp" file—step format, ".x_t" file—parasolid format etc. In this article, we use the first type to import to Patran (F2). This is the best way from Pro/ENGINEER to Patran without data loss.

S2: Finite element model generation

After importing the CAD model, Patran is used to create mesh, define the property of the material, add boundary condition and define the type of solver. A function written in Patran Command Language (PCL), which includes all of these command from Patran session file, called ".ses" file needs to be constructed. In the optimization design cycle, we need to regenerate the mesh according to the geometry every time. The ".ses" file is useful for users to generate a different initial design because it is parametric in the content.

S3: Preprocess CAE model import to Nastran

In this step, the analysis input file is produced as ".bdf" format for Nastran.

S4: Structure analysis

Finite element solver, Nastran in the current case, was used to solve the updated structural problem. It costs less than one minute per analysis (F4). Then iSIGHT is used to parse the maximum von Mises tension stored from the ".f06" file produced by Nastran.

S5: CAD model regeneration

This is the last step of one optimization cycle and the first step of the next. We use iSIGHT to store the value of design variables, state variables and objective function. Normalization of the unit is necessary when comparing and calculating the discrepancies with iSIGHT. Then according to the sequentially quadratic programming (SQP) algorithm, we change the value of the design variables and modify the geometry model in Pro/ENGINEER for the next cycle.

While in dynamic discipline, there are only three steps to be done:

D1: CAD model import to ADAMS

As mentioned before here we use step type to import to ADAMS (F2). It is better than any other format.

D2: Dynamic analysis

The important process in dynamic analysis is to define the joint correctly (F5). Revolute joint, spherical joint and fixed joint need to be changed according to the geometry moving. It is easy to implement by ADAMS ".cmd" file because it is also written by parametric value.

D3: CAD model regeneration

This step is the same as the S5 step in structure discipline.

4.3 Optimization result

Before the optimal process, we need to normalize the unit of every parameter before we calculate the discrepancies of the disciplines. In the suspension system, we use linear normalization to change the value to the domain from 0 to 1. The calculation rule is as follows:

$$X_n = \frac{X - X_{\min}}{X_{\max} - X_{\min}} (X_n \in [0,1]) \tag{7}$$

The initial and final value are X and X_n . The normalization precedes steps S5 and D3 that are illustrated in the data transmission part of this paper.

With the collaborative design and hierarchy optimization, we can get the optimal values listed in Table 1.

With the CO method, we can get that the mass of the suspension has decreased by 22.52%. The dynamic and structure performance of the system are greatly improved.

5. Conclusions

This paper developed an integrated design and simulation platform based on collaborative optimization. The application of active suspension indicates that CO integrated CAD and CAE software modeling and simulation is necessary and valid.

The presented cases show that the CO coupling process works. The analysis and optimization models of the active suspension were simple enough to develop the desired methodology without involving high computational load. If the model becomes more complicated and more design variables and constraints are added, we need to use an approximation method such as response surface to reduce the calculation and time, but at the same time the accuracy drops.

In the future, the complexity of models in each discipline will be increased to analyze realistic active suspension models. Furthermore, a stronger coupling will be developed by including the control effects of the hydraulic components in hydraulic and control disciplines. Finally, several decompositions will be implemented on the active suspension design process and products that are more comprehensive can be undertaken.

Acknowledgments

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Notation

d_u, d_d, d_k, d_p : Diameter of upper and lower wishbone, kingpin and knuckle

l_u, l_d, l_k, l_p : Length of upper and lower wish bone, kingpin and knuckle

Δl : Horizontal slip of the tire

x_{sl} : Design variables in system level

x_{sl}^* : Optimal values for system level

x_i : The i th subsystem design variables

x_i^* : Optimal values for subsystem level

σ_u, σ_d : Yield stress of upper and lower wishbone

σ_k : Yield stress of kingpin and knuckle (considered as a whole)

λ : Angle of tire plane

Constant in analysis

E : Modulus of Elasticity, gain=200GPa

M_1 : Sprung mass (quarter car model), gain=330 Kg

M_2 : Unsprung mass (car model), gain=25 Kg

ρ : Density of the rod in suspension system, gain $= 7.8 \times 10^3$ Kg/m^3

$[\sigma]$: Yield stress of steel, gain= 70MP

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