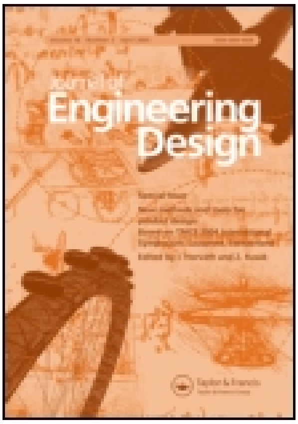

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A strategy for resolving evolutionary performance coupling at the early stages of complex engineering design

Yuliang Li [a], Wei Zhao [b] & Yongsheng Ma [c]

[a] Department of Mechanical Engineering, Zhejiang University, 38 Zheda Road, Hangzhou, Zhejiang Province, People's Republic of China

[b] Department of Foreign Language, Zhejiang University of Finance and Economics, 18 Xueyuan Street, Hangzhou, Zhejiang Province, People's Republic of China

[c] Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada

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A strategy for resolving evolutionary performance coupling at the early stages of complex engineering design

Yuliang Li[a]*, Wei Zhao[b] and Yongsheng Ma[c]

[a]*Department of Mechanical Engineering, Zhejiang University, 38 Zheda Road, Hangzhou, Zhejiang Province, People's Republic of China;* [b]*Department of Foreign Language, Zhejiang University of Finance and Economics, 18 Xueyuan Street, Hangzhou, Zhejiang Province, People's Republic of China;* [c]*Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada*

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In the performance-driven complex engineering design process, at an early design stage, some required design parameters or equations cannot be determined precisely, which can have significant impact on the chain of design decisions and have to be validated with the outcome of design results from the later stages requiring redesign effort to resolve inconsistencies. So it is imminent to evaluate the extent of, and systematically manage, the couplings of design models and develop an appropriate resolving strategy in order to obtain more accurate design results in the shortest time period. This paper presents the research work carried out via the analyses of performance evolution and potential performance coupling at the early stage of complex engineering design. Four strategies based on performance model transformation for resolving evolutionary performance coupling are studied (i.e. decoupling, coupling, first-decoupling-then-coupling and first-coupling-then-decoupling). A selection method for resolving performance coupling based on the synthetic analysis of sensitivity of uncertainty propagation, solvability of coupled models, coupling strength and performance interface and availability of design information is proposed. To demonstrate the related concepts and method, the solving process of a complex design problem related to a suspension system design for tracked vehicle is given.

Keywords: descriptive models of the design process; evolutionary design; process modelling

Nomenclature

v_{I}	input velocity of the component
F_{I}	input force of the component
P_{I}	input power of the component
v_{o}	output velocity of the component
F_{o}	output force of the component
P_{o}	output power of the component
σ_{H}	contact stress of the gear
F_t	transmitted tangential load

*Corresponding author. Email: lyl_zw@zju.edu.cn

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b_t	net face width of the narrowest member
ρ_1, ρ_2	radius of curvature
μ_1, μ_2	Poisson's ratios
E_1, E_2	modulus of elasticity
T_1	torque
d_1	diameter of the pinion
M	mass of the vehicle
F_{ki}	elastic force of the spring
F_{ci}	damping force of the damper
$x_{si}, \dot{x}_{si}, \ddot{x}_{si}$	vertical displacement, velocity and acceleration of the bogie
$x_{ri}, \dot{x}_{ri}, \ddot{x}_{ri}$	input excitations of the road surface
$\ddot{z}_{\mathrm{ds}}$	vertical acceleration at the driver's seat
$z, \ddot{z}$	vertical displacement and acceleration of the centroid of the vehicle
d_{ds}	horizontal distance between the driver seat and the centroid of the vehicle
$\varphi, \ddot{\varphi}$	angle displacement and acceleration of the vehicle
I	rotary inertia of the vehicle
l_i	horizontal distance between each bogie and the origin of the coordinate
x_c	horizontal coordinate of the centroid
y_c	vertical coordinate of the centroid
φ_0	initial trim angle of the vehicle
x_{si0}	initial vertical displacement of each bogie
F	vertical lifting force of the suspension system
p	pressure of the gas in the hypo-pneumatic spring
p_0	initial pressure of the gas
A	piston area
b	installing distance of the spring
x_1	horizontal coordinate of the top iron hinge centre of the spring
y_1	vertical coordinate of the top iron hinge centre of the spring
α_s	included angle between the equilibrium elbow and the horizontal axis when the vehicle is at rest and in equilibrium
α_c	included angle between the equilibrium elbow and the line through the local coordinate origin and the bottom iron hinge centre
s_i	piston stroke
h_0	initial height of the gas column
α_0	initial value of the included angle between the equilibrium elbow and the horizontal axis
l	distance between the top and bottom iron hinge centre of the spring
l_{OD}	distance between the top iron hinge centre and the equilibrium elbow
m	polytrophic exponent of the gas

1. Introduction

In order to make products competitive in the market, performance-driven product design methodologies are drawing more and more attention in both industry and academia since performance is closely related to product properties (Wen *et al.* 2006). In pursuit of this design trend, different definitions of performance have been given from different standpoints up to now. Kalay (1999) proposed a performance-based design paradigm and computer-aided design tool for architectural design after comparing the problem-solving and puzzle-making design notions. He defined performance as a measure of the desirability of the confluence form and function within a given context. Ullman (1997) defines performance as the measure of function and behaviour, Ulrich and Eppinger (1995) define performance as how well a product implements its intended functions and Zeng and Gu (1999) describe performance as the response of a product to external actions in its working environment. All these definitions of performance were cited in Osteras *et al*. (2006). Osteras *et al*. (2006) defined the performance as a vector of variables, where each variable is a measurable property of a product or its element. They identified three kinds of performance, desired, predictive and actual, according to different characteristics in different design stages. They classified the relationship between performance and specifications into one-to-many forward relationship (performance to specifications) and one-to-one backward relationship (specifications to performance). It can be recognised that the interactions between specifications and performance are the driving force that makes the product evolve, but the exact form that this evolution takes is not indicated. Since performance is generally associated with the measures of functional aspects of the product, performance evolution is closely related to product function evolution. Shimomura *et al*. (1998) introduced a functional evolution process model by extending the function-behaviour-state conceptual design model to better represent the designer's evolutionary intention in early product design process, and their model includes the functional operation, actualisation and evaluation. In this paper, the performance definition by Osteras *et al*. (2006) is adopted because the authors are mainly concerned about product properties.

When performance model evolves along the complex product design process, coupling between performance models often occurs. We call it evolutionary performance coupling. Two issues are concomitant of the evolutionary performance coupling. First, the estimation of performance in the early stage of design is not accurate. The performance model built at the beginning of design process is rough and the analysis results are only indicative. At later stages, newly generated design results or model derivatives substitute those rough parameter values or descriptions of constraints in the initial model, and get an updated design results, then obtain a more accurate performance model for further improvement. Such design iterations need to be carried out many times before the final design is determined. For example, in the initial concept design of a hydraulic excavator (a large digging machine used for making roads, etc.), in order to calculate the dynamic performance of the machine, the maximum allowed load, the values of mass, moment of inertia and centroid of the machine are required. These values can be initially given by estimation, while their more values can only be obtained after the detailed design of the machine structure through numerical integration, and so the performance of the hydraulic excavator has to be calibrated throughout the structural design of components. At any stage, if the performance attributes such as motion stability do not satisfy the initial requirement, the design cycle starting from concept design including the selection of hydraulic system and control system has to be revisited in order to obtain satisfactory results.

Another issue related to the performance coupling is the uncertainty that will be involved during the propagation of performance analysis and its impacts on the design model. At the early design stage, there are many kinds of uncertainties for a complex product in which many functions, components and performance model attributes are involved. This paper concentrates on design variable interval uncertainty because interval uncertainty can better approximate uncertainty caused by ignorance (Li *et al.* 2009). Generally, it is expected that uncertainties exist at the early design stage; ideally, uncertainties can be limited in either extent or scope such that they will not have much impact on the later design stages, and thus design iterations can be reduced. To limit uncertainties, constructing a sufficiently accurate performance model to predict whether the former uncertainties have significant impacts on the expected product performances or specifications is required. For example, in the design of suspension system for a tracked military vehicle, the centroid of the vehicle is a key function variable at the early design stage. It keeps changing throughout the design cycles; and even more demanding, the centroid changes in use have to be considered since the passenger, ammunition, fuel or other materials in the vehicle can vary at different times.

So the following questions arise: what influences will such operational variations of vehicle centroid have on the design of the suspension system and how the performance of the whole vehicle will be affected by the suspension system conversely.

In order to reduce design iterations and the impact of the early design uncertainty on later design decisions without influencing the product quality, performance coupling can be resolved via design management and the solving approach for coupled design problems. More specifically, when a performance model crosses several design phases such as concept design stage and embodiment design stage, an appropriate solving method is required to obtain satisfactory solutions for each phase. Krishnan *et al*. (1997) proposed four kinds of qualitative overlapping strategies, that is, iterative, distributive, divisive and preemptive, according to the upstream information evolution and downstream iteration sensitivity. Eppinger *et al*. (1994) put forward two different design management strategies using the Design Structure Matrix to capture both the sequence of, and the technique, relationships among the many design tasks to be performed, and they are a decoupling strategy to speed design up and an increasing coupling strategy to improve design quality. As for the specific method to implement the above strategies, they are limited to minimising or removing task dependences.

In terms of technical resolution for performance-coupled design problems, Karimian and Hermann (2009) introduced a separation-based design method by converting a design optimisation problem into decision-based design processes without considering the uncertainties existing in the 'progressive' design process. No matter whether it is decoupling or increasing coupling of different performance models, the selection of performance model is one of the most important issues to guarantee sufficient efficiency and resolution accuracy for coupled design tasks. Radhakrishnan and McAdams (2005) proposed a method for performance model selection in engineering design using utility theory, which uses a satisfactory level of performance model, and the uncertainties in parameters of the design model were handled by a confidence function in the selection of model. Panchal *et al*. (2009) took the improvement potential of utility as the measure to select which kind of interaction patterns to solve multidisciplinary and multi-scale design problems. They introduced intervals to model uncertainty of input variables resulting from decoupling of scales and decisions; and the range of utility, which was used to compute the improvement potential, can be determined by designer's preferences through utility functions of the output variables.

To facilitate the decision-making and uncertainty analysis according to the resultant performance attributes, it is necessary to appropriately incorporate those separate design models into a comprehensive design model, or to derive separated design views or models from a holistic model in order to support the analysis of a specific domain of performance objectives. However, it takes a lot of effort to integrate the separated models since performance coupling exists across many stages of the whole product design process, while the integrated model may not be solved analytically or numerically with enough accuracy. On the other hand, decomposing the integrated model can create errors because the boundary conditions of the original model are inserted into those decomposed models, and these boundary conditions may not reflect the real essence of the individual design subproblems.

The purpose of this paper is to develop effective strategies or actions to resolve the performance-coupled design problems. Performance coupling is evolutionary because of progressive design process, in which the performance models and parameter variation intervals are both changing. In order to deal with complicated dependencies and design uncertainties, we extend the substance-field analysis model (Semyon 2000) by qualitatively analysing five aspects of the performance-coupled design problems. Substance-field model is used because it can analyse the most important parts of a technical process or a system and to identify the core issues (Semyon 2000); in the performance-coupled design problems, components or subsystems are usually the key control links to materialise the holistic performance requirements.

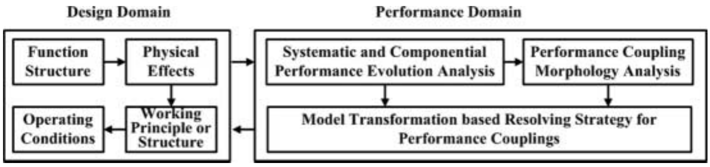


Figure 1. Research methodology of the paper.

The research methodology of this paper is shown in Figure 1. Product design such as function structure, selected physical effects, working principles or structure and operating conditions, etc. in design domain are taken as the input of the performance analysis domain. Results of this analysis will be fed back to the design domain if product requirements cannot be satisfied. The structure of this paper is organised as follows: The concept of performance evolution patterns at both componential and systematic levels is introduced first. These patterns are fundamental for detecting and handling performance couplings. Second, potential associative (non-hierarchical) and hierarchical performance couplings that could appear in performance evolution process are identified and analysed. Then, the strategies based on model transformation are presented to deal with different performance coupling cases followed by the introduction of a proposed selection method on the aforementioned different resolving strategies. Finally, a design case with a suspension system is used to demonstrate the concepts and the method proposed.

2. Performance evolution

Performance evolution patterns are classified into componential evolution pattern and systematic evolution pattern according to whether the specific evolution happens on the single-function modules or components or the combination of components (including the whole product) which may have more functions.

2.1. *Componential performance evolution pattern*

A component should be developed or selected when an indecomposable function is established in the clarification of the product function structure. This component, though may have existed for a very long time, affects the overall performance of the product fundamentally. Figure 2 shows the componential performance evolution pattern. The evolution has forward and backward directions.

The forward evolution starts from an indecomposable product function. Usually designers should first find a physical, chemical or geometrical effect to realise the function, and then the corresponding mechanism is designed or applied according to a design theory (Orloff 2006, Pahl *et al*. 2007). For example, a lever mechanism can be selected to realise the function of amplifying a force. The ideal functional result of the effect can be described as the desired performance by assuming that the conditions required by the mechanism are satisfied. This performance function can only be fully realised with the concrete working principles and structures to play its effective role and constrain its side effects to an utmost degree. Some of the design parameters in the design model have to be transformed, expanded or mapped to the specific desired performance parameters, where design parameters are used to describe the selected working principles or structures while performance parameters represent quantitative functional results of the implemented effect as the predictive performance model. In the design domain, most conceptual elements used to implement physical or geometrical effects are points, lines or surfaces when determining working principles or interacting structures for the given function or effect. Once the concept is adopted,

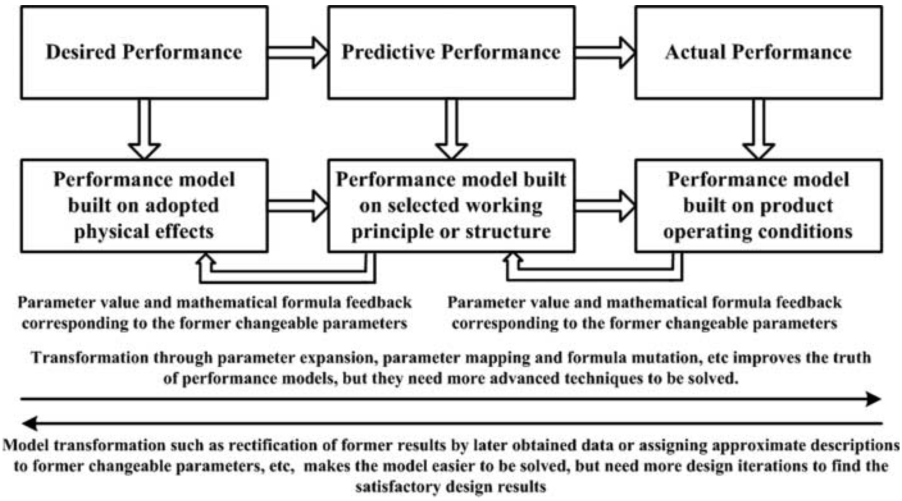
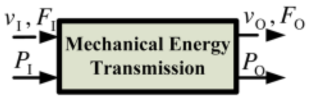
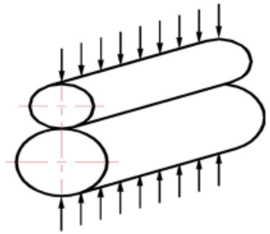
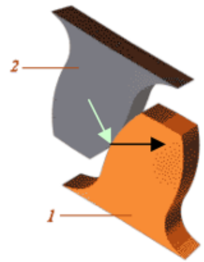
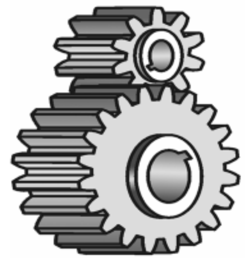


Figure 2. Performance model evolution pattern at componential level.

more detailed mechanisms or assembly features (Ma *et al.* 2007) should be created, updated and enriched via the corresponding driving design parameters such as the distance of the line, the curvature radius of the curve or surface, etc. At the same time, the desired performance parameters are updated in the performance model. With regard to the actual performance, the connotation of the concept is slightly different with the one in Osteras *et al.* (2006). Other considerations from the angles of fabrication, spatial layout or working conditions, etc. on the conceptual elements are applied to the design model and then to the predictive performance model by generating the predictive performance. Note that this work does not refer to the performance of the real fabricated component in order to define the actual performance as in Osteras *et al.* (2006). In an actual instance, the operational mechanism implemented may not meet the requirements completely, considering the parts may become deformed because of stress, temperature or abrasion and so some provisions should be incorporated in the predictive performance model in order to obtain a more accurate performance model. The backward evolution is involved when the designer cannot obtain an expected predictive performance model because the assumptions or conditions required by the functional mechanism cannot be fully satisfied. The design then has to roll back to the previous design states to constantly rectify the design model until the desired predictive performance model is obtained with sufficient consistency.

To demonstrate the forward performance evolution pattern, take the contact stress of a pair of spur gears (definitely bending stress is also an important performance parameter of the gear) as a performance parameter example (Table 1). The function of mechanical energy transmission can be actualised in many ways, for example, friction effect, lever law, contact effect, etc. But when the specifications are added to the function requirements, few choices are left. Suppose the Hertz contact transmission is selected as the physical mechanism, then the desired performance can be obtained according to the Hertz theory. This theory holds with some assumptions. For instance, no tangential forces are induced between the contacting bodies and these bodies are at rest and in equilibrium, etc. If these assumptions are met, the expected performance can be realised, and thus the specifications can be satisfied with the expected performances with the selection of the physical effect for this function. To realise the Hertz contact effect, the sweeping surface generated by the involute curve along a straight line is taken as the acting geometry, then the predicted performance is obtained by substituting the working parameters (the pitch radius) for the corresponding parts (the curvature radius of contact point) in the desired performance formula.

Table 1. Spur gears as an example to demonstrate the componential performance evolution pattern.

Required function	**Selected Physical Effect** (Hertz Contact Transmission)	**Working Principle or Structure**	**Actual Structure or Operating Condition**
Mechanical Energy Transmission 			
Specifications	**Desired Performance**	**Predicted Performance**	**Actual Performance**
1) Velocity direction should be reversed after transmission; **2)** Both the input and output motion type are rotation; **3)** The axes of the input and output motion are parallel; **4)** It should have above 90% transmission efficiency. **5)** The transmission ratio should be constant; **6)** The transmitted power is over 10 kw. **7)** The component has at least 20000h reliable working time. **8)** The bending stress of component must not exceed the allowable value if cantilever forces are involved.	${}_H = \sqrt{\dfrac{\frac{F_t}{b_t}(\frac{1}{{}_1} \pm \frac{1}{{}_2})}{[\frac{1-{}_1^2}{E_1} + \frac{1-{}_2^2}{E_2}]}}$ **Assumptions (Hamrock *et al.* 2005)**: A. No tangential force are induced between the solids; B. Contact is limited to a small portion of the surface; C. The solids are at rest and in equilibrium. If these assumptions are satisfied, the transmission efficiency maybe up to 99%. And the contact stress is the most critical factor that affects the specification 4), although it is not the direct mapping of the requirement.	${}_H = 2.5Z_E\sqrt{\dfrac{2T_1}{b_t d_1^2}\dfrac{u \pm 1}{u}}$ $Z_E = \sqrt{\dfrac{1}{[\frac{1-{}_1^2}{E_1} + \frac{1-{}_2^2}{E_2}]}}$ The predicted performance model is derived by replacing curvature of contact point with the pitch radius of the involute curve. This extension of the desired performance model reflects the characteristics of the operating zone of selected working principle.	${}_H = 2.5Z_E\sqrt{\dfrac{2KT_1}{b_t d_1^2}\dfrac{u \pm 1}{u}}$ $K = K_a K_v K_m$ The application factor K_a, dynamic factor K_v and load distribution factor K_m are introduced to account for the actual conditions that may not conform to the assumptions (**Hamrock *et al.* 2005**). The predicted transmission efficiency is related to the K, which may vary from 92% to 99%.

After the actual structure of the spur gear is designed, the actual performance of the spur gear pair can be derived from further revising the predicted performance model. However, in reality, the working conditions cannot thoroughly comply with the assumptions of Hertz contact effect since the material properties are not ideal, the distributed forces are not well-proportioned along a pair of contact tooth surfaces, the distribution of the load among the gear teeth that share the load is non-uniform and there are force fluctuations or dynamic impacts caused by other components in the transmission chain, etc. So the predictive performance model can be revised with some factors to account for the mismatches of the above conditions. All these factors will be embodied in the actual performance model of the spur gear.

2.2. *Systematic performance evolution pattern*

Two kinds of evolution patterns are identified at the systematic level: function-driving evolution pattern and interface-match-driving evolution pattern.

2.2.1. *Function-driving performance evolution pattern*

Function-driving performance evolution pattern is a forward qualitative performance evolution process originating from customer's design specifications. In literature, two functional representations exist, natural-language-like representation and mathematical representation (Chakrabarti and Bligh 2001). This paper models functional representation as mathematical equation(s) considering that mathematical representation is more precise and easy to express compound functions when the functional mechanisms or working structures have been mathematically expressed; they have been determined to implement the specific product functions. The function graph of a complex product consists of directionally connected function blocks with arrowed lines indicating flows of energy, information and material through each other (Figure 3). These function blocks can have further relations of *decomposed-into*, *conditioned-by*, *enhanced-by* and *described-as* (Shimomura *et al*. 1998). Each mechanism that implements the function can be seen as an assembly feature (Ma *et al*. 2007) that transforms the input of energy, information or material into the outputs. These functions can be expressed in the form of desired parameter values in the performance model. After the relevant analyses, these values will be updated to represent the predictive performance or eventually the actual performance. At least three kinds of performance model evolution can be identified, as is shown in Figure 3. For example, (1) performance attribute E_{o1} is first obtained by three successive functional mapping and then, (2) E_{o1} is amplified by the input signal of S_o and (3) all the inputs to a functional block (e.g. F_2 and F_5) become the addition operations in the performance model before handled by the function if these inputs are all energy flow, or all information flow or all material flow. In Figure 3, there are also

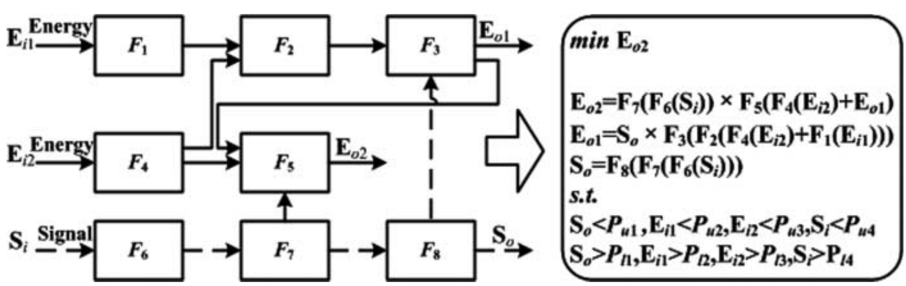


Figure 3. Function-driving qualitative performance evolution.

other similar evolution cases; however, not all are enumerated. When any functional operation such as adding or removing function relationships, adding or removing function blocks, etc. is executed on the function graph, the performance model of the product will change accordingly, that is, a functional mapping is updated.

2.2.2. *Interface-match-driving performance evolution pattern*

This kind of evolution pattern makes the performance models evolve quantitatively. A performance *interface* is defined with a set of design variables that transfer or share design information between coupled design modules related to a specific performance objective in the performance model. A *performance feature* is defined as the value space of an interface parameter with respect to the constraints associated with its determinant design variables in their value ranges. A performance feature can be dynamically changing or static. Take one input variable as the example to graphically demonstrate the concepts (Figure 4). Dynamic interface parameters change with respect to input variables at different times. Stable interface parameter will be constant once its value is set. An *interface match* is defined as the association between two or more *performance features*. Through the analyses of product configuration and the energy, information and signal flows in different function structures, four kinds of performance interfaces match are identified in a complex product design process according to the performance feature of the interface parameter, proportion, mergence, transmission and counteraction (Figure 4). (1) Proportion performance match occurs when a product specification requirement is simultaneously fulfilled by several similar subsystems, and these subsystems often have a proportional relationship in terms of their respective performance feature [Figure 4(a)]. (2) Mergence (decomposition) match pattern

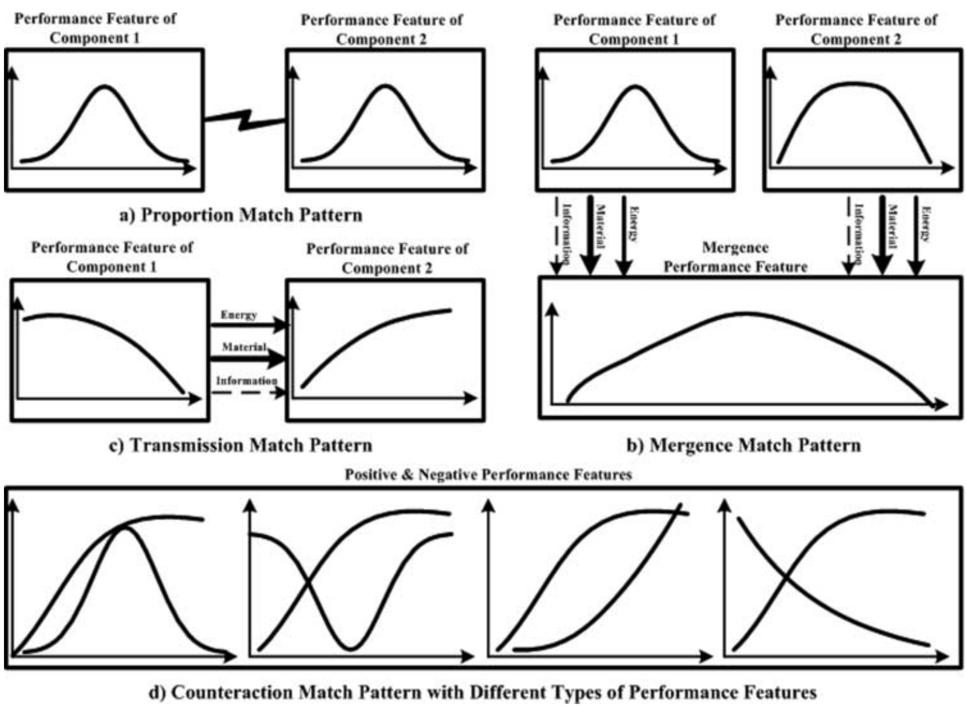


Figure 4. Performance interface match patterns.

occurs when several subsystems work together to meet the required product specifications, and the performance of these components and the required specification constitute the mergence evolution pattern. It can also be the decomposition evolution pattern in the converse viewpoint [Figure 4(b)]. (3) Transmission match pattern occurs when multiple physical effects or function units are needed to fulfil an overall product function, then transmission match pattern exists among these function chains for some performance objective [Figure 4(c)]. (4) Counteraction match pattern occurs when the performance objective of a product is realised by the counteraction of two or more contradictory performance attributes, and then counteraction match pattern comes into being between these counteractive performances. The difference between the counteraction match pattern and the transmission pattern is that the former is usually related to only one object or system, while the latter involves two subsystems, and the performance attributes output by the upstream subsystem is input into the downstream subsystem as the driving factors, and are also the goal to be converged by the upstream subsystems [Figure 4(d)]. As an example, assume in a design case, positive and negative performance features exist at the same time representing different groups of constraints, their interactions can be described as performance interface matches. Usually, a stable performance state can be worked out at the intersecting point in order to reach a compromise between both.

There are generally two cases wherein performance interface match can drive the performance model's evolution. The first case is that an interface match can allow the designer to assign different values to design variables which are associated with one or more performance functions, that is, variable values or value ranges change until the interfaces of those related performance functions converge. The second case is that when the performance interfaces of the related performance functions cannot converge, then those involved performance functions have to be modified, replaced or deleted. In this case, the current functioning mechanism defined with working principles as well as structures that determines the performance model state must be changed or replaced accordingly.

3. Performance coupling

Concurrent evolution coupling and sequential evolution coupling are identified in the product design process according to how the dependencies between the two related design modules (tasks or disciplines) interact dominantly. The interactions may involve the acceptability of their respective performance objectives, current design variable values and the corresponding ranges for those design variables. When this analysis is applied to the early design stage of product development in which performance model evolution and uncertainty of variable values exist, performance coupling can occur at the function, mechanism, working principle and structure, and/or parameter levels, which can involve desired, expected or actual performance states. Performance couplings can be found according to whether there is energy, information or material flow loops among the functional blocks in the function graph. These couplings usually have close relationships with the above performance evolution patterns, and we classify these performance couplings into associative (non-hierarchical) and hierarchical couplings according to whether performance inheritance or decomposition occurs in the coupled system and how many subsystems are involved. If a performance coupling problem occurs with two or more subsystems (in addition to the upper-level system) involved, then the coupling is hierarchical; otherwise it is associative (non-hierarchical). It should be pointed out that these two kinds of couplings are only the basic forms that performance coupling may take. They can be extended or combined to include more complicated couplings. In a relatively more complicated situation, for example, three or more subsystems or components that implement different functional mechanisms are involved in associative (non-hierarchical) performance coupling, a composed method by making use of the following two basic methods can be taken to analyse how any two of them interact and how all the couplings work out together.

3.1. *Associative (non-hierarchical) performance coupling*

When a physical, chemical or geometrical mechanism is selected as the means to implement a product function, potentially, side effects can arise together along with realising the required function. Since a complex product is composed of many subfunctions, probably many functional mechanisms are chosen and integrated to meet the specifications of the whole product. So it is possible that the side effects or the insufficient functions of a mechanism can spoil the necessary conditions of another related mechanism, and hence, lead to the functional deterioration of the product. Furthermore, the expected function of a mechanism can be used just for satisfying the conditions of another mechanism (Figure 5). When this phenomenon propagates through the whole design chain or associated design feature tree branches, performance coupling occurs. The uncertainty lies in the extent to which one function's side effects affect other functions or performance of other effects (mechanisms) if the performance variables of the related performance model have significant value ranges. The transmission match pattern and the counteraction match pattern could come up with this kind of performance coupling during a design process.

3.2. *Hierarchical performance coupling*

In the hierarchical performance cascading process, the performance attributes of the upper-level design object will be inherited or decomposed in the lower-level modules or components, while the lower-level modules or components will impose some constraints on the upper-level design object by merging all their output performance functions to strengthen or weaken the upper-level object performance objectives (Figure 6). When there are interdependences between performance attributes of the upper-level and the lower-level modules or components, hierarchical performance coupling occurs. Hierarchical performance coupling can be analysed according to the above principles of effect. However, since there are at least two modules or components in the lower-level configuration (otherwise it becomes associative or non-hierarchical coupling), the coupling becomes more complicated when the performance of these lower-level modules or components are also coupled. Definitely, the mergence (decomposition) performance match pattern can generate this kind of coupling during design process, and the coupling caused by the proportion, transmission and counteraction performance match patterns can also be involved in the lower-level components. Since the shared or inherited product attributes of the mergence modules and components could be associated with the accomplishment of the design

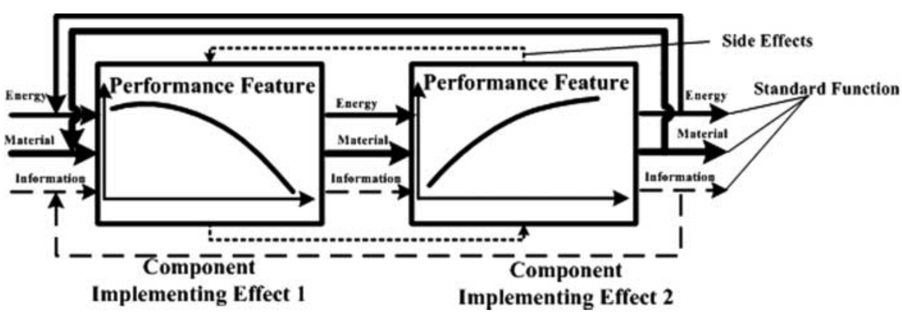


Figure 5. Associative performance coupling through effect analysis.

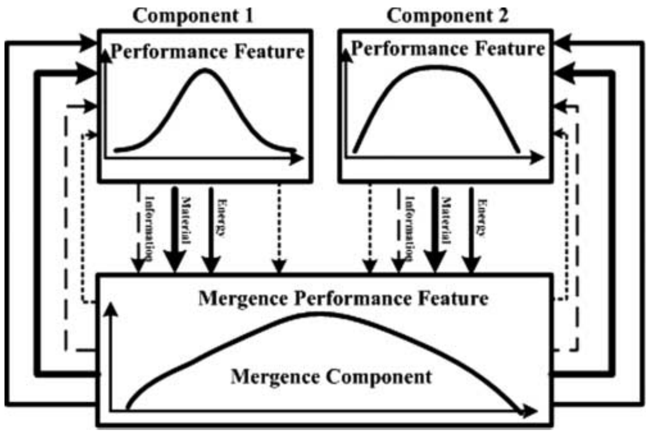


Figure 6. Hierarchical performance coupling through cascading effect analysis.

of lower-level components as described in introduction, there are performance attribute uncertainties among the relevant levels; the upper-level design object can cause significant impacts on the performance of the lower-level components, and conversely such side effects affect the performance objectives of the upper-level modules or component through the performance coupling loop.

4. Model transformation-based method for resolving performance coupling

Model transformation is to convert a complex and coupled design problem into solvable sub-models through substitution of variables, usage of surrogate models or change of optimisation objectives, etc., so that the design problem can be solved with high efficiency; or to change a single objective design problem into a multi-objective optimisation problem, and adopt a numerical and discrete method to solve a compound design task so as to obtain a more accurate design solution. Developing a model transformation method is a synthesis of modelling accuracy, solution error, time and computing ability (including hardware and software). It needs different routines in the light of a specific design problem. In accordance with the strategy of resolving evolutionary performance coupling, the transformation method can be divided into decoupling transformation and coupling transformation.

4.1. *Decoupling transformation of performance models*

Decoupling transformation is to separate the coupled design tasks through substituting constant values or less accurate mathematical description such as linear equations instead of nonlinear equations for the coupled variables or problems, and thus the separated design tasks can be solved independently. Decoupling transformation is carried out on the assumption that the transformed models are valid, and so usually it needs to evaluate the feasibility of design results and how much more design iterations have to be conducted to fulfil the initial design requirements. This method can be used in the following cases: (1) some design variables cannot be assigned with accurate values or value bounds at the early design stage limited by the design progress; (2) the stagnant design process can be pushed forward by modelling the coupled relationships among function blocks using less accurate equations without changing the boundary conditions on a large scale, and these equations can be utilised easily by the affected mechanisms; so designers can obtain a remarkable insight into the modular or componential performances quickly; (3) the performance coupling between the related components is not strong or the design variables have fairly large value ranges and hence it is not sensitive to eliminate the influences of the couplings.

4.2. *Coupling transformation of performance models*

In contrast to decoupling transformation, coupling transformation adds more complicated descriptions to the performance model so as to make the model represent the intrinsic part of the designed object comprehensively and solve the relevant constraints simultaneously. Coupling routine can be realised by converting a constraint of an optimisation model into an optimisation objective, or by substituting a constant value or variable with an equation or a submodel. Coupling transformation routine converts an explicit constant or an external variable into an implicit and internal variable constrained.

The most important issue for coupling transformation is that the coupled model becomes more difficult to solve because the characteristics of the performance model may change drastically after coupling transformation. So a mutation of solving technique of the model should be followed immediately. It is noteworthy that complicated coupling models do not necessarily ensure accurate results because solutions could have significant numerical errors, and sometimes these models may not be solvable. Since coupling transformation makes the problem-solving more time-consuming, then such coupled models can be used as the final evaluation stage criterion to determine the coherent design solution with those previously generated results.

4.3. *Synthetic utilisation of coupling and decoupling transformations*

The above description suggests that both decoupling transformation and coupling transformation routines have advantages and disadvantages. An interesting way to tackle evolutionary performance couplings is to use these two routines together but in the different cycles of design performance analysis. There could be two more strategies, that is first-decoupling-then-coupling transformation or first-coupling-then-decoupling transformation. The former strategy can be used when product specifications need to be further clarified, design uncertainties have significant impacts on design results and the initial values and value ranges for design variables should be determined to set appropriate constraints to avoid unreasonable computations or optimisations in coupling strategy. The latter strategy can be used when the coupling strength between the coupled problems should be checked and the occurrence of the coupling should be first cleared.

The conversion from decoupled solving strategy to coupled solving strategy is usually not automatic. Although it is easy to realise continual solving of the sequential design tasks by the process engine, amalgamation of performance models should be performed by designers in most cases. Therefore, the designer should prepare the decoupled performance models as well as the coupled ones before the conversion is carried out. To execute a smooth conversion, a process model should be built to determine when to use decoupled model or coupled model, and record the design information generated in the design activities for later comparisons, research and verification.

4.4. *Selection of resolving method*

To determine which one of the aforementioned strategies is appropriate for a coupled problem, we propose decomposing them into steps using the substance-field acting model to determine the operation zones (Orloff 2006) of their adopted effects or working structure precisely so as to recognise how they are coupled and the iterations involved. If the operation zone can be described with differential or polynomial equations, the solvability of coupled performance models, coupling strength and performance interface, and design information availability for coupling analysis can be qualitatively predicted. According to the evaluation result of these factors and the design analysis experience, the following resolving strategies are suggested to deal with different performance couplings (Figure 7):

- Use coupling transformation strategy to solve problems with sensitivity of uncertainty propagation. There are two issues related to the uncertainty sensitivity. First, the boundary conditions of the operation zone have uncertainties or the initial conditions have uncertainties for dynamic problems. Second, the parameters of the performance model have uncertainties. These uncertainties can propagate through the associative (non-hierarchical) or hierarchical coupling loops, and the propagation can have feedback impacts on the initial model where the uncertainties exist. Since we only think of value ranges as the parameter uncertainties in this paper, monotonicity analysis should be first adopted to decide the varying trend of performance objectives with regard to the uncertain input variables (Saltelli *et al*. 2004). If there is no monotonicity in the performance model, global sensitivity analysis can be conducted to evaluate the overall effect of entire range of model inputs on model outputs (Saltelli *et al*. 2008). Considering that the performance model that describes the operation zone usually involves differential equations, numerical simulation method should be first setup to obtain the responses to different inputs. After obtaining the sensitivity information, designers decide the sensitivity degree heuristically. If the feedback impact of the uncertainty propagation plays an important role in the total sensitivity, coupling transformation strategy is preferred to solve the coupled design problems.
- Choose the strategy according to the solvability of coupled performance model. Solvability of performance model has two meanings, that is, whether the model can be solved and whether the solution error of the model is acceptable. Generally, an analytical solution of the model is regarded to be the best result, but many models cannot be solved analytically. So numerical approximation is often used to obtain the solution of complex performance models. Conducting residual analysis is needed to analyse the accuracy of this kind of solution, which is beyond the scope of this paper. But if the step size or mesh size of the numerical approximation can be adjusted, or some other high-accuracy approximation methods can be used, the solvability of the coupled performance model can be regarded as good because reducing the step or mesh size can usually improve the solution accuracy greatly. If the solvability of coupled performance model is good, coupling transformation strategy is preferred; otherwise decoupling strategy should be adopted.
- Use coupling transformation strategy to solve strong performance coupling problem. Suppose the leading performance Model 1 has m design variables, and the dependent performance Model 2 has l design variables, and the two models have r interface parameters ($r \leq m,\ r \leq l$). (a) If these interface parameters have constant values after performance Model 1 is solved, and

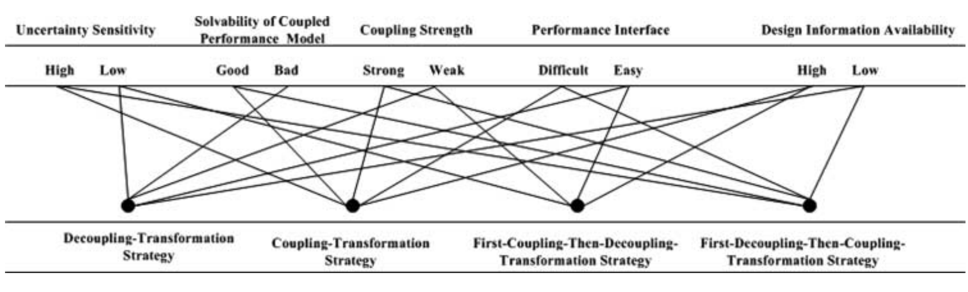


Figure 7. Mapping relationships between the resolving strategies and the influence factors of performance couplings.

performance Model 2 can directly take the interface parameters as the initial condition or objective to start its solving process, then coupling strength between the two performance models is weak, and decoupling transformation strategy can be used. (b) If any two interface parameters have linear function relationships, and these interface parameters can be replaced with some other constant coefficients, then decoupling transformation strategy can also be adopted because the solution of the performance Model 2 can be directly used in the computation of the Model 1 without generating any significant errors. (c) If there is any nonlinear function relationships among the two interfaces' parameters, coupling transformation strategy should be used because performance attributes of these two models are cohesive, and their coupling strength is strong.

- Use coupling transformation strategy if the design information is interdependent on availability. If design variables in the current performance model are only assigned with appropriate values after another performance model is solved, and this model is solved sequentially later than the current performance model, then these two models should be combined together to reduce the unnecessary error because the designer does not have prior knowledge to make a good estimate on values for those coupled design variables.

5. Case study

5.1. *Customer requirements and engineering specifications of suspension system*

The design of multi-degree-of-freedom hypo-pneumatic suspension systems is shown in Figure 8.[1] Each vehicle usually has five to seven pairs of bogies connected to the body through the suspension system. The suspension systems are used to attenuate the impact on the vehicle body of the random excitations generated by vertical track irregularity. To simplify the design and maintenance, all the suspension systems are of the same size. The general design requirement of the suspension system is how to design the suspension system in order to minimise the amplitude of vertical acceleration at the driver's seat when the vehicle is moving along the Grade E road surface at the given speed if the mass, length, width and height of the vehicle and the distance between any two bogies are known. In this vehicle design, five pairs of bogies are sufficient for bearing the total weight of the being-designed vehicle, and the influence of the caterpillar track on the riding smoothness of the vehicle is neglected, and the hydraulic damper is simplified as a linear model.

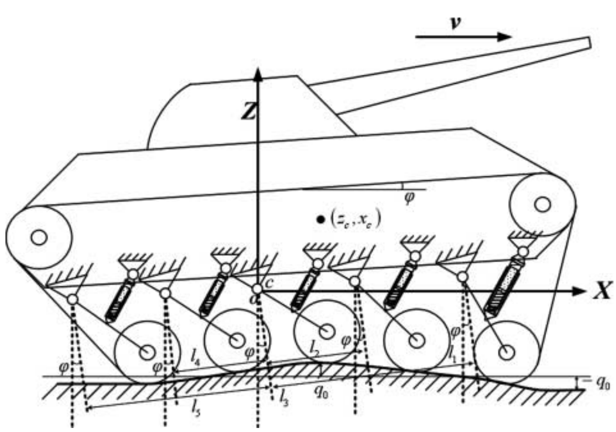


Figure 8. The example vehicle suspension system with hypo-pneumatic springs (modified from Ding 2004).

5.2. *Identification of performance evolution and coupling*

According to the substance-field model, the operation zone for the functions of upholding vehicle body and attenuating vibration mainly includes three components: vehicle body, suspension system (hypo-pneumatic spring) and bogies. Several physical fields are functioning between the vehicle body and the hypo-pneumatic spring. The vehicle body and bogies transfer their vertical displacements, velocities and accelerations to the suspension systems to determine their strokes and relative velocity of pistons of the hydraulic dampers, and the suspension system exports their lifting force to the vehicle body to determine its vertical displacement, velocity and acceleration, and so the vertical (angular) displacement field, vertical (angular) velocity field, and vertical (angular) acceleration field and acting force field have a significant influence on the suspension system. Figure 9 shows the qualitative evolution pattern in the systematic riding performance model. Upholding vehicle body and attenuating vibration play the most important role in constructing the performance model. According to this model, the information flow of the angular displacement, velocity and acceleration are major design variables in the performance model.

In the light of the above-operation zone between the vehicle body and the suspension system, interface parameters between the systematic riding performance model and the hypo-pneumatic spring performance model are lifting force of hypo-pneumatic spring, trim angle of vehicle body, position of centroids, etc. (Figure 10). All the lifting force and the gravity of vehicle body constitute the quantitative mergence (decomposition)-match-driving performance evolution pattern, and this pattern is embodied in the summation operator in the overall riding smoothness model. The lifting force of the spring is driven by the total weight of the vehicle body. As a result, the design variables of the hypo-pneumatic spring such as initial gas pressure, area of piston, strokes of piston, etc. have some definite value ranges. Furthermore, stroke of each bogie is proportionally driven by the trim angle of vehicle body because they are connected to the same stiff body, although the strokes are not very strictly proportional, especially when the road surface is not even.

It is evident that the above performance evolution pattern may have potential couplings because there are mutual information and energy flows between the suspension systems, as well as with the vehicle body. However according to the performance features of the selected effect to implement the suspension function, the characteristic model of the suspension stiffness should be further analysed, because whether the riding smoothness analysis has a high level of confidence, and whether the analysis result can be directly transferred to the structure design activity of the suspension system, depend on its representation. The componential performance evolution process of the hypo-pneumatic spring is shown in Table 2. According to this evolution process, the output force of the suspension system is a nonlinear function of the stroke of the bogie, which means the performance interface of the hypo-pneumatic spring in the overall riding smoothness model [Equations (3) and (5)] cannot be simply represented as suspension stiffness k_{si}. So the nonlinear model [Equations (3)–(13)] should be used, and thus makes the analysis of the overall riding smoothness and the design of the hypo-pneumatic spring closely coupled (Figure 10).

5.3. *Selecting a strategy*

The selection of solving strategy for this evolutionary performance coupling problem can be analysed from the following aspects. (1) The coupled resolving strategy is feasible because the coupled model is numerically solvable, and the step size for simulating the model is adjustable. (2) The uncertainty of the position of the vehicle centroid (X_c, Z_c) has significant influence on the riding smoothness performance because the centroid not only decides the initial value of the vertical angular displacement of the vehicle body [Equations (5)–(7)], but also affects the vertical angular acceleration of the vehicle body [Equations (2)–(4)], which will affect the vertical acceleration at the driver's seat position [Equation (1)]. (3) The maximum stroke of the single-chamber

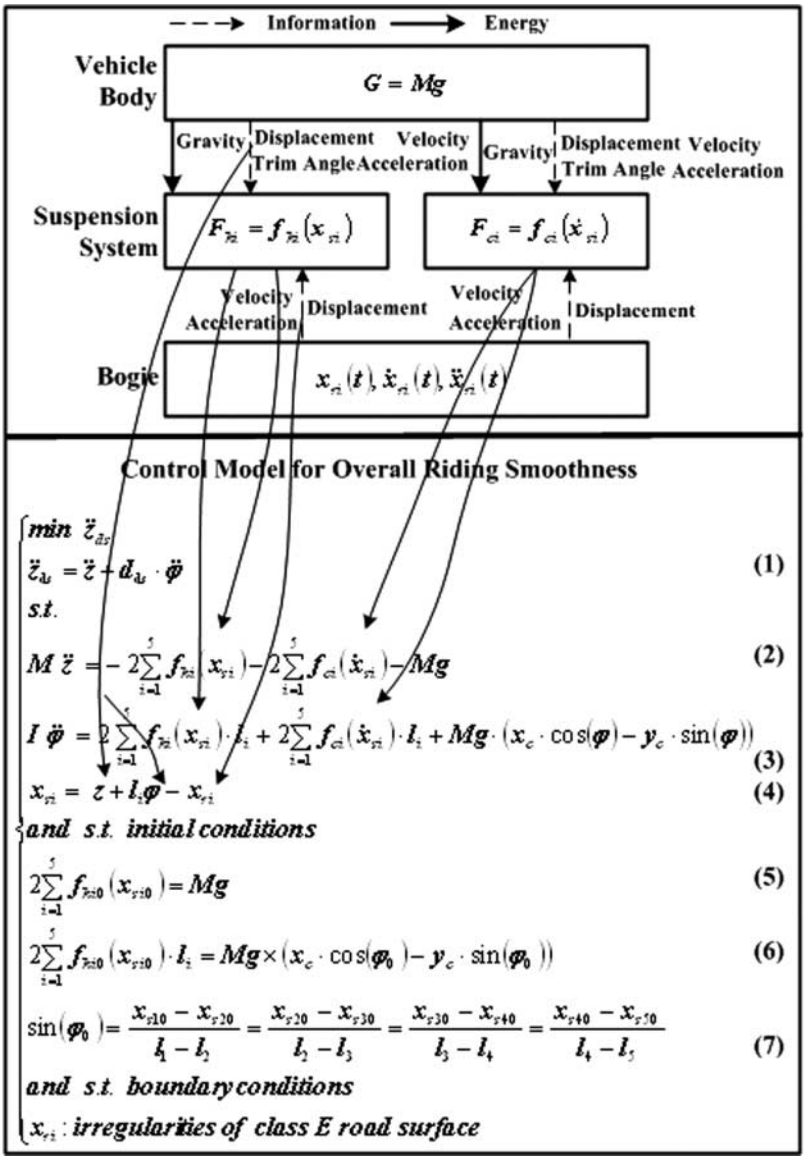


Figure 9. Qualitative performance evolution in the overall riding smoothness model.

hypo-pneumatic spring is limited; so the location uncertainty of the vehicle body centroid may cause some hypo-pneumatic spring exceeding its utmost stroke when the vehicle is moving at a high speed on an uneven road; so this uncertainty should be integrated into the analysis of riding smoothness of the vehicle body as the initial condition of the model. (4) The boundary conditions for the model and the road surface map (Grade E) also play an important role in the analysis. Since they are user requirements, they must be taken into consideration in the solving process. All the above analysis can lead to the selection of coupling transformation-based strategy; however, when the performance modules of hypo-pneumatic spring is merged into the overall riding smoothness model, many design variables and their variation bounds have to be decided beforehand. The intervals for these design variables have some weak or strong, geometric or physical dependence.

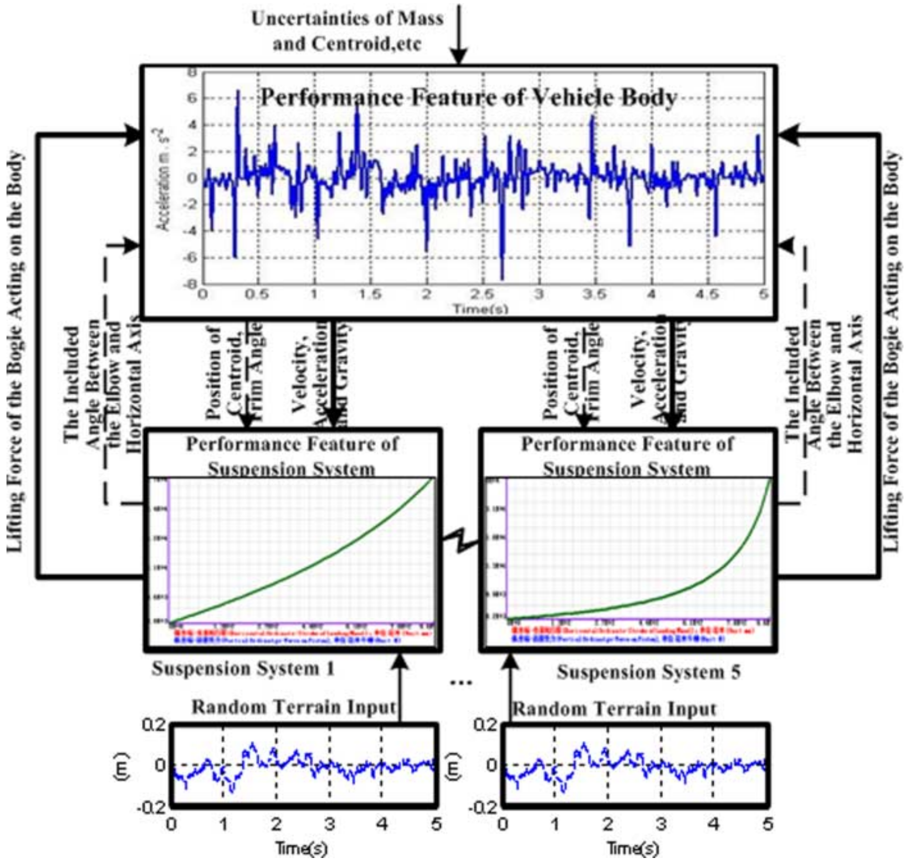


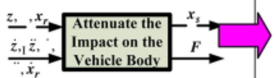
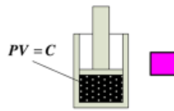
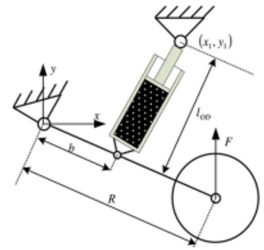
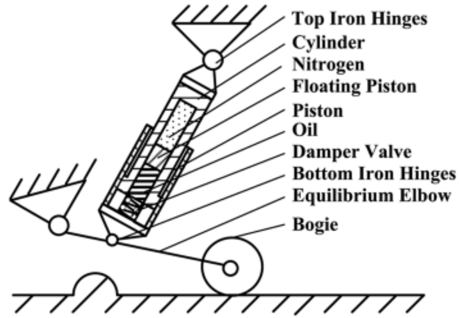
Figure 10. Performance evolution pattern in suspension system design process.

So in order to make these intervals compatible, it is necessary to determine their respective bounding values in a separate way, and design experts have the heuristic knowledge to decide whether these design variables' range are compatible and acceptable before the performance models are merged. Therefore, according to the five evaluation factors listed in Figure 6, the common choice of the first-decoupling-then-coupling transformation strategy is finally adopted for this problem because, for these performance modules, the availability of design information is low, interface parameters have nonlinear function relationship, coupling strength between them is strong, solvability of models is good and uncertainty sensitivity is high.

5.4. *Decoupled process*

Because the balanced bogie strokes and trim angle should be first determined to set the initial values for the riding smoothness model, nonlinear Equations (5)–(7) are solved using Newton–Raphson method. Figure 11 shows the distributions of the resultant lift force, and the gravity, and the resultant moment of the former two forces when the vehicle has -0.1 m horizontal offset of centroid (suppose the range of the horizontal offset of centroid is $[-0.1\text{ m}, 0.1\text{ m}]$, this range is actually larger than the permissible offset value limit). Here, we only take the lower bound offset value of the centroid into consideration because the absolute value of the offset of centroid has a monotone increasing influence on the maximum acceleration of the vehicle body. It can be

Table 2. Performance evolution of hypo-pneumatic spring.

Required Function	Selected Physical Effect	Working Principle or Structure	Actual Structure or Condition[a]
 The impact is caused by the random terrain input.	 State equation of gas is selected as the effect.		
Specifications	**Desired Performance**	**Predicted Performance[b]**	**Actual Performance**
The maximum vertical acceleration at the driver's seat should not exceed 1g at the speed of 20 m/s on the E-class road surface. (It should be pointed out that the attenuation effect is also closely related to the damping performance of the suspension system, but to make the problem simpler, we just consider the hypo-pneumatic spring here)	The riding smoothness could be converted into the lifting force and the damping force of the suspension system. $p = p_0 \frac{V_0}{V}$ (8) $F = p \cdot A$ (9)	$b = R / leverRatio$ (10) $l_{OD} = \frac{b[x_1 \sin({}_s - {}_c) + y_1 \cos({}_s - {}_c)]}{\sqrt{[y_1 + b\sin({}_s - {}_c)]^2 + [b\cos({}_s - {}_c) - x_1]^2}}$ (11) $p = p_0\left(1 - \frac{s_i}{h_0}\right)^{-1}$ (12) $L_{max} = \sqrt{[x_1 - b\cos({}_0 - {}_c)]^2 + [y_1 + b\sin({}_0 - {}_c)]^2}$ (13) $l = \sqrt{[x_1 - b\cdot\cos(- {}_c)]^2 + [y_1 + b\cdot\sin(- {}_c)]^2}$ (14) $s_i = L_{max} - l$ (15) $x_{si} = R(\sin {}_0 - \sin\ )$ (16) $F = p \cdot A \cdot l_{op} / (R \times \cos\ )$ (17)	$b = R / leverRatio$ (10) $l_{OD} = \frac{b[x_1 \sin({}_s - {}_c) + y_1 \cos({}_s - {}_c)]}{\sqrt{[y_1 + b\sin({}_s - {}_c)]^2 + [b\cos({}_s - {}_c) - x_1]^2}}$ (11) $p = p_0\left(1 - \frac{s_i}{h_0}\right)^{-m}$ (18) $L_{max} = \sqrt{[x_1 - b\cos({}_0 - {}_c)]^2 + [y_1 + b\sin({}_0 - {}_c)]^2}$ (13) $l = \sqrt{[x_1 - b\cdot\cos(- {}_c)]^2 + [y_1 + b\cdot\sin(- {}_c)]^2}$ (14) $s_i = L_{max} - l$ (15) $x_{si} = R(\sin {}_0 - \sin\ )$ (16) $F = p \cdot A \cdot l_{op} / (R \times \cos\ )$ (17)

[a]The actual working condition of the hypo-pneumatic spring includes the elimination of heat produced in the reciprocating motion of the piston, and the temperature change makes the transition of gas state different from the case of the constant temperature environment; so an expanded model of gas pressure versus volume is generated as Equation (13) by adding the polytrophic exponent of the gas m to Equation 12. And this exponent can be 1.2–1.4.

[b]It can be seen that the output force F is the nonlinear function of the stoke of the bogie x_{si} because of geometrical relationship, and the nonlinearity is further strengthened by the nonlinear physical characteristic of the gas state equation in the motion of piston.

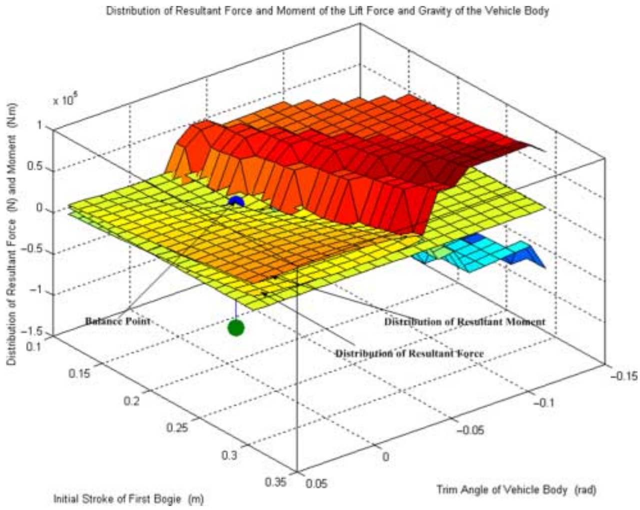


Figure 11. Distribution of resultant force and moment with −0.1 m horizontal offset of centroid.

seen that the trim angle and the bogie stroke is very sensitive to the centroid offset. Considering that the main goal of the decoupled solving process is to obtain the upper and lower bounds of each design variable of the suspension system, a process model is built to facilitate the flow of design information and regulate the sequence of design tasks according to the above performance equations (Figure 12). Each design activity node driven by the process engine is carried out by one design resource, and these resources' main purpose is to provide the initial and bounding intervals for the last optimisation node in addition to finding feasible design examples.

5.5. *Coupled process for verification and comparison of results*

After the solving technique for this nonlinear ordinary differential equations model is established, the designer can obtain the optimal riding smoothness performance of the vehicle as well as the structure parameters related to the hypo-pneumatic spring through the use of an optimisation package. It should be pointed out that the results obtained through the previous decoupled method play an important role in the current coupled optimisation process because on one hand, they give

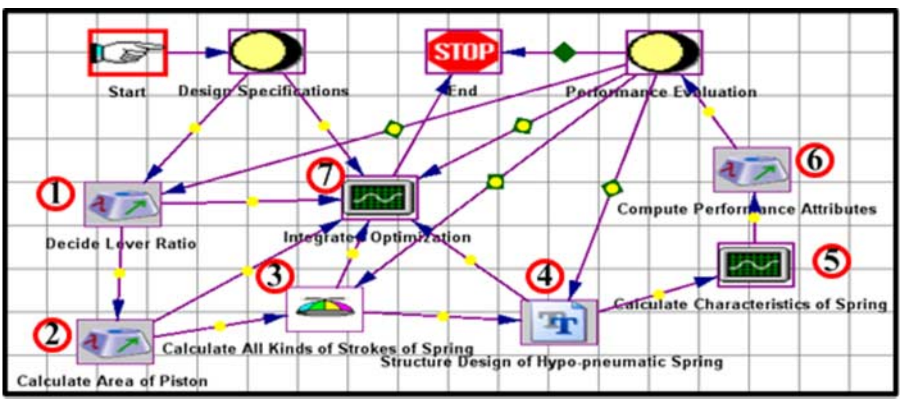


Figure 12. Design process model to facilitate the execution of first-decoupling-then-coupling solving strategy.

the starting point for optimisation, and on the other hand, they set a feasible variation interval for each design variable. Usually it takes a lot of time to finish the whole optimisation process since the time-consuming simulation is involved in each iteration, and non-gradient-based optimisation algorithm has to be adopted because differentiation is impossible; therefore the starting point and the value bounds for each design variable are critical for the algorithm to find the most optimum result. Before optimisation, the maximum value of the vertical acceleration at the driver's seat is $2.9\,\text{m/s}^2$ if there is no horizontal offset of centroid (Figure 13), and the maximum absolute value is $6.3\,\text{m/s}^2$ with -0.1 m horizontal offset of centroid (Figure 14), which is also less than the permissible value of 1 g. It is obvious that the displacement at the driver's seat without the horizontal offset of centroid is much less than that with -0.1 m offset. After optimisation, the maximum acceleration at the driver's seat is $2.7\,\text{m/s}^2$ if there is no offset (Figure 15) and the value will be $4.1\,\text{m/s}^2$ with -0.1 m horizontal offset (Figure 16). It can be seen that the initial

Figure 13. Simulation of nonlinear and coupled riding smoothness model based on the initial parameter values without considering the offset of centroid (separated design results).

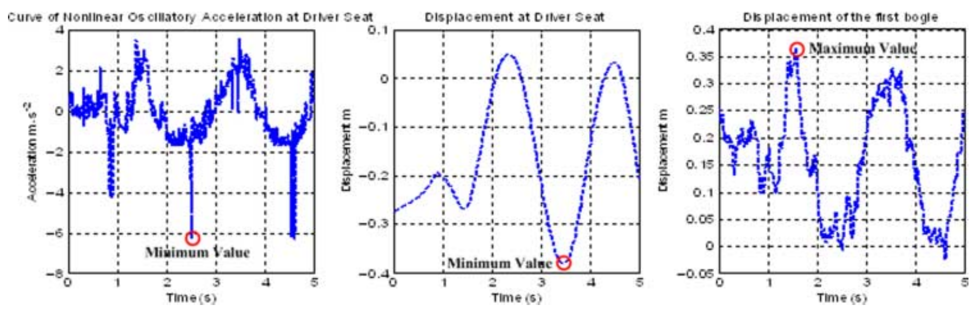


Figure 14. Simulation of nonlinear and coupled riding smoothness model based on the initial parameter values with the -0.1 m horizontal offset of the centroid (separated design results).

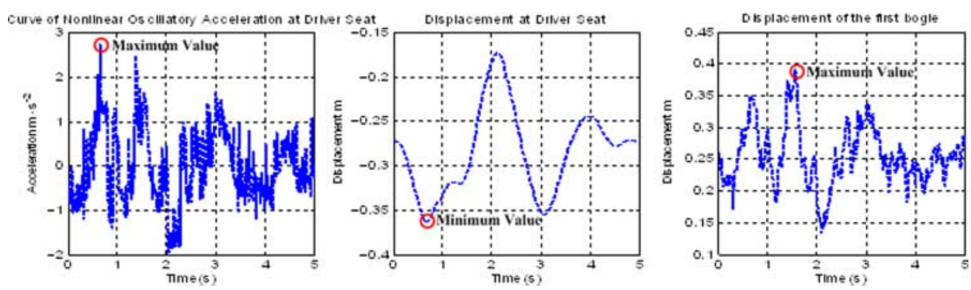


Figure 15. Simulation of nonlinear and coupled riding smoothness model based on the optimum parameter values without considering the offset of centroid (integrated optimal design results).

Figure 16. Simulation of nonlinear and coupled riding smoothness model based on the optimum parameter values with −0.1 m horizontal offset of centroid (integrated optimal design results).

value provided by the decoupled solving process for the integrated coupling optimisation activity is close to the optimum point. The maximum absolute values of displacement at the driver seat and displacement of the first bogie also show the above characteristics, and this can be analysed according to Figures 13–16.

6. Conclusion

To date, many researchers have discussed how to handle design coupling. Multi-disciplinary optimisation is a typical method to solve loosely coupled design problems (Balling and Sobieszczanski-Sobieski 1996), and sensitivity analysis and integrated optimisation are often used to facilitate making decisions for close-coupled design problems (Sobieszczanski-Sobieski 1990). All these methods focus on performance models that will not change during the solving process. There is few research works that deal with performance model evolution, especially at the early stages of complex product design. Cases of tightly coupled or loosely coupled design problems have not been distinguished. In this paper, we propose a performance coupling classification method based on the performance feature of coupled performance models, and summarise performance evolution patterns at systematic and componential levels. This paper also presented the reasons for performance coupling and put forward some model-transformation-based strategies for evolutionary performance coupling. The contributions of the paper can be concluded as follows:

(1) Classification of modular or componential and systematic performance evolution patterns. They evolve along the phases of product physical effect design (desired performance model), working principles and structure design (expected performance model) and actual structure design (actual performance model). Systematic performance evolution has qualitative and synthetic function-driving and quantitative interface-match-driving patterns. Potential performance coupling can be detected by analysing the loop of energy, information and material flows through the product function blocks at the early design stage of complex engineering design process.
(2) Four kinds of strategies, that is, decoupling transformation, coupling transformation, first-decoupling-then-coupling transformation and first-coupling-then-decoupling transformation strategies, are presented to handle different cases of evolutionary performance couplings. Selection of resolving strategy to handle the potential performance coupling is proposed based on the qualitative analysis of uncertainty propagation sensitivity, performance interface and coupling strength, solvability of coupled performance model and availability of design information.

(3) A real design case study of suspension system design. It shows that the proposed method can speed up the design process and obtain the satisfactory results for required performance goals with the specification uncertainties. The computer-aided design tools for the suspension system design reduce a lot of designer's workload to find the optimal design solutions. The working time needed for solving this problem is reduced up to 60%.

The method of selecting coupling resolving strategy proposed in this paper can be widely used in the performance-driven multidisciplinary concept design of complex product. In order to facilitate the application of four resolving strategies, especially for the first-decoupling-then-coupling and first-coupling-then-decoupling strategies, it is necessary for designers to build a performance solving process model, so that the strategy can be executed smoothly. Although designers may spend some time preparing the necessary performance models and design data at the beginning of the analysis process, the most satisfactory design results can be obtained more effectively and quickly if designers adopt an appropriate strategy, and set reasonable initial design values and variable value ranges for the integrated performance optimisation. Future work can be focused on the research of generating performance models automatically based on the modelling of available common physical effects and mechanisms and the related working principles and structures for quickly actualising the required design functions. By doing so, designers' quality of work can be further improved and the workload reduced.

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Note

1. To preserve confidentiality of the product, detailed specification variable values have been omitted.

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