EVS24
Stavanger, Norway, May 13-16, 2009

An Optimization Approach to Hybrid Electric Vehicle Preliminary Design

CHEN Xiao-kai, CHEN Yong, HE Hong-wen
Beijing Institute of Technology, Beijing, 100081, P.R. China. Email:chenxiaokai@263.net

Abstract

This presentation evaluates the contribution of Analytical Target Cascading in hybrid electric vehicle preliminary design. The preliminary design problem was formulated as a two-level design problem: vehicle level and subsystem level. At the vehicle level, the main parameters of engine, driving motor, battery, and transmission were determined by solving a multi-objective constrained optimization problem. At the subsystem level, the gear parameters of the transmission and final drive were gotten to make the ratios of transmission and final drive as close to the target values cascaded from vehicle level as possible. The results show that the vehicle performance and subsystem level design can be optimized currently; the optimization method in preliminary design can offer design insights in an effective way.

Keywords: Hybrid Electric Vehicle, Analytical Target Cascading, Optimization, Preliminary Design

1 Introduction

Proper preliminary design and control strategy of a hybrid electric vehicle is critical in achieving high over efficiency and maintaining performance. Multidisciplinary Design Optimization is a methodology for the design of complex, interdependent systems that is growing in popularity for use in the early phases of vehicle design [1]. The conceptual and preliminary design phases are particularly well suited to the application of MDO.

Analytical Target Cascading (ATC) is an optimization design framework of multidisciplinary, multi-level, and is developed on the basis of collaborative optimization for the needs of automotive engineering applications [2]. Compared with other multidisciplinary design optimization methods, ATC has better convergence [3]. In this paper, a hybrid electric vehicle optimization problem was used to demonstrate the optimization approach in vehicle preliminary design.

2 Theory of Analytical Target Cascading

According to a certain partition strategy, the original complex system can be decomposed into a hierarchical structure.

2.1 General Description of ATC Framework

In ATC, the initial objectives and the constraints are partitioned into several sub-problems in lower level. The optimization objective in a certain level is to achieve the least deviation between the upper and lower level. There are two types model in the ATC architecture: Optimization Design Model P and Analytical Model r.

The general description of ATC framework [4] is shown in Fig.1.

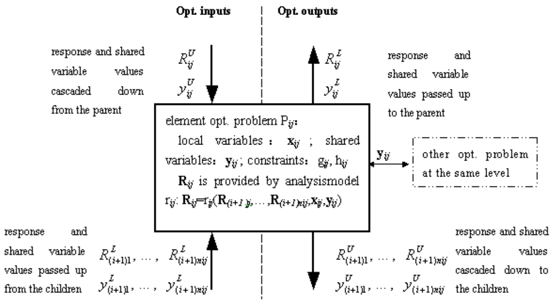

Figure1: ATC information flow at P_{ij}

2.2 General Formulation of ATC

The mathematical formulation [5] of problem P_{ij} for element j at level i is

$$\begin{cases} P_{ij}: \text{Minimize } w_{ij}^{R}\left\|R_{ij}-R_{ij}^{U}\right\|+w_{ij}^{y}\left\|y_{ij}-y_{ij}^{U}\right\|+\varepsilon_{\mathbf{R}}+\varepsilon_{\mathbf{y}}, \\ \text{respect to, } \tilde{\mathbf{x}}_{ij},\mathbf{y}_{ij},\mathbf{y}_{(i+1)j},\mathbf{R}_{(i+1)j},\varepsilon_{\mathbf{R}},\varepsilon_{\mathbf{y}}, \\ \text{where, } \mathbf{R}_{ij}=r_{ij}(\mathbf{R}_{(i+1)j},\tilde{\mathbf{x}}_{ij},\mathbf{y}_{ij}), \\ \text{subject to,} \\ \quad w_{(i+1)j}^{R}\left\|\mathbf{R}_{(i+1)}-\mathbf{R}_{(i+1)}^{L}\right\|\le\varepsilon_{\mathbf{R}}, \quad w_{(i+1)j}^{y}\left\|\mathbf{y}_{(i+1)}-\mathbf{y}_{(i+1)}^{L}\right\|\le\varepsilon_{\mathbf{y}}, \\ \quad g_{ij}(\mathbf{R}_{ij},\tilde{\mathbf{x}}_{ij},\mathbf{y}_{ij})\le 0, \\ \quad h_{ij}(\mathbf{R}_{ij},\tilde{\mathbf{x}}_{ij},\mathbf{y}_{ij})=0, \\ \quad \tilde{\mathbf{x}}_{ij}^{\min}\le\tilde{\mathbf{x}}_{ij}\le\tilde{\mathbf{x}}_{ij}^{\max}, \quad \mathbf{y}_{ij}^{\min}\le\mathbf{y}_{ij}\le\mathbf{y}_{ij}^{\max}. \end{cases} \tag{1}$$

Where, $\boldsymbol{R}$ is response provided by analysis model; $\boldsymbol{R}^{U}$ is response values cascaded down from the parent; $\boldsymbol{R}^{L}$ is response values passed up from the children; $\boldsymbol{y}$ is shared variable with other opt. problems at the same level; $\mathbf{y}^{U}$ is shared variable values cascaded down from the parent; $\mathbf{y}^{L}$ is shared variable values passed up from the children; w is the deviation weighting coefficient; ε_{R} is the response deviation tolerance variable; ε_{y} is the linking deviation tolerance variable; $\tilde{\boldsymbol{x}}$ is local variables; $\tilde{\boldsymbol{x}}^{\min}$ is the lower boundary; $\tilde{\boldsymbol{x}}^{\max}$ is the upper boundary; r is the analysis models; g is the inequality constraints; h is the equality constraints.

3 Demonstration of Hybrid Electric Vehicle Design

3.1 Design Tagets

To a HEV preliminary design, the max velocity, 0~100km/h acceleration time, energy consumption of driving cycle, and other design requirements were chosen to be the optimization targets.

3.2 Design Variables

The main parameters of engine, driving motor, battery, and transmission are chosen to be the design variables of the multi-objective constrained optimization problem on the vehicle level. The gears' parameters of the transmission and final drive are chosen to be the design variables on the subsystem level.

3.3 Design Constraints

Design constraints including the design variables of the possible range and other parameters or performance restrictions of vehicle and subsystems.

4 Model Description Based on ATC

In accordance with the theory of ATC, partition the overall vehicle optimization program into two-level design problem. Vehicle level (vehicle dynamic characteristics and energy consumption) and subsystem level (the optimization design of transmission and final drive gears), as shown in Fig. 2.

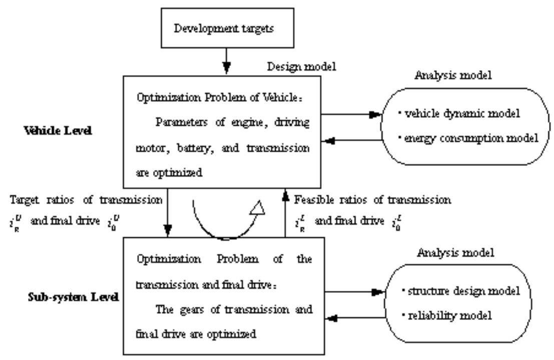

Figure2: Model framework based on ATC

4.1 Optimization Problem of Vehicle Level

In system lever, system optimization problem can be described as equation (2).

$$\begin{cases} P_{v}: \text{Minimize}\left\|w_{v\,i}\circ(R_{vi}-T_{i})\right\|_{2}^{2}+\varepsilon, \\ \text{respect to, } \mathbf{x}_{v},\varepsilon, \\ \text{where, } \mathbf{R}_{v}=r_{v}(\mathbf{x}_{v},R_{s}), \\ \text{subject to,} \\ \quad \left\|i_{0}-i_{0}^{L}\right\|\le\varepsilon, \\ \quad g_{v}(\mathbf{R}_{v},\mathbf{x}_{v})\le 0, \\ \quad h_{v}(\mathbf{R}_{v},\mathbf{x}_{v})=0, \\ \quad \mathbf{x}_{v\min}\le\mathbf{x}_{v}\le\mathbf{x}_{v\max}. \end{cases} \tag{2}$$

4.2 Optimization Problem of Subsystem Level

In subsystem level, system optimization problem can be described as equation (3).

$$\begin{cases} \mathrm{P_s}: \mathrm{Minimize} \left\| w_s \circ (i_s - i_0^U) \right\|_2^2, \\ \text{respect to,} \quad \mathbf{x}_s, \\ \text{where,} \quad i_s = r_s(\mathbf{x}_s), \\ \text{subject to,} \\ \qquad g_s(\mathbf{R}_s, \mathbf{x}_s) \le 0, \\ \qquad h_s(\mathbf{R}_s, \mathbf{x}_s) = 0, \\ \qquad \mathbf{x}_{s\min} \le \mathbf{x}_s \le \mathbf{x}_{s\max}. \end{cases} \quad (3)$$

5 Vehicle Description And Modelling

A Hybrid Electric Vehicle is selected in this article to demonstrate the implementation of the target cascading process. Vehicle dynamic and economic performance are the most fundamental properties, dynamic performance effects vehicle transport efficiency and cost, while the economic impact the cost of automobile use and the country's dependence on oil and vehicle emissions. While the important distinction between electric vehicles and traditional vehicles lies in its regenerative braking, it can change on part of kinetic energy to other forms of energy storage or use it continued to increase the mileage driven. This process usually through the method of takes pulling motor as generator to charges the battery.

In terms of hybrid vehicle, the most fundamental influence factors of dynamic and economic performances and regenerative braking performance are characteristics of engine and motor, transmission, control strategies, degree of mixing and the performance and number of battery. The location and the mass of the battery affect the wheelbase. So, it can affect the dynamic performance. While the dynamic performance affect the safety and comfort of the passenger. Thus, it is the most important target of the modern vehicle optimization.

The performance index and the target of the optimization design of the accelerate performance, economic performance and dynamic performance as shown in table 1.

Table 1: Original performance and opt. targets

	Original performance	Optimize targets
T_1: V_{max}(m/s)	176	180
T_2: t_{min}(s)	11	9
T_3: α_{max} (%)	33	35
T_4: E (kWh)	42	35
T_5: K	0.0034	0.0035
T_6: f_f(Hz)	1.02	1.2
T_7: f_r(Hz)	1.79	1.8
T_8: f_p(Hz)	1.75	1.8

5.1 Vehicle-Level model

5.1.1 Optimization model at the vehicle level

The design model of vehicle level is:

$$\min f = \sum_{i=1}^{8} w_i (v_i - T_i)^2 + \varepsilon_1 + \varepsilon_2$$

respect to, $\mathbf{x}_v, \varepsilon_1, \varepsilon_2$

subject to,

$$i_{0lo} \le i_0 \le i_{0up}$$
$$i_{li} \le i_{gi} \le i_{ui} (i \in (1,2,3,4,5))$$
$$b_{lo} \le b \le b_{up}$$
$$n_{lo} \le n \le n_{up}$$
$$P_{lo} \le P \le P_{up}$$
$$\lambda_{lo} \le \lambda \le \lambda_{up}$$
$$soctar_{lo} \le soctar \le soctar_{up}$$
$$(i_0 - i_0^L)^2 - \varepsilon_1 \le 0$$
$$\sum_{i=1}^{5} (i_{gi} - i_{gi}^L)^2 - \varepsilon_2 \le 0$$

5.1.2 Analysis model at the vehicle level

The analysis model of vehicle level is:

$$v = 0.377 \frac{nr}{i_0 i_g}$$

$$t = \frac{\delta m}{3.6} \int_{u_1}^{u_2} \frac{du}{\frac{3600 P_P \eta}{u} - mgf - \frac{C_D A u^2}{21.15}}$$

$$\alpha = \tan(\arcsin((\frac{M i_g i_0 \eta}{r} - \frac{C_D A u^2}{21.15}) / mg\sqrt{1+f^2}) - \arctan(f))$$

$$E = \int_0^T P_r dt + E(P_{fc}, n_{fc})$$

$$K = \frac{m}{L^2}\left(\frac{a}{k_2} - \frac{b}{k_1}\right)$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{K_f \cdot a^2 + K_r \cdot b^2}{2m}}$$

$$f_f = \frac{1}{2\pi}\sqrt{\frac{K_f \cdot L}{m \cdot b}}$$

$$f_r = \frac{1}{2\pi}\sqrt{\frac{K_r \cdot L}{m \cdot a}}$$

Where, i_{gi}^L is a optimization value from subsystem level. $w_i\,(i = 1,2,3,4)$ is the relative importance weight coefficient between response or linking variables and target; ε is the deflection (an additional design variable); i_0^L is a optimization value from subsystem level; λ is the mixed degree; E is the engine energy consumption.

5.2 Final drive design sub-problem

5.2.1 Optimization model

The design model of final drive is:

$$\min R = (i_0 - i_0^U)^2$$

respect to, z_0, c_0

subject to,

$$i_{0lo} \le i_0 \le i_{0up}$$

$$z_{0lo} \le z_0 \le z_{0up}$$

$$c_{0lo} \le c_0 \le c_{0up}$$

5.2.2 Analysis model

Analysis model of final drive gears is:

$$i_0 = \frac{c_0}{z_0}$$

Where, i_0^U is the optimization value of final drive from the system level； z_0 is the tooth number of driving gear; c_0 is the tooth number of driven gear.

5.3 Transmission design sub-problem

5.3.1 Optimization model

The design model of transmission is:

$$\min R = \sum_{i=1}^{5} (i_{gi} - i_{gi}^U)^2$$

respect to, z_i, c_i

subject to,

$$A_i = \frac{m_{ni}\left(z_i + c_i\right)}{2\cos\beta_i} = const$$

$$i_{gilo} \le i_{gi} \le i_{giup}$$

$$z_{ilo} \le z_i \le z_{iup}$$

$$c_{ilo} \le c_i \le c_{iup}$$

$$(i \in (1,2,3,4,5))$$

5.3.2 Analysis model

Analysis model of the transmission is:

$$i_{gi} = \frac{c_{gi}}{z_{gi}}$$

Where, i_{gi}^U is the optimization value of vehicle level; z is the tooth number of driving gear; c is the tooth number of driven gear; β is the spiral angle; m_n is the modulus.

6 Model Solution And Results Discussion

6.1 Process Relization

The optimal and analysis models were built in Matlab. In order to ensure reliable results, with the exception of the design variables, the other variables of the model in line with the prototype vehicle. Based on the theory of ATC, build optimization process in iSIGHT software environment and specify the parameters and design variables. Designed optimization process can automatically call in analytical model according to the need and the corresponding amendments to the model input and output files.

6.2 Selection of Optimization Algorithm

Combination of optimization strategies was used to improve the optimization results and computational effort. For the system level optimization problem, the combination algorithm of Adaptive Simulated Annealing and Generalized Reduced Gradient was adopted; for the transmission gears optimization design problem, combination algorithm of Multi-Island Genetic Algorithm and Sequential Quadratic Programming was used. By Adaptive Simulated Annealing and Multi-Island Genetic Algorithm for the initial optimization, get the better optimization results as the initial value of the Generalized Reduced Gradient and Sequential Quadratic Programming.

6.3 Results Discussion

The optimisation results are shown in table 2.

Table 2: Optimization results

Parameter	Initial value	Final value
i_0	3.77	3.92
i_{g1}	3.57	3.65
i_{g2}	2.01	2.32
i_{g3}	1.33	1.37
i_{g4}	1.00	1.00
i_{g5}	0.75	0.74
n_0	3000	3160
P	100	109
b	61	51
lx	0.5	0.82
λ	0.35	0.45
soctar	0.8	0.65
V_{max}	176	185
t_{min}	11	8.8
α_{max}	33	39
E	42	34
K	0.0034	0.0035
f_f	1.02	1.26
f_r	1.79	1.89
f_p	1.75	1.91

From the table, it can be seen that all of the performance meet the requirement of design targets; economic performance have greatly improved by 19%. Taking into account the time cost and the complexity of the optimization problems, we only optimized the basic parameters of the motor, drive system, the location and number of the battery. If taken into account more parameters of the vehicle, then the indicators of accelerate performance and economic performance can be improved further.

7 Conclusion

To introduce the simulation-based optimization approach, a hybrid electric vehicle preliminary design was used to demonstrate. The preliminary design problem was formulated as a two-level optimization problem: vehicle level and subsystem level. The application shows that: The application of analytical target cascading optimization approach can realize the optimization of the vehicle performance and subsystem level design currently. Besides the time of simulation and analysis can be cut down sharply, the ability to utilize the model fully and extract from it useful design information rises observably.

Acknowledgments

This work is supported by the National “863” High-Tech Development Project of China under the grant No. 2006AA04Z119. The authors gratefully acknowledge the support. Such support does not constitute an endorsement by the funding agencies of the opinions expressed in the article.

References

[1] *Joseph P. Giesing and Jean-Francois M. Barthelemy. A summary of industry MDO applications and needs [C]. 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Septermber, 1998.*

[2] *Kim H. M., Kokkolaras M., Louca L., et al. Target cascading in vehicle redesign: a class VI truck study[J]. Journal of Vehicle Design. 2001, 29(3):1-27.*

[3] *Kim H M, Michelena N F, Papalambros P Y, et al. Target cascading in optimal system design [J]. ASME Journal of Mechanical Design, 2003, 125(3): 474–480.*

[4] *Michael Kokkolaras, Zissimos P. Mourelatos, Panos Y. Papalambros. Design Optimization of Hierarchically Decomposed Multilevel Systems Under Uncertainty[J]. Journal of Mechanical Design, MARCH 2006, Vol. 128, 503-508.*

[5] *Jeremy J. Michalek, Panos Y. Papalambros. Weights, Norms, and Notation in Analytical Target Cascading [J]. Journal of Mechanical Design, MAY 2005, Vol. 127, 499-501*

Authors

Dr. CHEN Xiao-kai, School of Mechanical Engineering, Beijing Institute of Technology (BIT), 5 Zhongguancun South Street, Haidian District, Beijing, P. R. of China, 100081; Phone:+86-010-68914070, Fax:+86-010-68940589, E-mail :chenxiaokai@263.net.

CHEN Yong, Doctoral candidate of School of Mechanical Engineering, Beijing Institute of Technology (BIT), 5 Zhongguancun South Street, Haidian District, Beijing, P. R. of China, 100081; Phone:+86-010-68914070, Fax:+86-010-68940589, E-mail : cheny121@163.com.

Associate Prof. Dr. HE Hong-wen, School of Mechanical Engineering, Beijing Institute of Technology (BIT), 5 Zhongguancun South Street, Haidian District, Beijing, P. R. of China, 100081; Phone & Fax:+86-010-68914842, E-mail :hwhebit@bit.edu.cn.