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DESIGN EVALUATION OF NO SPIN DIFFERENTIAL MODELS USING THE AXIOMATIC APPROACH

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ABSTRACT–Two No Spin Differential (NSD) models were benchmarked for a project of Dual-Use Technology. The Axiomatic approach is utilized to evaluate the designs of the models. The Independence Axiom is satisfied at the top level of design but not at the second level, which implies the design exhibits coupling and will admit design improvements. The detailed process of design evaluation is described. It is shown that it is possible to develop a unique and evolutionary NSD design by solving the problems that cause coupling within two models.

KEY WORDS : Axiomatic approach, Off-road vehicle, NSD, No spin differential, Design evaluation

1. INTRODUCTION

The Research and Development Support Program for Dual-Use Technology (DUT), a core technology used for the civil industry as well as the defense industry, can sharpen international competitiveness and strengthen national security. The Spin-up strategy is adopted for new development, and the Spin-off strategy is adopted for technology transfer between two industries (Dual Use Technology Center, 1995).

Due to difficulties of international technology transfer of military technology, all industrial needs had to be filled through imports despite the growing demand of No Spin Differential (NSD) in military industry. So the Ministry of Commerce, Industry and Energy (MOCIE) designated "NSD Development for Off-road Vehicles" as a Spin-up project of DUT in 1999, which led to the development of unique design and manufacturing technologies for NSD (Pyun *et al.*, 2003).

Reverse engineering was adopted to analyze and identify major parameters and their values of design and manufacturing for two different NSD models which have been used in two leading countries. Relevant information about patents was also analyzed. In particular, the Axiomatic approach (Suh, 1999) was employed for performing design evaluation of two models and evolutionary design based on the evaluated results. Design- and process-related variables of NSD components or parts were optimized by utilizing finite element analysis (FEA) and computer aided engineering (CAE) software so as to satisfy customer needs and requirements. Test methodology and criteria of NSD which can confirm the success of evolutionary design and manufacturing have also been developed using the results of the Axiomatic approach and optimization process. Test results are very positive regarding functional performance (Lee, 2000).

The detail process of the Axiomatic approach in evaluating conventional NSD products is described in this paper. How the results of analysis can be used to formulate evolutionary design is also discussed. In particular, the Axiomatic approach can prevent production problems early on during the design stage, thus resulting in huge cost- and time-saving for development. There are many cases utilizing the axiomatic approach for design evaluation, conceptual design, and evolutionary design. Table 1 shows some of them.

2. AXIOMATIC DESIGN

2.1. Axiomatic Approach

The 'body' Design or design process is defined as the task of mapping the relationship between and among the customer domain, functional domain, physical domain and process domain as illustrated in Figure 1. A design

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Table 1. Examples of axiomatic approach utilization.

Group	Application	Researchers
Design evaluation	Analyze advantages and disadvantages of existing design and seek for improving design	Moon *et al.*, 1999a, 1999b, 1999c; Kim *et al.*, 2001; Kang *et al.*, 2001; Lee and Park, 2000; Do, 1997
Conceptual design	Save time and money of total development by application at the stage of conceptual design	Lossack and Grabowski, 2000; Housmand and Jamshidnezhad, 2002; Sozo *et al.*, 2001; Suh, 1995
Evolutionary design	Discovery of improved, less coupled, or fully decoupled, designs	Cha and Moon, 2000; Lee, 2002; Liu and Soderborg, 2000; Hu *et al.*, 2002; Fery *et al.*, 2002

step can be broken down into the 'product design' that selects design parameters (DPs) satisfying functional requirements (FRs) of functional domain, and the 'process design' that determines optimal process variables (PVs) from among numerous available PVs satisfying the DPs of physical domain.

Axiomatic design is an analytical tool for choosing a 'better' one among two or more design alternatives during the product design stage and composed of two axioms.

- Axiom 1: Independence Axiom
- Axiom 2: Information Axiom

The essence of the Independence Axiom is to maintain the independence of functional requirements, and in particular, between the FRs and corresponding DPs, in order to decouple a design. The Independence Axiom is used mainly for design evaluation and evolutionary design. The Information Axiom is a form of Occam's rule: minimize the information content. That is, among all design alternatives satisfying the Independence Axiom, the design holding the least amount of data (I) compared to other alternatives is a better choice.

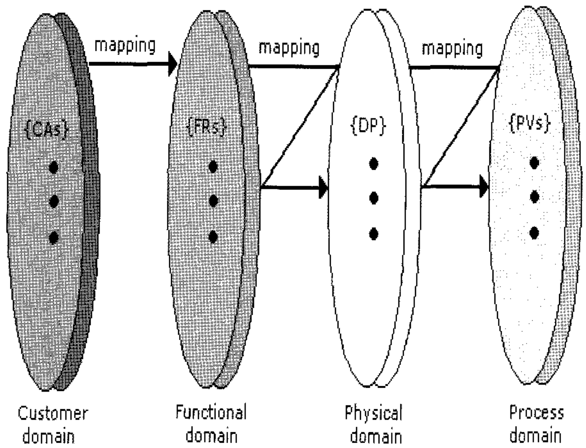

Figure 1. Design domains and mapping process.

The information value I can be defined as follow.

$$I = \log_2 1/P \text{ or } I = 1/P$$

where P is the probability of DP satisfying FR.

2.2. Design Matrix

The design matrix shown in Figure 2 can be used to quickly and accurately determine the relationship between FRs and DPs with regard to Independence Axiom, in particular, the extent of coupling or decoupling.

$$\{FRs\} = [A]\,\{DPs\} \qquad \{DPs\} = [B]\,\{PVs\} \qquad [A] = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix}$$

Figure 2. [A] and [B] are design matrices.

In the notation below, the matrix element *X* denotes closely related items and the element *O* denotes unrelated or loosely related items. As such, the design matrix becomes a simple means to verify functional independence.

$$[A] = \begin{bmatrix} X & O & O & O \\ O & X & O & O \\ O & O & X & O \\ O & O & O & X \end{bmatrix} \qquad [A] = \begin{bmatrix} X & O & O & O \\ X & X & O & O \\ X & X & X & O \\ X & X & X & X \end{bmatrix} \qquad [A] = \begin{bmatrix} X & X & X & X \\ X & X & X & X \\ X & X & X & X \\ X & X & X & X \end{bmatrix}$$

Uncoupled Decoupled Coupled

Figure 3. Structures of the design matrix.

As shown in Figure 3, the design matrix falls into the following three structure categories.`

(1) Uncoupled: a diagonal matrix, is most desirable as an uncoupled design satisfying the functionally independent axiom.
(2) Decoupled: a triangular matrix which is also a good design, however, it requires in advance the rearranging of DPs in proper order.
(3) Coupled: this is not a desirable design, because even after rearranging DPs into proper order, redundancy still remains, so improved or evolutionary design is needed

(Suh, 2001).

3. TOP LEVEL DESIGN EVALUTION FOR TWO NSD MODELS

When one wheel of normal differential looses traction force due to uneven road condition such as mud, snow, marsh, ditch, etc. the vehicle looses also driving force. But in the NSD installed axle, the opposite wheel of lost traction force does not slip and makes 100% traction force, so the vehicle can drive and escape from the uneven road. So NSD has been used widely in military trucks. The shape and structure of a typical NSD show in Figure 4.

In this section, a top level design evaluation is performed for the two NSD products using the Axiomatic approach in an effort to develop an objective understanding of problems and to seek solutions. First, FRs are identified to satisfy respective CAs, then corresponding DPs are set.

Table 2 below enumerates CAs for NSD as identified at the time of the designation by the MOCIE in 1999 of NSD as a DUT topic for "Research Project on NSD Development for Off-road Vehicles".

Table 3 shows FRs necessary for satisfying the CAs of Table 2. The FRs are based on the analysis and evaluation data generated by reverse-engineering two benchmarked samples.

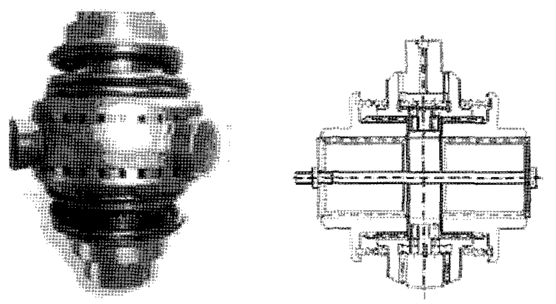

Figure 4. Picture and schematic drawing of a typical NSD.

Table 2. CAs of NSD.

CA_1	Speedy rotation
CA_2	Noise-free operation
CA_3	Swift escape

Table 3. FRs identification of NSD.

FR_1	Improved steerability (separation time: 8 sec. or shorter)
FR_2	Reduced noise (noise level: 90dB or less)
FR_3	Improved mobility (linkage time: 12 sec. or shorter)

The FRs are defined as follows:

- FR_1 – Improved steerability: When cornering or running on an uneven surface, the number of spins for wheels on one side must differ from that for the wheels on the other side. So it is important to improve steerability so as to minimize the turn radius by preventing outer wheels from skidding.
- FR_2 – Reduced noise: Internal NSD noise must be reduced to ensure quiet and pleasant driving.
- FR_3 – Improved mobility: It is important to improve mobility so as to help a vehicle escape quickly from bad road conditions by equalizing the wheels trapped in a puddle or a slough and the unaffected wheels on the other side in terms of torque.

Table 4 lists the DPs applied to satisfy the FRs, which also represent the objective of NSD design for two models.

The DPs are defined as follows:

- DP_1 – Holdout-ring structure: a design parameter for improving steerability to enable minimum-radius, skid-free spin through smooth engagement/separation of and precision control for NSD.
- DP_2 – Tooth-form profile: a design parameter greatly affecting noise generated during NSD engagement or separation.
- DP_3 – Operation mechanism: a design parameter that improves mobility to help a vehicle get off a bad road surface quickly.

The experts in manufacturers and customers who understand well about NSD requirement, function and system evaluated and confirmed each parameter of functional requirements, design parameters and the relationship between them

The holdout-ring structure (DP1) of both NSD has strong relationship with three elements of functional requirements; "improved steerability (FR1)", "reduced noise (FR2)", and "improved mobility (FR3)". The tooth form profile (DP2) of both NSD has very weak influence to "improved steerability (FR1), but strong influence to "reduced noise (FR2)", and "improved mobility (FR3)". The operational mechanism (DP3) of both NSD has strong influence to "improved mobility (FR3) only.

When the result of evaluation is summarized by using the structural layer advantage of the Axiomatic approach,

Table 4. DPs of NSD.

DP_1	Holdout-ring structure
DP_2	Tooth-form profile
DP_3	Operation mechanism

Table 5. Design matrix tuned for decoupling.

Functional Requirements	DP1 : Holdout Ring Structure	DP2 : Tooth Form Profile	DP3 : Operation Mechanism
FR1 : Improved Steerability	X	0	0
FR2 : Reduced Noise	X	X	0
FR3 : Improved Mobility	X	X	X

the design matrix of both NSD becomes a form of triangular matrix (see Table 5) and satisfies the Independence Axiom. The finding is not unexpected as it is based on the evaluation of products that have been used for decades.

4. THE SECOND LEVEL DESIGN EVALUATION FOR TWO NSD MODELS

The FRs and DPs are decomposed in a second level design, and are evaluated for steerability, noise and mobility.

4.1. NSD Design Eevaluation in Relation to Steerability

4.1.1. Decomposition for steerability

To keep the relationship between the top level FRs and the top level DPs, FR_1 is decomposed as follows:

- FR_{11} – Minimum turn radius: It is important to make a turn within the smallest radius possible during separation of NSD.
- FR_{12} – Speedy turn: It is desirable to minimize the time it takes for the turn during separation of NSD.
- FR_{13} – Smooth contact: Smooth contact between the center cam and the holdout ring during turning improves the steerability.
- FR_{14} – Improved turn receptiveness to turn: It is important to maximize receptiveness through precise control of differential during turning.

Similarly, DP_1 is decomposed as follows:

- DP_{11} – Spring: this greatly affects the process of minimizing turn radius by separating the NSD quickly when making a turn.
- DP_{12} – Minimum steering time: keeping steering time to minimum greatly affects turning speed.
- DP_{13} – Holdout-ring shape: the profile of tooth form affects contact strength between the center cam and the spider.

Table 6. Design matrix tuned for decoupling (Model A).

Functional Requirements	DP11 : Spring	DP12 : Steering Time	DP13 : Holdout Ring Shape(square)	DP14 : Number of Holdout Ring Teeth (4)
FR11 : Minimum Turn Radius	X	0	0	0
FR12 : Speedy Turn	X	X	X	X
FR13 : Smooth Contact	0	X	X	X
FR14 : Improved Turn Receptiveness	X	X	X	X

- DP_{14} – Number of holdout-ring teeth: tooth number synchronization vis-a-vis the center cam greatly improves receptiveness, thus effecting promptness of response.

4.1.2. Design evaluation in relation to steerability of the second level

Table 6 and Table 7 show the results of a design evaluation carried out for the two NSD models' steerability based on the aforementioned FRs and DPs.

As illustrated above, decoupling was performed to change the order of involved components. Numerous rounds of the order change, however, did not result in transformation into a decoupled design matrix. This confirms that it is possible to make improvements to the design for better fulfilling FRs.

4.2. NSD Design Evaluation in Relation to Noise of the Second Level

4.2.1. Decomposition for noise

The second level FRs and DPs for noise are decomposed to keep the relationship between the top level FRs and the top level DPs. The decomposition of FR_2 is as follows:

- FR_{21} – Simple structure: fewer parts and simpler design are required for reducing noise.
- FR_{22} – Refined surface precision: considering continuous interlocking of the teeth of various parts, including the spider, raising the precision level of tooth surface is crucial for noise suppression.
- FR_{23} – Smooth profile: noise should be minimized in consideration of the smooth profile of the clutch's tooth

Table 7. Design matrix tuned for decoupling (Model B).

Functional Requirements	DP11 : Spring	DP12 : Steering Time	DP13 : Holdout Ring Shape(trapezoid)	DP14 : Number of Holdout Ring Teeth(16)
FR11 : Minimum Turn Radius	X	0	0	0
FR12 : Speedy Turn	X	X	X	0
FR13 : Smooth Contact	0	X	X	X
FR14 : Improved Turn Receptiveness	X	X	X	X

form, which is easily separable and linkable.

- FR_{24} – Minimum friction: friction should be minimized since noise is generated by the rubbing and interference occurring during NSD operation.

Similarly, the decomposition of DP_2 is as follows:

- DP_{21} – Retainer structure: putting together the spring retainer and the side gear greatly simplifies overall structure.
- DP_{22} –Cam tooth surface processing: the roughness grade of the center cam's tooth surface greatly affects the level of noise.
- DP_{23} – Clutch tooth form: the tooth form of clutch has a significant effect on reducing noise generated while interacting with the center cam beside its smooth profile makes it easy to link.
- DP_{24} – Center cam tooth form: the smooth tooth form of the center cam greatly affects noise reduction by minimizing friction and interference.

4.2.2. Design evaluation in relation to noise of the second level

Table 8 and Table 9 show the results of a design evaluation carried out for the two NSD models' noise based on the aforementioned FRS and DPs.

As illustrated above, decoupling was performed to change the order of involved components. Numerous rounds of the order change, however, did not result in transformation into a decoupled design matrix. This confirms that it is possible to make improvements to the design for better fulfilling FRS.

Table 8. Design matrix tuned for decoupling (Model A).

Functional Requirements	DP21 : Retainer Structure (separable)	DP22 : Cam Tooth Surface Processing (powder metallurgy)	DP23 :Clutch Tooth Form (square)	DP24 : Center Cam Tooth Form (trapezoid)
FR21 : Simple Structure	X	0	0	0
FR22 : Refined Surface Precision	0	X	X	0
FR23 : Smooth Profile	0	X	X	X
FR24 : Minimum Friction	X	X	X	X

Table 9. Design matrix tuned for decoupling (Model B).

Functional Requirements	DP21 : Retainer Structure (unseparable)	DP22 : Cam Tooth Surface Processing (cold forging)	DP23 :Clutch Tooth Form(trapezoid)	DP24 : Center Cam Tooth Form (involute)
FR21 : Simple Structure	X	0	0	0
FR22 : Refined Surface Precision	0	X	0	X
FR23 : Smooth Profile	0	X	X	0
FR24 : Minimum Friction	X	X	X	X

4.3. NSD Evaluation in Relation to Mobility of the Second Level

4.3.1. Decomposition for mobility

The same analysis is now performed for mobility. The second level DPs for mobility are decomposed to keep the relationship between the top level FRS and the top level DPs. The decomposition of FR_3 is as follows:

- FR_{31} – Speedy movement: NSD activated by low RPM should escape from a swamp quickly.
- FR_{32} – Smooth operation: mobility should be improved through smooth and flawless NSD slipping.
- FR_{33} – Sufficient rigidity: attention must be paid to possible cracks at the spider and the clutch since severe deformation could result from external force experi-

enced suddenly when slipping on an uneven road surface.

- FR_{34} – Sufficient strength: as the clutch and the center cam operate along with the spider under highly repetitive cycle, they must be designed carefully to enhance durability, which is important for damage-free and reliable operation.

Similarly, the decomposition of DP_3 is as follows:

- DP_{31} – Movement time: a vehicle should move as quickly as possible to get out of a swamp. And speedy response greatly affects speedy movement.
- DP_{32} – Center cam structure: the form and width of the center cam do affect smooth and safe operation of NSD greatly.
- DP_{33} – Spider structure (rigidity/safety factor): the spider, which operates in synchro with the clutch, is crucial for safe driving without being deformed or destructed by sudden external force.
- DP_{34} – Clutch structure (rigidity/safety factor): the clutch, which operates frequently in synchro with the center cam, should not be vulnerable to damage or deformation in due consideration of its repetitive operation.

4.3.2. Design evaluation in relation to mobility of the second level

Table 10 and Table 11 show the outcome of a design evaluation performed for the two NSD models' mobility based on the aforementioned FRS and DPs. As illustrated above, decoupling was performed to change the order of involved components. Numerous rounds of the order change, however, did not result in transformation into a decoupled design matrix. This confirms that it is possible

Table 10. Design matrix tuned for decoupling (Model A).

Functional Requirements	DP31 : Movement Time	DP32 : Center Cam Structure(Narrow)	DP33 : Spider Structure(S: 1.5)	DP34 : Clutch Structure(S:1.5)
FR31 : Speedy Movement	X	X	O	O
FR32 : Smooth Operation	X	X	O	O
FR33 : Sufficient Rigidity	X	O	X	X
FR34 : Sufficient Strength	X	O	X	X

Table 11. Design matrix tuned for decoupling (Model B).

Functional Requirements	DP31 : Movement Time	DP32 : Center Cam Structure(wide)	DP33 : Spider Structure(S: 1.5)	DP34 : Clutch Structure(S:1.5)
FR31 : Speedy Movement	X	O	O	O
FR32 : Smooth Operation	X	X	O	O
FR33 : Sufficient Rigidity	X	X	X	X
FR34 : Sufficient Strength	X	X	X	X

to make improvements to the design for better fulfilling FRS.

5. EVALUATION FOR THE EXISTING NSD MODELS AND CONCLUSION

A design evaluation focusing on both top and the second level FRS and DPs was performed on two NSD models benchmarked based on the layer-structure advantage of the Axiomatic approach. The evaluation tells us that the design satisfies the Independence Axiom as a triangular matrix at the top level. But at the second level, the two design matrices, both being coupled in nature, do not satisfy the Independence Axiom. This leads to a conclusion that evolutionary design is indeed possible to better fulfill functional requirements. Problems identified through the design evaluation are as follows:

(1) If a vehicle is to make a turn or drive without skidding when running on a road surface that is extremely uneven, capability for contact smoothness and turn receptiveness should be improved through precise control of differential (e.g., same number of teeth for the holdout-ring and the center cam).

(2) It is necessary to reduce noise by adopting smooth profile of center cam/clutch tooth form and by improving surface roughness because the noise is generated from interacting of such elements.

(3) The greater the tooth-form width of the center cam is, the smoother the NSD operates. This helps a vehicle to get out of a swamp quickly through prompt NSD operation. And a simple structure is also needed to improve mobility through speedy linkage and separation.

It will be possible to develop a unique NSD design better in terms of performance and quality by applying solutions to deal with aforementioned problems carefully to existing DPs. This will be covered in a follow-up paper.

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REFERENCES

Cha, S. and Moon, Y. (2000). New vibration isolator made axiomatic approach. *1st Conf. Axiomatic Design*, 1–8.

Do, S. (1997). *Application of Design Axioms to the Design of Manufacturability for Television Glass Bulb*. Ph. D. Dissertation. Hanyang University. Korea

Dual Use Technology Center (1995). http://www dutc.re.kr/

Fery, D., Jahangir, E. and Engelhardt, F. (2000). Computing the information content of decoupled designs. *1st Conf. Axiomatic Design*, 151–160.

Houshmand, M. and Jamshidnezhad, B. (2002). Conceptual design of lean production systems through an axiomatic approach. *2nd Conf. Axiomatic Design*, 1–12.

Hu, M., Yang, K. and Taguchi, S. (2000). Enhancing robust design with the aid of TRIZ and axiomatic design. *1st Conf. Axiomatic Design*, 1–9.

Kang, Y., Hwang, Y., Cha, S. and Moon, Y. (2001). The development of tool for evaluating quantitative independency between FRS in axiomatic design. *J. KSPE* **18**, **3**, 122–130.

Kim, Y., Cho, K., Moon, Y. and Cha, S. (2001). Evolution methodology development of disassembly through axiomatic design. *J. KSPE* **18**, **4**, 197–202.

Lee, K. and Park, G. (2000). A structural optimization methodology using the independence axiom. *J. KSME* **24**, **10**, 2348–2450.

Lee, K., Yi, J., Lee, K. and Park, G. (2000). A structural optimization methodology using the independence axiom. *1st Conf. Axiomatic Design*, 145–150.

Lee, Y. (2002). *NSD Annual Project Report*. Dual Use Technology Center. 383–388.

Liu, X. and Soderborg, N. (2000). Improving an existing design based on axiomatic design principles. *1st Conf. Axiomatic Design*, 199–202.

Lossack, R. and Grabowski, H. (2000). The axiomatic approach in universal design theory. *1st Conf. Axiomatic Design*, 1–8.

Moon, Y., Cha, S. and Kim, Y. (1999a). Axiomatic approach for design appraisement and development DVD (I). *J. KSPE* **16**, **5**, 124–131.

Moon, Y., Cha, S. and Kim, Y. (1999b). Axiomatic approach for design appraisement and development DVD (II). *J. KSPE* **16**, **9**, 82–88.

Moon, Y., Cha, S. and Yoon, P. (1999c). Weight reduction in automobile design through axiomatic approach. *Trans. Korean Society of Automotive Engineers* **7**, **6**, 106–109.

Pyun, Y., Jang, Y., Lee, Y., Park, J. and Yea, J. (2003). A study on the development of no spin differential for an off-road vehicle. *Trans. Korean Society of Automotive Engineers* **11**, **6**, 127–133.

Sozo, V., Forcelline, F. and Ogliari, A. (2001). Axiomatic approach application during the product conceptual design phase. *Int. Conf. Mechanica*, 267–272.

Suh, N. (1995). Design and operation of large systems. *J. Manufacturing Systems* **14**, **3**, 203–213.

Suh, N. (1999). *The Principles of Design*. Oxford University Press, New York. 64–72.

Suh, N. (2001). *Axiomatic Design*. Oxford University Press, New York. 239–297.