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AN EVOLUTIONARY DESIGN OF NO SPIN DIFFERENTIAL USING THE AXIOMATIC APPROACH -- FOCUSING ON BETTER STEERABILITY

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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. New design parameters and process parameters for better steerability which satisfy the independent axiom are developed. How to obtain the optimal value of process parameter are presented with one case. Test methodology is developed and used to evaluate the newly developed sample. The test results on the steerability are very positive regarding functional performances.

KEY WORDS: axiomatic approach, off-road vehicle, NSD, no spin differential, evolutionary design, 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.

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.

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 was employed for performing design evaluation of two models and an 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.

Four papers about this research and development have been reported. This paper was prepared to describe how to utilize the axiomatixc approach effectively in evolutionary design.

2 TOP LEVEL DESIGN EVALUTION FOR TWO NSD MODELS

The 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, Functional requirements (FRs) are identified to satisfy respective Customers requirements (CRs), then corresponding Design parameters (DPs) are set.

Table 1 below enumerates CRs 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 1. CRs

CR_1	Speedy rotation
CR_2	Noise-free operation
CR_3	Swift escape

Table 2 shows the FRs necessary for satisfying the CRs of Table 1

Table 2. FR identification

FR$_1$	Better 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$_1$ – Better 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 roll radius by preventing outer wheels from skidding.
- FR$_2$ – Reduced noise
- FR$_3$ – Improved mobility

Table 3 lists the DPs applied to satisfy the FRs, which also represent the objective of NSD design for two models.

Table 3. DPs

DP$_1$	Holdout-ring structure
DP$_2$	Tooth-form profile
DP$_3$	Operation mechanism

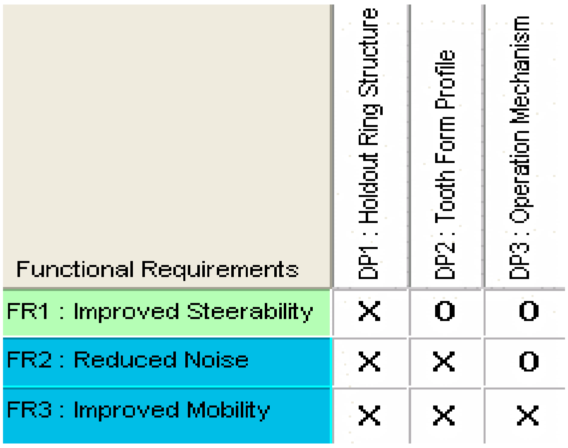
The DPs are defined as follows:

- 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
- DP$_3$ – Operation mechanism

A design evaluation was performed on the top level FRs and DPs of the two NSD models by using the structural layer advantage of the Axiomatic approach. The evaluation shows that the Independence Axiom is satisfied as a triangular matrix (see Table-4). The finding is not unexpected as it is based on the evaluation of products that have been used for decades.

Table 4. Design Matrix Tuned for Decoupling



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

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3 Design evaluation and improvement on better steerability

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

3.1 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 roll radius: It is important to make a roll within the smallest radius possible during separation of NSD.

- FR$_{12}$ – Speedy roll: It is desirable to minimize the time it takes for the roll during separation of NSD.
- FR$_{13}$ – Smooth contact: Smooth contact between the center cam and the holdout ring during rolling improves the steerability.

- FR$_{14}$ – Improved receptiveness to roll: It is important to maximize receptiveness through precise control of differential during rolling.

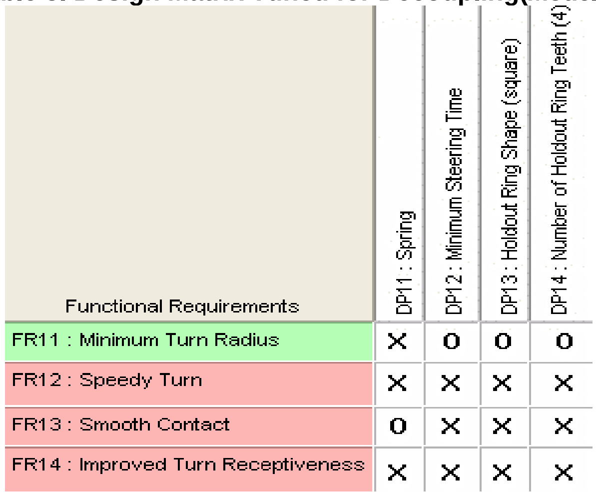
Similarly, DP$_1$ is decomposed as follows:

- DP$_{11}$ – Spring: this greatly affects the process of minimizing roll radius by separating the NSD quickly when making a roll.
- DP$_{12}$ – Minimum steering time: keeping steering time to minimum greatly affects rolling speed.
- DP$_{13}$ – Holdout-ring tooth form: the profile of tooth form affects contact strength between the center cam and the spider.
- DP$_{14}$ – Number of holdout-ring teeth: tooth number synchronization vis-a-vis the center cam greatly improves receptiveness, thus effecting promptness of response.

3.2 Design evaluation in relation to steerability of the second level

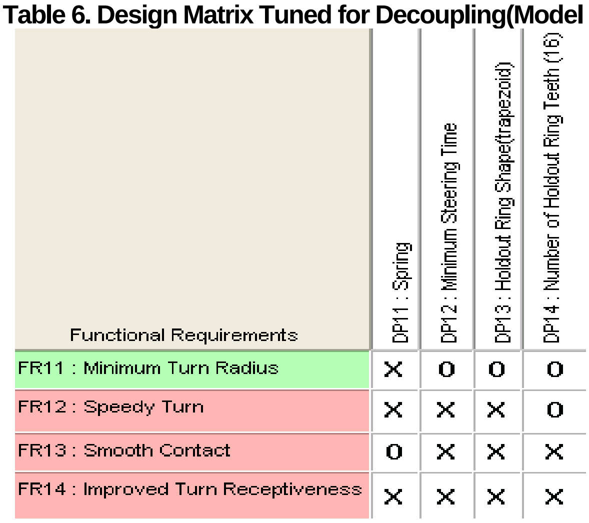
Table 5 and Table 6 show the results of a design evaluation carried out for the two NSD models' steerability based on the aforementioned FRs and DPs.

Table 5. Design Matrix Tuned for Decoupling(Model A)



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

Table 6. Design Matrix Tuned for Decoupling(Model B)



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

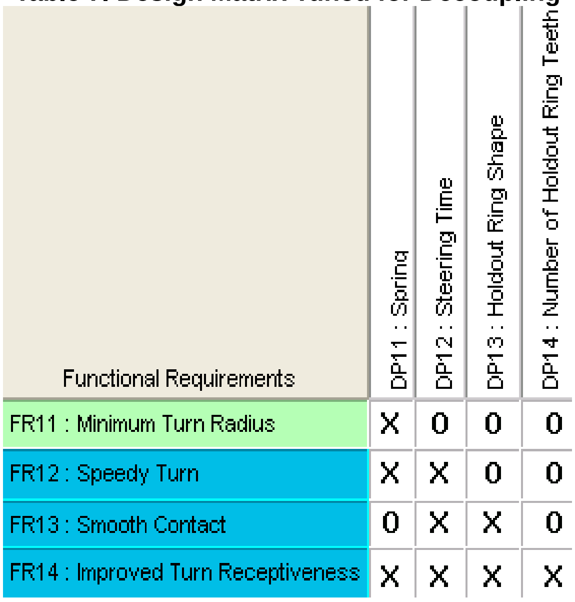
As illustrated above, decoupling was performed to change the order of involved components. Numerous rounds of the order change, however, did not result in transformation into a decoupled design matrix. This confirms that it is possible to make improvements to the design for better fulfilling FRs.

3.3. Modification of Design Parameters

The next step to make a decoupled design which can satisfy the Independence axiom is to modify the characteristics of the involved components and/or the involved components themselves. [8)-10)]

We modify the shape of the holdout ring (DP13) to be loosely related with the speedy turn (FR12) as in model B (Table 6), and the number of holdout ring teeth (DP14) to be loosely related with the smooth contact (FR13). A new design matrix results as shown in Table 7 which satisfies the Independence axiom.

Table 7. Design Matrix Tuned for Decoupling



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

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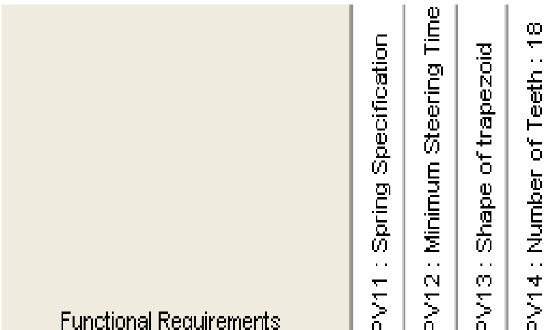
4 DETERMINING THE PROCESS PARAMETERS AND THEIR OPTIMAL VALUE

Process parameters (i.e., process variables or PVs) which satisfy DPs in the secondary level are developed. The design matrix which maps the relationship between DPs and PVs should be decoupled. Table 8 shows the result. CAE tools such as COSMOS, APM WinMachine, etc. are utilized for parameter optimization.

Four PVs are developed and tuned until the decoupling relationship with DPs is satisfied for steerability.

Table 8. Design Matrix Tuned for Decoupling



Functional Requirements	PV11 : Spring Specification	PV12 : Minimum Steering Time	PV13 : Shape of trapezoid	PV14 : Number of Teeth : 18

The most important PV for steerability is the spring force (PV11). The detailed process on how to obtain optimal value of the spring force (PV11) is as follows.

In order to minimize the turn radius (FR11), the driving clutch and the driven clutch should be engaged and disengaged properly by the role of the spring (DP11). So we have to determine optimal value of the spring specification (PV11) for engaging function and disengaging function.

For the disengagement, the spring force (F spring) must be weaker than the radial force (F radial) which is induced between the clutch cam of driven clutch and the center cam of driving clutch as shown in Fig.1. This function can be described by following equation.

$F_{Spring} < F_{Radial}$ (1)

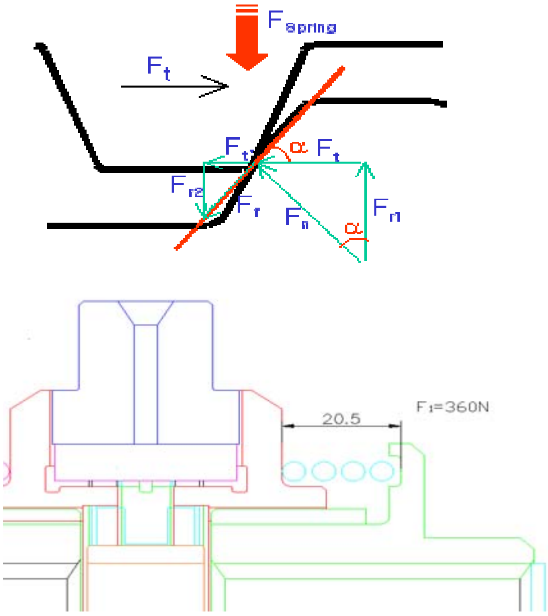


Fig. 1 The Force Diagram and spring length at the moment of disengagement.

The spring length at the moment of disengagement is determined as shown in Fig. 1. For engagement, the radial force (F radial) must be weaker than the spring force(F spring) which is induced between the clutch cam of driven clutch and the center cam of driving clutch as shown in Fig.2. This function can be described by following equation

$F_{Spring} > F_{Radial}$ (2)

The spring length at the moment of engagement is determined as shown in Fig. 2.

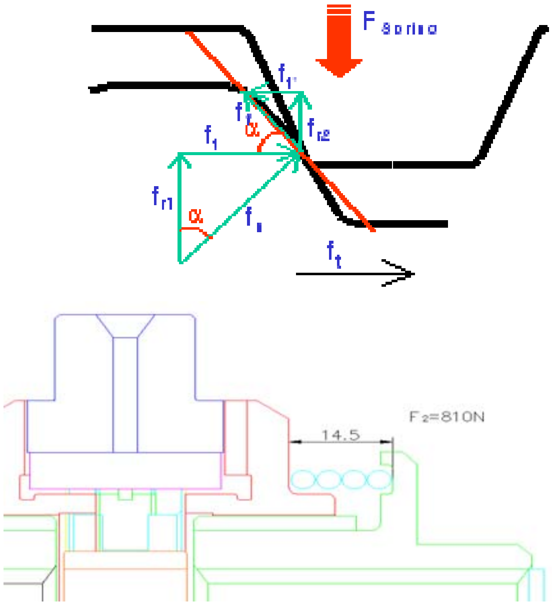
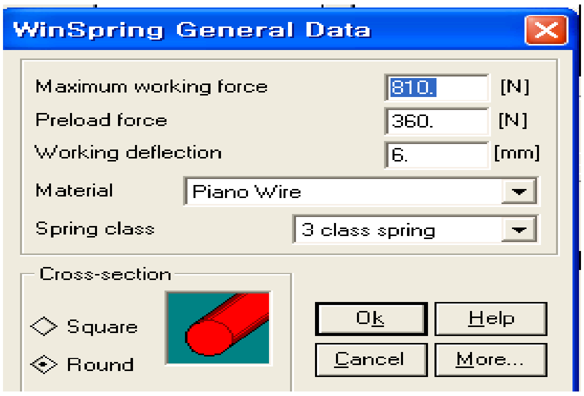


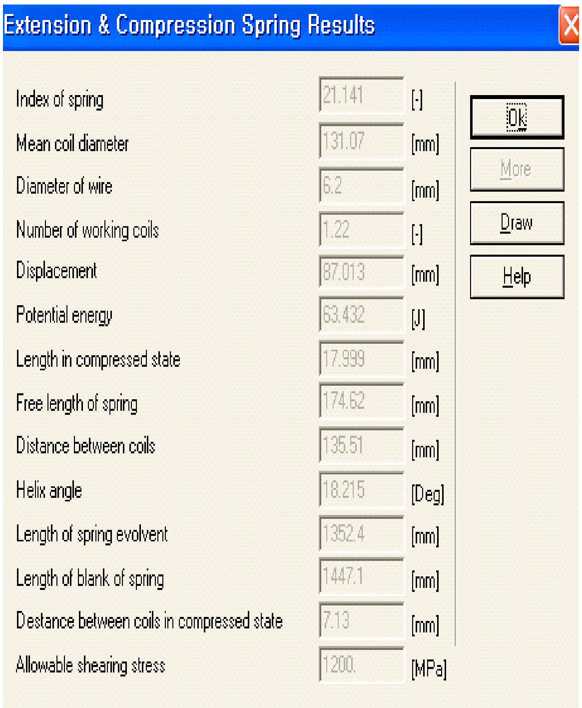
Fig. 2 Force Diagram and spring length at the moment of engagement.

In order to determine the spring force at the moment of disengagement and engagement, the results of reverse engineering analysis of two models are utilized. A CAE Tool "APM WinMachine" is used for this analysis. The other value of spring specification is preliminarily decided utilizing the APM WinMachine. Figure 3 shows the input icon of this tool for this deign and Fig. 4 shows the result of design.



Maximum working force 810. [N]
Preload force 360. [N]
Working deflection 6. [mm]
Material Piano Wire
Spring class 3 class spring

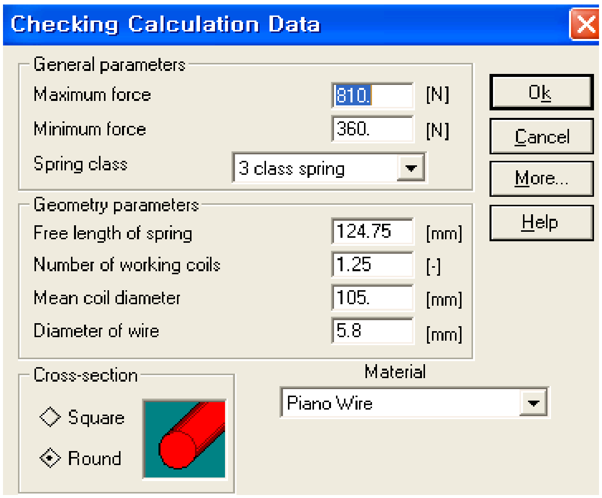
Fig. 3 Input data for spring design



Index of spring	21.141	[-]
Mean coil diameter	131.07	[mm]
Diameter of wire	6.2	[mm]
Number of working coils	1.22	[-]
Displacement	87.013	[mm]
Potential energy	63.432	[J]
Length in compressed state	17.999	[mm]
Free length of spring	174.62	[mm]
Distance between coils	135.51	[mm]
Helix angle	18.215	[Deg]
Length of spring evolvent	1352.4	[mm]
Length of blank of spring	1447.1	[mm]
Destance between coils in compressed state	7.13	[mm]
Allowable shearing stress	1200.	[MPa]

Fig. 4 Result data for spring design

The final value of spring specifications are determined after simulation and checking analysis of the safety factors of preliminarily determined specifications using same CAE Tool. Figure 5 shows the input icon of this analysis and Figure 6 show the output data of this analysis. The result implies the system is secure in fatigue life and stable in dynamics.

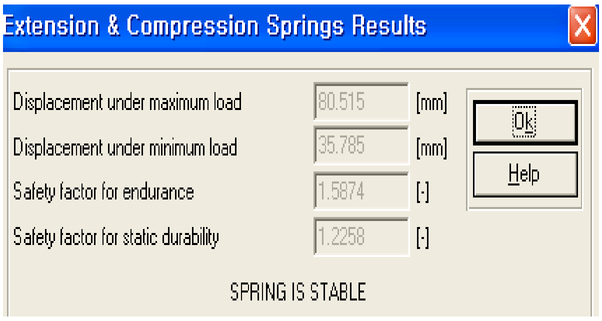


General parameters
Maximum force 810. [N]
Minimum force 360. [N]
Spring class 3 class spring

Geometry parameters
Free length of spring 124.75 [mm]
Number of working coils 1.25 [-]
Mean coil diameter 105. [mm]
Diameter of wire 5.8 [mm]

Material Piano Wire

Fig. 5 Input data for spring checking calculation



Displacement under maximum load	80.515	[mm]
Displacement under minimum load	35.785	[mm]
Safety factor for endurance	1.5874	[-]
Safety factor for static durability	1.2258	[-]

SPRING IS STABLE

Fig. 6 Result data for spring checking calculation

5 TEST FOR THE STEERABILITY

Axiomatic approach was also utilized when the test critera and methodology was developed[7]. Driving speed for steerability test is setted on 39.1 km/h. Three criteria are utilized for steerability test: the lag time till the second engagement, after the second disengagement, torque, and the RPM at the second engagement as shown on Fig. 7 and Fig. 8. 50 tests are carried out and the average of three criteria are obtained as shown in Table 9. The test results are very positive regarding the functional performance of the steerability.

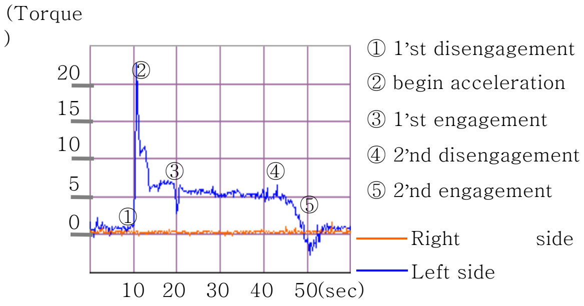


Fig. 7 Steerability test of newly developed model

(Torque
)

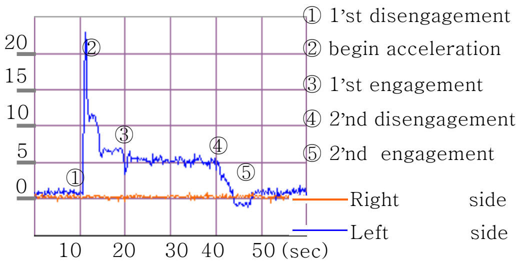


Fig. 8 A Steerability test of reference model(A)

Table 9. Test result of steerability

Criteria	Target	Result	Remarks
Lag time	7.23±5%	7.33	
RPM	5.81±5%	5.66	
Torque	1.23±5%	1.25	

6 CONCLUSION

The process of decomposition to the second level of the better steerability and modification of design matrix for improved design which satisfies the independent axiom are explained. The design matrix which maps the design parameters and process parameters while satisfying the independence axiom are developed. The optimal force and design parameters of spring are obtained. The results of steerability test show very positive regarding functional performances. As a result, the Axiomatic has proven very effective for the evolutionary development of NSD.

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