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EVOLUTIONARY DESIGN OF NO SPIN DIFFERENTIAL MODELS FOR OFF-ROAD VEHICLES USING THE AXIOMATIC APPROACH

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ABSTRACT–A No Spin Differential (NSD) design has been improved from evaluation of two NSD models utilizing the axiomatic approach. New design parameters of the second level are developed to satisfy the independence axiom. The design matrices are determined to decouple the relationship between design parameters and process parameters. The values of process parameters are then determined to optimize and improve the NSD design. Consequently a unique and evolutionary NSD design is achieved with the aid of the axiomatic approach.

KEY WORDS : Axiomatic approach, Evolutionary design, Design parameter, Process parameter, Mobility, Steerability

1. INTRODUCTION

No Spin Differential (NSD) is the most effective technology to help a vehicle escape quickly from bad road conditions. NSD equalizes the torque on wheels trapped in a puddle or a slough with the unaffected wheels on the other side. Thus, NSD has become increasingly necessary for military and special civil purpose vehicles. In that light, a project "No Spin Differential Development for Off-road Vehicles" was carried out under the Research and Development Support Program for Dual-Use Technology (DUT) supported by the Ministry of Commerce, Industry and Energy (MOCIE) from 1999 to 2002 (Pyoun *et al.*, 2003).

Two different NSD models used in two leading countries were adopted for benchmarking and design evaluation. Evaluation was performed on the two NSD models focusing on both top and the second level FRs (functional requirements) and DPs (design parameters).

The latter was benchmarked based on the layer-structure advantage of the Axiomatic approach. The evaluation revealed that the design satisfies the Independence Axiom as a triangular matrix at the top level, but at the second level, the two design matrices were coupled. Thus, the design fails to satisfy the Independence Axiom. This led us to conclude that evolutionary design was indeed possible to better fulfill the functional requirements.

A number of problems were identified through the design evaluation. They were as follows:

(1) If a vehicle is to turn, or drive without skidding. when running on an extremely uneven road surface, capability for contact smoothness and turn receptiveness should be improved through the precise control of differential (e.g., the same number of teeth for the holdout-ring and the center cam).
(2) It is necessary to reduce noise by adopting a smooth profile of center cam/clutch tooth form and by improving surface roughness because the noise is generated from their interaction.
(3) The greater the tooth-form width of the center cam, the smoother the NSD operates. This helps a vehicle to get out of a swamp quickly through prompt

NSD operation. A simple structure is also needed to improve mobility through speedy linkage and separation. By applying solutions carefully to existing DPs to deal with the aforementioned problems it is possible to develop a better and unique NSD design in terms of performance and quality. So, based on the results of the design evaluation, design improvements utilizing the axiomatic approach has been carried out. In particular, the detailed process of how to develop new design parameters of the second level which can satisfy the independence axiom is described in this paper. Furthermore, the decoupled design matrices which map the

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Corresponding author. e-mail: pyoun@sunmoon.ac.kr relationship between design parameters and process parameters are developed, and the method to obtain the value of process parameters that optimize or improve the NSD design is described (Lee *et al.*, 2002).

2. MODIFICATION OF DESIGN PARAMETERS

The design matrices of two NSD models were coupled at the second level and did not satisfy the Independence Axiom. There are two methods to make a decoupled design which can satisfy the Independence axiom. The first step is to change the order of involved components of matrix until the matrix is decoupled. But this operation had been performed already at the stage of design evaluation and was not successful. The next step is to modify the characteristic of the involved components and the involved components themselves (Suh, 1990, 2001; Moon *et al.*, 1999a, 1999b). This is described in the fellowing sections.

2.1. Modification of DPs for the Improved Steerability

Table 1 and Table 2 show the results of a design evaluation carried out for the two NSD models. We modify the shape of the holdout-ring (DP13) to have weak influence to the speedy turn (FR12) as in model B (Table 2), and the number of holdout-ring teeth (DP14) to have weak influence to the smooth contact (FR13). Finally the holdout-ring shape (DP13) becomes involute and the number of holdout-ring teeth (DP14) becomes 14. A new design matrix results as shown in Table 3 which satisfies the Independence axiom.

Table 1. 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	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

2.2 Modification of Design Parameters for the Reduced Noise

Table 4 and Table 5 show the results of a design evaluation carried out for the two NSD models. We adopt the outstanding feature of Model B and modify the tooth form of center cam (DP24) to involute feature which has weak influence to the refined surface precision (FR22). The design matrix in Table 6 results which satisfies the Independence axiom.

Table 2. 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	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 3. Design matrix tuned for decoupling.

Functional Requirements	DP11: Spring	DP12: Steering Time	DP13: Holdout Ring Shape (involute)	DP14: Number of Holdout Ring Teeth (18)
FR11: Minimum Turn Radius	X	O	O	O
FR12: Speedy Turn	X	X	O	O
FR13: Smooth Contact	O	X	X	O
FR14: Improved Turn Receptiveness	X	X	X	X

Table 4. 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	O	O	O
FR22: Refined Surface Precision	O	X	X	O
FR23: Smooth Profile	O	X	X	X
FR24: Minimum Friction	X	X	X	X

Table 5. 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	O	O	O
FR22: Refined Surface Precision	O	X	O	X
FR23: Smooth Profile	O	X	X	O
FR24: Minimum Friction	X	X	X	X

2.3. Modification of Design Parameters for the Improved Mobility

Table 7 and Table 8 show the results of a design evaluation carried out for the two NSD models. We modify the width of center cam (DP32) to have weak influence to the speedy movement (FR31) as shown in model B (Table 8), and improve the stiffness of clutch structure (DP34) as shown in the Table 9 and make it has weak influence to the sufficient rigidity (FR33). The improve design matrix in Table 9 results which satisfies the Independence axiom (Moon *et al.*, 2005).

Table 6. Design matrix tuned for decoupling.

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

Table 7. 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

3. 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. CAE tools such as COSMOS, APM WinMachine, etc. are utilized for parameter optimization. The result for only one element from each matrix is explained Table 10 (Suh *et al.*, 2000; Kim and Suh, 1999).

3.1. PVs and Their Optimal Value for the Improved Steerability

Table 8. 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

Table 9. Design matrix tuned for decoupling.

Functional Requirements	DP31: Movement Time	DP32: Center Cam Structure (wide)	DP33: Spider Structure (S:3.4)	DP34: Clutch Structure (S:3.4)
FR31: Speedy Movement	X	O	O	O
FR32: Smooth Operation	X	X	O	O
FR33: Sufficient Rigidity	X	X	X	O
FR34: Sufficient Strength	X	X	X	X

Four PVs are developed and tuned until the decoupling relationship with DPs is satisfied for the improved steerability. Table 10 shows the result. The most important PV for steerability is the spring force (DP11). The detailed process to obtain optimal value of the spring force (DP11) 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 the engaging and disengaging functions.

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 Figure 1. This function can be described by following equation.

Table 10. Design matrix tuned for decoupling.

	PV11: Spring force: 810N	PV12: Minimum Steering Time	PV13: Shape of involute	PV14: Number of Teeth: 18
DP11: Spring	X	O	O	O
[illegible] Time	X	X	O	O
[illegible] Ring Shape (Involute)	O	X	X	O
[illegible] Holdout Ring Teeth (18)	X	X	X	X

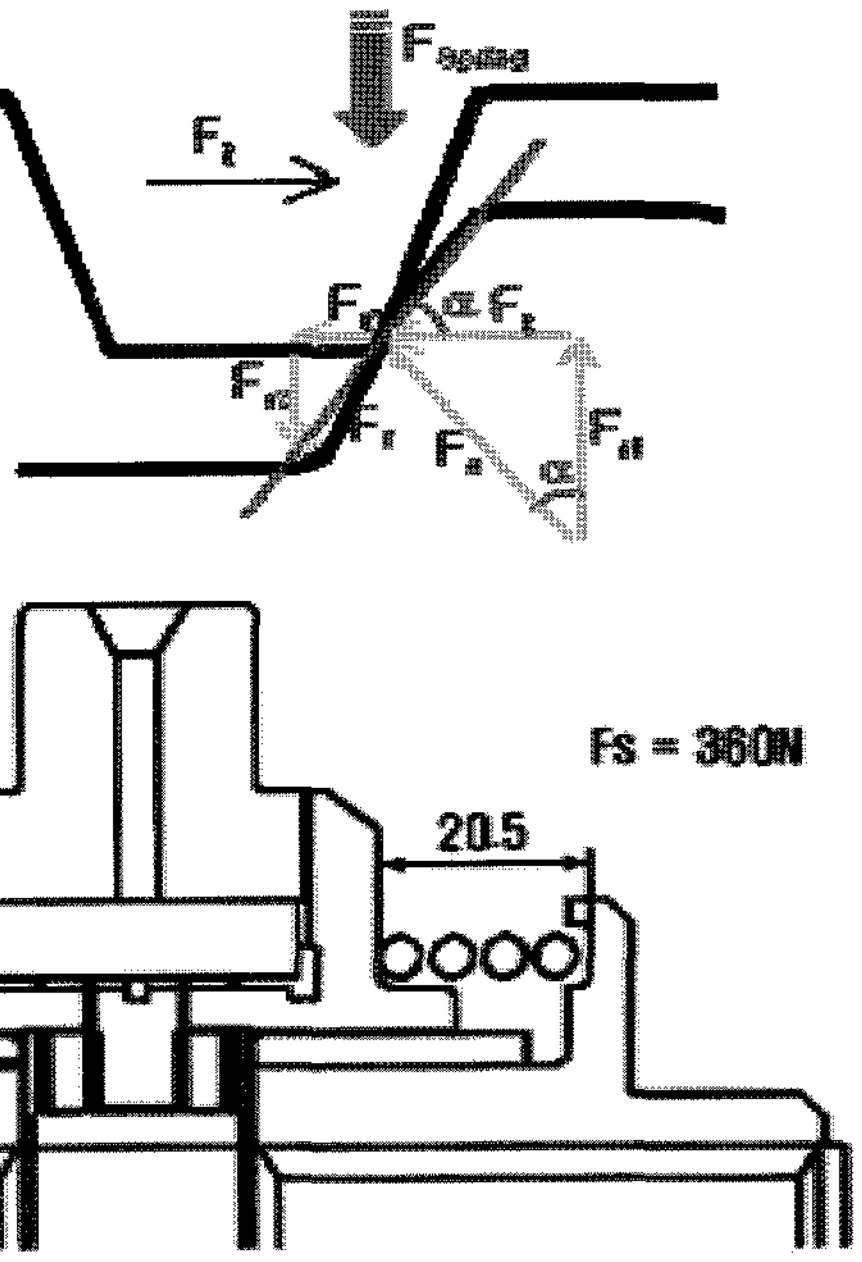


Figure 1. Force diagram and spring length at the moment of disengagement.

$$F_{spring} < F_{Radial} \tag{1}$$

The spring length at the moment of disengagement is determined as shown in Figure 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 Figure 2. This function can be described by following equation (Pu *et al.*, 2005).

$$F_{spring} > F_{Radial} \tag{2}$$

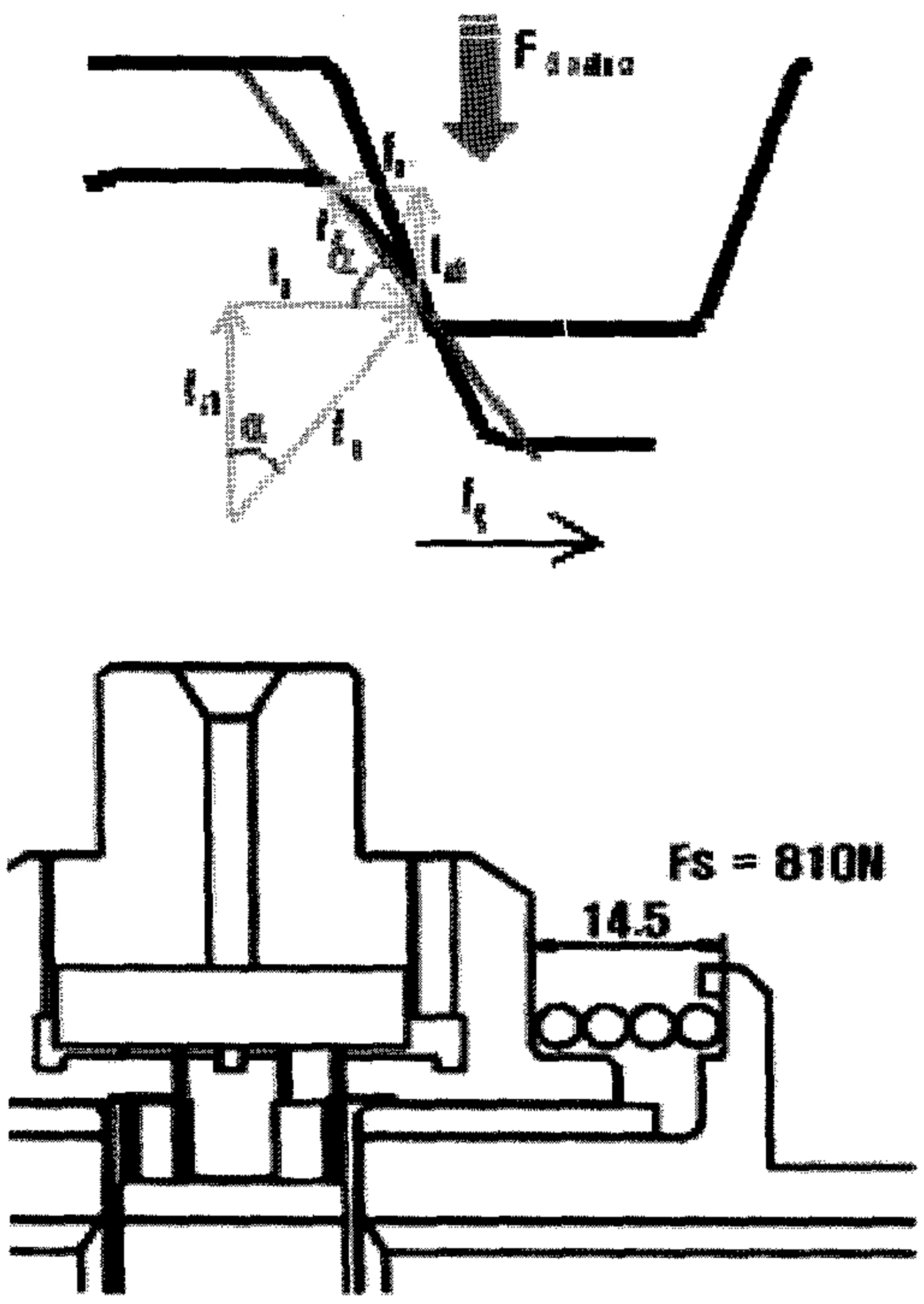
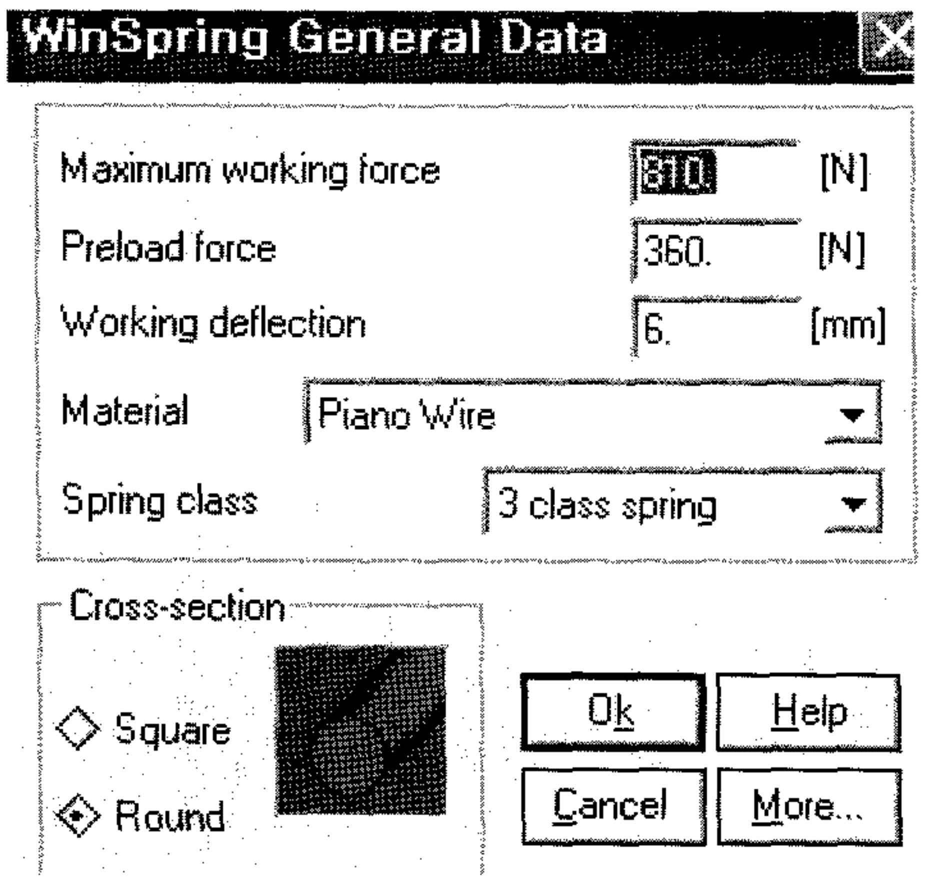


Figure 2. Force diagram and spring length at the moment of engagement.

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

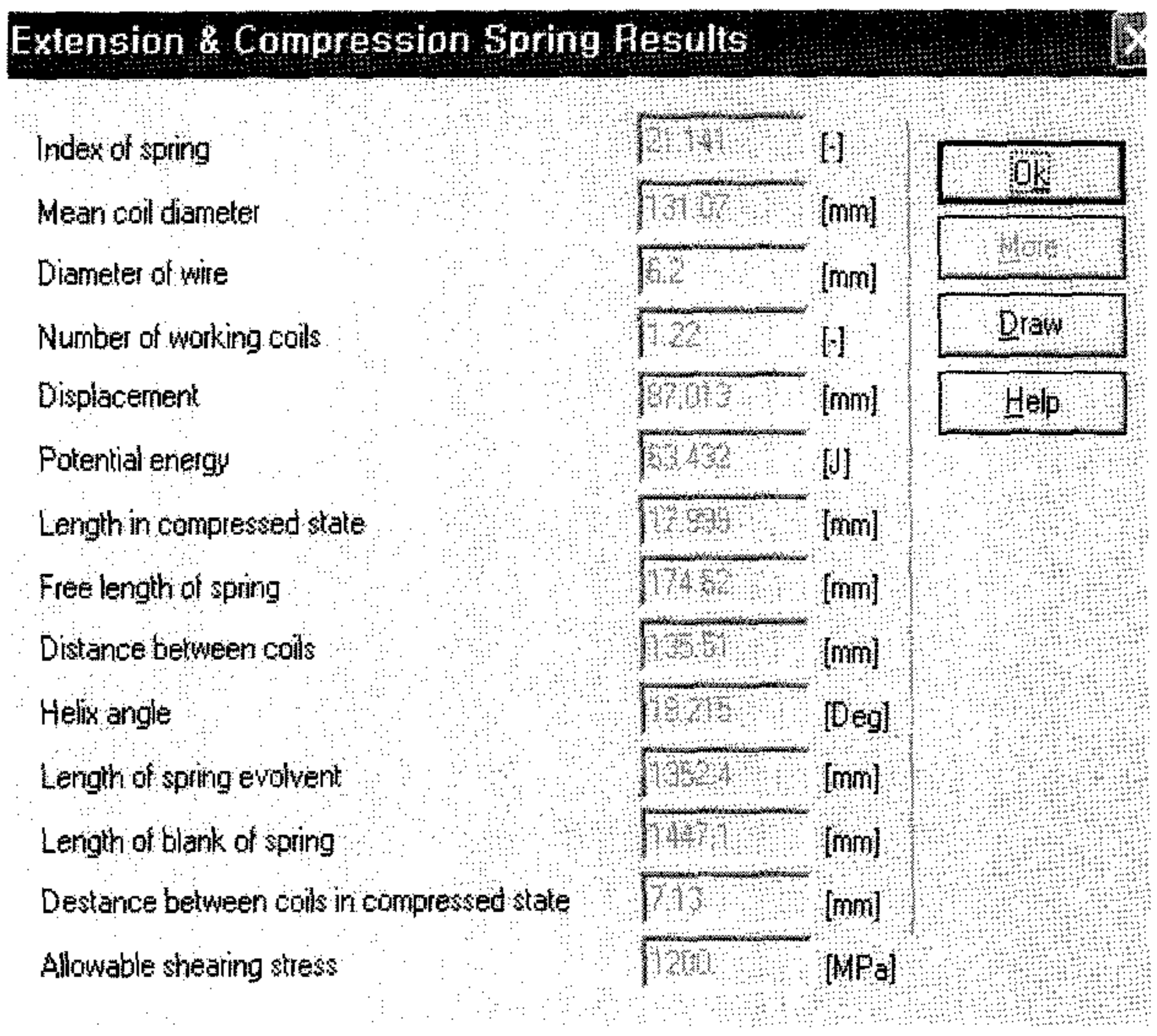
In order to determine the spring force at the moment of disengagement and engagement, the results of reverse engineering analysis of two models are utilized. A CAE Tool "APM WinMachine" is used for this analysis. The other value of spring specification is preliminarily decided utilizing the APM WinMachine.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

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


WinSpring General Data

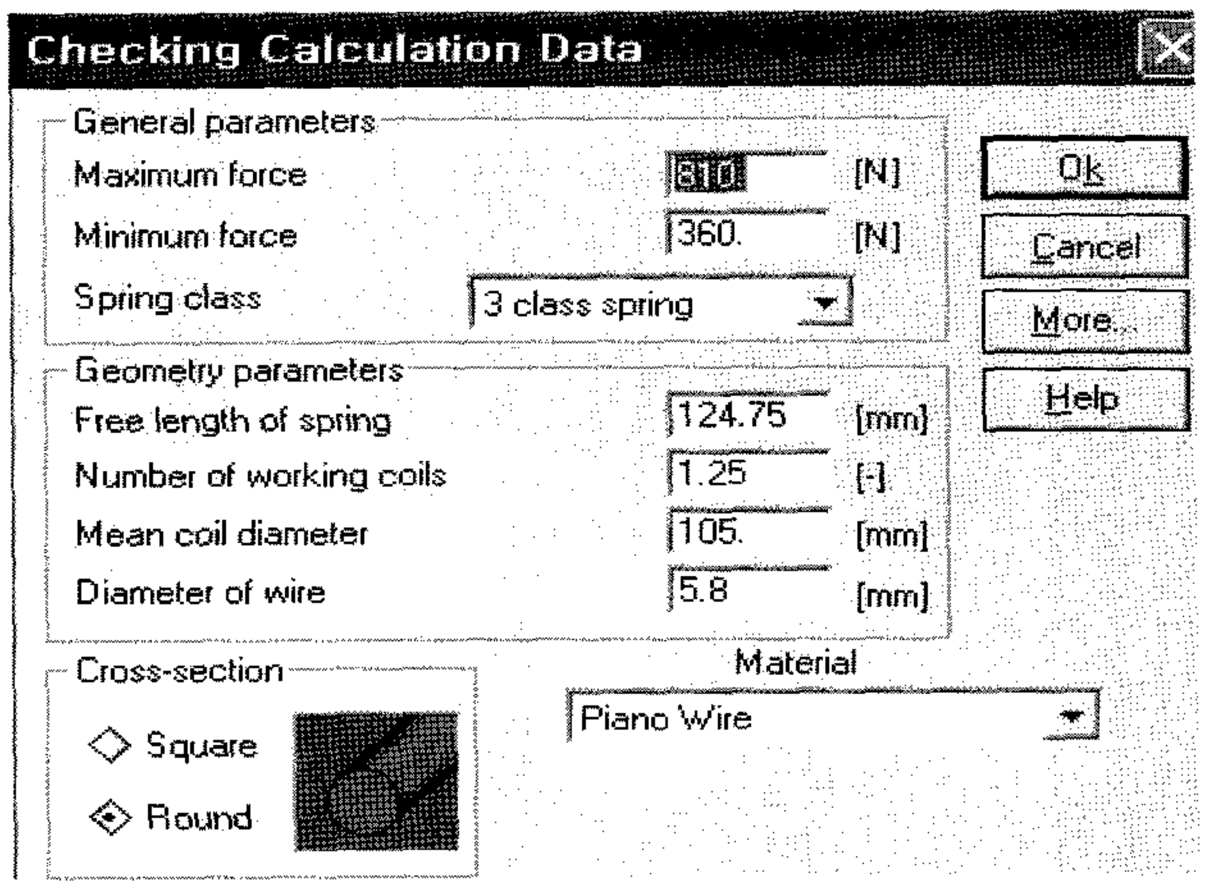
Maximum working force 810. [N]
Preload force 360. [N]
Working deflection 6. [mm]
Material: Piano Wire
Spring class: 3 class spring
Cross-section: ◇ Square ◈ Round

Figure 3. Input data for spring design.


Extension & Compression Spring Results

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 53.432 [J]
Length in compressed state 12.939 [mm]
Free length of spring 174.52 [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]

Figure 4. Result data for spring design.


Checking Calculation Data

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

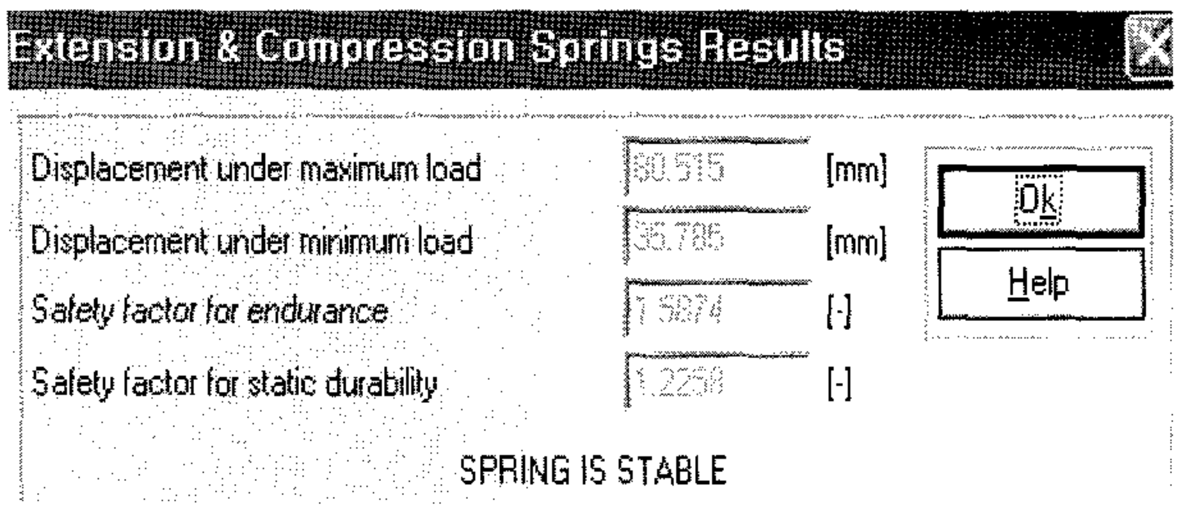
Geometry parameters
Free length of spring 124.75 [mm]
Number of working coils 1.25 [-]
Mean coil diameter 105. [mm]
Diameter of wire 5.8 [mm]

Cross-section: ◇ Square ◈ Round
Material: Piano Wire

Figure 5. Input data for checking calculation of spring.

3.2. PVs and their Optimal Value for the Reduced Noise

Four PVs are developed and tuned until the decoupling relationship with DPS is satisfied for the reduced noise. Table 11 shows the result. In order to improve noise characteristics, we choose a forming tool for surface finishing of the cam profile (PV22). Thus, we expect one class better surface roughness than those of the two models. One model was produced by a cold forging process and the other model was produced by a general milling operation. We cannot predict how much the noise value will be reduced, but it will be reduced somewhat



Displacement under maximum load 80.515 [mm]

Displacement under minimum load 35.786 [mm]

Safety factor for endurance 1.5874 [-]

Safety factor for static durability 1.2258 [-]

SPRING IS STABLE

Figure 6. Result data for checking calculation of spring.

due to the improved surface roughness. The forming tool process could be realized due to the recently developed CNC machining center and tungsten carbide forming tool without the burden of a cost increase (Kang and Lee, 2005).

3.3. PVs and their Optimal Value for the Improved Mobility

Four PVs are developed and tuned until the decoupling relationship with DPs is satisfied for the improved mobility. Table 12 shows the result. The new NSD should have a longer service life than those of the two models. We checked the static safety value and fatigue safety value of two models using the FEM tool COSMOS, and determined the criteria of the improved design. All values of the DPs are determined by satisfying these criteria (Park *et al.*, 2005).

One important part that determines the service life of the NSD is the clutch (DP34). We have checked the static and fatigue safety value of new design (DP34) utilizing COSMOS. Figure 7 show one analysis for checking the static safety factor (Ko *et al.*, 2003; Lee *et al.*, 2003).

Figure 8 show the 3-D model of the new design finally determined through the above process, and the pictures of the two models are compared.

Table 11. Design matrix tuned for decoupling.

	PV21: unseparable	PV22: manufacturing	PV23: involute	PV24: round involute
DP21: Retainer Structure (unseparable)	X	O	O	O
DP22: Cam Tooth Surface Processing (manufacturing)	O	X	O	O
DP23: Clutch Tooth Form (involute)	O	X	X	O
DP24: Center Cam Tooth Form (round involute)	X	X	X	X

Table 12. Design matrix tuned for decoupling.

	PV31: Minimum Movement Time	PV32: Wide Center Cam Structure	PV33: Secure Spider Structure	PV34: Secure Clutch Structure
DP31: Movement Time	X	O	O	O
DP32: Center Cam Structure (wide)	X	X	O	O
DP33: Spider Structure (S:3.4)	O	O	X	O
DP34: Clutch Structure (S:3.4)	O	O	X	X

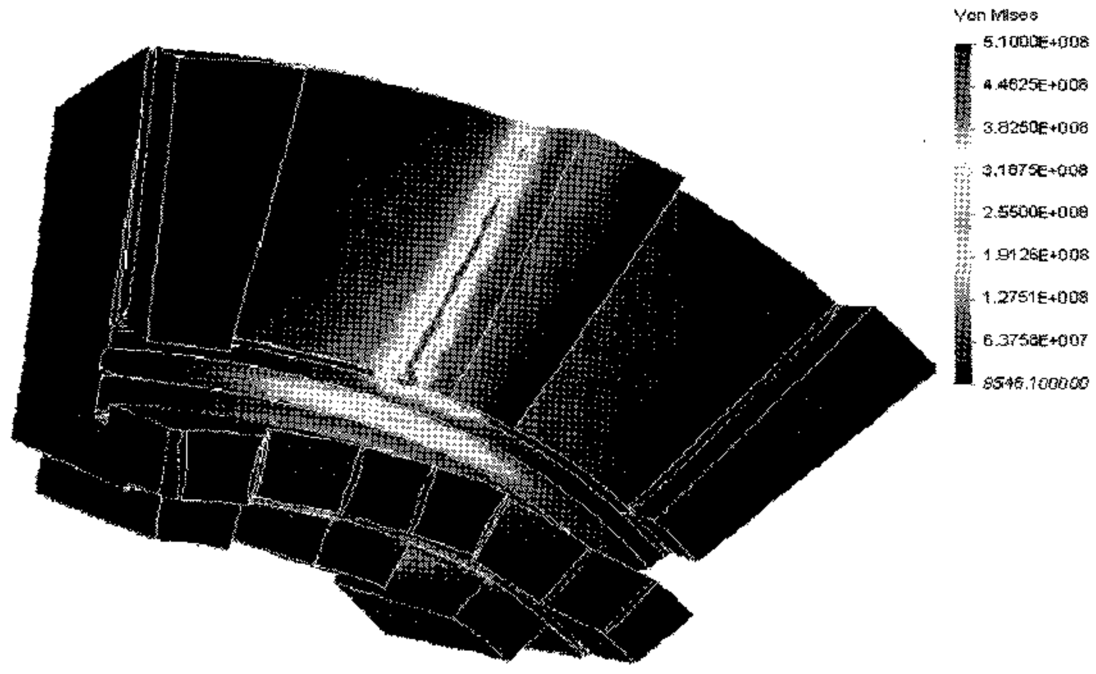
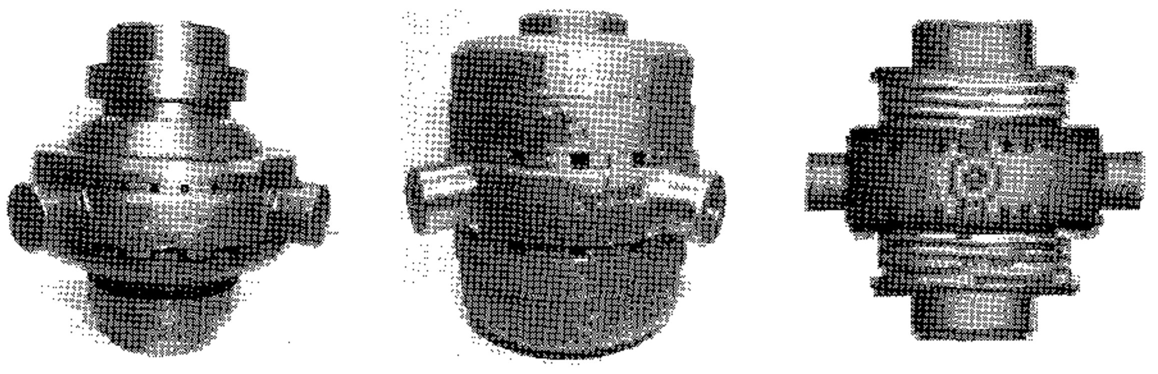


Figure 7. Result of stress analysis of driven clutch.



<Amodel> <B model> <New Improved Design>

Figure 8. Two benchmarked models and the improved model.

4. CONCLUSION

Based on the results of design evaluation of two No Spin Differential (NSD) models utilizing the Axiomatic approach, the design has been improved. This results in a decoupled design matrix which satisfies the Independence Axiom. Improvements consist of two steps. The first is to change the order of involved matrix components until the matrix is decoupled. This operation had been performed already at the stage of design evaluation and was not successful. Thus, a second step was performed which modified the characteristic of the involved components at the second level of design. This yields three decoupled design matrices that map the relationship between FRs and DPs. Three additional decoupled design matrices were developed mapping the relationship between DPs and PVs. The optimal value of PVs were obtained using CAE Tools and advanced manufacturing technology. This successive decoupling constitutes a unique and evolutionary NSD design.

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