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AXIOMATIC DESIGN OF THE OCCUPANT PROTECTION SYSTEM

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ABSTRACT

The functional requirements (FRs) and design equation change in a flexible system with a continuous manner with respect to a variable such as time. An event-driven flexible system is defined as a subcategory of the flexible system in that it changes in a discrete space. The design equation for each event should be defined by using the axiomatic approach and the design equations are assembled to form a full design equation. The design equations are made by sensitivity analysis. In conceptual design, the design order is determined based on the full design equation. Design parameters (DPs) are found to satisfy FRs in sequence. The occupant protection system is an event-driven flexible system because the design matrix and its elements change according to the impact speed. Functional requirements (FRs) at different impact speeds, corresponding design parameters (DPs) are defined to satisfy the FRs. In a detailed design, the full factorial design of experiments (DOE) is employed for the design variables of DPs to reduce the injury levels of the occupant. Computer simulation is utilized for the evaluation of the injuries. A detailed design is made and the results are discussed.

Keywords: Axiomatic Design, Fixed System, Flexible System, Occupant Protection System

1 INTRODUCTION

Axiomatic design is a highly effective design framework for achieving functional requirements from the early conceptualization phase [1-8]. Axiomatic design has two design axioms, the Independence Axiom and the Information Axiom. The Independence Axiom requires that the functional independence be satisfied during the mapping process between the functional requirements (FRs) and the design parameters (DPs). The Information Axiom states that the best design is the one with minimum information content among all the designs that satisfy the Independence Axiom.

In axiomatic design, the fixed system does not change the set of functional requirements at all times. In contrast, the flexible system is defined as a system whose functional requirements are functions of time [2-4]. Time is used in a general sense and has continuous characteristics. The event means instantaneous occurrences and conditions that change the state of a system. Generally, it has discrete characteristics. In this paper, the event-driven flexible system is defined as a system whose functional requirements and design matrix change as the events. Therefore, the event-driven flexible system is a subcategory of the flexible system. In this research, aspects for the event-driven flexible system are investigated.

In an event-driven flexible system, the same DP can be used for more than one FR. In this case the system must be designed so that the Independence Axiom is always satisfied at all events. The design process for an event-driven flexible system can be developed to maintain the independence of the FRs at the given events [2-4]. The FRs can be shared by different events. But it is difficult to identify the relationships between the shared FRs and manage the interactions between the elements of the design matrix at all events.

A design process is proposed to solve the event-driven flexible system by using a full design equation for conceptual design. The full design equation is created by using all the FRs at entire events of the system. The relationships of the shared FRs can be drawn and the design order of DPs can be determined. Detailed design can be conducted based on the design matrix as the design matrix indicates. The event-driven flexible system has the shared FRs by using the same DP and many constraints. Sometimes the off-diagonal terms of the full design matrix strongly affect the other FRs if the off-diagonal elements of the full design matrix are large. In a detailed design process, it may be difficult to determine the values of DPs. Therefore, multiple solutions of the detailed design are obtained. The multiple solutions can be acquired by using a full factorial design and the FRs are evaluated by the order of the design. The number of the design solution is reduced as the design proceeds.

The occupant protection system (OPS) is found to be an event-driven flexible system because various FRs should be satisfied for multiple vehicle impact speeds. FRs are defined by the safety regulations. In order to represent the design equation of the OPS at each event, the sensitivity analysis is performed by using orthogonal arrays and analysis of variance (ANOVA) [9-11]. The OPS is analyzed by using the full design matrix at all events. As a result, the design order of DPs for the OPS is determined. DPs are the knee bolster, the airbag and the seat belt. In the detailed design process, safety is measured by computer simulation. For computer simulation, a commercial occupant analysis system named MADYMO (MAthematical DYnamical MOdels) is utilized [12].

2 SYSTEM DESIGN IN AXIOMATIC DESIGN

2.1 Introduction of Axiomatic Design

Axiomatic Design has two design axioms as the scientific foundation of design [1-2]. The design axioms are defined from common principles for engineering activities as follows:

Axiom 1: The Independence Axiom
Maintain the independence of FRs.

Axiom 2: The Information Axiom
Minimize the information content of the design.

The Independence Axiom states that an optimal design always maintains the independence of FRs. The specific DP can be adjusted to satisfy its corresponding FR without affecting other functional requirements. When the number of FRs is equal to the number of DPs and the Independence Axiom is satisfied, the design is an ideal design. To satisfy the Independence Axiom, the design matrix must be diagonal (uncoupled design) or triangular (decoupled design).

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix} \quad (1)$$

where X means that there is a relationship and 0 means there is no relationship. Since the design matrix is diagonal, the independence of FRs can be guaranteed only if the DPs are determined in a proper sequence. DP_1 has to be determined first and DP_2 should be determined next. When the off-diagonal term is zero, the DPs can be determined in any order. If 0 in Eq. (1) becomes non-zero, the design is coupled and the design should be changed to an uncoupled or a decoupled design. One of the most significant benefits of the axiomatic design is a systematic approach to determine DPs. The establishment of the correct design order avoids costly redesign efforts. The Information Axiom states that the one with minimum information content is the best among multiple designs which satisfy the Independence Axiom. The Information Axiom is not utilized in this research.

2.2 Classification of a Flexible System

A system may be defined as an assemblage of sub-systems, hardware and software components, and people designed to perform a set of tasks to satisfy specified functional requirements and constraints [2]. It is useful to classify the system because a proper classification of systems helps to understand and focus on functional identification of the systems.
One of the most basic systems is the fixed system. The fixed system has a set of functional requirements at all times. On the other hand, FRs varies in a flexible system. Generally, time is used as a domain for FRs. Thus, the FRs are continuous functions of time. An event means a discrete circumstance or condition and generally has discrete characteristics. The event-driven flexible system is defined as a system whose functional requirements and design matrix may change according to the events. Therefore, an event-driven flexible system is a subcategory of the flexible system as illustrated in Fig. 1. If the FRs are different at all events, the system is regarded as a fixed system.

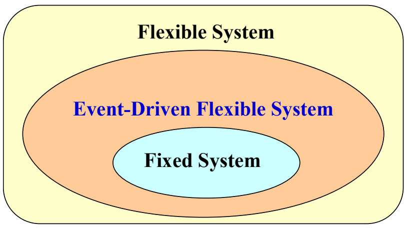


Fig. 1 Classification of the flexible system

2.3 Event-Driven Flexible System

The event-driven flexible system has many characteristics of the flexible system because FRs, DPs and design matrix (DM) are changed according to the discrete events. In this system, the DPs must be chosen at each event so that the FRs of an event are independently satisfied. Some of the FRs might appear in several events. Eq. (2) is a mathematical example of an event-driven flexible system and the vector of FRs at each event is composed of a set of FRs. In Eq. (2), FR_2, FR_3 and FR_5 are shared by multiple events.

$$\begin{aligned} &@\, event_0, \{FR\}_0 = \{FR_1, FR_3, FR_6\} \\ &@\, event_1, \{FR\}_1 = \{FR_2, FR_3, FR_5\} \\ &@\, event_2, \{FR\}_2 = \{FR_2, FR_4, FR_5\} \end{aligned} \quad (2)$$

All the FRs do not need to be active at each event and a DP may be used to satisfy multiple FRs of different events. Some of the FRs may be common to multiple events. The search process for DPs can be developed according to the events. It is important to maintain the independence of the FRs at each event. DPs have to be selected in order to make the design of each event be an uncoupled or a decoupled design.

As mentioned earlier a process is presented to solve the event-driven flexible system by using the full design matrix. The following guidelines describe the approach to make a full design matrix for the event-driven flexible system:

(1) At the beginning, determine the DPs to satisfy the Independence Axiom at each event.
(2) The FRs at each event are represented by $FR_{i,j}$ where i is the event number and j is the FR number. $FR_{i,j}$'s can represent the same FR (shared FR). For example, $FR_{1,1}$ can be the same as $FR_{2,1}$.
(3) The element of the design matrix is represented by X_i where i is the event number.
(4) The design equation for each event is made and the design equations for all the events are assembled to form a full design equation.

Consider the following group of events,

$$@event_1, \begin{Bmatrix} FR_{1,1} \\ FR_{1,2} \end{Bmatrix} = \begin{bmatrix} X_1 & 0 \\ X_1 & X_1 \end{bmatrix} \begin{Bmatrix} DP_{1,1} \\ DP_2 \end{Bmatrix} \quad (3)$$

$$@event_2, \begin{Bmatrix} FR_{2,1} \\ FR_{2,2} \end{Bmatrix} = \begin{bmatrix} X_2 & 0 \\ X_2 & X_2 \end{bmatrix} \begin{Bmatrix} DP_{2,1} \\ DP_2 \end{Bmatrix} \quad (4)$$

where X_i 's in Eqs. (3) and (4) can have different values. It is noted that the same DP (DP_2) is used in different events.

Equation (5) shows the full design equation using Eqs. (3) and (4). Equation (5) is reorganized as Eq. (6). Although a component of the FR vector consists of multiple FRs, the full design equation does not violate the Independence Axiom because only one FR is active for a given event.

$$\begin{Bmatrix} FR_{1,1} \\ FR_{1,2}, FR_{2,2} \\ FR_{2,1} \end{Bmatrix} = \begin{bmatrix} X_1 & 0 & 0 \\ X_1 & X_1, X_2 & X_2 \\ 0 & 0 & X_2 \end{bmatrix} \begin{Bmatrix} DP_{1,1} \\ DP_2 \\ DP_{2,1} \end{Bmatrix} \quad (5)$$

$$\begin{Bmatrix} FR_{1,1} \\ FR_{2,1} \\ FR_{1,2}, FR_{2,2} \end{Bmatrix} = \begin{bmatrix} X_1 & 0 & 0 \\ 0 & X_2 & 0 \\ X_1 & X_2 & X_1, X_2 \end{bmatrix} \begin{Bmatrix} DP_{1,1} \\ DP_{2,1} \\ DP_2 \end{Bmatrix} \quad (6)$$

When the full design equation is completed, the design order of DPs is determined. Now the conceptual design process is accomplished. A DP in conceptual design can have multiple design variables in the detailed design process. Generally, the full design equation of an event-driven system can have shared FRs and many constraints. Therefore, it is difficult to conduct a detailed design. Sometimes off-diagonal terms in the full design matrix can be important. It is the case where the off-diagonal elements of a full design matrix indicate large X relationships. So it strongly affects the other FRs. In this system design problem, it is difficult to determine the value of DPs by applying a single solution according to the design order of DPs. Therefore, multiple solutions for a detailed design are the most effective way of solving this system design problem. A full factorial design is employed to obtain multiple solutions.

3 AXIOMATIC DESIGN OF THE OCCUPANT PROTECTION SYSTEM

3.1 OCCUPANT PROTECTION SYSTEM AND REGULATIONS

The design of an automobile occupant protection system (OPS) plays an important role in vehicle development. Extensive government regulations for many impact conditions make the design and optimization of the OPS challenging work [13-15]. When a vehicle crash occurs, the occupant moves until it is restrained by the OPS. The design of the OPS is carried out based on the regulations for several vehicle impact speeds. The design matrix of the OPS and its elements change as the vehicle impact speed changes. Therefore, the OPS is an event-driven flexible system and the events are defined by the impact speed.

The most important regulations for the OPS are the Federal Motor Vehicle Safety Standard (FMVSS) No. 208 [15], the Occupant Crash Protection Standard, and consumer information programs such as the New Car Assessment Program (NCAP) [16]. The National Highway Traffic Safety Administration (NHTSA) administrates the FMVSS and NCAP to reduce deaths and injuries resulting from traffic accidents. In FMVSS No. 208 regulation, the running vehicle crashes into a fixed barrier at a specified speed and all the injury values shall not exceed the criteria as shown in Table 1. In NCAP, the vehicle crashes into a rigid concrete barrier at 35 mph (56 km/h). NHTSA provides consumers with star ratings as shown in Table 1 to help their decision for a vehicle purchase. The more number of stars, the safer the vehicle is. The methods and requirements for the frontal rigid impact test are illustrated in Table 1.

Table 1 Methods and requirements for frontal rigid impact test

Test method	FMVSS 208 (occupant crash protection)				NCAP
Purpose	Regulation				Marketing
Test dummy	50th male dummy		5th female dummy		50th male dummy
Safety device	Airbag only	Belt & airbag	Airbag only	Belt & airbag	Belt & airbag
Impact speed	20~25 mph	0~30 mph	20~25 mph	0~30 mph	35 mph
Test requirement	All injury values shall not exceed the criteria as follows.				NCAP provides consumers with vehicle safety information
HIC15	700		700		Star rating system (from 1 to 5 star) P_{comb} : 46% or greater : 1 star; 36% to 45% : 2 star; 21% to 35% : 3 star; 11% to 20% : 4 star; 10% or less : 5 star
Chest acceleration (g) (Chest G)	60		60		
Chest deflection (mm)	63		52		
Neck injury (N_{ij})	1.0		1.0		
Neck peak tension (N)	4170		2620		
Neck peak Compression (N)	4000		2520		
Femur load (N)	10000		6800		

$$HIC15 = SUP\ (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}$$ where $(t_2 - t_1) \le 15msec$ and $a(t)$ is the acceleration of the head.

$$HIC36 = SUP\ (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}$$ where $(t_2 - t_1) \le 36msec$ and $a(t)$ is the acceleration of the head.

$$P_{comb} = P_{head} + P_{chest} - P_{head} \times P_{chest}$$

$$P_{chest} = [1 + exp(5.55 - 0.0693 \times ChestG)]^{-1}$$

$P_{head} = [1+exp(5.02-0.00351\times HIC36)]^{-1}$

3.2 PROBLEM DEFINITION OF THE OPS WITH AXIOMATIC DESIGN

The OPS is evaluated from the viewpoint of the event-driven flexible system. Table 1 describes the test methods for the OPS and its requirements. The design purpose of the OPS is to minimize injuries under these test conditions. In earlier development of the vehicle, the worst speeds of Table 1 are utilized. Events are defined by the worst speeds. Table 2 shows the defined events for the OPS.

Table 2 Events of the OPS

Event No.	Impact speed	Dummy type	Safety device
Event 1	25 mph	5% female	Airbag only
Event 2	25 mph	50% male	Airbag only
Event 3	30 mph	5% female	Airbag & seat belt
Event 4	35 mph	50% male	Airbag & seat belt

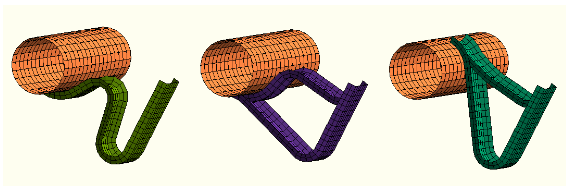
The functional requirements of the OPS are for occupant protection in a vehicle crash. The protection of the upper body and lower body are chosen as the FRs of the OPS. Detailed design criteria are needed because occupant protection is a quantitative concept. The injury criteria as shown in Table 1 are the physical quantity measured by the test dummy during the impact test. As mentioned earlier, the injury criteria are evaluated by computer simulation in this research. The injury criteria of the upper body include the injuries of head, neck and chest for a dummy. And the injury criteria of the lower body include the injuries of the femur. The sponsoring company of this research has constraints that all injuries are within 80% of the standard for sufficient safety. Therefore, 80% of the criteria is utilized in this research. It is summarized as follows.

At each event,
FR_1 : Protect the lower body
FR_2 : Protect the upper body
Constraints: All injuries are within 80% of the standard

An existing design of the OPS is analyzed. The OPS includes the knee bolster, the airbag and the seat belt and they are the DPs. Each DP can have multiple design variables in a detailed design. The knee bolster is for reducing femur injuries and a vehicle has a unique shape according to the intrusion angle and the contact point between the interior part and the knee bolster. The knee bolster absorbs the impact energy generated from contact between the femur and vehicle interior [17-19].
The airbag protects the occupant by the airbag pressure [20]. The design variables for the airbag are the inflator pressure, the bag size and the vent hole to control the leakage of gas. The seat belt restrains the occupant by using the webbing force, and the design variables to control the webbing force are webbing elongation and the load limiter. The load limiter releases the webbing when the webbing force is larger than a certain value.
Sensitivity analysis can be exploited to determine the elements of the design matrix. Because exact mathematical differentiation only represents local information, it may not be useful. Thus, regional sensitivity information is utilized. Regional sensitivity means sensitivity for a certain range of a design variable. The regional sensitivity is evaluated by analysis of variance (ANOVA). Orthogonal arrays are employed for calculation of the ANOVA [9-11]. The response of each row of an orthogonal array is calculated by computer simulation and the ANOVA is computed as the sum of squared deviations from the mean responses.
For sensitivity analysis, the levels of design variables are given in Table 3 and Fig. 2. L_{18} orthogonal array is used for events 1 and 2 in Table 2, and L_{36} orthogonal array is used for the events 3 and 4 [10,11]. Computer simulation is performed for all events. The simulation model is illustrated in Fig. 3.

Table 3 Design variables and levels for the OPS

Design group	Airbag			Knee bolster		Seat belt	
Level	Inflator	Vent hole size	Bag diameter	Shape	Thickness	Load limiter	Elongation
Level 1	190 kPa	20 mm	690 mm	Type 1	1.0 mm	3500 N	7 %
Level 2	200 kPa	25 mm	710 mm	Type 2	1.5 mm	4500 N	11 %
Level 3	210 kPa	30 mm	—	Type 3	2.0 mm	—	—



(a) Type 1 (b) Type 2 (c) Type 3

Fig. 2 Design variables for the knee bolster bracket

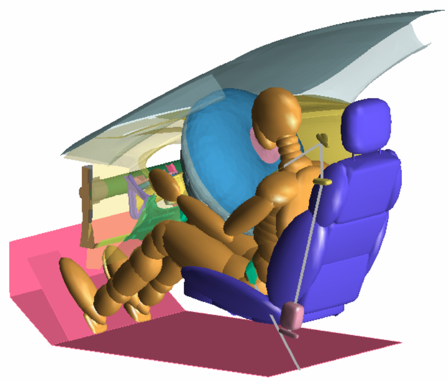


Fig. 3 Simulation model for the OPS

Tables 4 and 5 show the simulation results for all events. The analysis results are expressed as the percentage with respect to injury criteria in Table 1. The sums of squares of all events are obtained from the ANOVA as shown in Tables 6-9 and Tables 10-13 represent the relative magnitude.

Table 4 L_{18} orthogonal arrays and results for event 1 and event 2

DOE no.	Bag diameter	Shape	Thickness	Inflator	Vent hole	$FR_{1,1}$	$FR_{1,2}$	$FR_{2,1}$	$FR_{2,2}$
1	1	1	1	1	1	57.6	78.2	119.2	78.2
2	1	1	2	2	2	59.5	75.3	134.4	77.4
3	1	1	3	3	3	61.5	72.5	127.6	72.8
4	1	2	1	1	2	59.8	79.6	71.4	78.3
5	1	2	2	2	3	67.6	77.8	109.9	81.9
6	1	2	3	3	1	68.0	80.0	128.0	82.6
7	1	3	1	2	1	72.4	80.8	71.3	74.0
8	1	3	2	3	2	78.4	77.9	100.8	75.0
9	1	3	3	1	3	77.5	78.2	119.3	78.4
10	2	1	1	3	3	56.8	73.1	137.3	73.8
11	2	1	2	1	1	57.4	80.1	136.8	77.9
12	2	1	3	2	2	57.2	76.1	142.1	75.7
13	2	2	1	2	3	61.8	77.9	71.8	76.9
14	2	2	2	3	1	67.7	80.3	112.0	82.7
15	2	2	3	1	2	66.0	83.4	129.2	85.5
16	2	3	1	3	2	71.4	77.0	71.1	73.4
17	2	3	2	1	3	76.8	80.8	97.1	78.1
18	2	3	3	2	1	77.7	80.2	121.8	78.1

Table 5 L_{36} orthogonal arrays and results for event 3 and event 4

DOE no.	Load limiter	Elong ation	Bag diameter	Vent hole	Inflator	Shape	Thick ness	$FR_{3,1}$	$FR_{3,2}$	$FR_{4,1}$	$FR_{4,2}$
1	1	1	1	1	1	1	1	32.6	79.4	19.8	70.0
2	1	1	1	1	2	2	2	41.9	79.7	56.9	74.4
3	1	1	1	1	3	3	3	42.3	78.8	72.8	77.4
4	1	2	2	1	1	1	1	29.8	82.0	19.7	70.2
5	1	2	2	1	2	2	2	40.6	83.9	52.4	74.5
6	1	2	2	1	3	3	3	40.5	83.1	71.7	77.2
7	2	1	2	1	1	1	2	37.2	79.4	23.2	71.5
8	2	1	2	1	2	2	3	43.3	80.0	81.7	79.7
9	2	1	2	1	3	3	1	38.4	77.9	40.6	78.6
10	2	2	1	1	1	1	3	36.1	82.9	25.7	75.2
11	2	2	1	1	2	2	1	37.9	81.8	43.9	79.6
12	2	2	1	1	3	3	2	39.6	81.8	58.3	83.0
13	1	1	1	2	1	2	3	42.3	79.8	76.8	72.7
14	1	1	1	2	2	3	1	39.0	77.2	38.8	71.9
15	1	1	1	2	3	1	2	37.3	77.5	21.3	70.0
16	1	2	2	2	1	2	3	42.2	82.5	76.8	71.7
17	1	2	2	2	2	3	1	34.5	82.2	36.7	71.9
18	1	2	2	2	3	1	2	34.0	81.4	22.8	70.3
19	2	1	2	2	1	2	1	39.5	79.3	43.7	72.7
20	2	1	2	2	2	3	2	40.1	78.4	59.4	77.4
21	2	1	2	2	3	1	3	38.8	77.4	24.7	74.6
22	2	2	1	2	1	2	2	40.6	81.9	57.6	78.2
23	2	2	1	2	2	3	3	40.3	82.3	68.8	81.3
24	2	2	1	2	3	1	1	31.3	79.9	21.8	75.5
25	1	1	1	3	1	3	2	39.6	77.8	58.5	71.5
26	1	1	1	3	2	1	3	38.7	77.4	23.9	67.7
27	1	1	1	3	3	2	1	38.6	76.4	44.2	71.3
28	1	2	2	3	1	3	2	39.9	80.6	59.6	70.2
29	1	2	2	3	2	1	3	37.2	81.0	24.5	68.3
30	1	2	2	3	3	2	1	38.2	80.8	43.6	71.9
31	2	1	2	3	1	3	3	41.0	79.1	71.4	74.9
32	2	1	2	3	2	1	1	32.3	76.9	21.3	70.5
33	2	1	2	3	3	2	2	42.3	77.2	57.9	76.9
34	2	2	1	3	1	3	1	34.9	80.2	37.3	75.3
35	2	2	1	3	2	1	2	34.1	80.1	23.6	73.2
36	2	2	1	3	3	2	3	42.1	80.3	79.4	80.4

Table 6 Sum of squares for event 1

DP	Knee bolster	Airbag
$FR_{1,1}$	1000.1	21.3
$FR_{1,2}$	56.1	67.0

Table 7 Sum of squares for event 2

DP	Knee bolster	Airbag
$FR_{2,1}$	8789.8	277.5
$FR_{2,2}$	147.4	36.7

Table 8 Sum of squares for event 3

DP	Knee bolster	Airbag	Seat belt
$FR_{3,1}$	365.4	2.6	27.4
$FR_{3,2}$	7.6	30.0	98.9

Table 9 Sum of squares for event 4

DP	Knee bolster	Airbag	Seat belt
$FR_{4,1}$	13398.3	86.9	15.1
$FR_{4,2}$	162.3	128.0	220.6

Table 10 Relative magnitude of the sum of squares for event 1

DP	Knee bolster	Airbag
$FR_{1,1}$	1.0	0.021
$FR_{1,2}$	0.837	1.0

Table 11 Relative magnitude of the sum of squares for event 2

DP	Knee bolster	Airbag
$FR_{2,1}$	1.0	0.032
$FR_{2,2}$	1.0	0.249

Table 12 Relative magnitude of the sum of squares for event 3

DP	Knee bolster	Airbag	Seat belt
$FR_{3,1}$	1.0	0.007	0.075
$FR_{3,2}$	0.077	0.303	1.0

Table 13 Relative magnitude of the sum of squares for event 4

DP	Knee bolster	Airbag	Seat belt
$FR_{4,1}$	1.0	0.006	0.001
$FR_{4,2}$	0.736	0.580	1.0

An element of the design matrix is assumed to be zero if the relative magnitude is below the allowable tolerance. In this study, the allowable tolerance is defined as 0.1. From the sensitivity analysis, the design equation of the OPS at each event is defined as follows:

@event 1: 5% dummy, 25mph, unbelted

$$\begin{Bmatrix} FR_{1,1} \\ FR_{1,2} \end{Bmatrix} = \begin{bmatrix} X_1 & 0 \\ X_1 & X_1 \end{bmatrix} \begin{Bmatrix} KneeBolster \\ Airbag \end{Bmatrix}$$

@event 2: 50% dummy, 25mph, unbelted

$$\begin{Bmatrix} FR_{2,1} \\ FR_{2,2} \end{Bmatrix} = \begin{bmatrix} X_2 & 0 \\ X_2 & X_2 \end{bmatrix} \begin{Bmatrix} KneeBolster \\ Airbag \end{Bmatrix}$$

@event 3: 5% dummy, 30mph, belted (7)

$$\begin{Bmatrix} FR_{3,1} \\ FR_{3,2} \end{Bmatrix} = \begin{bmatrix} X_3 & 0 & 0 \\ 0 & X_3 & X_3 \end{bmatrix} \begin{Bmatrix} KneeBolster \\ Airbag \\ SeatBelt \end{Bmatrix}$$

@event 4: 50% dummy, 35mph, belted

$$\begin{Bmatrix} FR_{4,1} \\ FR_{4,2} \end{Bmatrix} = \begin{bmatrix} X_4 & 0 & 0 \\ X_4 & X_4 & X_4 \end{bmatrix} \begin{Bmatrix} KneeBolster \\ Airbag \\ SeatBelt \end{Bmatrix}$$

Some FRs exist in different events and these FRs have to be distinguished. Therefore the FRs at each event are represented by $FR_{i,j}$ where i is the event number and j is the FR number. Actually, $FR_{m,j}$ and $FR_{n,j}$ ($m \neq n$) are the same (shared FR). From Eq. (7), the full design equation is made as

$$\begin{Bmatrix} FR_{1,1}, FR_{2,1}, FR_{3,1}, FR_{4,1} \\ FR_{1,2}, FR_{2,2} \\ FR_{3,2}, FR_{4,2} \end{Bmatrix} = \begin{bmatrix} X_1, X_2, X_3, X_4 & 0 & 0 \\ X_1, X_2 & X_1, X_2 & 0 \\ X_4 & X_3, X_4 & X_3, X_4 \end{bmatrix} \begin{Bmatrix} KneeBolster \\ Airbag \\ SeatBelt \end{Bmatrix} \quad (8)$$

From Eq. (8), the order of determination for DPs is defined. A detailed design for DPs will be made based on the order in the next section.

4 DETAILED DESIGN OF THE OCCUPANT PROTECTION SYSTEM

The OPS has many constraints and shared FRs as shown in Eq. (8). Because the effect of the off-diagonal terms is large, a predetermined DP can considerably affect the FRs in the next process. Also, the constraints of the next process may not be satisfied if a DP of the previous process is fixed. Therefore, multiple solutions for each DP are obtained in the detailed design process. The multiple solutions can be acquired by using a full factorial design at each step of the design order. As mentioned earlier, a full factorial design is performed for computer simulation [21,22].

4.1 ANALYSIS OF THE KNEE BOLSTER

Figure 2 and Table 3 show the design variables and the levels for the knee bolster. The knee bolster protects the lower body and the corresponding injury is the femur load. The femur load is measured in two places of the left femur and the right femur. Based on Eq. (8), four events are involved for the knee bolster.
Table 14 shows the results of a full factorial simulation and the number of simulations is 36. The results are normalized percentages by the criteria in Table 1. Two feasible design conditions are selected based on the maximum femur load among the eight femur loads. In Table 14, the shadowed space represents the case when the femur load is above 80%, which means the constraint is violated. The two feasible designs are transmitted to the next process. Max(FR) in Table 14 is the maximum value of $FR_{i,1}$ (i=1,…,4).

Table 14 Simulation results for the knee bolster

DOE no.	Shape	Thickness (mm)	$FR_{1,1}$	$FR_{2,1}$	$FR_{3,1}$	$FR_{4,1}$	Max(FR)
1	type 1	1.0	60.9	118.7	22.3	19.9	118.7
2	type 1	1.5	59.5	134.4	25.3	21.0	134.4
3	type 1	2.0	59.7	125.3	26.4	24.1	125.3
4	type 2	1.0	61.1	71.5	26.2	45.3	71.5
5	type 2	1.5	68.5	111.0	28.3	56.8	111.0
6	type 2	2.0	68.0	126.6	29.1	77.0	126.6
7	type 3	1.0	69.5	70.7	26.5	38.8	70.7
8	type 3	1.5	77.0	101.7	26.8	58.4	101.7
9	type 3	2.0	78.8	122.7	28.9	72.0	122.7

4.2 ANALYSIS OF THE AIRBAG

The airbag protects the upper body and the corresponding injury is HIC15, the chest acceleration (chest G) and the neck injury in Table 1. In Eq. (8), two events are involved in the airbag. In the previous step, two feasible designs of the knee bolster are selected. The full factorial cases are defined including the two feasible designs. Therefore, the total number of cases is 72 as shown in Table 15.
The design variables and levels of the airbag are shown in Table 3. Table 15 shows the results of a full factorial simulation for the airbag. $FR_{i,2}$ is the maximum of HIC15, chest G and neck injury, and Max (FR) is the larger one of $FR_{1,2}$ and $FR_{2,2}$. The shadowed spaces represent the cases where the constraint is violated. From Table 15, 9 feasible design designs are selected and these include the design of the knee bolster and the airbag.

Table 15 Simulation results for the airbag

DOE no.	Shape	Thickness (mm)	Bag diameter	Inflator (kPa)	Vent hole (mm)	$FR_{1,2}$	$FR_{2,2}$	Max(FR)
1	type 2	1.0	680	190	20	81.4	78.8	81.4
2	type 2	1.0	680	190	25	79.6	78.3	79.6
3	type 2	1.0	680	190	30	77.0	77.1	77.1
4	type 2	1.0	680	200	20	80.1	76.7	80.1
5	type 2	1.0	680	200	25	78.6	77.3	78.6
6	type 2	1.0	680	200	30	77.2	76.9	77.2
7	type 2	1.0	680	210	20	77.2	75.0	77.2
8	type 2	1.0	680	210	25	77.0	74.7	77.0
9	type 2	1.0	680	210	30	75.0	74.6	75.0
10	type 2	1.0	710	190	20	83.0	78.1	83.0
11	type 2	1.0	710	190	25	81.2	79.0	81.2
12	type 2	1.0	710	190	30	80.6	78.1	80.6
13	type 2	1.0	710	200	20	79.4	78.0	79.4
14	type 2	1.0	710	200	25	77.6	77.1	77.6
15	type 2	1.0	710	200	30	77.9	76.9	77.9
16	type 2	1.0	710	210	20	78.6	77.1	78.6
17	type 2	1.0	710	210	25	77.9	76.4	77.9
18	type 2	1.0	710	210	30	77.4	75.5	77.4
19	type 3	1.0	680	190	20	80.7	75.8	80.7
20	type 3	1.0	680	190	25	79.2	75.7	79.2
21	type 3	1.0	680	190	30	77.9	74.4	77.9
22	type 3	1.0	680	200	20	80.8	74.0	80.8
23	type 3	1.0	680	200	25	78.8	74.1	78.8
24	type 3	1.0	680	200	30	77.4	73.9	77.4
25	type 3	1.0	680	210	20	77.7	72.8	77.7
26	type 3	1.0	680	210	25	77.3	71.9	77.3
27	type 3	1.0	680	210	30	75.7	71.6	75.7
28	type 3	1.0	710	190	20	83.2	73.6	83.2
29	type 3	1.0	710	190	25	81.8	77.3	81.8
30	type 3	1.0	710	190	30	80.2	76.2	80.2
31	type 3	1.0	710	200	20	79.1	74.7	79.1
32	type 3	1.0	710	200	25	78.2	74.2	78.2
33	type 3	1.0	710	200	30	77.3	74.1	77.3
34	type 3	1.0	710	210	20	78.2	74.2	78.2
35	type 3	1.0	710	210	25	77.0	73.4	77.0
36	type 3	1.0	710	210	30	77.9	72.7	77.9

Table 16 Simulation results for the seat belt

DOE no.	Shape	Thickness (mm)	Bag diameter	Inflator (kPa)	Vent hole (mm)	Load limiter (N)	Elongation (%)	$FR_{3,2}$	$FR_{4,2}$	Max(FR)
1	type 2	1.0	680	210	30	3500	7	76.4	71.3	76.4
2	type 2	1.0	680	210	30	3500	11	79.4	72.1	79.4
3	type 2	1.0	680	210	30	4500	7	75.7	75.6	75.7
4	type 2	1.0	680	210	30	4500	11	79.7	77.7	79.7
5	type 3	1.0	680	210	30	3500	7	76.2	71.3	76.2
6	type 3	1.0	680	210	30	3500	11	79.2	72.1	79.2
7	type 3	1.0	680	210	30	4500	7	75.5	75.8	75.8
8	type 3	1.0	680	210	30	4500	11	79.3	78.1	79.3
9	type 2	1.0	680	210	25	3500	7	77.5	73.2	77.5
10	type 2	1.0	680	210	25	3500	11	80.5	74.2	80.5
11	type 2	1.0	680	210	25	4500	7	76.9	77.1	77.1
12	type 2	1.0	680	210	25	4500	11	80.9	79.1	80.9
13	type 3	1.0	710	210	25	3500	7	78.3	72.6	78.3
14	type 3	1.0	710	210	25	3500	11	81.5	73.8	81.5
15	type 3	1.0	710	210	25	4500	7	77.1	76.7	77.1
16	type 3	1.0	710	210	25	4500	11	81.5	79.3	81.5
17	type 2	1.0	680	190	30	3500	7	77.7	69.0	77.7
18	type 2	1.0	680	190	30	3500	11	81.0	70.1	81.0
19	type 2	1.0	680	190	30	4500	7	77.2	72.2	77.2
20	type 2	1.0	680	190	30	4500	11	80.3	75.0	80.3
21	type 2	1.0	680	210	20	3500	7	78.2	74.8	78.2
22	type 2	1.0	680	210	20	3500	11	81.6	75.7	81.6
23	type 2	1.0	680	210	20	4500	7	78.0	79.3	79.3
24	type 2	1.0	680	210	20	4500	11	81.8	80.7	81.8
25	type 2	1.0	680	200	30	3500	7	77.2	70.2	77.2
26	type 2	1.0	680	200	30	3500	11	81.1	71.0	81.1
27	type 2	1.0	680	200	30	4500	7	76.6	74.5	76.6
28	type 2	1.0	680	200	30	4500	11	80.2	76.6	80.2
29	type 3	1.0	680	210	25	3500	7	77.3	73.2	77.3
30	type 3	1.0	680	210	25	3500	11	80.4	74.6	80.4
31	type 3	1.0	680	210	25	4500	7	76.8	77.4	77.4
32	type 3	1.0	680	210	25	4500	11	80.5	79.5	80.5
33	type 3	1.0	710	200	30	3500	7	77.3	69.6	77.3
34	type 3	1.0	710	200	30	3500	11	80.8	70.8	80.8
35	type 3	1.0	710	200	30	4500	7	77.3	72.8	77.3
36	type 3	1.0	710	200	30	4500	11	79.7	76.0	79.7

4.3 Analysis of the Seat Belt

In the previous step, 9 feasible designs are selected. Full factorial cases are made including the 9 designs. Thus the total number of the cases is 36. The seat belt design variables and levels are shown in Table 3. The seat protects the upper body and the corresponding injury is HIC15, Chest G and neck injury. In Eq. (8), two events are involved in the seat belt.

Table 16 shows the results of full factorial cases for the seat belt. $FR_{i,2}$ is the maximum of HIC15, chest G and neck injury, and Max (FR) is the larger one of $FR_{3,2}$ and $FR_{4,2}$. The shadowed spaces represent the cases where the constraint is violated. Therefore, multiple solutions are obtained. The final design will be selected in the next section by the NCAP test.

4.4 Discussion

The occupant protection system (OPS) is an event-driven flexible system and has to be designed to satisfy the FRs at all events. The OPS is evaluated by using the full design equation for the conceptual design and a full factorial design for the detailed design. The design order of DPs for the OPS is determined from the full design equation. The knee bolster is designed first, the airbag is designed second and the seat belt is designed last.

180 simulations are performed for a full factorial design. The design is carried out based on the full factorial design. In Table 14, the femur load of type 1 is high because the deformation of type 1 is very large and contact occurs between the femur and the cowl cross member. Thus, the knee bolster becomes stiffer. From Tables 15 and 16, multiple solutions are obtained.

In early development of the vehicle, it is advantageous to have multiple solutions. But sometimes the designers may want to obtain a single solution. In this case, new evaluation criterion can be used. In this study, the priority list is determined by using the NCAP star rating as shown in Table 1. The priority list is shown in Table 17 and the first row is the best. In the final design, the airbag inflator has low pressure and the vent hole becomes large. The seat belt is designed to have properties of 7% elongation and 3500N load limiter.

Table 17 Priority list based on the NCAP star rating

Shape	Thickness (mm)	Bag diameter (mm)	Inflator (kPa)	Vent hole (mm)	Load limiter (N)	Elongation (%)	NCAP star rate (%)
type 2	1.0	680	190	30	3500	7	8.23
type 3	1.0	710	200	30	3500	7	8.42
type 2	1.0	680	200	30	3500	7	8.61
type 2	1.0	680	210	30	3500	7	8.96
type 3	1.0	680	210	30	3500	7	8.98
type 2	1.0	680	190	30	4500	7	9.15
type 2	1.0	680	210	30	3500	11	9.21
type 3	1.0	680	210	30	3500	11	9.22
type 3	1.0	710	200	30	4500	7	9.40
type 3	1.0	710	210	25	3500	7	9.78
type 2	1.0	680	200	30	4500	7	9.94
type 3	1.0	680	210	25	3500	7	10.07
type 2	1.0	680	210	25	3500	7	10.07
type 2	1.0	680	210	30	4500	7	10.35
type 3	1.0	680	210	30	4500	7	10.39
type 3	1.0	710	200	30	4500	11	10.40
type 2	1.0	680	210	30	4500	11	11.09
type 3	1.0	710	210	25	4500	7	11.20
type 3	1.0	680	210	30	4500	11	11.21
type 2	1.0	680	210	20	3500	7	11.25
type 2	1.0	680	210	25	4500	7	11.43
type 3	1.0	680	210	25	4500	7	11.50
type 2	1.0	680	210	20	4500	7	12.92

5 CONCLUSIONS

The event-driven flexible system is defined as a system whose functional requirements and design equation change according to events. This system is a subcategory of the flexible system. When the full design equation is established, the relationships of the shared FRs can be drawn and the design order of DPs can be determined.

The Occupant Protection System (OPS) is an event-driven flexible system and it is investigated by using a full design equation for conceptual design. For a detailed design, the full factorial design is utilized for all the cases. Each case is evaluated by computer simulation and a design is determined based on the order of the conceptual design. From the full factorial simulation, multiple solutions can be acquired. The final solution is determined to have the best value in the NCAP test. In future work, the OPS for side impact will be studied.

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