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Research on Configuration Process of Nuclear Power Valve Design System based on Axiomatic Design

Li Yuan[1], Dai Ye[2]* and Li Kun[2]

[1]*School of Mechanical Engineering and Automation, University of Science and Technology LiaoNing, Liaoning Anshan 114051,China*
[2]*School of Mechanical & Power Engineering, Harbin University of Science and Technology, Heilongjiang Harbin 150080, China*
**daiye312@163.com*

Abstract

In order to construct the design system of nuclear power valve, the axiomatic design theory is introduced in configuration process of the valve structure design. According to the functional requirement and the complex mechanical structure of the nuclear power valves, the relationship model between design parameters and functional requirements is created by using the"zigzagging"mapping. Then the design matrix can be established and the design order can be planned. After that, the complete mapping table in design process is established through decoupling to quasi-coupling design, and the valve design process according to axiomatic method is constructed. On this basis, a rapid design system is constructed by combining the structural features with the multi-characteristic optimization requirement, in which the configuration process model established by axiomatic method provides valve design in integrated system with reasonable navigation and improves the rationality and the objectivity in design development process.

Keywords: *axiomatic design; decoupling design; integrated system; nuclear power valve*

1. Introduction

At present, the most of nuclear power valve design at home is given priority to with deformation design, namely, according to the customer's individuation demand with reference to the original mature products, a new type of nuclear power valve products is usually designed by the retrofit design on the basis of the introduced mature technology[1-3]. The traditional design pattern usually leads to the blindness of the design process and the repetition of design[4-6]. In addition, there is no reasonable design process model as guidance in the process of constructing the design flow of integrated system of the nuclear power valve products[7-10]. In order to avoid or eliminate the repetitive design phenomenon existing in the product design process, axiomatic design (AD) was proposed to solve this problem. AD was proposed by Prof. Suh from Massachusetts Institute of Technology, which focus on the theoretical rules in the field of design and manufacture [11]. Johnnesson studied the functional coupling problem in the axiom design and used graphics to analyze the coupling relationship among the product functions[12]. Shin divided the coupling design into three types, and decoupled each type of the coupling design respectively using appropriate TRIZ strategy. This approach is suitable for some simpler design problems[13]. A new method of product platform design is put forward guided by the axiomatic design framework, in which extension clustering algorithm was used to make the clustering algorithms of the design correlation matrix[14]. Cheng developed a planning

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method for product platform based on axiomatic design and sensitivity design structure matrix[15]. The mathematical model for design parameters satisfying common platform parameters was deduced according to axiomatic design. Then, through an example of automatic bookbinding machine platform design, it was verified that the proposed method was effective. In this paper, based on the ways of thinking above, axiomatic design theory is adopted to restructure the valve design process and guide the design process and sorting of the valve products in this paper. Axiomatic design method is applied to the configuration process of the nuclear power valve design system, its purpose is to reorganize the design process, decouple the relationship between product function unit and structure unit, and then propose the design sequence that conforms to the axiomatic design. The essence of which is to use the axiomatic design framework to decompose the product design process of nuclear power valve reasonably, establish the product design matrix, and then the design process can be adjusted to a no coupling or quasi coupling design through the matrix. Hence, the navigation process and the compute nodes of the computer aided design system of nuclear power valve can be arranged according to the restructured design process.

2. Axiomatic Design of a Typical Nuclear Power Gate Valve

There are many different kinds of plant valve products, and gate valve is one of the typical representatives, its application is very wide. As shown in Fig.1, the valve is a typical nuclear supercritical electric gate valves (DN230-CL2680), which is consist of valve body, valve plate, valve deck, valve rod, and electric motor, *etc*.

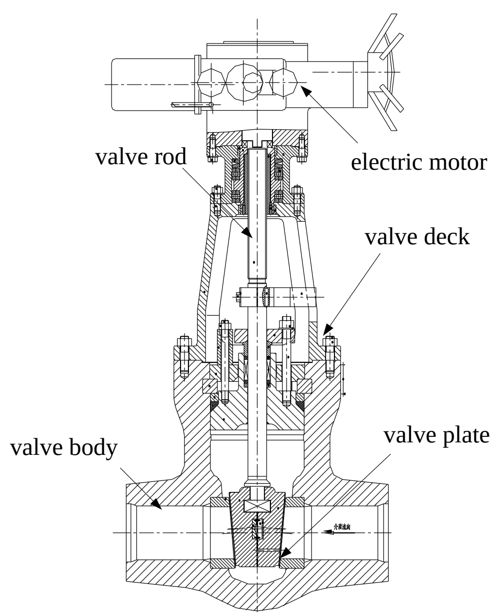

Figure 1 Structure Chart of Electric Gate Valve DN230-CL2680

Axiomatic design judges the advantages and disadvantages of the design quality through the functional independence axiom and information axiom. Axiomatic design theory divides the valve design problem into user domain, functional domain, physical domain and the process domain, as shown in Fig.2.

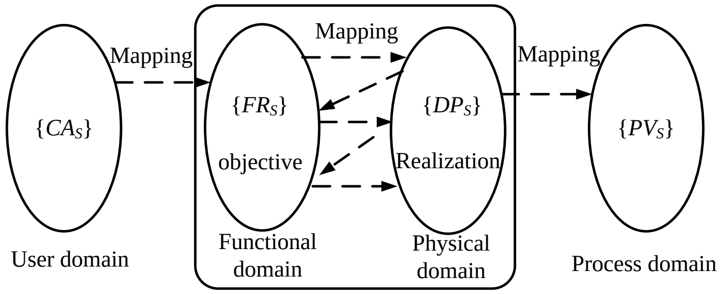

Figure 2 Design Domain and Mapping

Every domain has its own elements, that is, the user needs, functional requirements, design parameters and process variables. The parameters between adjacent two domains mutually transform, forming a top-down "zigzagging" decomposition mapping process. According to the structural characteristics of the gate valve, the valve design process based on axiomatic design can be described as shown in Fig.3.

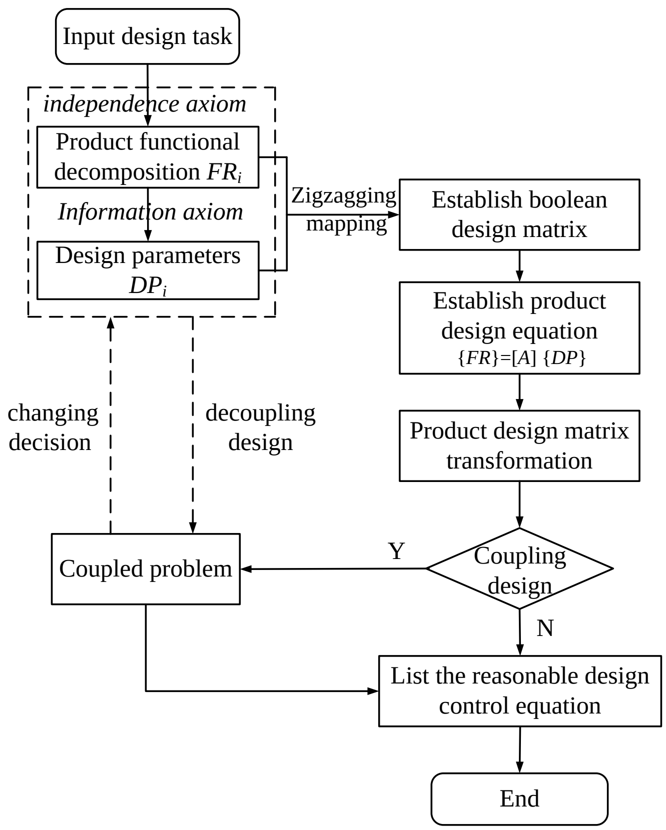

Figure 3 Valve Design Process Based on Axiomatic Design

3. Function Decomposition Based on the Independence Axiom

The particularity of nuclear power valve requirements is that the seismic performance and leak sealing problem of the valve must be considered when the earthquake happens. Therefore, the FRs of this gate valve on the highest design level can be decomposed into three levels: FR_1 —— Open/close function; FR_2 ——Sealing function; FR_3 ——Aseismatic function. The corresponding design parameters is: DP_1——Port open/close structure; DP_2 ——Sealing structure; DP_3 ——Aseismatic structure.

3.1. Function Decomposition of Each Level

According to the analysis above, the design equations can be represented as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix} \times \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \qquad (1)$$

In the design matrix above, there are three "1" on the off-diagonal elements, that is, A_{21}, A_{23} and A_{31}, representing that the DP_1 impacts FR_2, DP_3 impacts FR_2, DP_1 impacts FR_3, respectively. This relationship can be seen from the structure of the electric gate valve, namely, the movement of the valve's opening and closing mechanism may affect the sealing of the valve body, the connection between the valve body and pipelines can also affect the valve sealing, and the opening and closing mechanism movement affects aseismatic structure of the valve. At this point, the design matrix is not a diagonal matrix, through the design matrix transformation according to the formula (1), the new design equation can be transformed as:

$$\begin{Bmatrix} FR_1 \\ FR_3 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \times \begin{Bmatrix} DP_1 \\ DP_3 \\ DP_2 \end{Bmatrix} \qquad (2)$$

The design equation has been transformed into a lower triangular matrix, that is, the design at the highest level (the first level) is a quasi coupling design. The following work is to divide the functional requirements and design parameters on the lower decomposition level, until the emergence of leaf design parameters [16]. The second level structural decomposition needs to consider the first level design parameters, and determine the design parameters can meet the first level functional requirement, then the second level design parameters can be determined according to the functional requirement obtained.

Opening/closing function FR_1 must be provided with the following functions: opening and closing of port FR_{11}, driver support FR_{12} and driver provisioning FR_{13} for the corresponding design parameters of the opening and closing components DP_{11}, structural support DP_{12}, driving components DP_{13}, respectively. Hence, the second level design equation of FR_1 can be obtained as shown in Tab.1.

Similarly, sealing function FR_2 refers to the sealing of the body itself and the sealing pipe joint. Therefore, FR_2 can be decomposed into the opening/closing sealing FR_{21} and the pipeline sealing FR_{22}, and the corresponding design parameters are the sealing structure of the valve body $DP_{21}$and the interface sealing structure DP_{22}. Obviously, there is no interference between FR_{21} and FR_{22}, so the second level design equation of FR_2 can be obtained as shown in Tab.1.

The aseismatic structure parameter DR_3 consists of two parts: one is the aseismatic structure between the driving source source and the valve body, another is the connection structure between valve and pipeline. In the case of an earthquake, for instance, the two parts both have the function of locating constraints to play the role of resisting the earthquake load. Therefore, FR_3 can be decomposed into the astigmatic function FR_{31} and the pipeline connection FR_{32}, and the corresponding design parameters are the aseismatic structure DP_{31} and the pipeline connection structure DP_{32}. Similarly, there is no interference between FR_{31} and FR_{32}, so the second level design equation of FR_3 can be obtained as shown in Tab.1.

The third level structural decomposition is to realize the functional decomposition for the design parameters of DP_{11} (on-off structure) and DP_{13} (driving device). Similarly to the decomposition process, the functional requirements of FR_{11} can be decomposed into the fluid passageway FR_{111} and the opening and closing of pipeline FR_{112}, and the corresponding design parameters are the valve body DP_{111} and the gate segment DP_{112}. Then the third level design equation of FR_{11} can be obtained as shown in Tab.1.

Functional requirement FR_{13} can be decomposed into five parts: the power provisioning FR_{131}, the transmission device FR_{132}, the energy conversion FR_{133}, the power transmission FR_{134} and the dynamic seal FR_{135}, and the corresponding design parameters are the power unit, the transmission device structure DP_{132}, the transfer structure DP_{133}, Power transmission structure DP_{134}, and dynamic seal structure DP_{135}. Then the third level design equation of FR_{13} can be obtained. After decoupling transformation, the design matrix between the functional requirements and design parameters can be changed as shown in Tab.1.

Table 1 Design matrix between the functional requirements and design parameters

First level structural decomposition		Second level structural decomposition		Third level structural decomposition
FR	FR_1	$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \times \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix}$ Opening/closing function	FR_{11}	$\begin{Bmatrix} FR_{111} \\ FR_{112} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \times \begin{Bmatrix} DP_{111} \\ DP_{112} \end{Bmatrix}$ Opening and closing of port
$\begin{Bmatrix} FR_1 \\ FR_3 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \times \begin{Bmatrix} DP_1 \\ DP_3 \\ DP_2 \end{Bmatrix}$	FR_2	$\begin{Bmatrix} FR_{21} \\ FR_{22} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \times \begin{Bmatrix} DP_{21} \\ DP_{22} \end{Bmatrix}$ Sealing function	FR_{13}	$\begin{Bmatrix} FR_{131} \\ FR_{132} \\ FR_{134} \\ FR_{135} \\ FR_{133} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{Bmatrix} DP_{131} \\ DP_{132} \\ DP_{134} \\ DP_{135} \\ DP_{133} \end{Bmatrix}$ *Decoupling transformation*
	FR_3	$\begin{Bmatrix} FR_{31} \\ FR_{32} \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \times \begin{Bmatrix} DP_{31} \\ DP_{32} \end{Bmatrix}$ Aseismatic function		$\begin{Bmatrix} FR_{131} \\ FR_{132} \\ FR_{133} \\ FR_{134} \\ FR_{135} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix} \times \begin{Bmatrix} DP_{131} \\ DP_{132} \\ DP_{133} \\ DP_{134} \\ DP_{135} \end{Bmatrix}$ Driver Provisioning

3.2. Function Mapping Process Based on Zigzagging Mapping

From the function decomposition process and the valve design process above, the fundamental function of this nuclear power gate valve is *FR* (on-off control of pipe); the overall design parameters is *DP* (valve structure), and the design constraint is *Cs* (keeping the valve seal). In accordance with the decomposition principle of the independence axiom, the zigzagging mapping method is used in the mapping transformation between functional domain and structure domain. As shown in Fig.4, the whole mapping map can be obtained. From the top section of functional decomposition process, it can be seen that every design matrix in the three levels has been become uncoupled or quasi coupling form, so it can be verified that the nuclear power gate valve structure satisfies the requirements of axiomatic design.

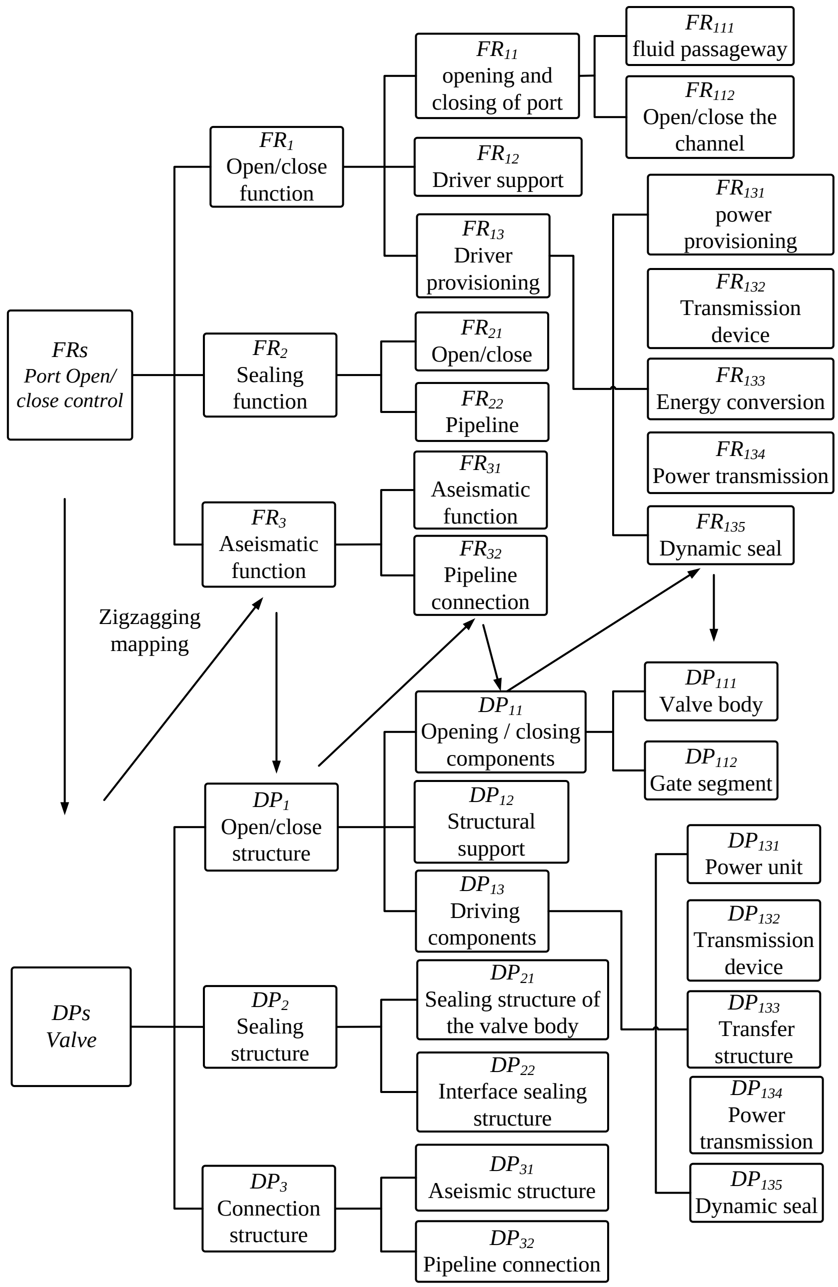

Figure 4 Mapping Between Functional Requirement and Design Parameter

4. Configuration Process of Valve Design System

In order to provide a visual representation of the configuration Process of the nuclear power valve design system, a module connection diagram is introduced here to describe the design process expressed by the design matrix above. The Symbol "○" is adopted to express the module joint operations so as to show the relationship among modules.

For no coupling design, "circle S" is used to represent the simple addition of *FRs*; "circle C" signifies that *DPs* and *Ms* must be controlled according to the decoupling order of the design matrix; "circle F", used for a coupling design, shows it is in violation of the independence axiom. Through the analysis of the design matrix in Tab.1, the nuclear power valve design flow chart can be generalized. As shown in Fig.5, the design of the gate valve design complies with the sequence from the outside to the inside, which embodies the requirement of the axiomatic design. "*M*" in the figure stands for the design parameters. At the highest level, the nuclear power valve is composed of three sequential modules: M_1 (port opening and closing module) ——M_3 (aseismatic module) ——M_2 (sealing module). And M_1 can also be divided into three parts: M_{11} (open-close structure module) ——M_{12} (support structure module) ——M_{13} (driving structure module). M_{11} is composed of parallel module $M_{111}$and M_{112}, so the design of DP_{111} and DP_{112} can first be determined. By the same token, the whole valve structure design order can be obtained.

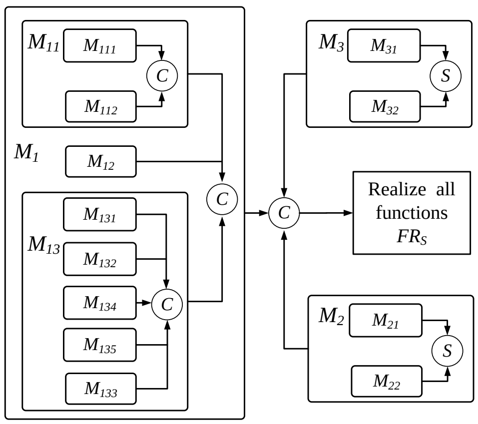

Figure 5 Valve Design Flow Chart

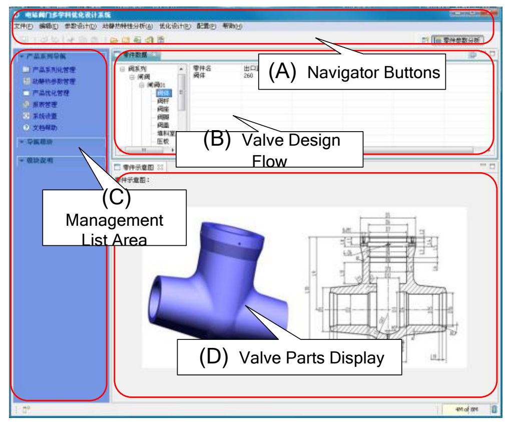

Figure 6 Main Interface of the Design System

Valve design flow chart describes all the influence relationships of the design tasks. Through the analysis of the complete design matrix, the valve design process model conformed to the axiomatic principle design is set up. Then, based on this process model, the design flow in the design system can be determined. As shown in Fig.6, the main interface of the integrated system for valve products is divided into four functional areas, namely, navigation buttons (A), valve design flow (B), management list area (C) and valve parts display (D). In the valve design flow area, the design process of valve parts fully embodies design thought of the axiomatic principle, which ensures the objectivity and correctness of the valve restructuring design process. And this process model can describe the whole process of valve design, which has a guiding role on the digital design and management. At the same time, the design process management model for the digital design behind provides the support of the valve data structure organization.

5. Conclusion

The application of axiomatic design method can not only propose a new product design, but also can analyze rationally the structure of the existing products and optimize the design process. In this paper, the axiomatic design method is applied to analyze the gate valve structure, which takes the interrelations between the various functional requirements and design parameters into consideration. Then, the configuretion process model of the design system is established by axiomatic method, which provides valve design in integrated system with reasonable navigation and improves the rationality and the objectivity in design development process.

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