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Study on the collaborative design PN-PDDP model for the multi-component coupling rotor system based on Petri nets

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Abstract

Based on the analysis of the characteristics for the design process in the complex multi-component coupling rotor system, and considering the fact that the multi-components co-design is demanded in the design process of the performance-driven target coupled rotor system, a PN-PDDP (Petri Network for Performance Driven Design Process) model based on the extended Petri nets is presented. The model defines the libraries of the performance and structure characteristics, the traces Token and firing rules. With the model, the flow process of the various coupled information flow is described, and the conflict resolution mechanism for the conflict information is developed. The model also offers guidance on the construction of the related database and design platform, which will provide the important design tools and implementation means for the design of the multi-component coupling turbopump rotor system in the liquid rocket engine.

Keywords: Petri nets; Performance-driven design; Multi-component coupling rotor system design; Coupled information; Information flow

1. Introduction

The design process of a complex system or project is, in effect, a collaborative process, even involving teams or individuals across different places. This is especially true when the teams are made up of engineers across widely different fields. There are a certain number of researchers who have conducted research on collaborative design and platform for a complex system or product in certain field. For example, in the field of aerospace, the NASA of the United States has developed the CEE (Collaborative Engineering Environment) so as to promote the collaboration among design teams geographically apart. The key idea of the CEE is the collaborative multi-discipline design and the whole life cycle design. In this paper, a design method on high-performance high-speed turbopumps is studied. At present, the separate developments of varied technologies involved in high-speed turbopumps have set the stage for the integration design. For example, great achievements have been made in bearings, seal, and balance discs by our research teams [1-3], which was impossible in the past. Nonetheless, the design of a complex multi- component integrated system is extremely complicated, calling for the collaboration of researchers from different departments and fields. Therefore, this paper proposes the collaborative design PN-PDDP model for the multi-component coupling rotor system based on Petri nets with a view to facilitating fast and efficient design. There has been some development in applying the Petri nets theory and computer technology into system design, such as making judgments on information or monitoring information flow, the characteristics and strengths of which are obvious [4-6]. Specifically, Xiao ZJ et al. advanced the work-flow planning method based on colored Petri nets, in which the integration of static and dynamic local optimization was achieved via effective task grouping and stage dividing [4]. Zhang GB et al. conducted modeling for assembly reliability based on generalized stochastic Petri nets [5]. Zhang JL et al. presented

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a stochastic Petri nets support for exception handling flexible workflow modeling and performance analysis method [6].

Quite a number of researchers have also conducted research on the development of Petri nets-based long-distance cooperation system or product collaborative design system [7-13]. For example, Kuisak A advanced a Petri nets-based complex system design model and analysed its characteristics [7]. Karniel A et al. summarized the designing process of complex products, and spoke highly of the Petri nets-based design [8]. An and Li presented a formalized method of process control Petri nets for entire collaborative design process, which allowed variability in the design process and multi tasks to be executed simultaneously according to the different process definitions [9]. Ouertani M Z examined the knowledge flow in the product design process from the perspective of collaborative design [10]. Han et al. presented a multilevel Petri nets-based distributed collaborative research and design system design model for complex products, and conducted a project analysis on the distributed collaborative research and development system of new regional aircraft ARJ21[11]. He et al. presented a multi-level colored Petri nets to characterize collaborative design, and developed a data-driven workflow engine according to the characteristics of collaborative design [12].

The present study presents a PN-PDDP (Petri Network for Performance Driven Design Process) model based on the extended Petri nets so as to enhance design efficiency and quality after analyzing the design process of the performance-driven multi-component coupling rotor system in the liquid rocket engine.

2. Design process of the performance-driven multi-component coupling rotor system

2.1. *Performance characteristics model and structure characteristics model of the multi-component coupling rotor system*

The performance-driven product design theories point out that the key to product design is to guarantee performance, which should guide the whole design process. Performance characteristics indicators have controlled the whole design process [13]. Meanwhile, modern design stresses that knowledge is the essential resource in design activities, and that the design process is the process of transforming knowledge from the task space in the solution space, which results in the mapping of product performance characteristics onto structure characteristics. The product performance characteristics model is a hierarchical model, in which the high-level characteristics are abstract and general, the low-level characteristics are instantiation of high-level ones, and accordingly the former can realize the latter. Unlike the performance characteristics model, the product structure characteristics model is a high-level model based on the product assembly relationship, which is realized by low-level substructures via the assembly relationship.

In the initial stage, the product performance model obtained through user requirements analyses includes only component of product performance characteristics, and the abstract higher component of those characteristics has yet found its counter-component in the extant structure characteristics, and demands further decomposition into more specific performance characteristics. The process of working on and decomposing the product performance characteristics is termed the performance decomposition process, which aims at realizing high-level performances and obtains low-level performance activities via decomposition. The complete product performance characteristics model finally obtains as a result of the whole design activities.

The product structure characteristics model in the initial design stage can only meet component of initial product performance requirements such that it calls for improvement. During the design process, the designers would constantly improve the structure model in order that the improved structure model would further meet the product performance requirements, which is termed the structure design process. Building a product structure characteristics model is to establish a mapping relationship between the product structure characteristics and the performance characteristics models so as to present the whole performance characteristics needs. Fig.1 displays the performance characteristics and the structure characteristics models of the multi-component coupling rotor systems.

The performance decomposition process and the structure design process are not independent but interactive. This is because the former is based on the latter, and the precondition of the former is that the concrete structure is determined. With reference to the multi-component coupling rotor systems focused on in this paper, the performance characteristics model refers to the rotor supporting components and its dynamic performances. If the relevant components are not determined, the performance decomposition cannot proceed. On the other hand, once the rotor support bearing and coupling components are determined, the performance of rotating rotor system, supported by this kind of bearings, could be further decomposed into the load performances and dynamic performances.

2.2. *Formalization of the design process*

To build a PN-PDDP (Petri Network for Performance Driven Design Process) model based on the extended Petri nets, the following attempts have been made on formalization in line with the performance-driven design process theory.

Definition 1: The product performance characteristics model [P] is to describe product performance characteristics as well as their interrelationships.

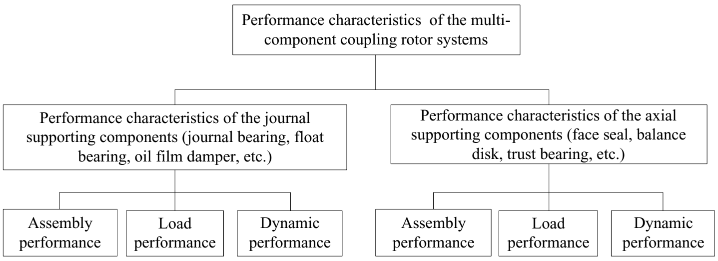
Definition 2: The product structure characteristics model [D] is to describe product structure characteristics as well as their interrelationships.

Definition 3: Design activities is defined as the mapping process, in which the product performance characteristics model is mapped onto the product structure characteristics model under the guidance of the defined performance characteristics.

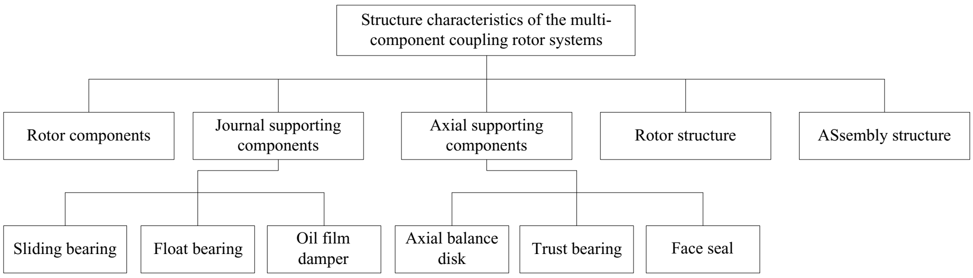
In this paper, design activities fall into two categories:

1) Performance decomposition activities are defined as the activities which operate on the product performance

characteristics model, symbolized as A_P, as shown in the following formula:



a. Performance characteristics model



b. Structure characteristics model

Fig. 1. The performance characteristics model and the structure characteristics model of the multi-component coupling rotor system.

$$A_P : \{[P]_i, [D]_i \mid [P]_i \to [P]_j\} \tag{1}$$

where i, j are the ordinal numbers of design activities, $[P]_i$ represents the performances to be decomposed, and $[D]_i$ represents their corresponding structure characteristics.

2) Structure design activities are defined as the design activities that operate on the product structure characteristics model, symbolized as A_D, as shown in the following formula:

$$A_D : \{[P]_i, [D]_i \mid [D]_i \to [D]_j\} \tag{2}$$

Where, $[P]_i$ represents the performances to be realized by the structure design, and $[D]_i$ represents their corresponding structure characteristics.

Definition 4: Design process DP consists of a series of design activities, which aim at obtaining perfect product performance and structure characteristics models and making the final product structure characteristics model comply with the final product performance characteristics model, as indicated by the following formula:

$$DP : \{\sum_{m}^{i=0} A_i, [D]_0, [P]_0 \mid [D]_0 \to [D]_i, [P]_0 \to [P]_i, [D]_i \to [P]_j\} \tag{3}$$

3. Petri nets model for design process

Only if the design process model is built, we can accurately describe the flow of information resources during the design process. In addition, after building the model, we can analyze the relationship between varied phenomena involved in the design process and model characteristics parameters, and study the effects of those phenomena on the design process and how to respond to them. And all these contribute to shortening the design cycle and enhancing the design efficiency. In this section, the descriptive model for the design process is first presented.

3.1. Petri Network for Performance Driven Design Process (PN-PDDP)

Taking the performance-driven modern mechanical product design theory as a starting point, this section suggests using the extended Petri nets to describe the design process of the multi-component coupling turbopump rotor system. The use of Petri nets makes possible the building of a more accurate design model, which is also not too complicated, and can achieve an effective analysis of the design process by simply revising the existing analysis tools. In this paper, the Petri network for performance driven design Process is shortened to PN-PDDP. Refer to Reference [14] for the terminologies pertinent to Petri nets.

A PN-PDDP consists of four unknowns, as shown in the following:

$$PN \cdot PDDP = (S, T; F, M_0) \tag{4}$$

Where, S is the set comprised of PN-PDDP performance and structure characteristics parameters, T is the set comprised of design activities, PN-PDDP is the Petri Network for Performance Driven Design Process, F is the set of the arc indicative of the relationship between the design performance and data characteristics parameters and design activities,

$F \subseteq (S \times T) \bigcup (T \times S)$, and M_0 describes the initial state of PN-PDDP. $X = U \bigcup T$ is called the element set of PN-PDDP. If $x \in X$, then define:

${}^*x$ is the before set of x, and ${}^*x = \{ y \mid (y, x) \in F \}$;

x^* is the after set of x, and $x^* = \{ y \mid (x, y) \in F \}$.

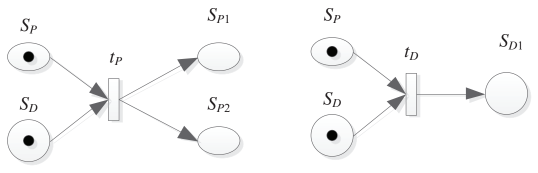
The necessary and sufficient conditions for PN-PDDP are as follows:

$$\begin{cases} S \bigcap T = \varphi \\ F \subseteq (S \times T) \bigcup (T \times S) \\ S \bigcup T \neq \varphi \\ dom(F) \bigcup cod(F) = S \bigcup T \end{cases} \tag{5}$$

Where, $dom(F) = \{ x \mid \exists y : (x, y) \in F \}$; $cod(F) = \{ x \mid \exists y : (y, x) \in F \}$.

The libraries of PN-PDDP are classified into two categories: performance and structure libraries (S_P and S_D), where the former describes the product performance characteristics and the latter the product structure characteristics. In the subsequent analysis, the former is signalled by ovals and the latter by circles.

Design activities t also fall into two categories, as shown in Fig.2.



a. Performance decomposition b. Structure design activities

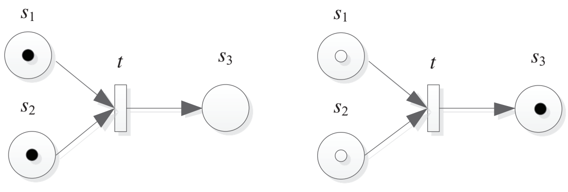
Fig. 2. Performance decomposition and structure design activities.

Performance decomposition activities t_p complete the process of decomposing the higher level performances into lower level performance (S_{P1} and S_{P2}). The input for this process is the performance and structure characteristics parameters of the higher level whereas its output is the sub-performance characteristics parameters of the lower level obtained after decomposition. Meanwhile, structure design activities t_D decompose the father structure into the son structure(S_{D1}), the input of such activities is the performance characteristics requirements for the structure and the relevant structure characteristics parameters, and its output is the structure characteristics parameters meeting the product performance requirements.

Petri nets describe the resource flow and consumption in the discrete events during the design process. However, neither structure characteristics nor performance characteristics parameters can be viewed as a kind of usable design resources. The common practice to deal with such problems is to define the respective libraries according to the data state of either structure or performance characteristics. Nonetheless, in reality, such practices fail to embody the idea of performance-driven design. Therefore, the extant Petri nets need to be expanded, and specifically, *Token* and change rules are redefined and in this paper.

3.2. Trace Token and firing rules

S belongs to the before set ${}^*t$ of activity *t*. It is specified that after activity *t* is fired, *Token* in *s* does not disappear and also leaves traces, which are called trace *Token*, as shown in Fig. 3, in which hollow circles represent trace *Token*.



a. before *t* fires b. after *t* fires

Fig. 3. Trace *Token* in the libraries.

As can be seen in Figure 3, before activity *t* fire, s_1 and s_2 have had *Token*, and after it, s_1 and s_2 do not lose *Token*. It is only that *Token* has turned into trace *Token*.

Therefore, the state function $M(s)$ can be defined as follows:

$$M(s) = \begin{cases} 0 & \text{When } s \text{ does not have } Token \\ 1 & \text{When } s \text{ has ordinary } Token \\ T & \text{When } s \text{ has } Token \text{ trace} \end{cases} \tag{6}$$

When the before set of activity *t* has the trace library, the firing condition of *t* is as follows:

$$\forall s \in^* t : M(s) \neq 0 \bigcap \exists s : M(s) = 1 \tag{7}$$

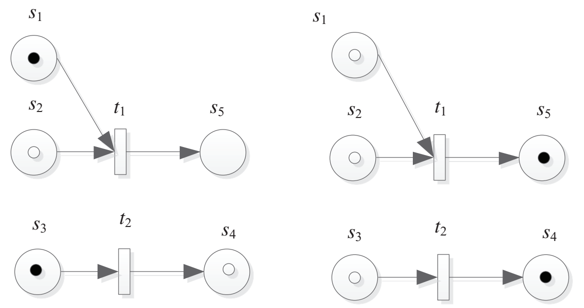
The above formula suggests two conditions for *t* to fire. One is that all the libraries of the before set of *t* must have *Token*, and another is that they must include libraries of ordinary *Token*. In other words, if all the libraries of the before set of *t* have *Token* and all *Token* s are trace *Token*, *t* cannot fire. As shown in Fig.3, once *t* fires, though s_1 and s_2 have *Token*, they are all trace *Token* such that *t* fails to fire again.

Based on the above discussion, the firing rules of PN-PDDP are defined as follows:

$$M'(s) = \begin{cases} 1 & s \in t^* - {}^*t \\ T & s \in {}^*t - t^* \end{cases} \tag{8}$$

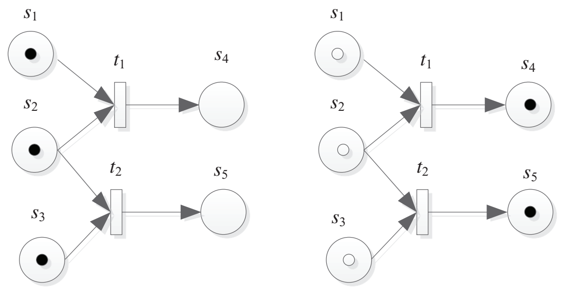
Two cases should be distinguished. When the libraries of the before set of *t* include libraries containing trace *Token* s, the *Token* s in the latter libraries keep their original state after *t* fires; when the libraries of the after set of *t* include libraries containing trace *Token* s, the *Token* s in the latter libraries change into ordinary *Token* s after *t* fires. This is illustrated in Fig.4.

The introduction of the libraries of trace *Token* would change the firing rules of PN-PDDP with Petri nets conflicts.



a. before t fires b. after t fires

Fig. 4. The transition rules of trace *Token*s.



a. before t fires b. after t fires

Fig. 5. The firing rules of PN-PDDP with Petri nets conflicts.

This is illustrated in Fig.5.As shown in Fig.5, the before sets of transitions t_1 and t_2 share certain libraries. If in certain , both t_1 and t_2 meet the firing conditions, they would occur concurrently instead of occurring selectively due to the competition between the two for shared resources. The introduction of the libraries of trace *Token* would change the firing rules of PN-PDDP with Petri nets conflicts. As shown in Fig.5, the before sets of transitions t_1 and t_2 share certain libraries. If in certain $M(s)$, both t_1 and t_2 meet the firing conditions, they would occur concurrently instead of occurring selectively due to the competition between the two for shared resources.

As can be seen in the Fig.6, the design starts with the rotor's structure design on the basis of rotor's positioning and transmitting performance characteristics parameters, and rotor system's components structure and turbopump's shell structure characteristics parameters, thus generating rotor's structure characteristics parameters.

Taken together, the fundamental goal of building the libraries of trace *Token* is to describe the nature of design data. Therefore, when we take design data as libraries, they lose the feature of being consumable. At the same time, the appearance of certain design data leads the relevant design activities to restart. Accordingly, the concepts of trace libraries lend itself to the changeability of design data, and are able to offer a convenient model for the analysis of design activities.

4. Building a PN-PDDP model for the multi-component coupling turbopump rotor system

Fig. 6 presents the PN-PDDP model for the multi-component coupling turbopump rotor system in line with the definition of PN-PDDP. The each symbol in Fig.6 is shown in Table 1.

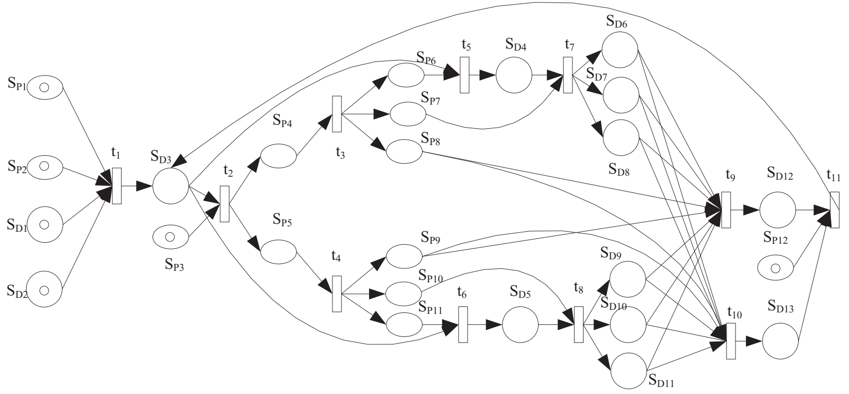


Fig. 6. PN-PDDP for the multi-component coupling turbopump rotor system.

Then bearing assembly design is done based on the load carrying properties characteristics of rotational support, producing the radial and axial load carrying properties characteristics. Next, performance decomposition is done on radial multi-component coupling and thrust multi-component coupling, generating the installation, load capacity, and dynamics performance. The rotor and stator design is then done based on all these performances.

What follows is the design of power amplifier controller and sensor according to the rotor and stator's structure characteristics and performance requirements. Finally, dynamic check is made. If it does not meet the requirements, the process would iterate through revising the rotor's structure characteristics.

Table 1. Explanations of each symbol in Fig.6.

Symbol	Explanations of the symbol	Symbol	Explanations of the symbol	Symbol	Explanations of the symbol
S_{P1}	rotor’s positioning performance characteristics	S_{D1}	rotor system components’ structure characteristics	t_1	rotor’s structure design
S_{P2}	rotor’s rotational performance characteristics	S_{D2}	turbopump shell’s structure characteristics	t_2	bearing and its components’ coupling design
S_{P3}	rotational support’s components performance characteristics	S_{D3}	rotor’s structure characteristics	t_3	radial support components’ design
S_{P4}	radial support components’ performance characteristics	S_{D4}	radial support components’ structure characteristics	t_4	axial load bearing components’ performance design
S_{P5}	axial vibration-proof components’ performance characteristics	S_{D5}	axial load bearing components’ structure characteristics	t_5	radial components and rotor’ s coupling structure design
S_{P6}	radial components’ installation performance characteristics	S_{D6}	sliding bearing’s structure characteristics	t_6	axial components and rotor’ s coupling structure design
S_{P7}	radial support components’ load carrying capacity performance characteristics	S_{D7}	floating-ring seal’s structure characteristics	t_7	radial components-rotor’s load carrying properties design
S_{P8}	radial components’ dynamics performance characteristics	S_{D8}	oil film damper’s structure characteristics	t_8	axial components-rotor’s load carrying properties design
S_{P9}	axial components’ dynamics performance characteristics	S_{D9}	thrust bearing’s structure characteristics	t_9	radial multi-component’s coupling dynamics design
S_{P10}	axial components’ load carrying capacity performance characteristics	S_{D10}	axial balance disc’s structure characteristics	t_{10}	axial multi-component’s coupling dynamics design
S_{P11}	axial components’ installation performance characteristics	S_{D11}	shaft-end seal’s structure characteristics	t_{11}	turbopump rotor system’s overall dynamics design
S_{P12}	components’ dynamics performance characteristics	S_{D12}	radial support components’ assembly structure characteristics	S_{D13}	axial vibration-proof components’ assembly structure characteristics

5. Conclusion

1) This paper has analyzed and developed the performance and structure characteristics models for the multi-component coupling rotor system, which are driven by its load bearing properties and dynamics performance requirements, with high-speed turbopump rotors as the typical example.

2) It has also built a PN-PDDP model based on the extended Petri nets in view of the fact that the performance-driven multi-component coupling rotor system design calls for multi-component collaborative design. In the model building process, performance characteristics libraries, structure characteristics libraries, trace Token, and firing rules are defined.

3) Lastly, it has developed the flow process model of the various coupled information flow in the design process of the high-speed turbopump multi-component coupling rotor system, which will provide the important design tools and implementation means for the design of the multi-component coupling turbopump rotor system in the liquid rocket engine.

Acknowledgements

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