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A Digital Expression Method to Support Concurrent Engineering by Providing Interface Information Management in a Practical Bus Chassis Modular Design Application and Case History

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Abstract:

Modular design of products can effectively reduce product development cycle with the idea of concurrent engineering, the efficient management of module interface information in the design process is the premise and foundation for module sharing. This study aims to develop a methodology for interface information management in bus chassis modular design. The characteristics of module interfaces in mechanical design are firstly investigated by the comparison with USB interfaces. A digital expression method is then proposed to describe the characteristics of interface geometry information using two matrices with mapping relationships. An encoding method is then developed for the interface information management in modular design. Finally, the implementation of the above method was illustrated with a case study of an electric bus chassis modular design. Novelty of the research is to provide a methodology to represent the characteristics of interface in mechanical design through digital expression.

Key words:

concurrent engineering; modular design; bus chassis; module interface; digital expression; matrix

0 Introduction

Concurrent engineering is a systematic approach to product design and its related processes (manufacturing process and support process) in parallel and integrated. This approach requires designers to take into account all factors that cover the life cycle of the product in the initial stage of the design, the product model that meets the requirements of the user is established through the cooperation and sharing of information from various departments^[1-4]. For modular products, concurrent design of multiple modules with the idea of concurrent engineering can effectively reduce the development cycle of products. In the design process, the module interface is the basis for the product module to realize the connection, establish a unified "language" to achieve interface information management is a useful way to improve the design efficiency.

Authors have already made positive contributions concerning the design and information management of the module interface. For example, **Definitions of interface has shown firstly and the importance of minimize interfaces during a product realization process is emphasized^[5]**; Development of an interface design method based on an axiomatic design, which evaluates and selects the interface design scheme with the use of a DFMA software tool^[6]; also, definition the performance parameters of the modular machine tool which interfaces and analyses the influence of these performance parameters on the overall performance of machine tools^[7]; A researcher divided interfaces into internal interfaces and external interfaces, discussed the relationship between modular product interfaces and product innovation design, and established the theoretical matrix of interfaces^[8]; Development of a coding and serialisation design method of the loader module interface, which improved the versatility and interchangeability of the module^[9]; Taking a hydraulic press as an example, and proposing a concept of flexible interface, researchers expanded the application of modular design concept into mechanical products^[10]. Another researcher took hard brittle material processing equipment as an example, based on the information of the integrated interface type, shape, parameter and function flow direction, producing an interface information model for module matching judgment and module combination^[11].

As indicated above, meaningful work has already been carried out on the module interfaces of machine tools, hydraulic presses and other products. The target of this research is to focus on the flexible design of the interface. A limitation under investigation is that the geometry of the designed interface is regular and orderly, and the interface information management method is inclined to summarise the simple and intuitive information. For the module interface with complex structural designs and complex geometric forms, such as the bus truss type chassis assembled with many non-standard structural components, the non-standard characteristics of module interface are prominent. Therefore, the above methods are insufficient for the distinction and management of the interface information of this type of module.

In this study, a digital expression method is proposed to characterise the geometric location information of the module interface. Firstly, a node network was built to locate the pre-connected structural components of the module interface, and then the feature point method is introduced to identify and describe the geometric characteristics of the connected section of the structural components. Finally, the corresponding digital expression model is constructed for different types of interfaces and used in the coding management of bus chassis module interfaces. Moreover, the use of the above method was illustrated with an example of an electric bus chassis module.

1 Analysis of the bus chassis module interface characteristics

1.1 Definition and classification of the module interfaces

The module interface is a boundary binding surface with a certain geometry, size and precision^[12]. Modular products are composed of modules that have independent functions and are connected by module interfaces. Therefore, the module interface has the following functions: achieve the connection positioning through the coordination of the geometric structure of the interface, and fulfil the material, motion, energy or information exchange between the modules^[13].

The classification and analysis of the module interface can effectively lead to a fundamental understanding of the mechanism and function of the interface. As shown in Table 1, according to different classification methods, the same interface can have different classification results^[14].

Table 1 Classification of interfaces^[14]

Classification basis	Interface types
Interface function	zero interface, passive interface, active interface and intelligent interface
Interface contact mode	direct interface and indirect interface
Interface mechanism	mechanical interface, electrical interface, mechanical and electrical interface, software interface, etc.
Interface Existence position	external interface, internal interface
Connection form	plug and socket interface, flange connection interface, welding connection interface, etc.

1.2 Analysis of the bus chassis module interface characteristics

The computer industry is one that typically applies a modular design methodology, in which the design of standard interfaces has greatly promoted the development of the industry^[15]. Taking the USB interface as an analogy^[16], the characteristics of the bus chassis module interface are described in detail in Table 2.

Table 2 Comparison of USB interface and bus chassis module interface

Type of interface	USB interface	Bus chassis module interface
Contact mode	Direct interface	Direct interface
Structure form	Plug and socket interface	Welding connection interface
Shape	Standard layout	Structural style changeable
Interface mechanism	Mechanical interface and electromechanical interface	Mechanical interface
Existence position	External interface	Internal interface

This analysis shows that there is an obvious difference between the chassis module interface and the USB interface. As far as the structure is concerned, the USB interface belongs to the movable Plug and socket interface, while the chassis module interface belongs to the fixed welding interface. As far as the interface shape, the USB interface adopts a unified standard layout, while the chassis

module interface is composed of several structural components with the same or different cross section shape, which have variability and non-standard features.

According to the layout direction of the consisting structural components, the interfaces of the bus chassis module can be divided into two types: plug type and socket type. The corresponding modules are plug module and socket module. As shown in Figure 1 and Figure 2[insert Figure 1 and Figure 2], the plug interface has an open feature, and the layout direction of the consisting structural components is consistent with the direction of the module pre-connected. The socket interface has a closed feature, and the layout direction of the consisting structural components is perpendicular to the direction of the module pre-connected.

2 Location and characterisation of consisting structural components of the module interface

In the process of modular design, the connectivity and combination between the chassis modules can be expressed as the matching relationship of the interface structural components, which is embodied by two aspects: the location matching of the pre-connected structural components and the matching of the geometry and size of the connected section of the pre-connected structural components. Therefore, the management of the information of the interface should include the positioning of the structural components and the characterisation of the connected section geometry of the structural components.

2.1 Location of pre-connected structural components

A node network method is proposed to locate the interface pre-connected structural components. The node network consists of parent and child node, the parent node is the central fixed point of the module interface, the child node representing the pre-connected structural components of the interface, and there is a one-to-one correspondence between the pre-connected structural component and the child node. On the basis of the parent and child nodes are created, the space rectangular coordinate system is set up with the parent node as the original point. In this coordinate

system of the interface, the positive direction of the x axis represents the pre-connection direction of the module interface, the positive direction of the y axis represents the direction from the parent node to the left or right side frame of the bus, and the positive direction of the z axis represents the direction from the bus chassis to the top frame. Finally, the module interface node network is formed by connecting the parent and the child nodes in a straight line. The position of the pre-connected structural component is determined by the relative direction and distance between the parent and the child nodes.

2.1.1 Establishment criterion for the parent node in the node network

Guidelines were developed to determine the location of the parent node.

- 1) Symmetrical central line criterion: when the module interface is symmetrical in the y direction or other directions, the parent node should be chosen as the central line of the interface symmetry.
- 2) Contact point criterion: the parent node should be selected as the interface position of the structural component, which means the node is located on a specific pre-connected structural component.
- 3) Fixed point criterion: the parent node should be selected on a fixed pre-connected structural component as far as possible, and when the module is redesigned, the position of the parent node does not change.

2.1.2 Establishment criterion for the child node in the node network

The shape and size characteristics of the connected section of the pre-connected structural component are analysed, and its child nodes are established according to the following criteria:

- 1) One to one correspondence criterion: each pre-connected structural component of the module interface corresponds to a child node, and the one-to-one correspondence between the structural component and the child node is satisfied during the creation process;
- 2) Geometric central point criterion: for the plug interface, when the connected section of the pre-connected structural component is geometrically symmetric, such as a rectangle, square, etc., the

child node should be created at the symmetrical centre position of the connected section of the structural component.

- 3) Minimum circle centre criterion: for the plug interface, when the geometry of the connected section of the pre-connected structural component is irregular. A circle as small as possible is then drawn to include the irregular section, and then the centre of this circle is the position of the child node.
- 4) Central criterion: for the socket interface, the connected section of the pre-connected structural component is mostly rectangular with vertical or oblique directions. The corresponding child node should be created at the centre of the rectangle.

2.1.3 Construction of the module interface node network

A bus chassis module was employed to demonstrate as an example, that the parent and child nodes are created according to the above criteria, after that the network and the relative coordinate system of the interface are built. Also, considering the characteristics of the interface stratified along the z direction, the child nodes are layered based on the z direction of the relative coordinate system, and the nodes of the same or very similar value in the z direction are placed on the same layer. The construction and stratification of the node network are shown in Figure 3 and Figure 4[insert Figure 3 and Figure 4].

2.2 Digital characterisation of connected sections of pre-connected structural components

The non-standardised feature of the connected section of structural components are very significant. Common geometry includes regular square, rectangle, round and other irregular shapes. The feature point method^[17] is introduced to describe the connected section. The feature points are created with the child nodes as basis points to describe the connected section. Thereafter, the digital characterisation of the connected section is realised by locating the feature points in the form of relative coordinates. The number of feature points of the connected section of structural components depends on the complexity of the section geometry. The more complex the shape is, the more feature

points are required to define it. The creation and identification of the feature points of a regular structural component are shown in Figure 5[insert Figure 5].

3 Construction of interface digital expression model

The digital expression model of the module interface is composed of two matrices with mapping relations, and the difference of interface types means there are differences in the digital expression model. The expression model of the plug interface is composed of an interface location matrix and characterisation matrix of the connected section, while the expression model of the socket interface is composed of an interface location matrix and an interface acceptable range matrix. The schematic diagram of the module interface digital expression is shown in Figure 6[insert Figure 6].

3.1 Digital expression model of plug interface

When the parent and child nodes are created according to the above criteria, the relative coordinate system and the node network of the interface are established with the parent node as the original point and the pre-connected direction of the module is in the x direction. The coordinates values in the direction of x, y and z are obtained from the relative distance of each child node to the plane YOZ, XOZ, and XOY. The location matrix M of the pre-connected structural component of the module interface is generated by the coordinate distance of each child node. The element $M_i = (M_{ix} \ M_{iy} \ M_{iz})$ in the matrix, where M_{ix} represents the distance from the structural component numbered i to the YOZ plane, and so on.

Based on the feature points to be selected, the relative direction and distance of all the feature points on a structural component to their corresponding child node are sorted out in a sequential manner. It is classified and collated in the form of a coordinate to realise the digitisation of the geometric characteristics information of the connected section of the structural component. Further, the coordinates of feature points of all the pre-connected structural components on the interface are summed and then the relative characterisation matrix Q of the interface connected section is established.

Each element in matrix Q is the relative coordinate of a feature point, which reflects the relative direction and distance between the feature point on the connected section and the corresponding child node of the structural component. For example, Q_{ef} is the relative coordinate of the number f feature points of the structural component numbered e , $Q_{ef} = (u \ v \ z)$, where u , v , z are the coordinates of the feature point relative to the x, y, and z directions of the child node. Each row of the matrix Q represents the coordinates of all feature points of a structural component, which reflects the geometry and dimension information of the connected section of the structural component.

The complexity of the connected section of the structural component is proportional to the number of feature points, so each row in the matrix Q may have different columns. For the convenience of calculation, in the process of establishing the relative characterisation matrix Q of the connected section, the number of feature points of the most complex connect section of the structural component determines the number of columns of the matrix. The other simple structural components add some additional feature points on the basis of not changing the original feature points. Thereafter, the number of feature points of each structure is equal, which means each row in the matrix Q has the same number of columns.

There is a mapping relationship between the relative characterisation matrix Q and the interface location matrix M . The mapping relation is expressed in such a way that the two matrices have the same number of rows, and the number of rows of the matrix indicates the number of the pre-connected structural components of the module interface. The row i of the matrix M represents the position of the pre-connected structural component numbered i , at the same time, the row i of the matrix Q reflects the geometry and dimension of the connected section of the pre-connected structural component numbered i . The digital expression model of plug interface as shown in Figure 7[insert Figure 7].

Amongst them, m is the number of the interface pre-connected structural components, and n is the number of feature points of the connected section of each structural component.

Through the formula (1) calculation, the characterisation matrix Q' of the connected section of the plug interface can be obtained.

$$Q' = M \times (1 \quad 1 \quad L \quad 1) + Q \quad (1)$$

3.2 Digital expression model of the socket interface

The socket interface is composed of structural components which are perpendicular to the direction of the module pre-connected. The layout direction of the structural components on the vertical YOZ plane includes three forms: parallel to the y direction, parallel to the z direction and have an angle with the coordinate axis. The location matrix of the socket interface, on the one hand, needs to locate the pre-connected structural components of the interface, on the other hand, it is necessary to describe the possible acceptable range of the component, so the location matrix can be expressed as the range matrix. On the basis of meeting the central criterion, the location of the pre-connected structural component which is parallel to the y direction is expressed as a fixed value of x and z coordinates, and the y coordinate is taken in a certain range. The range of the value represents the acceptable range of the structural component. Similarly, the acceptable structural component which is parallel to the z direction only takes the z coordinate in a certain range; the acceptable structural components which have an angle with the coordinate axis takes y and z coordinates both in a certain range, also the two coordinates value has a certain linear relationship.

According to the above analysis, the location matrix A of the socket interface is constructed, and each element in the matrix is a block matrix, which reflects the positioning and acceptable range of a certain structural component. Taking the pre-connected structural component numbered k as an

example, when the structural component is parallel to the y direction, $A_k = \begin{pmatrix} A_{kx} & A_{ky1} & A_{kz} \\ A_{kx} & M & A_{kz} \\ A_{kx} & A_{kyp} & A_{kz} \end{pmatrix}$, the

numerical fixation of x direction and z direction in the block matrix A_k , and the y direction can be an

arbitrary value within the range of A_{ky1} to A_{kyp} , which reflects the acceptable range of the component in the y direction. The structural components of other layout directions are similar.

The acceptable section of pre-connected structural components is digitised expressed as a range matrix. All the matrices corresponding to the pre-connected structural components are aggregated in order, and then the acceptable range matrix B of the interface is constructed. Each element in the matrix B is a block matrix, which reflects the acceptable range of a certain structure.

Taking the pre-connected structural component numbered k as an example, $B_k = \begin{pmatrix} B_{kx1} & B_{ky1} & B_{kz1} \\ M & M & M \\ B_{kxo} & B_{kyp} & B_{kzq} \end{pmatrix}$

, The first, second, and third columns in the block matrix B_k represent the range that the structural component can be acceptable in the direction of x, y, and z.

There is a mapping relationship between the acceptable range matrix B and the location matrix A . The mapping relation is expressed in such a way that the two matrix has the same number of rows, and the number of rows of the matrix indicates the number of the pre-connected components of the module interface. The row k in the matrix A represents the coordinate location of the pre-connected structural component numbered k . At the same time, the row k in the matrix B reflects the acceptable range of the pre-connected structural component numbered k . The digital expression model of socket interface as shown in Figure 8[insert Figure 8].

In the figure 8, m is the number of pre-connected structural components of the interface.

4 Coding of a bus chassis module interface

Module interface encoding is used to retrieve, query, and manage module interface information^[9]. The establishment of a unified, concise, exact and unambiguous module interface coding can classify and manage the module interface information effectively. It can also improve the modular design efficiency of the product.

The bus chassis module interface code is shown in figure 9[insert Figure 9].

In the figure 9:

① represents the interface code.

The first letter I means the module interface

② represents bus model code.

The second part represents bus length. For example, 10.5m means the bus is 10.5 meters in length.

The third part represents the primary motive driving power of the bus.

Regulations:

E(Electric) represents pure electric drive;

H(Hybrid electric)represents hybrid drive;

FC(Fuel cell)represents Fuel cell drive;

FF(fossil fuels)represents traditional fossil fuels drive.

The fourth part represents the ladder type of the bus. Regulations:

1 means first step;

2 means two steps.

③ represents the code of the module that the interface belongs to.

Regulations:

A represents the front frame module of the bus chassis;

B represents the front suspension frame module of the bus chassis;

C represents the middle frame module of the bus chassis;

D represents the rear suspension frame module of the bus chassis;

E represents the rear frame module of the bus chassis.

④ represents the location of the interface.

As shown in Figure 10[insert Figure 10], a module may have two interfaces, when the interface is close to the front end of the bus, the interface is defined as the front interface of the module, and which means the pre-connected direction of the interface is from the module to the front end of the bus; Similarly, when the interface close to the rear end of the bus, the interface is defined as is the rear interface of the module, and the pre-connected direction of the interface is from the module to the rear end of the bus. Take module B as an example, p-B represents the front interface of module B, and B-p represents the rear interface of module B.

⑤ represents the type of the interface.

Regulations:

0 represents socket interface;

1 represents plug interface.

⑥ represents the digital expression model of the interface.

The eighth part is delimiter “-”

The ninth and tenth parts combination becomes the digital expression model of the interface. When the module interface is a plug interface, the ninth part represents the location matrix of the plug interface, tenth part represents the characterisation matrix of the connected section of the interface. When the module interface is a socket interface, the ninth part represents the location matrix of the socket interface while the tenth part represents the acceptable range matrix of the interface.

An example of module interface coding is shown below as the interface coding of the front suspension frame module of 10.5m length and one step traditional fuel driven bus chassis:

I	10.5m	FF	1	B	B-p	0	-	A	B
								/	/
Interface	Bus length 10.5m	Traditional fossil fuel driven	One step	one step suspension frame module	The rear interface	Socket interface		Locating matrix of socket interface	Acceptable range matrix

5 Case study

The digital expression model and interface coding of the rear interface the front suspension frame module and the front interface of the middle module of an 8.5m pure electric drive bus chassis are taken as an example.

5.1 Digital expression model and coding of the front interface of the middle frame module

The layout direction of the pre-connected structural components shows that the front interface of the middle frame module of the bus chassis is a plug interface. Subsequently, the relative coordinate system, the parent and child nodes, are created according to the above criteria. The interface node network is constructed by the linear connection of the parent and the child nodes as shown in Figure 11 and Figure 12^[insert Figure 11 and Figure 12]. On this basis, the connected section of the interface pre-connected structural component is described by the feature points method. This results in the interface information as shown in Table 3.

Table 3 Information of the front interface of the middle frame module (mm)

Node numbering	Location of child nodes			Description of pre-connected structural components	Relative coordinates of feature points				
	x	y	z						
1	0	0	145	Square 40X40	Number	①	②	③	④
					Coordinate	(0,20,-20)	(0,20,20)	(0,-20,20)	(0,-20,-20)
2	0	-450	485	Rectangle 50X40	Number	①	②	③	④
					Coordinate	(0,25,-20)	(0,25,20)	(0,-25,20)	(0,-25,-20)
3	0	-800	485	Rectangle 50X40	Number	①	②	③	④
					Coordinate	(0,25,-20)	(0,25,20)	(0,-25,20)	(0,-25,-20)
4	0	-455	145	Square 50X50	Number	①	②	③	④
					Coordinate	(0,25,-25)	(0,25,25)	(0,-25,25)	(0,-25,-25)

					ate				
5	0	-455	25	Square 50X50	Number	①	②	③	④
					Coordin ate	(0,25,-25)	(0,25,25)	(0,-25,25)	(0,-25,-25)
6	0	455	25	Square 50X50	Number	①	②	③	④
					Coordin ate	(0,25,-25)	(0,25,25)	(0,-25,25)	(0,-25,-25)
7	0	455	145	Square 50X50	Number	①	②	③	④
					Coordin ate	(0,25,-25)	(0,25,25)	(0,-25,25)	(0,-25,-25)
8	0	800	485	Rectangle 50X40	Number	①	②	③	④
					Coordin ate	(0,25,-20)	(0,25,20)	(0,-25,20)	(0,-25,-20)
9	0	450	485	Rectangle 50X40	Number	①	②	③	④
					Coordin ate	(0,25,-20)	(0,25,20)	(0,-25,20)	(0,-25,-20)

According to the information of the module interface in Table 3, the location matrix M and the relative characterisation matrix Q of connected section of the interface are constructed. By using the formula $Q' = M \times (1 \ 1 \ 1 \ 1) + Q$, the characterisation matrix Q' of connected section of the interface is solved. Hence the digital expression model of the interface is obtained.

After the digital model is constructed, the coding of the front interface of the middle frame module is shown below:

5.2 Digital expression model and coding of the rear interface of the front suspension frame module

The layout direction of the pre-connected structural component shows that the rear interface of the front suspension frame module of the bus chassis is a socket interface, and the relative coordinate system, the parent and the child nodes, are created according to the above criteria. The interface node network is constructed by the linear connection of the parent and the child nodes as shown in Figure 13[insert Figure 13]. On this basis, the acceptable range of each pre-connected structural component is analysed. This results in the information about the interface as shown in Table 4.

Table 4 Information of the rear interface of the front suspension frame module

Node numbering	Layout direction of structural component	Location of structural components			Relative acceptable range of structural components				
		x direction	y direction	z direction					
1	Parallel to the y direction	0	-800	500	Direction	y		z	
					Range value	400	400	-25	25
2	Parallel to the y direction	0	800	500	direction	y		z	
					Range value	400	400	-25	25
3	Parallel to the y direction	0	0	165	Direction	y		z	
					Range value	1200	1200	-25	25
4	Parallel to the y direction	0	0	25	Direction	y		z	
					Range value	1200	1200	-25	25

According to the information of the module interface in Table 4, the digital expression model of the interface is constructed, including the location matrix A of socket interface and the acceptable range matrix B . In the matrix A and matrix B , the acceptable range of the structural component is obtained by adding the location coordinate and the relative acceptable range.

After the digital model is constructed, the coding of the rear interface of the front suspension frame module as shown below:

6 Conclusion

In this paper, the relevant information about the interface of the bus chassis module is studied, and a digital expression and coding method is put forward to manage the interface information. It further explores the connection and matching of interfaces for module integration and interchangeability, so as to enhance the integrity and validity of the expression method.

(1) Considering the challenges of variability of the bus chassis module interface and non-standardisation of the pre-connected structural components, a digital expression method of interface is proposed to solve this. By developing and applying two matrices with a mapping relationship, the digital display of module interface information is realised.

(2) Once the basis of the digital expression of interface is established, the coding method for the bus chassis module interface is developed to realise information management. The feasibility of

the method is verified by taking a chassis module of an electric bus as an example. Also, the coding method can be used for the classification and management of interface information of other product modules.

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